THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

XR Enabled Operator Training

Applying Extended Reality technology in manufacturing training and education for shop floor operators

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“*Tell me and I will forget, show me and I may remember,*
involve me and I will understand.”

- Confucius

ABSTRACT

The manufacturing industry is undergoing rapid transformation due to geopolitical shifts, climate goals, and demographic changes, driving a growing demand for skilled labour. In Sweden alone, it is estimated that 300,000 manufacturing workers will need training in the coming three years. Traditional training approaches struggle to effectively integrate practical and theoretical learning, highlighting the need for innovative, scalable, and immersive training solutions to meet future workforce demands.

Advancements in Extended Reality (XR) technology have paved the way for an alternative to traditional training, offering the potential of safe, efficient and scalable training with a high degree of realism and practical learning. Despite recent technological advances and reduced hardware costs, few large-scale industrial implementations of XR trainings have been observed, and 75% of all XR training projects fail to move beyond the prototype stage.

This thesis aims to lower the barrier to implementing XR trainings in manufacturing industry by addressing two main identified challenges. (1). Lacking design guidelines for how XR trainings in manufacturing should be developed and used from a knowledge perspective. (2) Resource intense development process of XR training content in manufacturing. Two case studies and one systematic literature review was deployed as part of the research to identify and theorize over the stated challenges.

The literature of XR training showed that the design of the XR training environment is heavily dependent on the applied learning style, and the manufacturing use case. A mapping of the applied learning styles and manufacturing use case are provided, giving a first indication of how design guidelines of XR training in manufacturing could be drawn from a knowledge perspective.

Addressing the second identified challenge, a method towards automated XR training development utilizing Product Lifecycle Management (PLM) data structure is presented. The highlighted method shows high potential for drastically reducing the time needed for XR training development.

Finally, this thesis contributes by introducing an initial framework of design and development guidelines based on the manufacturing use case and learning objective. The presented framework that is expected to address both of the stated challenges, lowering the barrier of implementation of XR training in manufacturing industry.

Keywords: Manufacturing, Extended Reality, Virtual Reality, Mixed Reality, Augmented Reality, Training, Education, Operator, Worker

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Henrik Söderlund
Gothenburg, August 2025

LIST OF APPENDED PAPERS

The three appended papers in this thesis are listed here, along with the contributions and distribution of work among the authors.

Paper A **The creation of a multi-user virtual training environment for operator training in VR**

Henrik Söderlund, Sebastian Zamola, Jim Boström, Dan Li, Puranjay Mugur, Huizhong Cao, Björn Johansson (2024)

Presented at the *SPS 2024*, Trollhättan, 23-26 April 2024.
Published in *Advances in Transdisciplinary Engineering*, vol. 52, pp. 173-184.

Distribution of work: First author. Henrik designed and developed the case study with support from co-authors and lead the academic writing process and presentation at the conference.

Paper B **Learning in virtual reality: A systematic literature review of VR trainings in manufacturing**

Henrik Söderlund, Greta Braun, Fredrik Trella, Huizhong Cao, Mélanie Despeisse, Björn Johansson (2025)

Submitted to *Journal of Computers in Education (March 2025)*

Distribution of work: First author. Henrik framed and designed the literature review together with supervisors and executed the review and analysis of the literature. Henrik also led the academic writing part with support from co-authors.

Paper C **Training Operators in VR: a scalable solution for the creation of VR training scenes**

Geoffery Melzani, Tony Quach, Henrik Söderlund, Dan Li, Puranjay Mugur, Huizhong Cao, Björn Johansson (2024)

Presented at the *IN4PL 2024*, Porto, 21-22 November 2024.
Published in *Communications in Computer and Information Science*, vol. 2373, no. 2 pp. 332-342.

Distribution of work: Third author. Henrik formulated the hypotheses, designed the case study and supervised its execution performed by his student. Henrik also supervised the academic writing process and later presented the publication at the conference.

LIST OF ADDITIONAL PAPERS

This list of additional papers includes related work, important for the content of this thesis but outside the direct scope for answering the research questions.

Paper 1 **Interaction design for multi-user virtual reality systems: An automotive case study**

Liang Gong, Henrik Söderlund, Leonard Bogojevic, Xiaoxia Chen, Anton Berce, Åsa Fasth Berglund, Björn Johansson (2020)

Presented at the *CIRP CMS 2020*, Chicago, 1-3 July.
Published in *Procedia CIRP*, vol. 93, pp. 1259-1264.

Paper 2 **Simulation of Ergonomic Assembly Through a Digital Human Modeling Software**

Henrik Söderlund, Leonard Bogojevic, Liang Gong, Björn Johansson, Roland Örtengren (2023)

Presented at the *8th DHM Symposium*, Antwerpen, 4-6 September.
Published in *Lecture Notes in Network and Systems*, vol. 744, pp. 220-228.

Paper 3 **VR interaction for efficient virtual manufacturing: mini map for multi-user VR navigation platform**

Huizhong Cao, Henrik Söderlund, Mélanie Despeisse, Francisco Garcia Rivera, Björn Johansson (2024)

Presented at the *SPS 2024*, Trollhättan, 23-26 April 2024.
Published in *Advances in Transdisciplinary Engineering*, vol. 52, pp. 335-345.

Paper 4 **How Can XR Enhance Collaboration with CAD/CAE Tools in Remote Design Reviews?**

Francisco Garcia Rivera, Asreen Rostami, Sandra Mattsson, Henrik Söderlund (2024)

Presented at the *SPS 2024*, Trollhättan, 23-26 April 2024.
Published in *Advances in Transdisciplinary Engineering*, vol. 52, pp. 383-394.

Paper 5 **Challenges and opportunities to advance manufacturing research for sustainable battery life cycles**

Björn Johansson, Mélanie Despeisse, Jon Bokrantz, Greta Braun, Huizhong Cao, Arpita Chari, Qi Fang, Clarissa Alejandra Gonzáles Chávez, Anders Skoogh, Henrik Söderlund, Hao Wang, Kristina Wärmefjord, Lars Nyborg, Jinhua Sun, Roland Örtengren, Kelsea Schumacher, Laura, Espinal, K.C. Morris, Jason Nunley Jr, Yusuke Kishita, Yasushi Umeda, Frederica Acerbi, Marta Pinzone, Hanna Persson, Sophie Charpentier, Kristina Edstrom, Daniel Brandell, Maheshwaran Gopalakrishna, Hossein Rahnama, Lena Abrahamsson, Anna Öhrwall-Rönnbäck, Johan Stahre (2024)

Published in *Frontiers in Manufacturing Technology*, vol. 4

Paper 6 **Exploring the current applications and potential of extended reality for environmental sustainability in manufacturing**

Huizhong Cao, Henrik Söderlund, Mélanie Despeisse, Björn Johansson (2025)

Presented at the *EcoDesign Conference*, Nara, 29-30 November 2023. Published in *EcoDesign for Circular Value Creation*, vol. 1, pp. 515-531.

Paper 7 **Evaluating Multi-User VR for Ergonomic Assessments Using a DHM Software**

Soureesh De, Henrik Söderlund, Jose Maria van der Ploeg Feriche, Björn Johansson (2025)

Presented at the *HCI conference 2025*, Gothenburg, 25-27 June 2025. Published in L*ecture Notes in Computer Science,* vol. 15770, pp. 289-300.

Paper 8 **The Ethics of Extended Realities: Insights from a Systematic Literature Review**

Karthik Meenaakshisundaram, Henrik Söderlund, Asreen Rostami (2025)

Presented at the *HCI conference 2025*, Gothenburg, 25-27 June 2025. Published in L*ecture Notes in Computer Science,* vol. 15770, pp. 243-261.

Paper 9 **Human-centered design of VR interface features to support mental workload and spatial cognition during collaboration tasks in manufacturing**

Huizhong Cao, Francisco Garcia Rivera, Henrik Söderlund, Cecilia Berlin, Johan Stahre, Björn Johansson (2025)

Published in Cognition, Technology & Work*,* June 2025.

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LIST OF ABBREVIATIONS

AR	Augmented reality
BOE	Bill of equipment
BOM	Bill of materials
BOP	Bill of process
HMD	Head-mounted display
LLM	Large language model
MR	Mixed reality
PLM	Product lifecycle management
RQ	Research question
TRL	Technology readiness level
VR	Virtual reality
XR	Extended reality

1
INTRODUCTION

This chapter introduces the background of the thesis in regard to challenges and problems addressed. Furthermore, the vision, aim and research questions drawn up to guide the research are described as well as the limitation and scope that frames the work. Lastly the outline of the thesis is presented.

1.1 BACKGROUND

The manufacturing industry is today subjected to a global and economic landscape that creates new demands in its capabilities. Changing geo-politics is dictating where we can produce and what to produce, disrupting the manufacturing supply chains and ecosystems (World Manufacturing Foundation, 2024). Moreover, the threatening climate crisis and the need to reach net zero emissions goals also influence our decisions on what to produce and how to produce it in a more sustainable way (Stern & Valero, 2021). All these external factors give way for a faster transformation of the manufacturing industry, creating a surge of changing manufacturing processes, workspaces and jobs (Smil, 2022). Thus, the need for new skills and workers equipped to tackle the transformation is growing (World Manufacturing Foundation, 2024). Employees once trained in one job will need to upskill to be able to adapt to the job transformation or reskill to be able to transition into another job or industry now in demand.

In Europe, it is estimated that approximately 800 000 workers need to be trained in the battery sector alone to enable the electric transition in the EU (European Commission, 2022). A similar need for training is seen in other emerging manufacturing sectors where new technology and changing business needs sees a demand for new jobs and talent. At the same time as this transformation unfolds, many countries are also experiencing an ongoing demographic shift, leading to a decrease in the working population. Meaning that the same work and production will have to be carried out by less people in the future (Braun et al. 2023). The combination of these leads to an increased need for vocational upskilling and reskilling to keep up with the transformation and growing need for more skilled labour (Rikala et al., 2024). In Sweden, the combination of these factors, is resulting in the need of training an estimated 300 000 workers in the manufacturing industry by 2028 (Industrirådet, 2024).

Upskilling or reskilling efforts for manufacturing operators are often tied to vocation education and training programmes off-site, or workplace training through on-the-job training (Souza et al., 2021). Both with the goal of teaching personnel new skills to carry out new manufacturing tasks with quality and efficiency (Doolani, 2020). The trainings could include both cognitive elements such as understanding a new task, process or complex system, and practical elements such as equipment handling, task execution and craftmanship (Souza et al., 2021). In this context, traditional education methods like online courses or classroom training often lack real-life experiences to adequately teach practical skills and to successfully integrate theory in practice (Illeris, 2007) (Kilbrink et al., 2015). While at the same time, on-the-job training exposes inexperienced workers to a live production system introducing safety concerns or production quality and efficiency implications (Hermawati et al., 2015). Both methods of training entail substantial costs in terms of the trainer availability, training material and training equipment.

Advancements in Extended Reality (XR) technology have paved the way for an alternative to traditional training, providing a simulated, near-to-real, virtual representation of a workstation or training scenario enabling practical hands-on training from a safe distance. First explored as a training tool by NASA in the 1990s, Virtual Reality (VR) was used to train their astronauts on complex tasks, difficult to simulate or replicate on earth (Garcia et al., 2020). This sparked a wave of research in the area and realization was made of the technology's potential in the training domain. Benefits such as safer training environments that minimize the risks of personal harm, quality issues or negative effects on lead times and production efficiency have been established (Hermawati et al., 2015). At the same time, the immersive nature of XR and virtual training has the ability to boost students learning process by increased engagement and contextualization (Dalgarno & Lee, 2009). Early adaptation of the technology for training purposes was low due to substantial cost and technical complexity of the systems. In recent years however, the landscape of XR has since drastically changed with a surge of consumer platforms and headsets reaching the market at an affordable price (Forbes, 2019).

Despite this, adaptation of the technology within manufacturing is still low, and to date, few actual full-scale implementations have been seen as 75% of all XR training projects fail to reach higher than technology readiness level (TRL) 4 (De Giorgio, 2023). Furthermore, almost 60% of european manufacturing companies responded in a survey made by Jalo et al. (2022) that they have never even piloted or tried XR technology within their organisation. High investment costs and economic uncertainties hinders large scale implementation, and it has been proven difficult to provide a solid business cases for XR technology in manufacturing (Berg & Vance, 2017). Reasons for this being the resource intensive development process of creating XR training content (Ipsita, 2025), while difficulties tied to measuring success, value and learning outcomes of the XR trainings remains (De Giorgio, 2023).

Research also shows that few XR training applications are designed with specific learning theories in mind and little efforts are given to the pedagogical adaptation of XR as part of the training curriculum. Which is thought to further hinder the rapid adoption of the technology in the training and teaching domain as uncertainties of its efficiency and value remain (Radianti et al., 2020). Combined, this results in organisations and financial decision makers being hesitant to invest in XR training programmes (Khandelwal et al., 2021).

In order to scale up the use and implementations in industry clear frameworks and use cases with a pedagogical basis need to be defined to lower the uncertainties in the technology as a training medium. Furthermore, there is a need for alternative, less resource intense, content creation methods with measurable value to build solid business cases that would advocate for the needed investment.

1.2 VISION, AIM AND RESEARCH QUESTIONS

The vision of the author is that of a manufacturing workforce with the right skills and competence to meet the demand of the industry, eliminating the current skill gap in manufacturing. The workforce should be well-equipped and supported by technology to quickly upskill themselves to be able to take on a large variety of tasks with quality, ensuring quick response to changing demand and industry transformations.

To meet this vision, this thesis proposes workforce training using XR technology to mitigate the current skill-gap in manufacturing. XR technology has the possibility to provide unique and immersive learning experiences in a safe and cost-efficient manner, yet its use in industry is still low and most XR training projects never reach beyond TRL 4. There is an incomprehensive understanding of how to create meaningful, valuable and scalable XR training experiences in manufacturing.

The aim of this thesis is thus to raise the awareness of XR as a training medium and how it can effectively be applied in manufacturing. By looking into the best practices of XR trainings tied to existing knowledge frameworks and pedagogics, an initial understanding of how to create meaningful and valuable XR training experiences is created. This includes, not only, *how* the XR trainings itself should be designed from a pedagogical perspective, but also *when* it should be used to generate knowledge in manufacturing – and more importantly when it should not be used. Providing reasoning for the following research question:

RQ1: How can XR trainings be designed and used to create knowledge and skills for shop floor workers?

By answering this question, trust in XR as a learning medium by manufacturing companies will be improved as well as pitfalls of non-valuable or unsuccessful XR training cases can be avoided. Less attention and investments are thus needed by the industry in the start-up phase of their XR training programs in order to develop trust in the technology and define their use-cases and best practices. Unlocking the benefits of XR as well as lowering the threshold of implementation and potential resistance in industry. Furthermore, the identified XR training experiences need to be developed in a financially viable and scalable way in order to see larger industrial application. This is addressed by the following research question:

RQ2: How can scalability be introduced in the development process of XR trainings for shop floor workers?

By understanding how the development of content for XR trainings could be made more efficiently and in a more automated and scalable way the main concern and threshold of XR training implementation, being the investment for development and integration, is addressed. By generating knowledge in this area, more cost efficient XR training creation processes can be developed, lowering the threshold for industry acceptance and large-scale implementation.

1.3 SCOPE AND DELIMITATIONS

The research focuses on the design, development, and evaluation of XR applications for upskilling and training of manufacturing shop floor workers and blue-collar workers. This scope includes all technical related upskilling and reskilling needs, and knowledge generations that are of relevance to a blue-collar worker in today's manufacturing industry. This includes onboarding and orientation, health and safety, human-machine interaction, manufacturing concepts and theory, explicit work instructions, task-specific knowledge, and craftsmanship. This delimits the work in this thesis from the user groups of white-collar workers such as managers, engineers, IT personnel, or other supportive or organisational staff. As well as any training that is typically not directly associated with the manufacturing system, such as workplace harassment training or other HR related trainings.

Furthermore, this work focuses on training applications that are used for adult education and training either as part of vocational education through an education provider or platform, or as part of employee training directly provided by the employer itself. This excludes applications used in formal education, such as elementary or secondary education as well as university courses with manufacturing connections.

Lastly, the delimitation of this thesis has been drawn to only explore wearable XR technologies and applications, either using head-mounted display (HMD), mobile devices or other wearable technologies with XR capabilities. This excludes stationary XR technologies such as VR Cave systems or AR light projections etc.

1.4 OUTLINE OF THE THESIS

This thesis is structured into six different chapters. An overview of the thesis structure as well as description and key deliverables can be seen in Table 1.

Table 1. Overview of the chapters in this thesis

Chapters	**Description**	**Key deliverables**
1. Introduction *What is this thesis about?*	The chapter introduces the topic, background, aim and research questions of this thesis.	Background: *Low adaptation of XR trainings in manufacturing but a growing need* RQ1: How *to design XR trainings for knowledge creation* RQ2. *Scalability in the development process of XR trainings* Scope: *Wearable XR for manufacturing training of shop floor workers*
2. Frame of Reference *What is the theoretical context of this thesis?*	The chapter introduces key concepts and theories used to support the research. Providing contextualization and theory in the intersection between manufacturing, XR and learning theories.	Manufacturing: *Context and future outlook of the shop floor workers in manufacturing* Learning theories: *Learning theories and knowledge creation in a manufacturing context* XR and virtual training: *History and state-of-the-art of XR in a manufacturing training context*
3. Research Approach *How was the research conducted?*	The chapter explains the underlying worldviews and academic perspectives that have framed the research as well as the methods used in answering the research questions.	Research philosophy: Pragmatic constructivism Research process: Exploration, Theory Building, Theory Validation, Theory Refinement Research method: Multiple case-study

4. Summary of the Appended Papers *What are the contributions of each appended paper?*	The chapter provides an overview of the appended papers focusing on the main results and contributions relevant for this thesis in answering the stated research questions.	Paper A: Summary of method, main results and discussion of Paper A Paper B: Summary of method, main results and discussion of Paper B Paper C: Summary of method, main results and discussion of Paper C Contributions: Highlighting each paper's contribution towards the research questions of this thesis
5. Discussion *What are the findings and contributions of the thesis? What are the limitations and future works in this thesis?*	The chapter combines findings from the appended paper, and additional work, to answer the two research questions and forming the contribution of this thesis. Furthermore, this chapter also discusses the methods used and future research directions.	RQ1: Findings and discussion regarding RQ1 RQ2: Findings and discussion regarding RQ2 Contributions: Highlighting and discussing the scientific and practical contribution of this thesis Limitations: Discussion on the scientific quality and limitation of the thesis Future work: Proposed future work and studies as part of the authors continued PhD studied
6. Conclusion *What are the conclusions of the thesis?*	The chapter offers a summary of the thesis, focusing on providing an overview of the problem formulation, key contributions and answers to the research questions.	Summary of the key takeaways and contributions of the thesis

2

FRAME OF REFERENCE

This chapter introduces the theory that composes the frame of reference for the thesis. The presented theory sets the foundation and creates an understanding of the underlying concepts that this thesis is built upon. The chapter will introduce the concept of knowledge transfer and its application in manufacturing as well as learning theories referenced in this thesis. Followed by an introduction to the topic of XR technology and its application and design in industry. Lastly this section will introduce the topic of XR training development and its relationship with the virtual production system.

The topic of this thesis lies in the intersection of three main theoretical fields defining its context, see Figure 1. The field of manufacturing defines the scope and application area of the research. The unique problem statement and nature of manufacturing creates case specific requirements on the research to fit its application area and need. XR, in terms of the deployed technology to solve skill shortage in manufacturing, remains central. The capability of the technology defines potential solutions and best practices. Lastly, the field of learning theories is essential in order to understand how pedagogics can be applied to create meaningful XR trainings and experiences for knowledge retention and skill development within manufacturing. Below subsections incorporate theories and state-of-the-art from all three fields to providing a solid theoretical background and context for the reader to be able to grasp the content of the thesis and its findings.

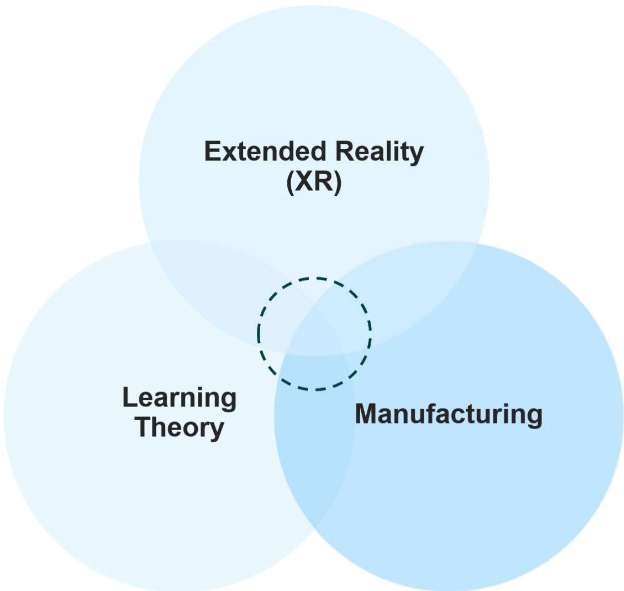

Figure 1. Intersection of areas defining the theoretical context of this thesis

2.1 OPERATORS IN THE MANUFACTURING SYSTEM

Caggiano (2019) defines the manufacturing system as a process that combines humans, machines and equipment to refine raw material coming from an upstream supplier into finished goods to a downstream customer. Similar definitions like the one used by Zarte et al. (2019) describes the manufacturing system as an Input-Process-Output (IPO) model, combining several different inputs to processes material and waste outputs. In this system, labour, together with raw material, is seen as the most important input. Common for most definitions are that humans and the workforce is depicted as a core part of the manufacturing system, either by directly adding value to the product through e.g. assembly and fabrication, or indirectly by operating, controlling, or maintaining an automated refinement process (Caggiano, 2019).

The evolving role of the operator in the manufacturing system

Historically the role and perception of the human workers in the manufacturing system has evolved in parallel with the major industrial transformations and shifts. During the first industrial revolution, human workers were often viewed as expendable with humans primarily fulfilling the role of physical power in mechanized production (Thompson, 1964). During the second industrial revolution, Fredrick Taylor (1911) introduced the principles of scientific management, which sought to maximize efficiency by deconstructing work tasks into simple, well-defined and repetitive elements. This approach often rendered the human operator interchangeable (Womack et al., 1990) and reduced to a mechanical component within the system (Dooley, 2011), as iconically illustrated in Charlie Chaplin's Modern Times.

With the third industrial revolution, computer-based control systems and automation were introduced in the manufacturing process. During which an interest in minimizing human labour was seen with early conceptualization of fully automated manufacturing systems (Walker, 1957). Initiatives such as IBM's and General Motors' experiments with fully autonomous production in the 1980s aimed to minimize labour costs and human involvement through extensive use of robotics in so called "lights-out" factories (Dassbach, 1986). However, such initiatives faced huge technological and organisational challenges.

At about the same time the global adaptation of lean manufacturing meant a shift towards re-focusing on human operator as an essential contributor towards continuous improvements and quality was seen (Womack et al., 1990). The lean philosophy emphasizes the value of knowledge and expertise in the human worker, eliminating the view of the human worker as interchangeable (Liker, 2004).

In the fourth industrial revolution renewed efforts towards process automation and maximized productivity powered by connectivity and cyber-physical systems are taken (Maddikunta, 2021), while in many cases incorporating the mind set of lean. This also entails reduced physical human intervention in the manufacturing process by instead encouraging the human participation to quality, decision-support and supervisory tasks (Maddikunta, 2021). Physical and cognitive augmentation of the operators still left to do physical tasks in the manufacturing system is encouraged to maximize the efficiency and capabilities of the human worker (Moencks et al. 2022).

However, the technology-centric vision of the fourth industrial revolution is accused for overshadows the role of the operator in the manufacturing system and challenges such as changing job roles, changing job complexity and upskilling needs are not considered (European Commission, 2021). This in combination with recent disruptions in the global manufacturing industry and supply chain, such as pandemics and changing geo-politics, triggered the fifth industrial transformation which seeks to establish human-centric values together with resilience and sustainability in manufacturing (European Commission, 2021).

Although it's difficult to anticipate exactly how the role of the human operator will change in the future, Wilhelm et al. (2024) underscores the continued importance of the human operator. In his review of future trends in the operator role he anticipates an increase of high skilled tasks such as error monitoring and intervention (Wilhelm et al., 2024). Similar predictions are also made by Autor (2015), who sees a trend of "low-skill" jobs evolving into "middle-skill" jobs, as technology and automation enables workers to take on a broader mixture of tasks as well as more decision-making functions. Consequently, there is a growing demand for operators with a deeper understanding of the operational processes and machinery as the complexity of the job role increases. Which emphasize the need for upskilling of today's manufacturing operators as well as a human-centered approach (Wilhelm et al., 2024) (European Commission, 2021).

2.2 KNOWLEDGE AND SKILLS IN MANUFACTURING

In the late 1980s Rosenbrock (1989) suggested that human-centered manufacturing need to consider the skill of the worker and that the ability to develop skills within the organisation is essential for the success of the manufacturing system. Lately, this statement has gotten increased attention as the skill shortage in manufacturing is growing and as manufacturing becomes increasingly complex. The ability to continually build new knowledge and skills in manufacturing is seen essential for maintaining competitiveness and have become a critical component of the modern manufacturing systems in accordance with Industry 5.0 (European Commission, 2021).

Skills could be defined as the ability to apply knowledge to solve a specific problem or task (European Parliament, 2008). Suggesting that skills development is the results of a knowledge creating process with the intent of application to a real-world task. Furthermore, modern knowledge management literature often depicts knowledge as dichotomous, categorizing it on a one-dimension axis, either as *Procedural / Declarative*, *Personal / Organisational* or *Tacit / Explicit* (Gamble, 2020). The concept of *Tacit* or *Explicit* knowledge was introduced in the 1960s by Michael Polanyi (Polanyi, 1966) and have since been widely used in knowledge management at manufacturing companies as large amount of both tacit and explicit exist (Ang et al., 2022). This is thus the definition that will be referenced in this thesis.

Explicit Knowledge refers to formulated knowledge that can be structured in a communicative way. Often this knowledge includes structural information and can be printed and shared in manuals, instruction or lectures (Polanyi, 1966). In the context of manufacturing, explicit knowledge consists of e.g. written assembly instructions, safety procedures and policies or tutorials. For instance, the iconic IKEA assembly instructions sheets proving explicit step-by-step instructions on an assembly task.

Tacit Knowledge on the other hand is knowledge deeply rooted in action or experience and often referred to as "know-how". This knowledge is often difficult to articulate or formulate as it is often acquired over time and tied to a particular physical skill (Polanyi, 1966). In the context of manufacturing, tacit knowledge could for instance be knowing how to make a perfect weld. It would be near impossible learn how to weld solely by reading an instruction. It is a knowledge or skill that needs to be practiced over a period of time and preferably with the help of an instructor.

Through various social, cognitive or reflective processes tacit and explicit knowledge within a company can be created, shared or amplified (Alavi & Leidner, 2001). To better understand how these knowledge creating processes might look like, Japanese organisational theorists Ikujiro Nonaka and Hirotaka Takeuchi (1995) developed the SECI (*Socialization*, *Externalization*, *Combination*, and *Internalization*) model. The model proposes four different knowledge creation modes highlighting the interplay between *Tacit* and *Explicit* knowledge within an organisation and could help us to identify various activities that facilitates knowledge creation also within a manufacturing system. The four different modes could, if the right condition in the organisation is met, result in a continuous cycle of knowledge generation (Nonaka & Takeuchi, 2001). See Figure 2.

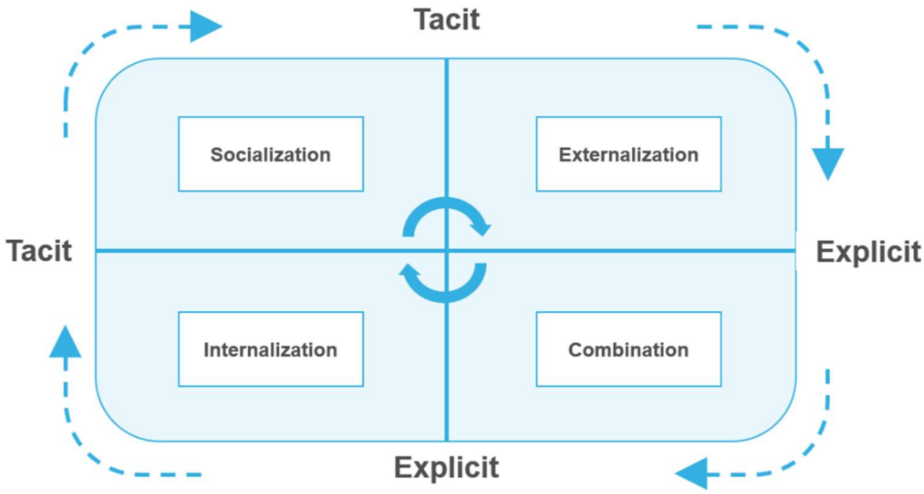

Figure 2. The SECI model, adapted from Nonaka (2001)

Socialization (Tacit-to-Tacit) is the mode of sharing mental models and tacit knowledge through social interaction. In the context of manufacturing this can be exemplified through apprenticeship or learning on the job from observing and socializing with colleagues.

Externalization (Tacit-to-Explicit) is the mode of articulating tacit knowledge into explicit concepts, often through dialogue, reflection and note taking. In the context of manufacturing this can be exemplified through documentation and development of worksheets or work instructions based on tacit knowledge and observations of a manufacturing process.

Combination (Explicit-to-Explicit) is the mode of systematically combining different pieces of explicit knowledge to create new or more complex sets of knowledge. In the context of manufacturing this can be exemplified through studying written information and manuals to develop new improved and documented worksheets, instructions or processes.

Internalization (Explicit-to-Tacit) is the mode of turning explicit knowledge into tacit knowledge through learning by doing and experiential processes. In the context of manufacturing this could be exemplified by applying explicit written instructions to solve an assemby or manufacturing task, creating new tacit knowledge and "know-how".

As demonstrated by Figure 2, each mode is highly interdependent, and both relies on, and contributes to, the neighbouring modes in the cycle (Alavi & Leidner, 2001). For instance, the mode of socialization can result in the creation of new knowledge from insights gained when collaborating and interacting with a task over time. This new knowledge could be formulated and structured in the externalization mode into explicit instructions used for spreading the knowledge in the internalization mode. Thus, contributing to the continuous cycle of knowledge creation.

2.3 LEARNING THEORY

To facilitate the creation of tacit or explicit knowledge, a manufacturing operator would need to engage in an activity of learning. Learning can take on many different forms based on student preferences, application area, learning objective and learning medium (Illeris, 2007). In the case of vocational education with adult and industrial learners, Lewis & Wiliams (1994) suggests experiential learning as an effective means of developing new skills and knowledge. Experiential learning requires the learner to actively participate in an exercise or experience while cognitively processing what is unfolding to generate knowledge (Lewis & Wiliams, 1994). XR technology, with its possibility to offer highly immersive experiences with multi-sensory feedback, is thus particularly well suited to support experiential learning (Majgaard & Weitze, 2020).

In 1984 David Kolb published his model of experiential learning, focusing on learning through experiences (Kolb, 1984). He presented a four-stage model, often referred to the Kolb's learning cycle, that describes how to transform experiences to concepts and knowledge. Kolb (2006) also introduced four learning styles, based on the dimensions of *Doing* vs *Seeing* and *Thinking* vs *Feeling*, that could be applied though out the experimental learning cycle, see Figure 3.

Diverging (See & Feel) learning style promotes observation and personal reflection. Here, subjective interpretations, imagination and emotions dictates over logic and facts. Exercises such as brainstorming, group discussions and personal reflection are often applied.

Assimilating (See & Think) learning style promotes observation and theory. Here, being able to understand theories, ideas and abstract concepts are favoured over emotions and personal reflection. Exercises such as seminars, lectures and analytical models are often applied.

Converging (Do & Think) learning style promotes ideation and practical problem solving. Here, finding practical use for ideas and theories to solve actual technical tasks or problems are often favoured over social or interpersonal issues. Exercises such as experiments, labs or simulations are often applied.

Accommodating (Do & Feel) learning style promotes learning by doing. Here, "hands-on" involvement in new challenges acting on gut or intuition is favoured rather than on logical analysis. The learning style also relies more on people and systems for information rather than personal technical analysis. Exercises such as field work and group work are often applied.

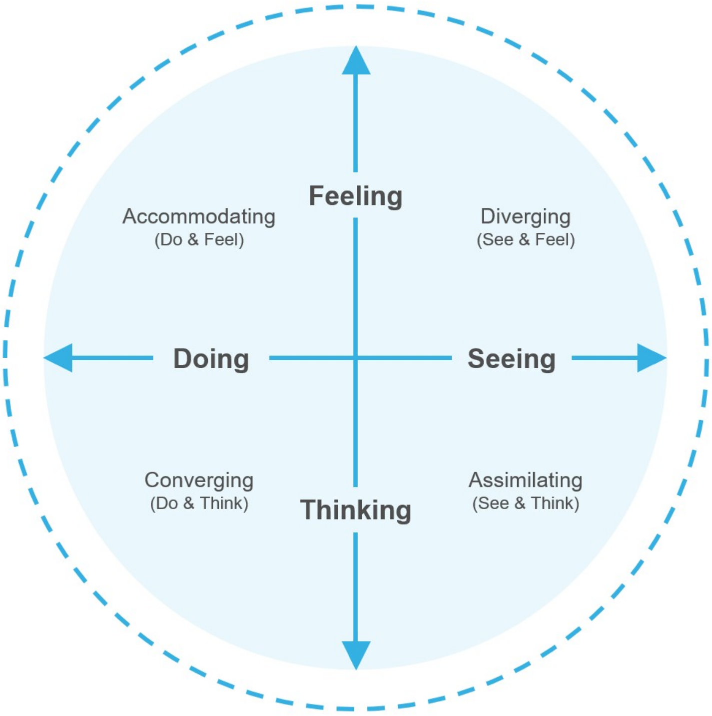

Figure 3. Kolb's experiential learning styles

The use of learning styles has been debated in research and Kolb himself acknowledges that learning styles are highly subjective and affected by personal preferences (Kolb & Kolb, 2013). Thus, developing trainings and courses with a particular learning style in mind might not guarantee the same learning experience for all participants. Kirschner (2017) takes his criticism even further questioning the concepts of learning styles altogether. He argues that a personal preference towards a particular leaning style does not guarantee knowledge creation, as the way that someone prefers to learn might not be the most efficient method of learning (Kirschner, 2017). Pelley (2014) highlights that even though learning styles could be used to identify preferences and potential learning skills in the trainees, the instructional design and course content should not be limited by the learning style but dictated by the outcomes-based learning objectives of the training.

Bloom et al. (1956) divided learning objectives into three domains, namely the cognitive, psychomotor and affective domains. The cognitive domain focuses on knowledge and skills of intellectual nature, such as being able to recall and develop theory and instructions. The psychomotor domain focuses on acquisition of motor-skills and coordination requiring physical performance such as handling tools. Finally, the affective domain focuses on training outcomes developing values, motivation and behaviour change in the student. Bloom et al. (1956) also developed the taxonomy of leaning objectives accompanying the three domains of learning outcomes, dividing the three domains into additional levels of learning objectives with varying complexity. The taxonomy of learning objectives for the cognitive domain, revised in 2001 by Bloom's former students (Anderson & Krathwhol, 2001) is to date the most referenced categorizations of learning objectives and goals. The taxonomy introduces six different levels of educational goals and objectives in a sequential level formation with increasing complexity. An education or training can target any of the levels as the objective, but the higher the level, the more complex of a task the learner is expected to be able to partake in after completed education and the more complex activities is part of the learning (Forehand, 2005).

The first level is the *Remember level*, in which after completed education the student is expected to be able to list, define and retell the relayed information without reflecting or necessarily understanding it. The second level is the *Understand level*, in which after completed education the student is expected to be able to summarize and interpret information to possibly translate the information to new contexts. The third level is the *Apply level*, in which after completed education the student is expected to be able to replicate or solve a real task by applying the cognitive knowledge gained. The fourth level is the *Analyze level*, in which after completed education the student is expected to be able to do critical thinking when identify and differentiate relationships in the information. The fifth level is the *Evaluation level*, in which after completed education the student is expected to be able to make judgments and evaluations of different problems or potential solutions. Lastly, in the sixth level, the *Create level*, the student is expected to be able to relate or combine different pieces of information to create new solutions or ideas.

For the development of a particular manufacturing skills, the learning would need to consider knowledge that could be applied to solve a particular manufacturing task or problem (European Parliament, 2008). Implying that the apply level from the Bloom's taxonomy should be the targeted learning objective for manufacturing skills training. For the acquisition of practical and applicable knowledge Ebbinghaus (1913) proposes that the learning is an evolving process and a result of practice over time with increased performance. In the context of manufacturing Dar El et al. (1995) argues that such skill acquisition has two main components. One cognitive element with large presence in the early phase of the training and one motor element with large presence in the later phase of training. The two phases of skill acquisition are often explained using learning curves (Peña et al., 2022), and the learning curve created by Fitts & Posner (1967) is one of the most well-referenced. Their learning curve includes three stages of skill acquisition with increased performance that follows. When applied in the context of manufacturing, improved performance over time could be expressed as decreasing cycle time over a number of cycles (Peña et al., 2022), see Figure 4.

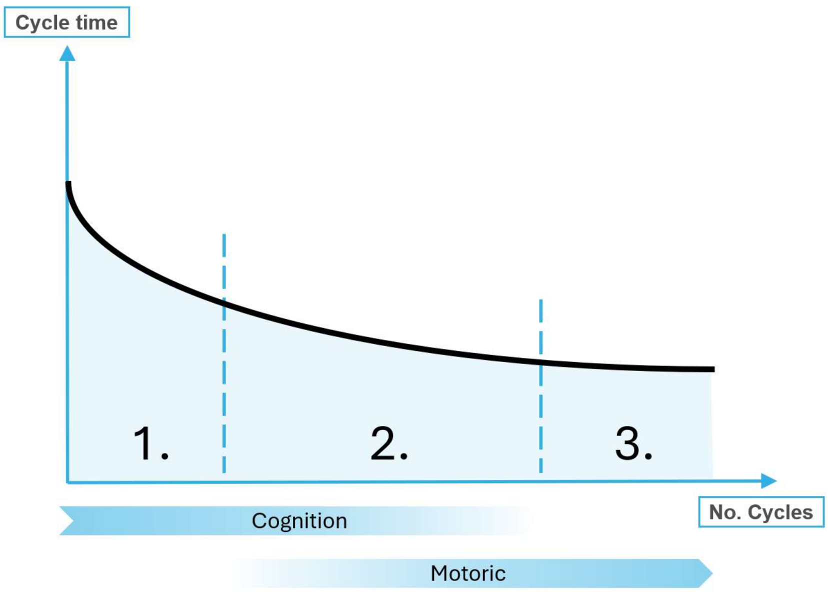

Figure 4. The learning curve and the two components of procedural knowledge in manufacturing, adapted from Fitts & Posner (1967) and Dar El et al. (1995)

The Cognitive Stage represents the initial phase of learning, where individuals focus on developing the cognitive knowledge needed for the task. Performance is often inconsistent, with frequent errors due to a lack of familiarity with the task and feedback from peers is crucial (Fitts & Posner, 1967). In the context of manufacturing, practice under supervision mixed with demonstrations, readings or classroom style training is common, as trainees focus on memorizing cognitive information such as work instructions and task sequence (Souza, 2021).

The Associative Stage, performance becomes more refined as learners develop a deeper understanding of the task. Movements are more fluid, and errors occur less frequently. At this stage, learners begin to integrate feedback more effectively, making necessary adjustments to enhance accuracy and efficiency. Development of motor skills become more dominant over cognitive information as execution becomes more natural (Fitts & Posner, 1967). In the context of manufacturing this often includes supervised or unsupervised practice with high repetition in the physical workstation (Souza, 2021).

The Autonomous Stage represents the final phase of the skill acquisition, where performance is highly efficient and requires minimal conscious control with minimal errors. Actions are executed automatically, allowing the individual to focus on higher-level aspects of the task and to develop instincts or motor skills for enhanced performance (Fitts & Posner, 1967).

Gustafsson (2008) addresses the learning curve in his doctoral dissertation from the perspective of virtual training and the modern assembly worker. He concludes that due to the many social mental models and very tactile work of the assembly operators, virtual training (as of 2008) was only able to positively influence the learning process during the cognitive stage. This was also confirmed by Malmsköld (2012) (2007) who confirmed the use of virtual training in preparatory training of assembly operators as well as proposed a design framework of adopting screen-based virtual training in the cognitive learning stage of the learning curve. Their work concluded that virtual training could not support the development of motor skills and tactile feeling needed in the later phases of training of manufacturing workers. However, newer advancements in virtual technology using XR and haptics have shown promising results also in the later stages of the learning curve, training motor skills across various domains and industries (Darsha et al., 2018). For instance, a review on XR training for motor skills of welding operators, performed by Chan et al. (2022), shows that the number of publications on the topic has quadrupled since 2012. In the case of welding, XR trainings shows great promise for motor skills acquisition (Chen et al., 2022) and some commercial applications such as Soldamatic[1] is already available on the market, arguing for the use of virtual trainings also in the associative stage.

2.4 EXTENDED REALITY

XR is a term commonly used to describe technologies that facilitate an interface between the real and the virtual world, with different levels of immersion. This commonly includes VR, MR and AR. The technologies act on the spectrum of immersion levels referred to as the virtual continuum, defined by Milgram & Kishino (1994), see Figure 5.

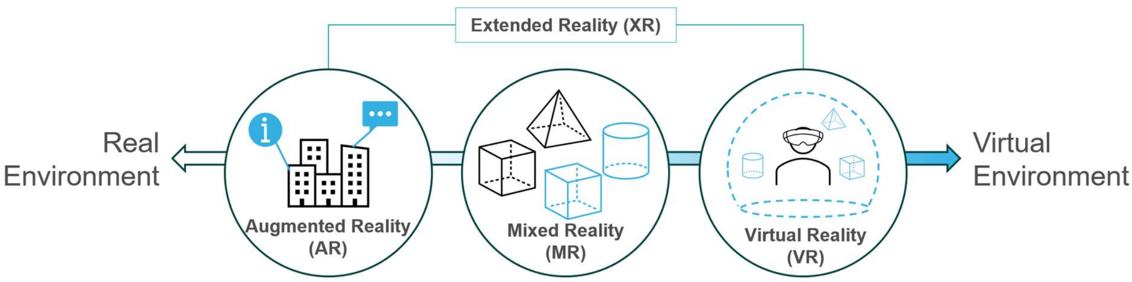

Figure 5. The XR technologies displayed on a virtual continuum spectrum

The virtual continuum spans from reality with only physical artifacts to a fully virtual world with only virtual artifacts (Milgram & Kishino, 1994). AR, which is closest to the real environment on the continuum, superimposes digital information and visuals on top of physical artifacts and objects in the real-world space and time (Billinghurst et al., 2014). This is most often achieved either using an HMD or smart glasses with transparent holographical displays where users can see the true real world with added holographical elements (Billinghurst et al., 2014). Or using a mobile device that captures the real world through a camera while imposing virtual elements on to the video feed displayed on a 2D screen (Billinghurst et al., 2014). MR technology takes the concept of mixing virtual

[1] https://www.soldamatic.com/

and real worlds to the next level. Using spatial computing MR can blend the two environments by seamlessly introducing digital objects in the real world, and vice versa, allowing interaction between the two worlds (Mohd et al., 2023). Today this is most often achieved using multiple cameras and an HMD with stereoscopic displays capable of displaying the real world in 3D while allowing for virtual elements to be added to the 3D space (Mohd et al., 2023). MR headsets like the Apple Vision Pro[2] or the Meta Quest 3[3] have popularized the technology.

VR however acts completely in the virtual space and real objects or artifacts are not needed for the experience. Instead, the user is fully immersed in a digital space using a HMD, that fully encloses and immerses the user without the view of the surrounding, real, environment (Jerald, 2016). For VR experiences the same or similar headsets HMDs as in MR can be used. To interact with the virtual environment most of the XR devices on the market today rely on either hand and body tracking or trackable controllers but other sensory input devices such as eye tracking, facial tracking and voice commands exist (Sayyed, M., 2024). Research on the topic of XR is still evolving and new advancements are made continuously (Dias et al., 2025). The HMDs are getting smaller and smarter, integrating AI and spatial computing for seamless experiences and communication (Dias et al., 2025). Research on brain-computer interfaces also shows promise as potential future sensory input devices to interact with XR environments (Sayyed, M., 2024).

Virtual Training and XR

Simulation-based training for skill acquisition and knowledge transfer have been used for decades in various forms. It was first successfully adopted by the growing aviation industry in the 1920s. The Link Trainer consisted of a wooden cockpit positioned on a motorized and spinning platform to simulate rudder input movements by the pilot in training (Link, 1931) (Baarspul, 1990). Similar physical simulation-based training applications were continuously developed during the first half of the 20th century in the defence industry, introducing more miniature game-based experiences (McCluskey, 1973). With the rise of the computer and 3D graphics in the latter half of the century the simulations went from physical miniatures and mockups to computer based, and by the 1980s flight and military simulators using computer graphics were being used more widely (Baarspul, 1990).

In 1990 NASA developed the very first VR simulation-based training using an HMD (Garcia et al., 2020) and the topic of VR trainings started to attract attention in the scientific community. Reigan et al. (1992) acknowledged the future potential of VR training due to its ability to preserve (a) visual-spatial characteristics of the simulated world, and (b) the linkage between motor actions of the student and resulting effects in the simulated world. The concepts of VR based virtual training were now born (Reigan

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[2] https://www.apple.com/apple-vision-pro/
[3] https://www.meta.com/quest/quest-3/

et al., 1992). At about the same time, researchers at Boeing started to developed the very first application of AR training and instructions. The AR application being developed at Boeing superimposed markings of where to drill/rivet on the aircraft's fuselage in the operators' field of view using an HMD with transparent display (Caudell & Mizell, 1992). Today, the topic of XR training is widely known and spread to many industries including medicine, defence and manufacturing (Chiang et al., 2022).

The use of XR training has been observed in various domains of manufacturing such as applications within assembly, maintenance, welding, quality, additive manufacturing, casting and safety (De Giorgio et al., 2023). Often these trainings emerge users in a simulated manufacturing scenario to promote hands-on training with virtual or physical tools, equipment and parts following a set of work-instructions. De Giorgio et al. (2023) identified that 57% of the XR trainings in manufacturing uses VR technology, while 37% address AR and the last 7% address MR (or a mix of VR and AR). The decision between the different XR technologies in manufacturing training is often dependent on which stage of the manufacturing life cycle is targeted by the training. VR training is predominantly used in the early phases of manufacturing, such as design and commission phase where physical artifacts to train on is hard to come by (Doolani et al., 2020). Meanwhile, AR and MR trainings are predominantly used in the later phases of the lifecycle such as in the operational and end phase (Doolani et al., 2020).

Benefits of using XR trainings in manufacturing such as safer training environments that minimize the risks of personal harm, quality issues or negative effects on lead times and production efficiency have been established (Hermawati et al., 2015). At the same time, the immersive nature of XR and virtual training has the ability to boost students learning process by increased engagement and contextualization (Dalgarno & Lee, 2009).

While XR trainings in manufacturing has seen broad domain and application use in literature, very few large-scale industrial implementations with high TRL have been observed. 75% of all XR trainings in manufacturing never reaches above TRL 4 and far less leaves the prototype or demonstrator stage (above TRL 7) (De Giorgio et al., 2023). High initial investment costs and a resource intensive development process of creating XR training content creates a barrier for its wider industrial implementation (Berg & Vance, 2017) (Ipsita, 2025). However, ongoing and future development of, for instance, generative AI to reduce cost in content creation and cloud-based cross-platform solutions is predicted to lower the barriers of adaptation by industry (Ipsita, 2025).

2.5 THE VIRTUAL MANUFACTURING SYSTEM

Virtual Manufacturing is generally defined as "manufacturing in the computer" and entails executing manufacturing processes virtually in a computer in order to simulate or predict potential problems (Bharath & Rajashekar, 2015). Virtual manufacturing as a tool can help manufacturers to simulate, analyze and identify risks and issues related to low manufacturability and performance early in the design process of a manufacturing system. By virtually simulating and visualizing the intended manufacturing and product designs, decision support can be given to optimize the design of the physical manufacturing system (Dépincé et al., 2004).

To run a virtual manufacturing application, 3D elements and virtual representations of actual manufacturing are in most cases needed. These virtual assets and 3D models could be supplied from the product lifecycle management (PLM) system (Hincapie et al., 2014). The PLM system includes various information related to the product, such as the Bill-Of-Material (BOM), a structured list of components and parts, often represented by CAD models (Saaksvuori & Immonen, 2008). Variations of BOM's exist, providing various structured information related to the product and its production, such as outlining the sequence of its assembly or production (Bill-of-Process), or the equipment and tools used in the manufacturing (Bill-of-Equipment) of the product (Saaksvuori & Immonen, 2008). Other source of 3D assets to be used in the virtual manufacturing process could include the Building Information Modeling (BIM) System, which can hold CAD or 3D scans of the factory or workstation. By combining the manufacturing 3D data within a simulation tool or digital twin software, we can visualize and simulate a manufacturing process thus achieving virtual manufacturing (Bharath & Rajashekar, 2015).

In the context of virtual training, virtual manufacturing could be seen as a foundational enabler for the creation and deployment of the trainings (Elmounayri et al., 2005). Both as a source of training content through assembly instructions, work descriptions and manufacturing process data, and as the virtual environment in which training is delivered. A simulation model or digital twin of the manufacturing could facilitate enough fidelity and graphical elements to immerse users into a representative training environment of the intended manufacturing site or station (Bharath & Rajashekar, 2015).

However, virtual manufacturing software is usually highly data-driven and physics-focused, and not optimized for smooth, real-time XR rendering (Kamdjou et al., 2024). The usability and flexibilities of creating pedagogical learning elements and environments could also be limited as this seldomly is the focus of the virtual manufacturing software (Jankovskis et al., 2024). Thus, the majority of industrial XR trainings are today developed in game engines such as Unity 3D or Unreal (Lampropoulos & Kinshuk, 2024) (Naranjo et al. 2020).

For companies with already established virtual manufacturing capabilities, this means that the 3D data and manufacturing data need to be manually extracted from the PLM system to be further refined before being implemented into the XR trainings using game engines (Gong, 2020). The engineers that are proficient in virtual manufacturing at the company are necessarily not proficient in using game engines, as a higher degree of programming and software development is needed, creating a competence gap and a barrier for XR training development (Ipsita et al., 2025). For companies with lower digital maturity, lacking virtual manufacturing capabilities and assets, the barrier is even higher as virtual assets first need to be created in order to build a representative virtual environment for the XR training (Ipsita et al., 2025).

Fernández-Caramés & Fraga-Lamas (2024) argues that the next generation XR trainings for manufacturing will be developed inside the industrial-metaverse. A real-time, physics-based digital twin synchronized with the factory data and streamable to multiple different devices, including XR, for social interaction. Today several platforms offering versions of the industrial-metaverse already exists including the Omniverse[4] platform from Nvidia, the 3D Experience[5] platform from Dassault Systems, and many more (Grand View Research, 2024). The field of industrial-metaverse is still relatively new but constant development is ongoing. In the coming years the annual growth of the industrial metaverse market size is estimated to more than 30% (Grand View Research, 2024). As the topic of industrial metaverse -platforms mature, the distinction between PLM, virtual manufacturing and XR trainings is expected to blur, and no code solutions are expected to lower the barrier for adoption (Fernández-Caramés & Fraga-Lamas, 2024).

[4] https://www.nvidia.com/en-us/omniverse/
[5] https://www.3ds.com/3dexperience/

3

RESEARCH APPROACH

This chapter provides a short description of the authors worldview, background and context that has set the research approach and strategy for the thesis. Furthermore, the research design is presented, and the chosen methodology and methods are explained and presented per appended paper.

3.1 SCIENTIFIC BACKGROUND AND WORLDVIEW

Our previous experiences and personal beliefs guides dictate how we observe the world and research (Säfsten & Gustavsson, 2019). Making it possible for two individuals observing the same phenomena to have two very different perceptions and come to different conclusions. As of result of this, knowledge can be ambiguous as the same experiment or event can result in different insights and knowledge depending on the lens of the observer. By understanding our observer, we can better understand the result and conclusions drawn.

In the initial steps of his research the author of this thesis adopts a pragmatic world view. A choice or world view driven by the authors background as an engineer in industry as well as the prerequisites of the field of research. Pragmatism in research is driven by a perceived societal or industrial need and is verified by its practical contribution and usefulness (Säfsten & Gustavsson, 2019). For this purpose, the studies composing of this thesis have been carried out in close collaboration with industry. Both building on the perceived need by the industry and validating the usefulness of the results in a practical industrial setting. Furthermore, the nature of the topic of operator training, that frames the research, emphasizes the human perspective and the human knowledge acquisition as the study subject. This has pivoted the used research philosophy towards that of constructivism (Saliya, 2023).

The combination pragmatic constructivism (Nørreklit, 2006) has coloured and enhanced the research aim and strategy. The pragmatic view sets the scope and aim of the research towards creating XR applications and methodologies that works, and that brings proven value to industry to scale its use and benefits. Meanwhile, the constructivism helps to direct the research strategy and methodology used to focus on the human behaviour, perspective and mental capabilities. The pragmatic constructivism philosophical framework is often applied in management and social science and focuses on how to create knowledge that is both useful and practical while grounded in reality (Nørreklit, 2006). Its core principles are that of using the reality and real use-cases as its construction while seeking action-oriented knowledge through practical usefulness and coherency (Nørreklit, 2006).

3.2 RESEARCH DESIGN

This thesis constructs of the work and studies carried out over a period covering a little more than the first two years of the authors doctoral studies. This means that the presented studies and research will sets the foundation for continued research as part of authors continued PhD studies. The author's close collaboration with industry presented the opportunity to run multiple case studies in an actual industrial setting. Hence, the methodology applied currently, and in the foreseen continuation of the research, to answer the stated research questions is a multiple-case study methodology. A case study could be defined as a research approach that involves an in-depth, contextual analysis of a specific subject (or "case"), such as an individual, application, event, or organisation, within its real-life context (Yin, 2014). The selection of the multiple-case study methodology allows enhance external validity as well as mitigating potential biases found in a single case (Karlsson et al. 2016). The multiple-case studies also allow for the development of theories validated across disciplines and industries contributing to more generic theories with larger base of application. Furthermore, an iterative process of building, validating and refining those theories used to answer research questions is conducted (Meredith, 1995).

In order to build an understanding of the state-of-the-art as well as to start formulating ideas and research questions to guide the authors research an *Exploration* through a first industry case-study was used and published in *Paper A*. This case-study used an inductive approach by observing an XR training application being tested and used in industry, to identify challenges and research gaps to be further explored and theorised over. From the *Exploration* the two research questions got formulated setting the foundation for the continued research.

Theory building for each research question was conducted to further identify key concepts and theories that could validate the ideation and build the theory behind each research question. The activities and results of the *theory building* for RQ1 and RQ2 was published in *Paper B* and *Paper C* respectively. *Paper B* takes on an inductive approach through a systematic literature review of current XR applications helping to build the theory and ideation. *Paper C* is a case-study that adopts an inductive approach though observations and lessons learnt through an XR implementation at an automotive case company.

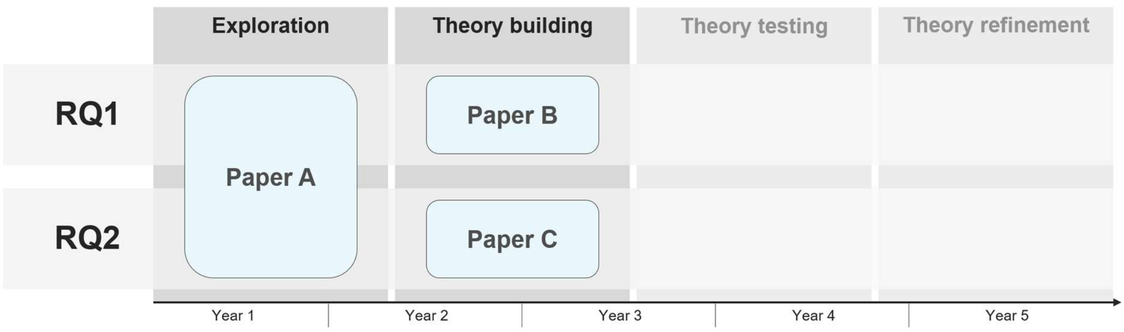

Figure 6. The research process for the thesis

In Figure 6 the research process and the papers included in this thesis are illustrated. The figure also includes the two following steps of *Theory testing* and *Theory refinement*. These steps are part of the foreseen continued research to be made in the continuation of the authors' PhD studies. The theories and hypotheses presented in this thesis will be implemented in various XR applications and tested using a deductive approach and empirical data in case-studies with industrial partners. The findings of these envisioned case-studies will further lay the foundation for the refinement of the theory and solutions presented.

3.3 RESEARCH METHODS

The three studies represented in the appended papers of this thesis used various research methodologies and strategies depending on the needed theoretical contribution to the research. In Table 2 the research activities and methodologies per the three studies and papers are presented.

Table 2. Research activities and their alignment with the appended papers.

	Paper A	Paper B	Paper C
Type of study	Case-study: Demonstrator	Systematic literature review	Case-study: Experiment
Case selection	Automotive manufacturer	VR training applications in manufacturing	Automotive manufacturer
Data collection	- Focus group interviews - Inductive reasoning	Literature review	- Interviews - Empirical measurement
Data analysis	Thematical analysis	Systematic coding of 60 papers	Performance metric
Documentation	Conference publication	Journal publication	Conference publication

Paper A

To address the exploration of the topic of XR training in manufacturing and to start drafting the research question framing the research, a case-study was carried out together with an automotive manufacturer. To gather practical knowledge and foundational theory in the topic of XR training development and use, a practical exercise took place. A demonstrator of a multi-user VR training application for automotive assembly was developed using the Unity Game Engine following methodologies explored in literature. Three separate assembly use cases provided by the automotive manufacturer was implemented in the VR training demonstrator. The three VR training use cases was later used in two focus group studies consisting of plant launch and training specialists. The participants of each focus group got to try the multi-user VR training demonstrator before participating in a semi-structured focus group interview. A thematic analysis (Braun & Clarke, 2019) of the focus group interviews as well as insights and inductive reasoning gathered from the development process made up for the results of the study. The study thus highlighted both challenges and opportunities in the development process and the use of VR trainings in manufacturing.

Paper B

To build theory and deepened understanding behind RQ1 a systematic literature review flowing the guidelines presented by Snyder (2019) was conducted. Relevant publications targeting the validation of implemented VR training application in manufacturing was selected using a systematic approach of inclusion/exclusion criteria as well as a snowballing exercise (Wohlin, 2014). A total of 60 publications were included in the study and subjected to further analysis. The literature was coded systematically against existing frameworks of knowledge and learning theories and by collecting and synthesizing said data patterns of best practices emerged. The literature study highlighted the current trends of learning styles and theories applied in VR training for manufacturing and showcased how the decision of learning styles in VR is affected by the use case and objectives of the training.

Paper C

To start theorizing around RQ2 and to formulate a hypothesis another case-study was carried out at an automotive manufacturer. The industrial case provider put up the challenge of increasing automatization of their development of new VR training environments. The case-study started off with a current state analysis through a semi structured interview study with XR training process owners, method developers and trainers at the case company, to map out their data needs and requirements for a XR training environment. A methodology, fulfilling the data requirements highlighted in the interview meanwhile increasing the automatization in the VR environment creation using BOM and Bill-Of-Process (BOP) data from the PLM, was theorized about. An experiment was thereafter designed in the simulation software IPS to test the theory and strengthen the hypothesis made. The experiment was validated by stakeholders from the case company while empirical data was collected to evaluate the performance of the methodology and strengthen the hypothesis.

4

SUMMARY OF APPENDED PAPERS

In this chapter the main findings of the thesis and the appended papers are presented. The chapter starts off by highlighting the relation and contribution each of the appended papers has to the research questions in scope for this thesis. Furthermore, a summarization of each appended paper is given. The contribution and results of each paper is further discussed in the discussion chapter stating the answers to the two research questions.

4.1 CONTRIBUTIONS TO RQ'S

The below table has been drawn to provide an overview of the purpose of the appended papers and their individual contribution toward each of the stated research questions. The main contributions of each paper towards defining methods and frameworks of designing XR trainings for efficient knowledge transfer (RQ1) and introducing scalability through an increased automatic development process of XR trainings (RQ2) can be seen in Table 3.

RQ1: How can XR trainings be designed to achieve knowledge transfer for shop floor workers?

RQ2: How can scalability be introduced in the development process of XR trainings for shop floor workers?

Table 3. Summary of main contribution of each paper towards the research questions.

	Purpose	Contribution RQ1	Contribution RQ2
Paper A	Explore and understand the main challenges, preventing XR training in manufacturing to be scale and used in wider extent	Identified research direction: There is a research gap in understanding how to design and use XR for efficient knowledge transfer in industry	Identified research direction: There is a need for faster XR environment and content creation for training in manufacturing to scale
Paper B	Identify suitable learning theories and styles to be applied in manufacturing use cases	Overview of current learning theories and practices in VR trainings in manufacturing Proposed learning style per manufacturing use case and knowledge mode	*Minor contribution: Current state of VR content development explored in literature*
Paper C	Understand data requirements for VR training environment creation and provide hypothesis for automatic XR environment creation in manufacturing	*Minor contribution: Insights on limitations and trade-offs between scalability in development process and learning design*	Overview of data requirements mapped towards manufacturing data bases Hypothesis of automatic XR environment creation drawn and validated through experiment

4.2 PAPER A

THE CREATION OF A MULTI-USER VIRTUAL TRAINING ENVIRONMENT FOR OPERATOR TRAINING IN VR

Short Description

This paper exemplifies the current state of XR training development for manufacturing applications following common trends seen in literature and the manufacturing industry. The purpose of the paper is thus to further evaluate the current state development approach as well as the use of such XR applications in assembly training from a scalability perspective. The study was carried out together with Volvo Cars Corporation, acting as the case provider. A multi-user VR training environment was developed for the purpose of this study and three separate training cases provided by Volvo Cars were implemented. The multi-user VR training was then used for the purpose of two semi-structured focus group interview with domain experts at Volvo Cars, evaluating its potential and challenges for further scaled implementation and use by their operators.

Main Results

In order to create the VR training environment and to digitalize the work instructions for training purposes the development workflow considers extraction of data from Volvo Cars PLM system, conversion and harmonizing of data and development using the Unity Game Engine. A visualization of the applied workflow can be seen in Figure 7.

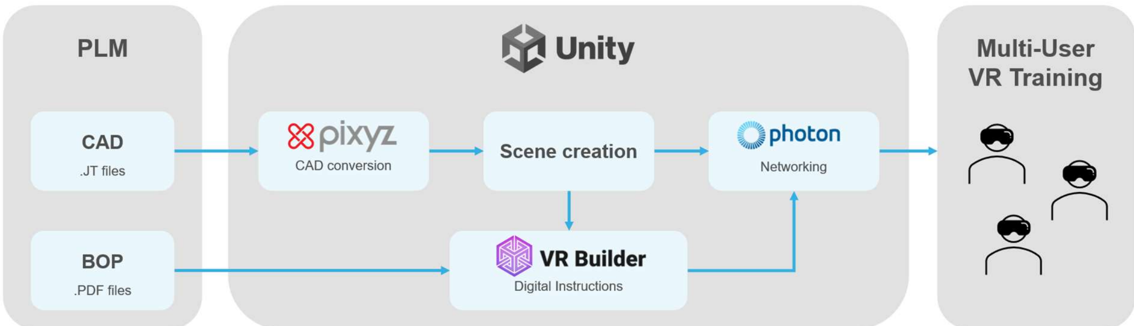

Figure 7. Workflow of the development of VR training application used for the case study

To represent the task and part to assembly in the most realistic and accurate way, CAD drawings of the actual parts and products to be assembled were used. These were exported as JT-CAD files directly from the BOM of Volvo Cars and thus not optimized for VR applications. To make the geometry presentable and suitable for VR the PIXYZ plugin to Unity was used to optimize and convert the CAD files to a FBX file format. The now optimized geometry was used to create and populate the VR scene and environment in the Unity Game Engine. Likewise, the assembly instructions that were used as the basis of the training activities in the VR application were exported from the BOP of Volvo Cars. The assembly instructions were manually interpreted and translated into the VR environment using VR Builder, a Unity plugin using visual block scripting to create tasks sequences and interactions for VR instructions. Once the VR scene and task sequence was created, the Photon Networking plugin to Unity was introduced to create multi-user capability. By using Photon to synchronize the translation of the objects in the VR scene as well as synchronizing the task execution according to the VR Builder block structure between all clients connected to the same server real time multi-user training sessions were achieved. The final multi-user application allowed for up to 16 users to connect to the same VR environment and partake in the training jointly. Each user was represented with an avatar tracking the head and hands movements of each user meanwhile communication was enabled through voice chat. See Figure 8 for a screenshot from within the multi-user VR application.

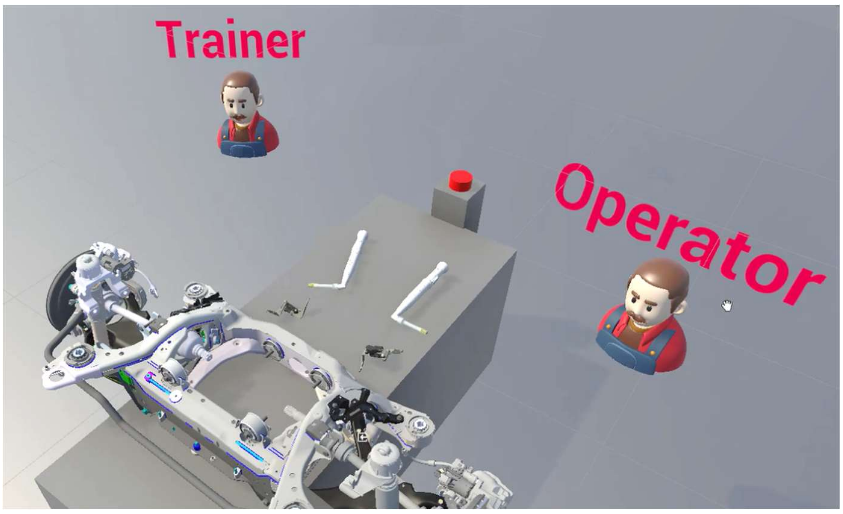

Figure 8. A trainer and an operator partaking in training on a rear axle assembly inside the developed multi-user VR training application

The two focus groups identified two beneficial areas of usage for multi-user VR training applications in manufacturing. Supervised training with an instructor in VR (1) and improved learning by having multiple operators train together in VR (2).

Having an instructor present in the VR environment (1) meant that each participant could have a personal interaction and dialogue with the instructor allowing for questions, feedback and evaluation. Something that was seen as crucial to allow for more personalized and flexible VR learning paths as the instructor could adapt the training content, instructions and offer support as they saw needed. However, several members of the focus groups pointed out that it is impossible to fully evaluate the students' performance in a manufacturing setting using VR, as VR has limited possibility to simulate physical feedback and load on the operator as well as the stress level of an actual running production. Furthermore, the focus groups elaborated on the ability for an instructor to join the session for an "in person" demonstrations of "*do's*" and "*don't*" in the VR environment as well as enabled the possibility for interactive classroom sessions and joint virtual factory tours. The focus groups determined that for these purposes VR would be considered a much more powerful visualization tool than traditional video demonstrations or classroom demonstrations.

Being able to have multiple operators or students joining the same VR training session (2) was seen as beneficial from a learning perspective. Although the focus groups pointed out that there are very few assembly stations in their respective plants that would require multiple operators in collaboration, they could see the potential elsewhere. For instance, a few of the focus group members pointed out the possibility to practice and build awareness on more complex and indirect collaborations, not directly tied to the assembly task at hand. By having multiple operators training inside the same virtual factory, trainings to understand station- and supply dependencies, Lean concepts or standardization through 5S could be created. Moreover, the focus group pointed out that being able to train together with other operators in the same VR environment might contribute to increased learning as operators with shared learning experience could learn from each other. It was also pointed out that the shared learning experience between operators might also increase the enjoyment and the fun of the training, making it more attractive and engaging for operators, which might increase their learning and engagement.

Discussion and Conclusion

The results of the developed VR creation methodology and the two focus groups showcased that manufacturing companies have the ability to create and use VR environments to improve or complement existing operator training. However, it became evident in the focus group interviews that industrial users, such as trainers and training developers as of now don't have clear frameworks or best practices of how to apply the technology in the best way.

More efforts need to be put towards understanding when and how to apply VR in manufacturing training and which tasks or concepts are more beneficial to train on in VR versus in a physical setting. Learning styles, pedagogical frameworks and best practices for industrial VR training needs to be defined and adopted by the industry in order to find use cases and benefits of VR. For instance, is the best learning experience in VR achieved from repeatedly training on a correct and accurate sequence of assembly tasks? Or would intentionally introducing complexity and errors in the simulated assembly improve the learnings by introducing aspects of critical thinking and problem solving? Likewise, is multi-user VR more suitable for training operators together with hands on training and sequencing of assembly tasks or is it more beneficial to use as a complement of classroom style teaching to create better awareness on certain manufacturing concepts and topics, such as safety and 5S? These questions need to be answered in order for industrial users to defined clear use cases and benefits of XR trainings. - *This discussion point led to the formulation of RQ1 in this thesis.*

Furthermore, the methodology and workflow for the development of the multi-user VR environment presented in this paper, using the Unity Game Engine, is arguably not a scalable approach that would most likely not enable wide adaptation by OEMs. The workflow includes manual exportation, conversion and implementation of PLM data into the VR environment as well as manual interpretations and programming of the assembly instructions into the VR environment. These are all time-consuming activities with relatively high engineering effort, creating a barrier for successful large-scale implementations at manufacturing companies. To overcome these barriers, future efforts need to be put towards proposing simplified, and to some extent automated, VR training environment creation using commercially available platforms and software's integrated with the existing PLM infrastructure and virtual factories of OEMs. - *This discussion point led to the formulation of RQ2 in this thesis.*

Contribution towards research questions

Paper A was conducted in the exploration phase of the authors research process and contributed to the formulation of the research questions and scope of the thesis. The identified challenges and pain points of the case study acted as a stepping stone for the continued research.

The methodology applied in the development of the multi-user VR training environment followed current industry practice as seen in literature but was deemed highly inefficient for extensive use by the case company. This finding highlighted the need for more scalable and automated development processes solidifying RQ2. At the same time the case study confirmed the possibility of using PLM data for XR creation, setting the foundation for continued work on RQ2 and the following paper C.

The results of the case study and the held focus group interviews also showed a lack of design guidelines and framework of how XR should be designed and used in a manufacturing context. Questions raised by the interviewees at the case company could not be answered with current literature and a need for continued work and RQ1 was seen.

4.3 PAPER B

LEARNING IN VIRTUAL REALITY: A SYSTEMATIC LITERATURE REVIEW OF VR TRAININGS IN MANUFACTURING

Short Description

To provide a theoretical foundation for RQ1, this systematic literature review maps existing VR training applications and studies towards manufacturing use cases and various learning theories to define best practices and industry standards. The literature search was conducted in the Scopus database and adopted inclusion and exclusion criteria to make sure that the publication in scope showed clear manufacturing application of VR training as well as relevance to the study. See Figure 9 for an illustration of the article search and selection process.

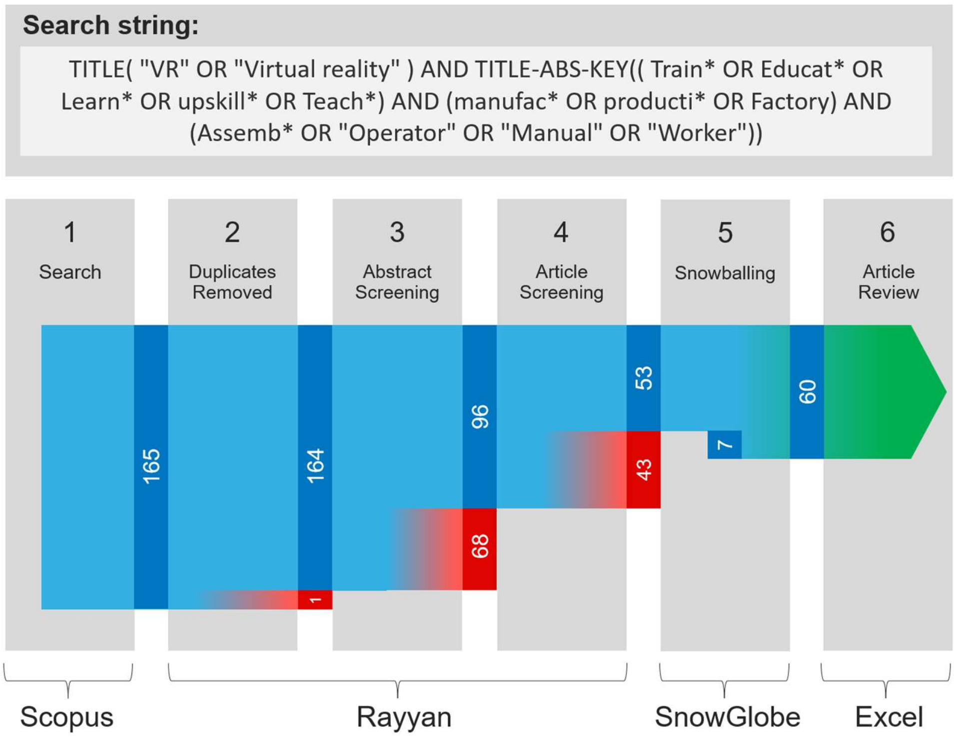

Figure 9. Illustration of the search and article selection process

The 60 papers went through a full review and systematic coding using the definitions of Nonaka's SECI model, Kolb's learning styles and Bloom's taxonomy of learning objectives. The results show that the vast majority of the manufacturing VR training applications apply an accommodating learning style. However, the results were very use case dependent. The different manufacturing use cases and targeted job roles of the trainings as well as the targeted knowledge mode according to the SECI model and Bloom's taxonomy all see various dominating learning styles. Suggesting that an accommodating learning style might not be preferable in all scenarios and manufacturing use cases.

Main Results

The results of the literature study show that VR trainings in manufacturing are primarily adopting an accommodating learning style – *Do & Feel* - (65%). These trainings often use explicit work instructions for task execution. Students are thus expected to follow the instructions and practice repetition and muscle memory. A smaller portion of the VR trainings are adopting converging learning style – *Do & Think* - (22%). Often this is done through a problem-solving approach, lacking explicit task instructions the student is meant to reflect on and to use critical thinking to solve the task or problem at hand. About the same amount of VR trainings adopts a diverging learning style – *See & Feel* - (18%). These trainings often entail visualizations, demonstrations or exploration in VR for instance using 360° videos, virtual factory tours or product exploration and interaction without explicit purpose or tasks to be solved. Finally, a very small part of the VR trainings reviewed applied an assimilating learning style – *See & Think* – (5%). These trainings added a reflective exercise or task to be solved based on a virtual demonstration or exploration of a product or process. For instance, asking the students to complete a value stream mapping or identifying bottlenecks in a production system based on their virtual experience.

However, the accommodating learning style is not the dominating learning style in all manufacturing use-cases. In fact, we can see that its dominance comes from an overrepresentation of VR trainings targeting assembly workers (47%), where perhaps an accommodating learning style is preferred. Meanwhile other use-cases and manufacturing job roles have a much more even split between the kind of VR training scenarios and learning styles that have been applied. See Figure 10 for a breakdown of the various targeted job roles found in the literature review and the VR training scenarios that were applied as the main mode of training in the VR experiences.

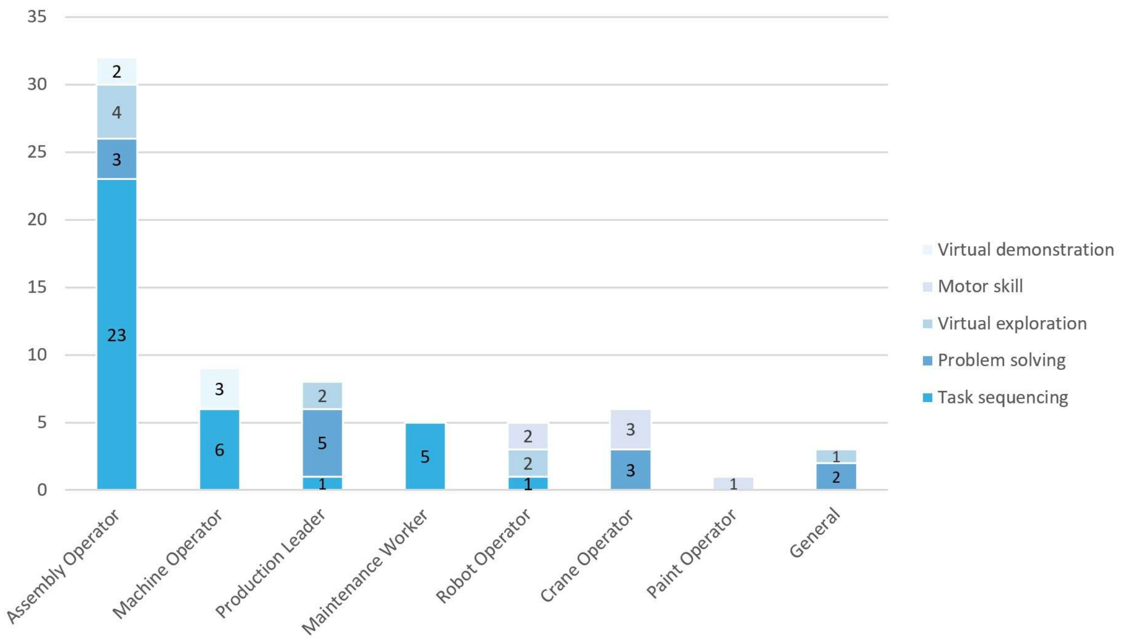

Figure 10. Applied training scenario per targeted job role in the VR trainings

When examining the SECI knowledge modes that the VR trainings aim to address, we can see that the majority of the trainings are targeting an internalization knowledge transfer – *Explicit-to-Tacit* – (72%). These trainings use explicit information and work instructions provided through the VR environment to the users to build tacit knowledge through hands-on practice, memorization and repetition. About a fifth of the VR trainings in review were targeting an externalization knowledge transfer – *Tacit-to-Explicit* – (22%). In contrast, these trainings often lack explicit information or instructions but instead focus on the students to reflect on and formulate solutions to problems experienced from a hands-on tacit task in the VR environment. Slightly less VR trainings target a socialization knowledge transfer – *Tacit-to-Tacit* – (13%). Such VR training applications emphasize learning through collaboration and social interaction in VR as well as observing and mimicking a demonstration performed by an avatar or other VR users. Finally, the least targeted knowledge transfer mode see in the study is the combination knowledge transfer – *Explicit-to-Explicit* – (7%). Few examples were found in the literature, but some included using 360° videos and virtual demonstrators as part of an onboarding in combination with knowledge tests to create and capture explicit knowledge from the students.

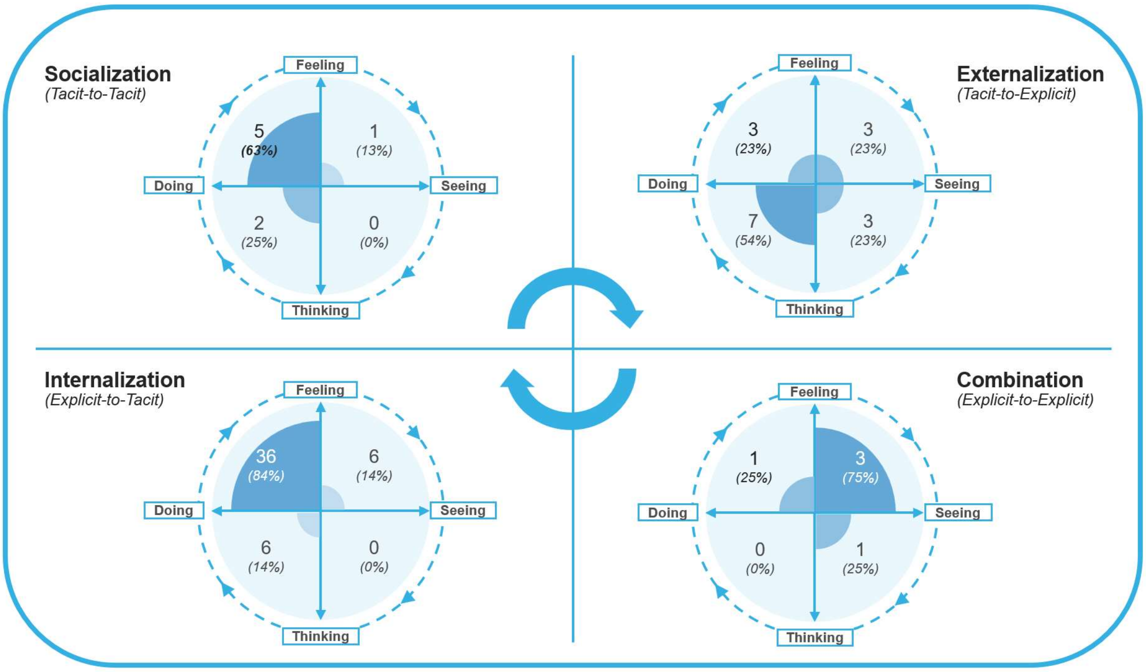

Figure 11. Applied learning style per targeted SECI knowledge mode in the VR trainings

When cross referencing the mapping of the SECI knowledge modes and the learning styles applied in the training, we can see that the applied learning style differs depending on the SECI knowledge mode that is targeted. Again, highlighting that various manufacturing use cases have specific requirements on learning styles. See Figure 11 for a cross referencing of the learning styles applied per SECI knowledge mode.

Similar results can also be seen when cross referencing the applied learning styles and the targeted learning objectives in the VR trainings according to Bloom's taxonomy. The vast majority of the trainings target the apply level of the Bloom's taxonomy (70%), most of which are predominantly adopting an accommodating learning style – *Do & Think* –. Meanwhile, for the VR trainings targeting the lower levels of the taxonomy (15%), diverging learning style – *See & Feel* – is the predominant one. Likewise, the VR training targeting the higher levels of the taxonomy (15%) also adopts a different learning style as the converging learning style – *Do & Think* – is seen as the dominant one. See Figure 12 for the cross reference between applied learning styles and targeted learning objectives according to Bloom's taxonomy.

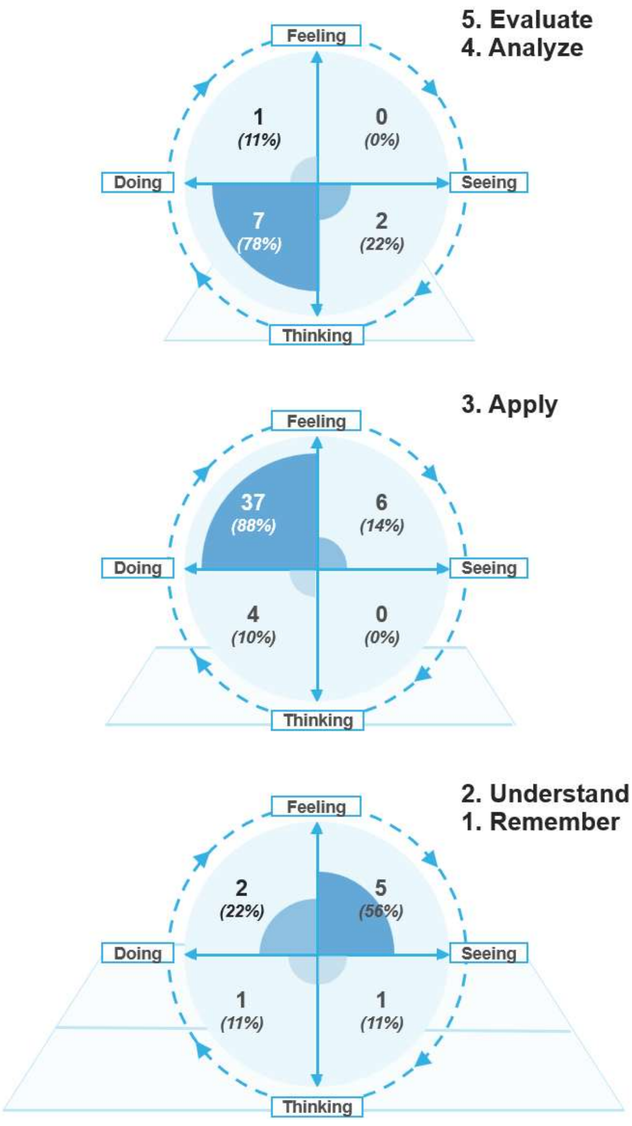

Figure 12. Applied learning style per targeted learning objective according to Bloom's taxonomy in the VR trainings

Discussion and Conclusion

The findings in the study suggest that various manufacturing use case have different requirements on learning styles and pedagogics used in its trainings and there is not one solution that fits all. Consciously or unconsciously industrial users and developers of XR training need to be aware of such different requirements and understand how to adopt the XR trainings depending on the desired learning outcome, knowledge mode and use case. As currently there is no standardized framework or methodology available providing best practices for various use cases, developers and users need to rely on intuition and previous experiences when developing and adopting XR specific trainings. Future work should include a framework or tool to provide clear design guidance and best practices on particular manufacturing use cases based on the findings in this literature study.

But before such a tool or framework can be developed, we need to verify the results of this study to confirm the findings as best practice. This study only presents insight on how VR trainings previously has been applied based on learning styles, use cases and knowledge modes. No concern is currently given to the measured learning outcome or results in the studied literature. As each study included in this literature review represents different manufacturing scenarios and use cases as well as adopts different validation methods of the learning outcomes, a fair comparison between the studies in regard to measured success is very difficult to conduct. This emphasizes the need of a standardized method of evaluating XR trainings effectiveness to safeguard efficient knowledge transfer and learning outcome as well as making future comparison of best practices possible. Until such standard is presented and in use, one way to validate the findings in this literature study, and to strengthen the statements of best practices made, would be to test the hypotheses in a specially designed user study allow a fair one-to-one comparison between each of the learning styles and use-cases addressed in this study.

Contribution towards research questions

Paper B was primarily used in the theory building phase of RQ1 and its contribution aimed to identify suitable knowledge frameworks and learning styles to be used in the design of XR trainings in a manufacturing context. The review of the current literature showed that clear patterns of preferred learning styles per manufacturing use cases exists.

For the training of muscle memory in assembly workers, maintenance personal and machine operators, an Accommodating learning style and an Internalization knowledge transfer is seen as the currently preferred XR training design. This is often done by visualising a digital replica of the workstation and visual instructions highlighting the correct assembly sequence, routine maintenance instructions or machine setup and operations.

A Converging learning styles in an Internalization knowledge mode were primarily seen in training applications that aimed to address learning objectives above the Apply level.

For instance, this was the primary design used in training applications meant to teach production management skills such as bottle neck analysis or lean principles. Similar trainings can also be seen used in affective trainings such as teaching safety and quality mindset and motivation.

The Diverging and Assimilating learning styles are seen in training applications across tasks and job roles but with a dominance in training applications targeting learning objectives lower than the Apply level and in teaching explicit knowledge.

4.4 PAPER C

TRAINING OPERATORS IN VR: A SCALABLE SOLUTION FOR THE CREATION OF VR TRAINING SCENES

Short Description

To provide a theoretical foundation and a hypothesis for RQ2, this case study takes an innovative approach towards developing and demonstrating a hypothesis of how to increase scalability and automation of XR training environment creations. The objective of the study is to summarize the data need and requirements to create industrial XR training scenes, highlight a potential workflow that automatically generates parts of XR operator training scenes, evaluates the value-gained in the XR creation process using automation.

The study was carried out in collaboration with Volvo Cars Corporation acting as the case and requirement owner. A current state analysis through a semi structured interview study was conducted with domain experts at Volvo Cars, including trainers, training developers and manufacturing engineers. The interviews provided an overview of the requirements that the XR environment needed to fulfil as well as which data that was seen as crucial to be represented in the XR scene. After which, an exercise was held together with the manufacturing department at Volvo Cars to pinpoint the availability and accessibility of identified data points within their PLM system. A hypothesis of how to automatically identify and populate a XR scene using the identified data points was formulated and an experiment using the simulation software IPS was created to demonstrate the hypothesis in a VR assembly training. The results of the experiments showed that utilizing existing data and connections to the PLM system enables possible automation of XR training scenes and showed a substantial time gain in the development process.

Main Results

Based on the interviews, six unique data points emerged as especially important to be represented in the XR training scenes dictated by the intended training scenario. In the case of final assembly at Volvo Cars these data points were all dictated by: *What car model to train on? What car variant to train on? Which assembly operation / station number to train on?* By answering these three questions we should be able to determine; what 3D data to import to the scene (both of the parts to assemble and the tools and equipment used), which station layout and part of the factory point cloud should be represented in the training scene and what assembly sequence and explicit work instructions to base the training on. See Figure 13 for a visualization of the six data points and the dictating training scenario.

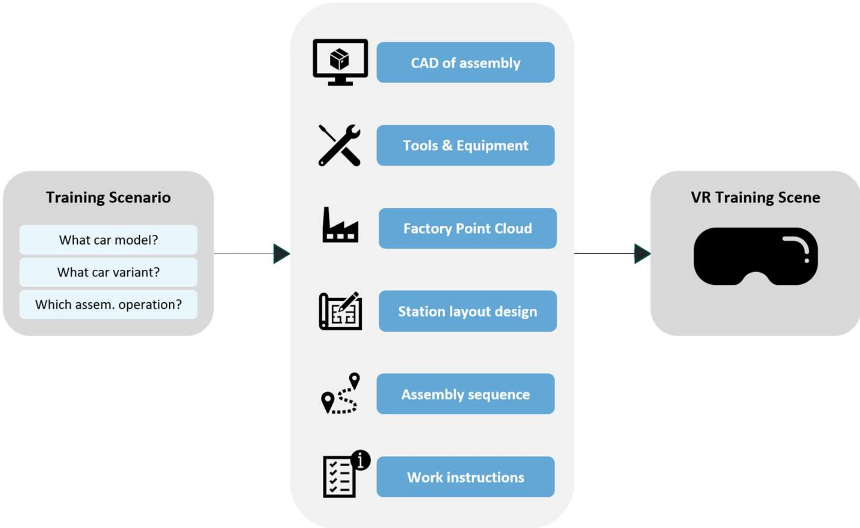

Figure 13. The six identified data points from the Volvo Cars use case and its dictating training scenario parameters

It was quickly identified that the majority of the identified required data points were already represented in the case company's PLM system. The CAD data of the parts to assembly would be accessible through the BOM tree structure of the selected product or variant. In the same way the information and drawings of the tools and equipment to use is present in the Bill-Of-Equipment (BOE), again structured per product and variant. Lastly, the assembly sequence and the explicit work instructions would be present under the BOP and available per product variant and workstation.

The work instructions could be seen as a consumer of both the BOM and the BOE as it provides instructions on how each object in the BOM is assembled or processed with the use of equipment and tools, and often explicitly refers to parts and tools present in these databases. Theoretically, it is possible to connect and link each instruction and step indicated in the work instructions to a specific CAD model in the BOM and tool drawing or description in the BOE. This could be the very first step in automatically identifying models and tools as part of a training task based on the work instructions and could also be seen as the first step in realizing automatic XR training creation for final assembly. See Figure 14 for a simplified illustration of the PLM data structure and the theoretical relationship between the works instructions, the CAD models and tools.

Currently, the data points of the station layout design and factory point were not present in the PLM system architecture and although the station number was indicated on the work instructions, no real connection between the work instruction and the virtual representation of the factory or station layout could be established in the current use case. However, in theory, it would be possible to also connect the virtual representation of the factory and station to the work instruction, if such virtual representation (3D scanning, simulation model or digital twin) were to be present in the PLM, MES or ERP system of the company and accurately labeled and partitioned by workstation.

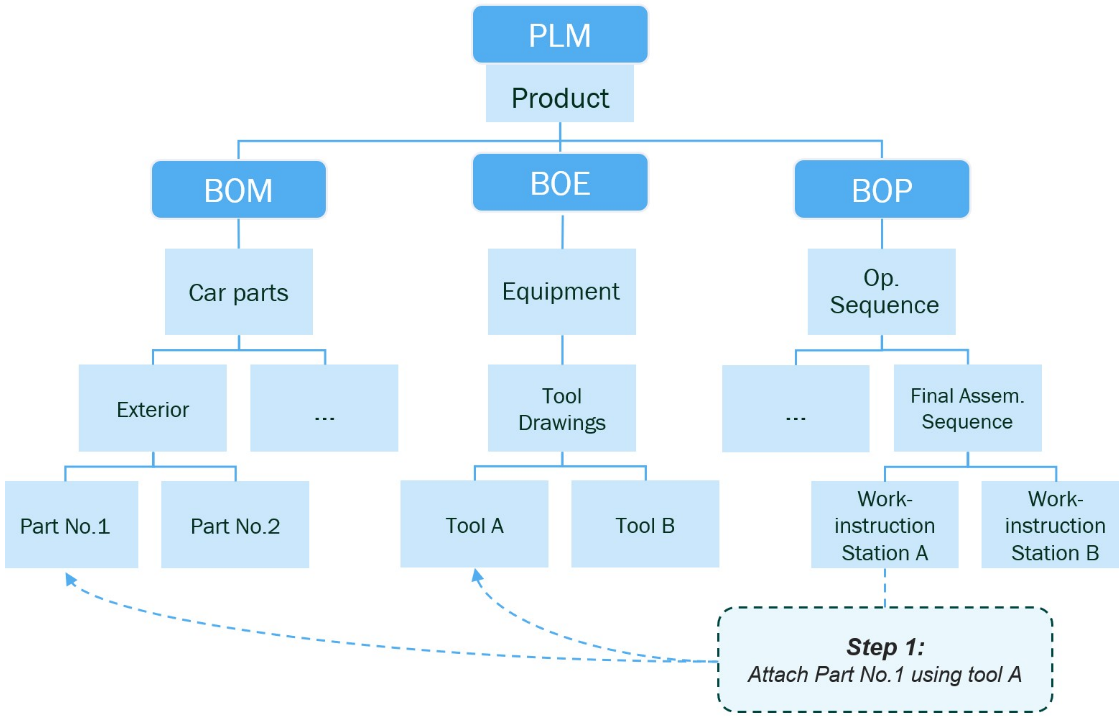

Figure 14. Simplified illustration of the PLM system structure

With the goal to prove the theoretical connection between the work instructions in the BOP, the part specific CAD models under the BOM and the tools and equipment information in the BOE, as well as its contribution toward automatic XR training creation a pilot test was carried out. This pilot was developed using the software IPS and utilized the PLM connections presented above to prove the potential of automatic XR training creation, in terms of time-gain. Several custom scripts were created allowing for the import of work instructions as CSV-files and the parts to be assembled as CAD-files from the PLM system. The scripts also allowed for automatically matching those CAD-files to specific steps in the work instructions to create a training scene representing the work instruction at hand.

In the developed pilot a user was able to upload a work instruction sheet to the software, it would then read the CSV-files, containing the work instructions, line by line and automatically highlight and import the 3D geometries needed to carry out the task into the VR scene. Since the BOM already contained position and rotation data for the parts in relationship to its final position in the car, snap zones could automatically be generated indicating where to place each part for a correct assembly. The work instructions were then automatically presented in a stepwise manner to the user in the VR environment though a text element. The user would begin by reading the first step of the instruction and could thereafter carry out the assembly task by grabbing the mentioned part and installing it in the correct position based on the predefined snap zones. Once correctly placed inside the assembly, the next step of the instruction could be displayed. See Figure 15 for a collection of screenshots from the developed pilot in IPS.

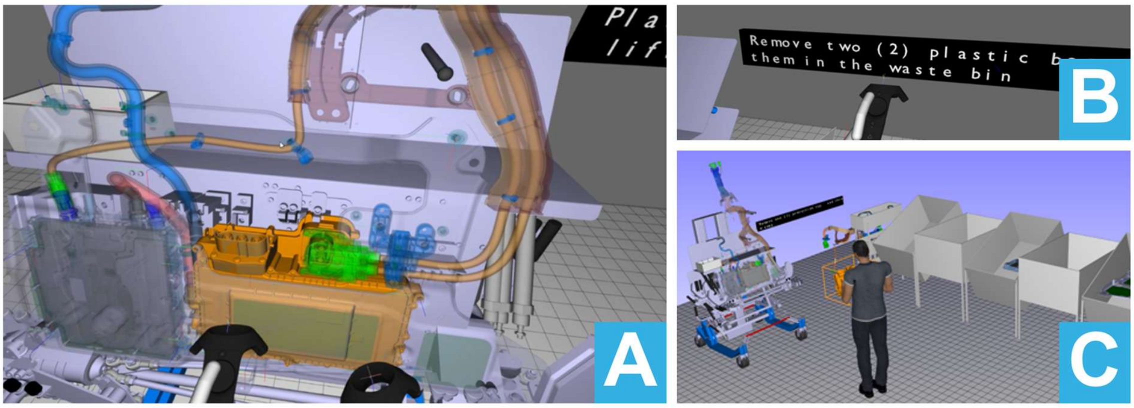

Figure 15. Screenshots from the developed pilot. (A) Point-of-view from the VR user placing a part in the assembly snap zone. (B) The step-by-step work instruction displayed in a text element to the VR user. (C) Overview of the VR training scene with a manikin representing the VR user.

The time necessary to create the VR training scene using the automatic approach presented above was measured and evaluated, comparing it to the same time it would take to manually create the same training scenario in IPS. For the experiment the work instructions of one station with the takt time of 60 seconds and 20 tasks were used. The test was carried out measuring the efficiency against an experienced IPS user, under the preconditions that the data was already available and imported into IPS. For the experienced IPS user it took 106 minutes to populate the VR training scene and prepare it for training and interaction by a VR user. The same training scene was created in 36 minutes using the developed scripts enabling the automatic approach. Although the low sample size of the experiment, it validates the theory and hypothesis presented. The study shows that there is a huge potential value, in terms of both time-gain and reduced competence need, in utilizing this or similar automatic approaches towards XR training development in the future.

Discussion and Conclusion

The findings from this study strongly suggest that the current mainstream approach to XR development—relying on disconnected game engines or standalone simulation software—is far from the most time- and competence-efficient method. There is significant potential in exploring automatic generation methods based on demonstrated or similar workflows, which could streamline processes and reduce the engineering effort needed in the development process.

However, in this study, full automation was not achieved. Certain tasks, particularly data cleaning, still required manual effort. One challenge identified was the inconsistency in the naming and labelling of parts across the PLM systems. For example, a component listed as "PN.876288" in the BOM might be referred to as "*the plastic hood cover*" in the work instructions available in the BOP. These discrepancies made it impossible to automatically identify and match parts within the BOM tree structure. To overcome such issues, it is crucial to establish consistent and standardized labelling of part data across the PLM system. Alternatively, a LLM specifically trained on the BOM and related datasets could serve as a powerful tool to bridge the gap, interpreting and resolving discrepancies in part naming and descriptions between systems.

Additionally, the absence of information regarding storage positions in the workspace presented another obstacle. Locations for picking had to be manually selected, adding to the manual workload and reducing system efficiency. Furthermore, integration with point cloud data and workstations designs and simulations must be improved. This data needs to be partitioned in a structured manner and made easily accessible to support seamless automation of the VR environment creation.

This pilot study was limited to pick-and-place tasks, which raises questions about the validity of the results in other kinds of trainings. It is still unclear how the presented approach would cope in more complex training operations involving tools handling or machine operations etc.

Contribution towards research questions

Paper C was primarily used in the theory building phase of RQ2 and its contribution aimed to map the required data inputs to XR trainings in manufacturing and to start theorizing about potential solutions towards more automated XR development processes.

During the case study, six categories of data inputs were found as essential to the development of the XR training, see Figure 13. These ranged from CAD of products, parts, tools and equipment, drawings of station layout and factory design, to assembly sequences and explicit instructions.

Relationships and dependencies between the six categories of data inputs towards the PLM system of the case company was also found highlighting a potential integration point. Furthermore, relationships between the available data points inside the PLM system was found, see Figure 14, and the possibility to exploit said relationship for increased automation in the development process of XR trainings were confirmed by the performed proof-of-concept.

5
Discussion

In this chapter the main findings and results of the two research questions are discussed. The contribution of knowledge in the area of each research question is presented and elaborate long side a proposed XR training framework and future work. The presented framework and future work will encompass activities and research to be verified during the continuation of the authors PhD studies. Lastly, the methodology used, and its potential limitations are discussed.

5.1 ADDRESSING RESEARCH QUESTION 1

RQ1: How can XR trainings be designed to achieve knowledge transfer for shop floor workers?

As shown by Nonaka & Takeuchi (1995) knowledge within an organisation or company can be transferred or created through four different modes and can take on both tacit and explicit form. This thesis shows that XR trainings in manufacturing has the ability to support knowledge transfer in all four modes and could be effective in creating both tacit and explicit knowledge in a manufacturing context. However, as shown in paper B the conditions, designs and learning styles applied in the XR trainings for each of the four knowledge modes and learning objectives differs.

Paper B shows that most of the reviewed XR training in manufacturing focuses on training muscle memory through repetition of task execution while applying the accommodating learning style for the Internalization (Explicit-to-Tacit) knowledge mode. Unquestionably, this is a great way of moving existing on-the-job, non-value-added, training with paper instructions away from the production system and into a safe and virtual environment. However, it is necessarily not confirmed to be the best use of the XR trainings for efficient knowledge transfer in manufacturing. Furthermore, it is also not certain that this provides a holistic enough training that enabling the development of a complete manufacturing skills applicable for a particular job or task.

As pointed out by Bloom et al. (1956) there are three different domains of learning, the *cognitive*, the *psychomotor* and the *affective*. Ellström and Kock (2008) confirms that in order to develop work related competent and to be able to perform in a manual work task all three domains need to be addressed. Paper B supports that the first two domains (*cognitive* and *psychomotor*) could be covered by the current manufacturing XR training found in the review. Kaplan et al. (2021) reports that these XR training have similar performance outcome to traditional trainings. Confirming that repetition and practice trough an accommodating learning style in XR have a proven effects on our ability to memorize instructions and task information to build the needed cognitive knowledge for the task, while building muscle memory.

At the same time VR in particular have been criticised for lacking sufficient haptics and physical feedback to develop motor skills well-needed in manufacturing (Kaplan, 2020) (Ipsita, 2025). This was also addressed as a challenge by most of the participants in the focus groups of paper A. In some cases, VR training has even reported no, or negative, transfer of knowledge when it comes to motor skills to the physical environment (Jensen & Konradsen, 2018) (Martirosov et al., 2021). Since simulating weight, tactile feel and touch in a virtual environment is notoriously difficult and significantly affects our ability to develop motor skills, suggestions of using MR or AR trainings, interacting with partly real and physical objects in motor skills trainings are made.

For the *affective domain*, far fewer (5 out of 60) XR training application in paper B was found. These primarily focused on training behaviour and attitudes tied towards safety or quality in manufacturing. Common for all of these XR trainings was that they promoted experienced based learning through a converging learning style. Outside of the manufacturing industry however, the topic of affective behaviour training in XR have received a lot more attention and its effectiveness as a medium to change attitudes and behaviour has been well established (Bailenson, 2018).

For instance, Hansdotter (2023) created BeEarth#13, a pro-environmental behaviour training in VR that allows the users to embody earth while experience stages of deforestation. In her study the students that underwent the VR behaviour training demonstrated significant higher degree of motivation to engage in pro-environmental behaviour and learning activities compared to the control group. In a similar study Slater et al. (2019) studied the effects of self-embodiment in VR trainings of personal traits, mental health and social skills. Students were able to embody a therapist (Simon Freud) while participating in an internal dialog with a 3D scanned version of themselves sitting across a table. The study confirmed the effects of VR, and particularly self-embodiment, in the training of personality traits, internal change and self-counselling. Future work in manufacturing XR trainings could compose of understanding how similar behaviour and social training should be applied for affective behaviour training in the manufacturing field. For instance, when training safety behaviour, emergency response, quality and standardized mindsets, conflict resolution and collaboration.

With XR we have the ability to use multiple senses at once to bend our perspectives and realities in very innovative ways to maximize our learning of new skills and behaviours. But as seen in paper B, the majority of XR trainings in manufacturing have taken a very pragmatic approach of translating already existing written training material and work instructions into a virtual instruction just visualized in XR (e.g. translating the physical IKEA instruction manual to a virtual instruction in VR for muscle memory training). Historically, the approach of reusing existing medium concepts and bringing them into a new emerging medium is not uncommon. The very first movies were recorded stage performances and theatres (Musser, 1994), many of the first TV broadcasts were of popular radio shows (Thomson, 2016) and many early internet sites were digitalized bulletin boards or newspapers. It is therefore not surprising that many of today's manufacturing XR trainings are following the same pattern and are based on physical work instructions or trainings from an older written medium. As the new technologies and mediums are explored, new ways of interacting with the technology and its content is developed and for XR it is just now being defined. The way we interact with XR content in the future could look very different from the way we interact and experience it today.

5.2 ADDRESSING RESEARCH QUESTION 2

RQ2: How can scalability be introduced in the development process of XR trainings for shop floor workers?

As seen in both paper A and C one of the major obstacles for large scale implementation of XR in the day-to-day operator training in manufacturing is the lack of scalability in the development process of the current available solutions. Without the possibility to scale or update the content of the XR trainings to new tasks or workstations with minimum effort, the financial argument for XR trainings will be difficult to make. A previous study conducted at the case company from Paper A and C by two previous master students of the author, found that creating an XR training for a workstation with a takt time of one minute took on average four hours to development in Unity (Boström & Zamola, 2023). For a company of similar size as the case company used in paper A and C, none of these lead times would be financially viable if they wanted to consider rolling out XR trainings widely on most of their stations. Hence, the case company used in paper A and C have been forced to leave many of their XR trainings on a pilot study stage and only prioritize crucial stations with special quality or safety concerns.

Similar observed was also made while carrying out the literature review in paper B as the majority of the VR trainings reviewed was developed custom made for the intended task in a game engine. Which confirms that high engineering effort and investments often goes into the development of, in many times, relativity simple and short training session. In paper C however, it was observed that the same training took 106 minutes for an experienced simulation engineer to create inside a virtual manufacturing software (IPS software suite) using conventional methods and 34 minutes with the proposed semi-automatic workflow leveraging PLM data structure presented in the study. This indicates that utilizing existing competence, libraries and data bases used in virtual manufacturing could substantially decrease the needed development time and efforts.

Some of the reviewed papers from the literature study in paper B also showcased alternative methods that arguably would require less engineering effort and investment, thus have the potential of being more scalable. For instance, Wall et al. (2021) explored exchanging part of the 3D models-based VR training to 360° video style VR training. Their study shows that whereas 3D model-based VR trainings allow for more interaction and higher involvement by the student it also more than quadruple the development time and cost compared to a to a 360° video style VR training. If *Seeing* is chosen over *Doing* as the preferred learning style, a 360° video style VR training should be considered as it is an inexpensive approach while affective for Diverging and Assimilating learning styles. Paulsen et al. (2024) further confirms the use of 360° videos as a tool to reduce the barrier of entry into VR trainings promoting Diverging and Assimilating learning styles. His review also established that 360° video-based VR trainings also allows educators and trainers to be in charge of the design and development of the VR training using only a video camera, as very limited programming or XR development experience is needed, leading to better pedagogics and learning elements in the training (Paulsen et al., 2024).

For trainings with learning styles promoting *Doing* (Accommodating / Converging), 3D model based XR trainings is most likely needed to allow for sufficient interactions and personal involvement by the student. Depending on the requirements of the trainings and the desired learning outcome these trainings will need various degree of customizability and custom features tailored for the task or workstation at hand. For instance, Lu et al. (2022) presented an experienced based learning experience for safety behaviour training working in hazardous conditions. This, and similar application, could be reused for several job roles in various fields of industry and does not necessarily need to be created with a specific job role, work site or company in mind. The same would be applicable for other trainings targeting generic manufacturing knowledge and behaviour such as safety, standardization (5S), LEAN, quality management etc. These concepts and trainings often remain similar across industries and are seldomly designed with a specific job role in mind but more generically applies to manufacturing in broad sense. By keeping the XR trainings generic without being job role or site-specific, only a one-time investment is needed company wide. The financial case could thus be easier to make and sourcing an off-the-shelf solution from a third-party supplier becomes possible.

For task specific training however, generic scenarios could not be applied and custom made XR trainings for the intended task is needed. Here the approach presented in paper C could be seen as a solution that would increase the scalability by increasing the automation in the creation process. Although, this approach is still subjected to further research to validate its workings and practical implications the findings in paper C shows positive results and significant time gain in the XR creation process.

The presented approach is however dependent on the company to have a mature PLM data strategy and structure as it is dependent on sufficient and correct documentation of work instructions in the BOP and the 3D CAD data in the BOM. Moreover, the data needs to be labeled in such way that a correlation between the explicit work instructions and the CAD files could automatically be drawn (e.g. using unique part numbers). The approach would also greatly benefit from the company already having an existing virtual model or digital twin of the intended workstation in a software that supports XR and PLM integration to directly make use of the automatic workflow. For companies currently lacking sufficient PLM documentation and virtual assets the investment for reaching sufficient maturity level to utilize this approach could be significant. By itself XR trainings would most likely not be able to justify the total investment, thus only making this approach feasible at companies with already high digital maturity.

As discussed in this section there are several ways to tackle the problem of scalability in the development process of XR trainings. This thesis emphasizes a pragmatic approach and to avoid over-engineering, practitioners should carefully consider alternatives and existing solutions before developing custom made fully interactable models. Depending on the applied learning style and intended learning subject or outcome more or less generic or interactive XR environments can be utilized.

5.3 CONTRIBUTIONS

Throughout the work composing this thesis, as well as the additional relevant papers and demonstrators carried out within the authors PhD Studies, it has become clear that there is a time and a place for XR training in manufacturing. The interest from industry have been high and so have the expectations on the technology to serve as an effective training medium. This thesis shows that in order to deliver on the expectations from the industry, while yet at a reasonable financial expense, we carefully need to consider how we design and adopt our XR trainings for manufacturing. Depending on the intended use case and learning outcome, various learning styles with different demands on the XR environment and its training content could be adopted. The students position on the learning curve also puts up different requirements on the XR environment and trainings.

The three stages along the learning curve introduced by Fitts & Posner (1967) focuses on skill acquisition by building muscle memory and motor skills while targeting the apply level of Bloom's taxonomy. This thesis proposes that XR training with accommodating learning styles could be used in all three stages with various degrees of immersion. The author's recommendation is to use VR technology in the *Cognitive stage* in order to create a safe, fully virtual training environment where mistakes have no consequences. As the student progresses along the learning curve towards the *Associative stage* more attention is given to motor skill, MR or AR technology is thus recommended to allow the student to train with partly physical objects to build correct motor skills and tactile senses. As the purpose of these trainings is to build task specific motor skills, they will need to be developed custom for the intended task, preferably using the methodology described in paper C.

Besides the three stages defined by Fitts & Posner (1967), Doolani et al. (2020) also proposed the use of XR technology in an even earlier stage of the training, being the *Introduction stage*. These are often onboarding or orientation trainings that target the lower end of Bloom's taxonomy of learning objectives, for which paper B shows that a learning style promoting *Seeing* is often applied in XR trainings. From a scalability perspective this could be a perfect case for 360° video styled VR trainings. Lund et al. (2023) studied the use of 360° video orientations of new manufacturing employees using smartphones and google cardboard headsets. The pragmatic and low-cost approach of virtual onboarding was seen effective in preparing the new employees for their new workstation and tasks.

Finally, as addressed by Ellström & Kock (2008), manufacturing skills does not only consist of motor skills and cognitive knowledge, but also consist of a series of affective factors, personal traits and social skills. This also opens up for a new set of trainings where XR could be applied in manufacturing. In this thesis the author has decided to group these into what he calls the *Affective stage*. Here XR trainings focusing on training manufacturing behaviour, mindset and communication can be applied. As seen in paper B these trainings often adopt a converging learning style and emphasize learning through experience, hence VR is to be recommended to be able to maximize immersion. With high level of immersion, methodologies from behaviour science in XR such as self-embodiment (Slater et al. 2019) (Bailenson, 2018) could be leveraged to solidify the new behaviour in the student. These trainings also have the potential to be applied across job roles, companies and industries. Thus, from a scalability perspective, this would open up for the possibility to source off-the-shelf solutions, avoiding custom built in-house applications. See Figure 16 for an overview of the purposed XR trainings made per learning stage.

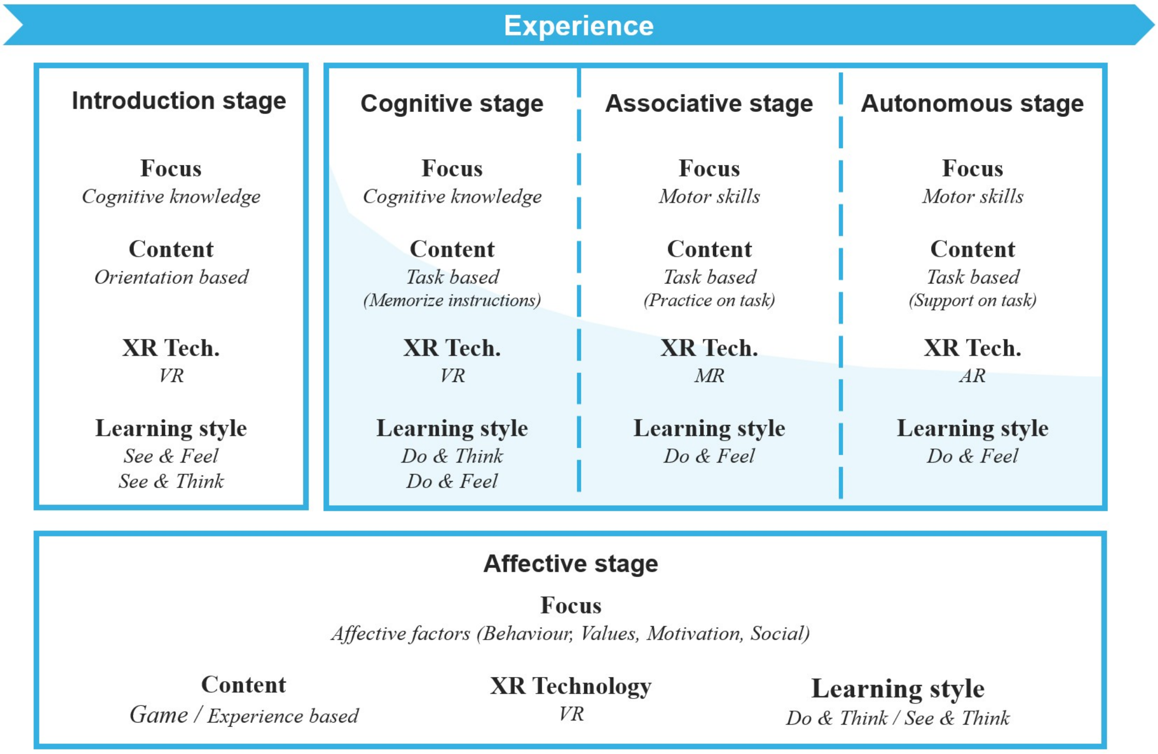

Figure 16. XR training per learning stage in manufacturing training

5.4 RESEARCH QUALITY

The research carried out as part of this thesis has primarily adopted qualitative methods using an inductive research approach. To safeguard research quality in this context Tracy (2010) proposes several criteria that should guid qualitative research. For instance, Tracy (2010) emphasizes that the topic of the research should be relevant, that the study should be rigours and sincere, that the results should be credible and resonance with the audience while carried out in an ethical way.

To ensure rigours and sincere results the studies of this thesis have a slight overlap and have been used collectively to answer the stated research questions. This means that several studies, with different qualitative methods, as well as additional sources have been used when formulating the results of this thesis to ensure rigours and credible results. Furthermore, to ensure relevance and resonance with the intended audience, the author has worked in close collaboration with industry and the intended end users.

The close collaboration with industry, and the authors internal drive to develop applications and research that can see implementation in a near future, has led to the usage of pragmatism. The pragmatic worldview is often criticised for not achieving the highest scientific quality. Hampson & McKinley (2023) highlights that pragmatism only considering evidence towards practical contribution and as a result this could lead to bias as researchers rejects findings that does not reach the desired practical outcome. Hence, the pragmatic world view is often being accused often only focusing on “what works”, failing in uncovering the “absolute truth” (Saliya, 2023).

In the research process, presented in this thesis, the pragmatic approach helped in the early exploration phase to quickly explore the research topic and draw early conclusions and to frame the two research questions. It also enabled to the author to quickly explore a broad theoretical landscape narrowing the scope and research towards a more well-defined area during the theory building phase. However, in the upcoming theory validation and theory refinement phases of the research a different scientific approach should be taken in order to reach the highest scientific quality.

5.5 METHODS AND LIMITATIONS

The formulation of the research questions started to develop in paper A, in which two focus groups with industry subject matter experts (industry trainers and training developers) were able to voice their concerns and challenges with XR adaptation. Allowing the industry needs to shape and guide the research from the start. The focus group participants interviewed for this study were all from the same company and all located in Sweden, which potentially could have left a one-sided picture of the concerns and challenges leading up to the formulation of research questions. However, the research questions have later been verified both in literature and in personal communication with peers and practitioners across multiple industries and geographical locations. The literature reviews, presented in Paper B and in additional paper 6 (Cao et al. 2025), gave a better understanding of the current landscape of XR trainings in manufacturing; its workings, use cases, and challenges. Allowing the author to zoom out and to incorporate a wider perspective on multiple geographical- and industrial domains. Strengthening the understanding of the identified challenges and the stated research questions.

In paper B knowledge- and learning theories defined by David Kolb (Kolb, 1984), Benjamin Bloom (Bloom et al. 1956) and Ikujiro Nonaka (Nonaka & Takeuchi, 1994) were used to map existing VR trainings in manufacturing towards knowledge creating mechanism and designs. This contributed to the theory building and the formulation of the answers to RQ1. The results towards RQ1 was therefore heavily influenced by the selection of referenced knowledge- and learning theories. The learning theories map by Millwood (2013) shows that this thesis only references a small part of the knowledge- and learning theories available. Additional theories or adaptation of the referenced theories would perhaps have put the results in a different light.

For instance, adaptations of Blooms taxonomy specifically developed for psychomotor skills (manual labour) exists and would arguably be more applicable to use in a manufacturing context (Simpson, 1972). However, these are less well-referenced, and the decision was made to keep referencing the original definition of Bloom's taxonomy to maintain high familiarity among practitioners and to avoid domain specific findings. Likewise, alternatives learning theories like the constructivism learning theory (Von Glasersfeld, 1989) have shown positive effective when applied in XR (Song et al. 2023) and could have been seen as a complimentary learning theory used in this thesis.

Besides the results presented in paper B, insights and discussions to RQ1 have also been derived through various other activities throughout the authors PhD studies. For instance, a study visits to the Virtual Human Interaction Lab at Stanford University in Palo Alto, USA, exposed the author to the topic of behavioural training in XR and the work of Prof. Jeremy Bailenson. Prof. Beilenson's research focuses on social science and the psychology of XR. His research has perspectives of XR trainings that are seldomly explored in the field of manufacturing. Interdisciplinary research, mixing insights from several fields of industry and social sciences, could lead to novel and creative solutions that would greatly benefit the manufacturing training field (Jyothsna, 2024).

The study carried out in Paper C acted as the main contributor to answer RQ2 when it comes to proposing a more scalable and automated approach to XR environment development. The study was carried out together with an automotive case company and the result of which was heavily influenced by the available data and PLM system at the case company. A replication of the study in another industry or at another company could have different results, making a generic assumption of the studies success difficult to make. However, it still highlights a possible way forward towards more automated XR training creation, acting as a benchmark and inspiration for other industries, while at the same time identifying several generic challenges. Furthermore, results to RQ2 also evolved during the work on paper A and paper B, where various XR creation methods were found and documented, providing insights into alternative methods. However, the literature review in Paper B was not designed with the explicit purpose of mapping content creation methods and thus the design of the study could have contributed to a limited scope of different XR content creation methods found.

So far, qualitative research methods have dominated the studied carried out as part of this thesis, with the purpose of providing a wide view of the current XR training landscape in manufacturing. Which, in the early phases of the authors PhD studies, has allowed the author to quickly catch up on the subject and propose early results and insights to the research questions. However, qualitative research only gives a picture of the current state and could struggle in suggesting improvements and actions (Easterby-Smith et al. 2018). Combining interdisciplinary research finding could help in proposing innovative solutions and actions (Jyothsna, 2024) and complementary quantitative research could verify and solidify the findings. More quantitative research, verifying the findings presented in this thesis, will encompass the later part of the authors PhD studies.

5.6 FUTURE WORK

Future work consists of validating the results of this thesis and the use of XR training through the various operator learning stages as proposed in Figure 16. This shall be done using empirical data in a deductive research approach. Furthermore, the results of this thesis have primarily been based on current industry practice and trends without extensive investigation the long-term retention of knowledge and skills acquired through XR training. The durability of learning outcomes and their transfer to real-world manufacturing contexts beyond immediate post-training periods remains unclear and needs to be verified throughout the identified stages on the learning curve. Thus, series of case studies testing and measuring the learning outcome and retention of XR trainings in each learning stage against a control group to verify the answers and results of this thesis is proposed.

The methodology of scalable XR content creation presented in paper C is also subjected to future work. Remaining challenges exists, for instance insufficient and inconsistent data labelling that could render the proposed solution useless. Therefore, future research should be put towards mitigating those identified challenges, potentially by utilizing an LLM, trained on PLM data, to interpret the work instructions and correctly identify and populate the XR environment thereby.

Furthermore, this thesis only addressed development time as the largest contributing factor to scalability in development. Meanwhile the decision by industry to investments in XR trainings is taken based on a cost-benefit analysis considering the return of investment (Berg & Vance, 2017). Therefore, a comprehensive cost-benefit analysis including hardware, maintenance and creation costs in relation with the gained value and benefits should be seen as a future work.

6
CONCLUSION

Lately, attention has been given towards XR trainings as one of the technologies that will help to battle the growing skill gap in manufacturing. However, literature shows that few efforts towards large scale adaptation by industry have been seen to date and most XR trainings remain on a low TRL. Uncertainties of the application, effectiveness and cost of XR trainings have left a threshold towards its implementation in industry. The aim of this thesis was thus to lower the threshold of implementation by provide a base understanding of when XR trainings could be applied and how they should be designed from both a learner's perspective and from a development effort perspective. This has been done by addressing two areas seen as major obstacles for industrial acceptance and adoptability.

The first area, addressed by RQ1, focused on minimizing the uncertainty of *when* to use XR trainings and *how* to design them from a pedagogical perspective to increase the learning and value of XR trainings in industry. The answer to RQ1 presented in this thesis showed that the there is a wide usage of XR training in manufacturing and use cases targeting eight different job roles in manufacturing were presented. Furthermore, the results show how the design of the trainings in terms of learning styles varies between the use cases depending on the learning objective and the knowledge transfer mode in question. Although the accommodating learning style is seen as most predominantly applied, the results show that there is no one-fits-all solution but the learning objective and the knowledge mode dictates the selected learning style and design of the XR trainings.

The second area, addressed by RQ2, focused on lowering the time spent on the development of XR trainings by introducing scalability and automation in the development process. This thesis showed how automation could be increased by leveraging existing PLM data and data structure. A proof-of-concept was conducted with promising results, achieving a 66% reduction in development time. Furthermore, leveraging AI models, and in particular an LLM, to mitigate challenges identified in interpreting PLM data was discussed as a future research direction enabling even bigger time reductions in the XR development process. Moreover, a discussion is held regarding the level of detail, immersion and customization of the XR environment that is necessary for the various learning stages and use cases, proposing other means of XR content creation with arguably higher potential of scalability.

The practical contribution of the thesis outlines an approach to XR trainings throughout the learning curve of the manufacturing operator. A recommendation for using VR technology and a converging learning style in the early phase of the learning curve was given. Meanwhile the AR/MR technology together with an accommodating learning style to train muscle memory and motor skills in the later stage of the learning curve was presented. Furthermore, experienced based affective training through a converging learning style in VR could be seen as a complement to the learning curve to train safety behaviour, quality mindset and soft skills.

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the script. The 3D texts were then visible in VR in IPS but only the one corresponding to the first step was rendered. In addition, a second Lua script was written, enabling the display of the next instruction with a click on the VR controllers. See Fig. 2 below for an example of 3D text automatically generated in IPS.

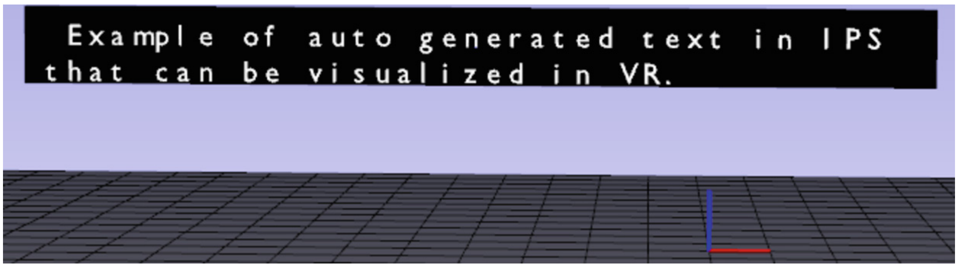

Fig. 2. 3D text in IPS.

4 VR Scene Set-Up

A script was executed for each part to be assembled by the trainee. The script would place the part in a predefined logistic position in the workstation, it would also create a transparent copy of the part in its assembled position, indicating to the trainee where to assemble it and once picked by the trainee in VR, the part could snap into its assembled position if held close enough to it. That snapping feature, available in IPS was also enhanced by the script, by adapting the control frame of the part automatically. In addition, the script would also create a motion of the part going from its stored to assembled position and a corresponding replay of the motion. All this is generated automatically by the Lua script. The motion associated with the different parts can be visualized in Fig. 3 below, where they are represented by white lines.

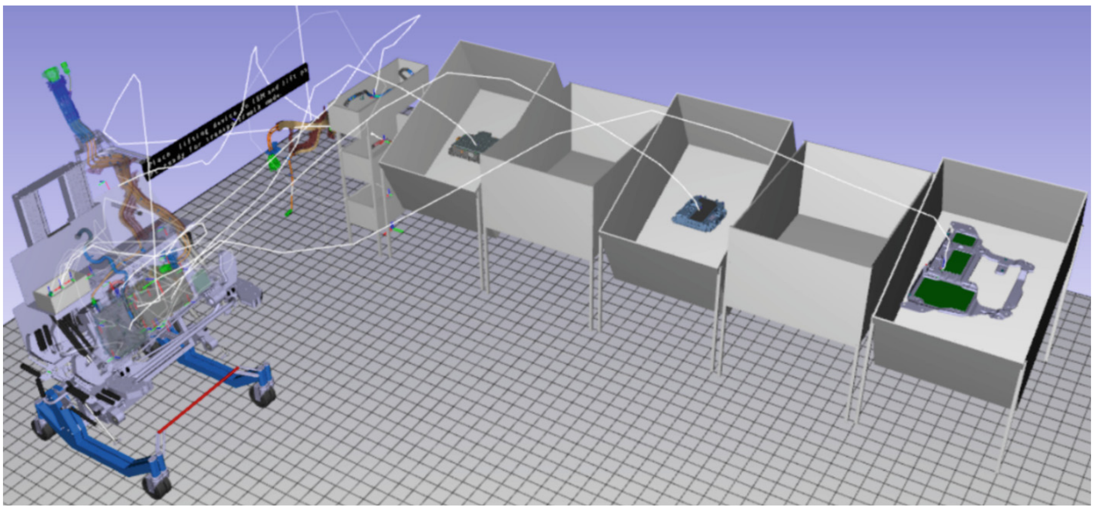

Fig. 3. VR training scene with the motions' paths displayed.

It should be noted that the second step began with manually placing the different elements to the places they belong, such as for instance, placing the assembly on the trolley, corresponding to the assembled positions of the parts. Identifying the coordinates of the stored positions of each part was also necessary and had to be done manually as well.

After executing this script for all the parts that are to be interacted with, the final step was to organize the motion's replays so that their order respected that of the assembly sequence's order.

5 VR Training Scene Overview

The VR training scene created had the following characteristics. It had a decent level of realism, as the layout in the virtual world was the same as the intended workstation. It allowed interactions between the user and the parts of the assembly and was populated with pedagogical elements, respectively the 3D text instructions and the visual cues (transparent copies of the parts in their assembled position).

When it comes to using such a VR scene for training, the first activity suggested would be to visualize the replay of the whole assembly. Then, the trainee would be invited to perform the steps of the assembly sequence, by picking the parts one by one, from their stored positions and placing them to their assembled positions, with respect to the text instructions that would have to be read and displayed one after the other after the completion of each step. Figure 4 below shows what it can look like when a trainee is in the virtual environment, performing the training.

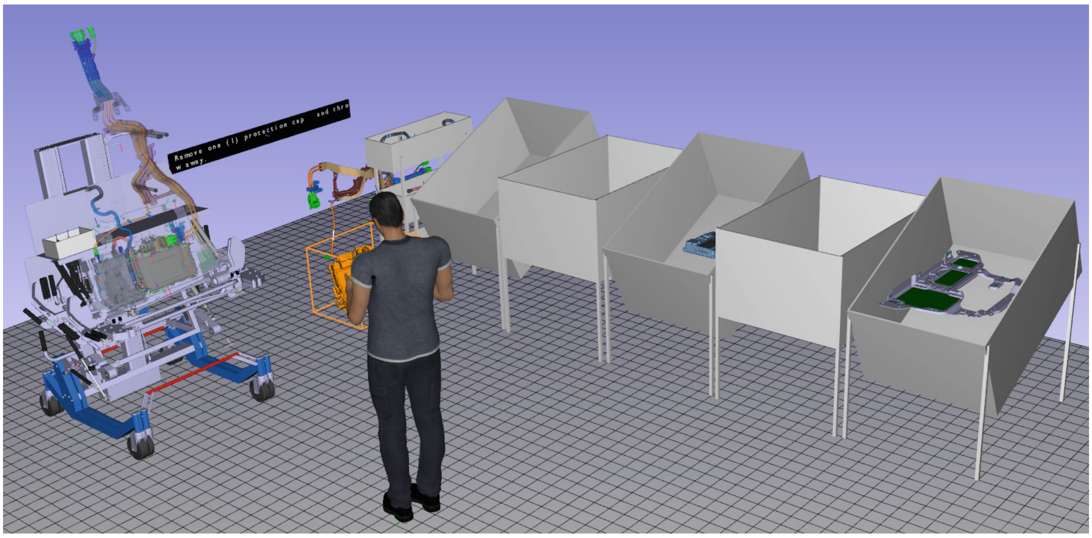

Fig. 4. Overview of the VR training scene, with a trainee represented as a manikin.

5.1 Benefits of the Automatic Generation Process

The time necessary to create the VR training scene using scripts to automatically generate parts of it was evaluated and compared to the time needed to create the same VR training scene manually. The results of the time comparison of the studied use case, consisting of 20 pick-and-place operations, are displayed in Table 1 below.

Table 1. Time comparison for VR training scene creation with and without scripting.

		VR training scene creation	
		Automatic generation	**Manual creation**
1	Environment re-creation	1min	1min
2	Geometries import	1min	1min
3	Pick parts in geometry tree	20*20sec	20min
4	Import of work instructions	1min	*na*
5	Motion start point definition	20*40sec	20*1min
	Snapping enhancing		20*1min
	Motions creation		20*1min
	Transparent copies creation		20*10sec
6	Sequence creation	4min	15min
	Sequence re-ordering		4min
	Total time estimate	*36min*	*106min*
	Normalized results	*0.34*	*1*

As can be seen in Table 1 above, the time needed for the creation of the scene is reduced by 66%. Furthermore, being proficient in using IPS is not necessary to use the automatic generation features, as the scene creation is performed automatically.

6 Discussion

In the ideal case, only one Lua script would have been written, that would, all by itself automatically generate the whole VR training scene. As some manual inputs were required, there were gaps in the automatic generation workflow, thus the need to create several scripts instead. Although, there are ways to try to fix the barriers to the automatic generation process.

For the VR training scene set-up, it was necessary to manually select the parts in the geometry tree structure and it was also required to manually reorganize the motions' replays. To have these tasks performed automatically by a script would necessitate taking better advantage of the data. Indeed, the csv file where each assembly step is detailed is enough to indicate the assembly sequence's order but the parts' names in that data source were not the same as the ones in the assembly CAD file. Should a link between these two data sources be implemented, it would be possible to automatically select the parts in the tree structure of the CAD assembly and also to organize their motions' replays in the correct order, without any additional input.

The remaining gap in the automatic generation process was the required input of the workstation's coordinates in reference to the assembly as well as the parts to pick. It was found that this could be acquired automatically if the CAD files used to constitute the stations' layout included location data of where parts can be stored relative to their geometries.

To minimize the gaps and automatize the VR training scene set-up, a future research direction could be to use AI (Artificial Intelligence). Using a Large Language Model (LLM) [20], one could train the AI to automatize the desired sequence and VR environment. By using common identifier and traces throughout the PLM system and virtual production system, AI could potentially support in identifying and map the data requirements found in Fig. 1. For instance, AI could be used to identify the correct CAD part in the BOM family tree structure as well as automatically identifying and visualizing corresponding work instruction from the PLM and BOP relevant for assembling said part.

Research on AI generated virtual environments have previously been discussed in literature and is currently under commercial development. For instance, Nvidia have introduced generative AI solutions to their Omniverse platform together with OpenAI. Enabling the automatic generation of virtual 3D assets and environments based on users prompts [21]. However, the use of generative AI introduces randomness and uncertainty to the 3D model. For training purposes, we ideally want to rely on actual data and models stored in our PLM to maintain accuracy to the real task replicated in the VR environment while still introducing a small level of randomness to the simulated task conditions to prepare operators for random events. Hence, creating a solution combining Omniverse generative AI solution with the connection to the real BOM and assembly instructions in our PLM system could be seen as a potential next step for this area of research. If doing so, we could see a big step towards automatic VR training generation and achieving a truly scalable solution. This would in its turn represent a big step forward towards increased cognitive support and augmentation of our operators enabling Operator 5.0.

7 Conclusion

This paper highlighted the data requirement for the creation of VR operator training scenes, which can be summarized as being, for each pre-identified station: CAD of the assembly and required tools, point cloud or CAD of the station layout and step-by-step assembly instructions. We also suggested a way to achieve the large-scale implementation of VR training, by putting in place a workflow that would prevent the two main identified barriers to its implementation, respectively time needed to create VR scenes and lack of specific skills. In fact, by using automation through Lua scripting in the selected use case, the creation time was reduced by 66%, even if there were some gaps in the automatic generation creation process, which means that the time reduction could be even more significant, should the identified issues be fixed in the future. Furthermore, using scripts that automatically generate the VR training scene leads to less skills needed, as mastering IPS is not needed.

The data needed to create VR training scenes are already available in most large manufacturing companies' PLM systems, furthermore, this paper showed that automatically generating elements of VR training scenes is already feasible, such as for the core of the scene mechanisms (enabling interactions with the parts in VR) as well as several pedagogical elements (visual indications and text instructions) based on assembly sequence and work instructions.

This new way of operator training creation appears to be more adapted to the fast-changing production requirements as it is based on automatic, and therefore quick, generation principles. Automatic VR creation for operator training could therefore be seen as a potential pillar for enabling the resilient Operator 5.0.

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