Industrial xReality (XR): Design, Application Scenarios, and Adoption Strategy in the Context of Industrial Maintenance
Alisa Burova

Industrial xReality (XR): Design, Application Scenarios, and Adoption Strategy in the Context of Industrial Maintenance

ACADEMIC DISSERTATION
To be presented with the permission of the Faculty of Information Technology and Communication Sciences of Tampere University, for public discussion in the Pinni B1096 on February 9th, 2024, at noon.

Faculty of Information Technology and Communication Sciences
Tampere University
| **Supervisor:** | Professor Markku Turunen, Ph.D.  
Faculty of Information Technology and Communication Sciences,  
Tampere University,  
Finland |
|-----------------|--------------------------------------------------------------------------------------------------|
| **Second supervisor:** | Docent Sanni Siltanen, D.Sc. (Tech.)  
Faculty of Information Technology and Communication Sciences,  
Tampere University,  
Finland |
| **Opponent:** | Associate Professor Pradipta Biswas, Ph.D.  
Centre for Product Design & Manufacturing,  
Indian Institute of Science,  
India |
| **Reviewers:** | Leif P. Berg, Ph.D.  
Mechanical Engineering Department,  
Iowa State University,  
USA  
Professor Philipp Rauschnabel, Ph.D.  
Institute of Organizational Communication,  
Universität der Bundeswehr München,  
Germany |

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Abstract

Emerging xReality (XR) technology, which encompasses Augmented and Virtual realities (AR and VR), blurs the borders between real and virtual, opening a yet undefined spectrum of benefits for the industry sector. Being one of the key drivers of 4th and 5th Industrial revolutions (Industry 4.0 and Industry 5.0), the adoption of XR has the potential to advance or even shift many traditional industrial operations to safe and sustainable technology-supported processes. This, in turn, leads to resource efficiency, overall optimization of industrial processes, and increased competitiveness, enforcing the desire to integrate xReality in the industrial context.

In the field of industrial maintenance, the application of XR technologies is commonly reviewed from two perspectives. Augmented reality, due to the possibility of visualising digital information in a context-sensitive manner, can aid the operations of workers in hazardous industrial contexts. This would increase their efficiency and occupational safety, positively affecting their well-being and performance. Virtual reality, which facilitates collaboration and realistic interactions with virtual objects in simulated environments, can be used to aid and enhance a large number of internal industrial operations related to product development and service design. This would help advance industrial collaboration and deeply integrate lean and agile methodologies, creating value creation and costs and other resources. Therefore, the application of AR and VR is expected to dramatically transform work operations in the field, leading to human-centricity and other positive impacts on organisational and individual levels.

However, the adoption of xReality has slowed down due to many factors, including, yet limited technological capabilities, human resistance to novel technologies, and the lack of unified design, development, and adoption practices. This dissertation aims to uncover hidden stones on the way to a smooth and responsible adoption of industrial XR to meet the requirements of Industry 4.0 and deliver maximum value to users and organisations. Based on action-based research in a tight academia-industry collaboration with KONE Corporation, a global elevator manufacturer and maintenance provider, this work provides generalisable knowledge on how to design and develop XR solutions, extracting insights from two case studies with domain experts. As an outcome, this work demonstrates the potential application scenarios of integrating XR in the context of
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industrial maintenance and suggests the design and adoption strategy, focusing on scalability and inclusion.
This dissertation wouldn't have come together without the collaborative effort of diverse, talented, and inspiring individuals. Their dedication, creativity, and energy played a critical role in the success of this project, delivering valuable and insightful data that laid the foundation for this work. The academic-industrial collaboration took place between the research center TAUCHI at Tampere University and KONE Corporation, a globally operating manufacturing and maintenance company from Finland. Over five years, we learned together, made new discoveries, generated numerous ideas and common research agendas, co-wrote, participated in events and conferences, and spent countless hours in meetings. Most importantly, we formed an amazing team based on trust, respect, and common understanding. I cannot express how grateful I am for this experience.

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you strive for perfection in all our joint work. The old good days at the office before COVID would not have been so warm and bright without you, and I miss it so much. I am grateful to have you in my life. Jaakko Hakulinen, who is no longer with us, was an extremely intelligent and pleasant person who formed a bond for the whole team. I still remember how I knocked on your door a hundred times, and you were always ready to help and explain difficult matters. We all deeply miss you. My colleagues and co-authors, John Mäkela and Kimmo Ronkainen, who were responsible for implementing the research software in coordination with research assistants, Topi Nieminen and Jesse Sydänmäki, this work would never see the light without your involvement. John and Kimmo, thank you for taking care of the technical side (and not only) of the project and your openness to create, develop, demonstrate, and redesign. Further, I extend my appreciation to all who were involved in Dynavis and HUMOR projects and funding acquisition.

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Tampere, January 5, 2024

Alisa Burova
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## Abbreviations

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<td>VR</td>
<td>Virtual Reality</td>
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<tr>
<td>AR</td>
<td>Augmented Reality</td>
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<tr>
<td>XR</td>
<td>xReality</td>
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<tr>
<td>AV</td>
<td>Augmented Virtuality</td>
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<tr>
<td>MR</td>
<td>Mixed Reality</td>
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<tr>
<td>AI</td>
<td>Artificial Intelligence</td>
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<tr>
<td>IoT</td>
<td>Internet of Things</td>
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<tr>
<td>IoS</td>
<td>Internet Services</td>
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<td>VE</td>
<td>Virtual Environment</td>
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<tr>
<td>CVE</td>
<td>Collaborative Virtual Environment</td>
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<tr>
<td>CPs</td>
<td>Centralized Production systems</td>
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<tr>
<td>CPS</td>
<td>Cyber Physical Systems</td>
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<tr>
<td>CPPs</td>
<td>Cyber-Physical Production systems</td>
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<tr>
<td>HMD</td>
<td>Head-Mounted Display</td>
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<tr>
<td>HUD</td>
<td>Head-Up Display</td>
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<tr>
<td>FoV</td>
<td>Field of view</td>
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<tr>
<td>HCI</td>
<td>Human-Computer Interaction</td>
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<td>CSCW</td>
<td>Computer-Supported Cooperation Work</td>
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<td>UCD</td>
<td>User-Centred Design</td>
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<td>UX</td>
<td>User Experience</td>
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<td>MVP</td>
<td>Minimum Viable Product</td>
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<tr>
<td>R&amp;D</td>
<td>Research and Development</td>
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<td>KPIs</td>
<td>Key Performance Indicators</td>
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<td>TAM</td>
<td>Technology Acceptance Model</td>
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<tr>
<td>3D</td>
<td>Three-dimensional</td>
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<tr>
<td>CAD</td>
<td>Computer-aided design</td>
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<tr>
<td>TD</td>
<td>Technical Documentation</td>
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<tr>
<td>MDD</td>
<td>Maintenance Development Department</td>
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<td>TDD</td>
<td>Technical Documentation Department</td>
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<tr>
<td>CRediT</td>
<td>Contributor Roles Taxonomy</td>
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List of Publications

This dissertation is composed of the five following original publications. The publications are reproduced here by permission and presented in chronological order. All research activities were performed in two projects: DYNAVIS and HUMOR between 2018-2022 years.


The Author’s Contribution to the Publications

This dissertation is a part of two research projects and would never be possible without my colleagues from the TAUCHI research centre (PIRG research group) and industrial researchers from KONE corporation. Table 1 shows the contribution of the authors based on the Contributor Roles Taxonomy (CRediT), while a more detailed overview of my contribution can be found on the next page.

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Table 1. Author contribution to the articles based on CRediT
Overall, all project work presented in this dissertation is a result of collaborative efforts: The success of the project is the outcome of joint work and contributions from both academia and industry sides. The author of this dissertation was responsible for management and organizational practicalities for both projects – e.g., organising the related research activities and events; planning, designing, and conducting user studies; analysing the results and reporting them. Every author’s plan or proposal was evaluated, validated, and advanced by colleagues and supervisors. The author did not contribute to the coding and technical development process of VR systems but was involved in the design and development process (e.g., ideating, designing, and testing of features) focusing on user experience and visual design.

I. This article describes the case study 1 on utilizing VR and gaze tracking for industrial AR-prototyping. In this article, I (Alisa Burova) contributed to the preliminary design of the user study procedure, and data collection methods (which were further iterated by senior academic and industrial researchers), as well as the moderation of the user studies. Additionally, I was responsible for the analysis of qualitative data and descriptive statistics, including data visualisation and drawing research outcomes. As well, I participated in and contributed to the development of AR-based in-field guidance from the perspective of interaction and visual design of the Documentation Panel and Safety warnings. As for the article, I was the leading author, who drafted the initial version (with input from colleagues) and finalized it prior to submission.

II. This article describes the collaborative design and development process of the COVE-VR platform. I was responsible for managing and organizing the collaborative process and related activities, including communication with industrial colleagues, creation of the methodology, which eventually led to the described framework. In addition, I was managing the design and development process of the COVE-VR platform, defining the functionality based on the needs of industrial experts, balancing between providing a good a user experience and resource-efficient development of needed features and delivering visual elements for the user interface. Similarly, as a leading author, I planned and drafted the article and iterated it prior submission based on the input of other authors.

III. This article describes the first user study with the COVE-VR platform on asynchronous collaboration. I have created the preliminary user study plan, procedure, and data collection methods (survey); the industrial tasks of the user study, as well as the interview questions, were created by industrial researchers. The plan was finalised in collaboration. Additionally, I have remotely observed user study sessions and analysed the survey data, including visualisations. Based on the observations,
analysis of the interview data, made by the industrial researchers, and the survey data, I have drawn the conclusion of the study and summarised the insight in a form of design guidelines on how to develop virtual tools. As the first author, I planned, drafted, and iterated the article based on the input of other authors.

IV. This article describes the second user study with COVE-VR with an asymmetric VR-Microsoft Team setup. I participated in the creation of the user study plan and data collection methods and remotely observed the user study procedure. In addition, I have analysed the survey data and, based on the observations and interview results (analysed by industrial researchers), I have created guidelines on how to support remote industrial collaboration with asymmetric VR. Asymmetric scenarios and the benefits of asymmetry were drawn in collaboration.

V. This article describes the third user study of COVE-VR on synchronous collaboration. I participated in the user study by creating a survey and commenting on the procedure. I have remotely observed the user study procedures and analysed the survey data. In the article, I have contributed to the Related Work section, Results section (reporting the survey data analysis), and proofreading of the manuscript.
Introduction

Today, technologies are becoming more ubiquitous and deeply integrated into human life, rapidly evolving to address the needs of humanity, and shaping the reality of today. Living in the era of the Fourth Industrial Revolution (Industry 4.0), we have observed the magnitude of the impact of technological development on humankind and planet. This, in addition to the positive impact, also initiated the realisation of the risks and dangers technological progress may possess.

"The machine does not isolate man from the great problems of nature but plunges him more deeply into them."
- Antoine de Saint-Exupéry

The field of human-computer interaction (HCI), which aims to enhance the interaction between humans and technologies, is becoming more important with the expansion of technology in all spheres of human activities (Card et al., 2018). As researchers, it is our direct responsibility to inform the design of technologies, so they not only deliver value and cater to the needs of target users but also have a positive effect on the society and the environment we live in. The same ideas are reflected in the novel concepts of Industry 5.0 and Society 5.0, which target human centricity, sustainability, and resilience through responsible technology development and multidisciplinary collaboration (Harayama, 2017; Xu et al., 2021). This dissertation is written with a personal motivation to achieve responsible xReality technology integration, and adoption, which would positively affect industries, businesses, society, and, most importantly, humans. To accomplish it, I aim to provide generalisable knowledge regarding the design, development, and adoption of industrial xReality technologies, targeting both academics and industrial practitioners.
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Novel emerging technologies of the mixed reality continuum (Milgram et al., 1994), such as Augmented Reality (AR) and Virtual Reality (VR), also widely referred to as XR or xReality (Rauschnabel et al., 2022), hold the undeniable potential to transform the world as we know it today. Due to the possibility to merge the border between real and virtual, these technologies can massively change work-related activities and industrial operations. As technology advances and becomes pervasive, potential use cases for the xReality application grow and appear to be highly beneficial to industrial companies. This is especially relevant for large manufacturers and service providers, whose traditional ways of working can be shifted into novel technology-supported processes, causing overall optimisation, cost and resource savings, and sustainability of operations (Chua, 2019; Jetter et al., 2018; Schina et al., 2016; Wolfartsberger et al., 2020). Furthermore, the adoption of XR technology is highly desired by industries and business, since it is a critical element of Industry 4.0 interventions and a key driver for Industry 5.0 ideology (Adriana Cárdenas-Robledo et al., 2022; Cifolilli et al., 2018; Müller, 2020).

In the field of industrial maintenance, in the context of which this dissertation is devoted, XR technologies possess many advantages to both in-field maintenance operations and other maintenance and service-related activities performed in an office environment. Maintenance operations have a significant impact on revenues (Haroun et al., 2009), while their reliability is a critical factor for company success and competitiveness. Therefore, the adoption of XR together with other emerging technologies is of high priority. In addition to staying competitive on the market, this would allow the transformation towards smart and digital maintenance practices, optimizing the company’s processes for the concept of Maintenance 4.0 and preparing the foundation for moving towards Maintenance 5.0 and Operator 5.0 ideology.

The adoption of XR technologies can positively affect in-field maintenance operations in many ways. The primary case is providing in-field assistance and guidance through various forms of augmented reality, including handheld devices (e.g., smartphones and tablet devices) and, specifically, head-mounted-based solutions that promote ‘heads-up’ interaction (de Souza Cardoso et al., 2020; Funk et al., 2016; Henderson et al., 2011; Palmarini et al., 2018). Due to the ability to visualise work-related instructions in a context-sensitive manner, AR can improve the speed, quality, and safety of maintenance work processes (Jetter et al., 2018). Furthermore, AR assistance increases worker efficiency by reducing mental and physical workload (Henderson et al., 2011). Another case is to enable communication and coordination between the on-site maintenance technician and the remote maintenance expert. This is already possible to accomplish via traditional tools, e.g., calls and video conferencing; however, both AR and VR may significantly benefit the communication
and advance the process of knowledge transfer (Guo et al., 2020; Palmarini et al., 2018).

**Virtual reality** is another critical technology in the context of industrial maintenance, since it is capable of facilitating realistic experiences in completely virtual environments (VEs). In particular, VR makes it possible to simulate any dangerous industrial context and replicate the natural interaction with industrial virtual objects (3D CAD models) and other people in a safe and controlled manner (Schwarz et al., 2020; Shaw et al., 2019). Often, in many industrial tasks and operations (such as training, product design and review, etc.), industry experts have limited or no access to actual industrial spaces or machinery. For instance, the required machinery might exist in a single copy, situated in a geographically distant location, which would require travelling, special permission, and safety training to visit it. The inability of industrial workers to visit and interact with a machinery in a realistic context can negatively influence work outcomes and increase the chance of error. Therefore, VR provides a solution to many industrial challenges and offers a way to advance industrial operations, where access to an industrial context is critical but complex or impossible in reality. Furthermore, the flexibility of virtual reality can transform and enhance the communication and collaboration activities of globally scattered industrial experts through the provision of a shared workspace. All the factors mentioned make virtual reality a viable technology to facilitate and advance many of the industrial scenarios. Coupled with the implementation of AR, the mix of technologies can drive the field of industrial maintenance towards a novel innovative transformation.

Despite all technological progress and verified benefits, **XR is not yet fully adopted in industrial settings**. Regardless of a large body of research and theoretical foundations, the practical knowledge on how to design and develop industrial XR platforms is fragmented from field to field, additionally complicated by a lack of generalisable knowledge on how to approach the integration of XR in the industry and how to adopt it to use in the daily work routine. The adoption of XR in industry is also affected by other factors. From one side, XR technologies are not mature enough to fully replace existing technology-supported practices, while the lack of infrastructure prevents a deploying of a stable XR work environment. From another side, human factors, such as technology perception, mistrust, and possible resistance to new technologies, multiply the barriers and slow down the pace of XR adoption.

In my dissertation work, I address these gaps by exploring how XR systems should be designed, developed, and adopted in an industrial context based on close collaboration with the industrial corporation KONE Oyj. Academy-industry collaboration is a valuable approach to
epistemically research the development and application of novel technologies in a real industrial context, which delivers mutual benefits for both parties. Industries driven by short-term goals and urgent timeframes often have no time and resources to deeply investigate how new technologies may truly benefit the organisation (Ryöppy et al., 2021). Additionally, there is a lack of knowledge and skills in how to design and adopt these technologies. The development of XR in the industry is rarely based on user studies and involvement of actual target users, but rather is being carried out relying on nonverified assumptions, driven by overall hype and competition. Academics, in turn, although having time and expertise to generate critical and verified knowledge on this topic, usually lack access to industrial employees and have a limited understanding of industrial operations. Therefore, uniting academic expertise and research methods with exposure to realistic industrial problems and access to industrial experts provides a valuable composition of factors to deliver relevant research findings.

In my work, the application of XR is addressed from two perspectives, based on two industrial case studies. The first perspective covers the exploration of AR for in-field guidance, particularly, how to design and evaluate it within VR. Despite a large body of research has contributed to this topic and delivered evident benefits of AR-based assistance (de Souza Cardoso et al., 2020; Henderson et al., 2011; Palmarini et al., 2018; Relji´c et al., 2021), the development of industrial AR solutions is still frozen in the “proof-of-concept” stage (Gavish et al., 2015), mainly due to the risks associated with testing in hazardous industrial environments. Consequently, there is a lack of generalized knowledge (Fernández del Amo et al., 2018) on how to design for safe and efficient in-field guidance, including the challenges of technical documentation representation (Siltanen et al., 2020) and evaluation. VR can partly address these challenges, since AR design and content (such as technical instructions and safety warnings) can be tested in a safe and controlled simulated environment, advanced by objective data collection, impossible or hard to collect otherwise - e.g., head movement and gaze data.

The second perspective covers the exploration of VR for industrial collaboration in the pipeline of technical documentation creation. In practice, this means integrating the industrial process of method development as well as documentation creation, and evaluation into virtual environments. Originating from the first case study and inspired by the potential of VR for product design activities (Berg et al., 2017; Schina et al., 2016; Silva et al., 2018), VR is applied to support the collaboration of global departments and teams, which potentially led to improved communication, knowledge sharing and effortless digital content creation (e.g., text, pictures, and videos in virtual environment)
Therefore, the novelty of my dissertation work lies in the adaptation of VR to facilitate industrial service-oriented processes: AR-prototyping and evaluation within VR and VR-based collaboration of departments, jointly working to deliver technical documentation.

1.1 Research Aims and Research Questions
Since this research topic was initiated in response to the real industrial challenge, it followed the applied research processes in close cooperation with KONE. The primary aim of this work was to uncover the opportunities, barriers, and influencing factors of industrial XR to accelerate the adoption of the technology in the field. Despite the proven potential of these technologies in the context of Industrial Maintenance, there are still hidden challenges on the way towards a complete and appropriate integration of emerging technologies into industrial work processes. While only a few companies are experimenting with XR to support their operations, there is no generalized knowledge on how to initiate the adoption process to ensure the delivery of short-term and long-term benefits for the organisation and workers. This also includes the lack of understanding in which situation and scenarios XR should be utilized and how it should be designed to address the industrial needs and requirements.

Augmented and Virtual reality in the context of Industrial Maintenance can be applied to address multiple purposes and optimize several scenarios, while maintaining connection and fluid data transfer between both technologies would be a key for effectiveness. Instead of investigating a single technology in the context, this work assumes that combined it delivers more value and attempts to build a holistic picture of how it can be integrated into industrial work processes. Therefore, one of the goals of the study is to verify the potential of XR technology and illustrate how it can shift traditional work processes. Therefore, the first research question is stated as follows:

RQ1: How do XR technologies potentially impact the field of Industrial Maintenance?

By answering this question, I am to provide a comprehensive overview of how augmented and virtual realities can be applied in line with Industry 4.0 interventions to transform traditional workflows into technology-supported practices and what would be the potential outcomes of integrating these technologies.

Since human factor plays a critical role in technology adoption, the second research question was formulated to understand how industrial employees perceive XR technology. Answering the second research
question would help to estimate the current vision towards xReality in an industrial context and draw action points to beneficially influence the technology acceptance.

**RQ2: How do industrial experts perceive the use of Virtual Reality and related technologies in the context of their work?**

Despite this work is built linking VR and AR together, the main research subject is still VR technology. Therefore, the study is concentrated on the exploration of how VR should be designed, developed, and utilized to address the actual needs of industrial workers considering the connection with other emerging technologies. This knowledge is further expanded towards xReality in overall, formulizing the third research question as follows:

**RQ3: How to design and adopt XR systems to address the needs of industrial workers and organisations?**

This question explores the technological aspects of XR technology adoption. By answering this question, I aim to provide practical implications on how to approach the design of industrial VR and AR, which would be generalisable to other industries and fields. Additionally, I aim to summarize the study results into practical suggestions and technological setups on how to adopt XR technology in the industrial context, focusing on the scalability and inclusion of different user groups in the process.

In summary, by answering the stated research questions, I aim to deliver practical knowledge, which would help to minimize the barriers towards the adoption of XR technologies in industrial settings and clarify the need and application scenarios of XR integration.

### 1.2 CONTEXT OF RESEARCH

KONE\(^1\) is the largest manufacturing and maintenance company in Finland, who produces solutions for people flow, including elevators, escalators, and automatic building doors. A large part of the company’s revenue comes from maintenance of the produced equipment, which guarantees the safety and smooth operation of KONE products during the whole lifespan. Therefore, reliable and efficient maintenance plays a crucial role in the success of the company, while the optimisation of maintenance services is among the main objectives of the company.

Technical documentation (TD), a concept arising from the field of Technical Communication, is a primary element of industrial maintenance,

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as it conveys educational information about maintenance methods and safety-related aspects. Technical documentation provides a base for learning, training, and constant support of methods for maintenance workers. The same TD is used both in training and in fieldwork, being represented in various forms and modalities (for example, on a printed paper, on a PC screen, tablet, or smartphone). Furthermore, the same documentation is reutilized in combination with XR technology: for example, with AR for in-field guidance of maintenance technicians, or in VR for training purposes. As follows, technical documentation as a concept links both extremes of XR technology into a single research topic.

The pipeline of technical documentation creation is itself a challenge, which takes a large part of the company’s human and other resources. The process is iterative and involves the collaboration between multiple departments, scattered over different geographical locations and working in different time zones. The optimisation of this process with the help of xReality technology potentially can solve many challenges and advance the quality of maintenance methods and technical documentation.

In summary, this dissertation focuses on the context of Industrial Maintenance and related exploration of the development, use, and adoption of technical documentation for various use cases. My work is built on the investigation of how to apply the technology of XR to both simplify the processes behind the service-related work routine in an office environment and how to use XR to advance in-field operations. By positively affecting the office routine of employees involved in the pipeline of maintenance methods and technical documentation creation, I aim to advance service delivery in the field.

1.3 Methodology
My dissertation belongs to the applied science of research, which stands on the intersection of Human-Computer Interaction (HCI), Computer-Supported Cooperative Work (CSCW), and Technical Communication (TechComms). It seeks to contribute to the academic and industrial research by delivering both practical and theoretical knowledge about the design and adoption of industrial xReality, as shown in Figure 1. To empirically address the stated research questions, this work is based on Action Design Research, working together with the industrial corporation and, therefore, applying scientific knowledge and research methods over realistic industrial cases. The driving force behind the work is the real industrial challenge, extracted from the industrial company.
The collaboration with KONE established certain restrictions and requirements on the research design specifics, such as a requirement to include only target users and domain experts to extract research data. This caused the major limitation and, at the same time, the advantage of the study. The case studies have a relatively small sample size, since recruiting participants among industrial workers is a complicated task. On the other hand, both studies have a high ecological validity, since all research activity was performed with domain experts, rather than with large samples of people without real knowledge of the context and work specifics.

Both case studies utilised a Mixed-Methods Research design, focusing on the analysis of qualitative data and supporting it by quantitative data. The summary of the research activities included in this dissertation is shown in Table 2.

The presented case studies were performed in an iterative manner and followed the same pattern. First, the experimental XR software (the XR Safety Kit from the first case study and the COVE-VR from the second case study) were designed following agile and user-centred design processes in collaboration among academic and industrial researchers. The design process was iterative and based on the involvement of industrial focus groups in the phases, which helped to identify the user needs and requirements as well as the specifics of the industrial context prior to implementation. The software was further validated and evaluated in different scenarios with varying numbers of expert participants. The results of the expert evaluations were analysed by both academic and industrial researchers, followed by collaborative discussions to formulate
the main study findings and practical implications. The findings from the previous cases were utilized to make improvements to the software and define the direction for future evaluations.

<table>
<thead>
<tr>
<th>Publication</th>
<th>Research Activity</th>
<th>Data Collection Methods</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Iterative case study #1</td>
<td>Semi-structured interviews, online and paper-based surveys, gaze data, and other objective metrics</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>Online survey</td>
<td>Video-based online survey</td>
<td>12</td>
</tr>
<tr>
<td>II</td>
<td>System development and validation</td>
<td>User-centred design process, workshops with domain experts, video-based online survey</td>
<td>18</td>
</tr>
<tr>
<td>II, III</td>
<td>Case study #2 (Scenario 1)</td>
<td>Semi-structured expert interview, pre- and post- online survey</td>
<td>7</td>
</tr>
<tr>
<td>IV</td>
<td>Case study #2 (Scenario 2)</td>
<td>Semi-structured group interview + pre- and post- online survey</td>
<td>20</td>
</tr>
<tr>
<td>V</td>
<td>Case study #2 (Scenario 3)</td>
<td>Semi-structured group interview + pre- and post- online survey</td>
<td>9</td>
</tr>
</tbody>
</table>

Table 2. Summary of the performed research activities

A more detailed overview on the study methodology and methods of data collection and analysis are presented in Section 4.1.

1.4 RESULTS AND CONTRIBUTIONS

This dissertation demonstrates the value and xReality application scenarios in the domain of Industrial Maintenance. Based on case studies, performed in equal collaboration with a large manufacturing and maintenance company, this work extracts practical and theoretical knowledge on how to design, develop, and adopt XR in an industrial context. Hence, my contributions would be valuable not only for academic circles, but also for industrial researchers and practitioners. The results of my work can be divided into three categories, each representing a single perspective of XR adoption.

Firstly, based on the performed joint work with the industrial corporation, I demonstrate the usefulness and efficiency of academia-industry collaboration as an approach towards XR software design and development. The joint forces of academia and industry deliver a unique set of skills and conditions to benefit both parties, and most importantly, to deliver a technical solution to address the actual needs of the industrial workers. To support and promote such collaboration, I provide a theoretical methodology adopted from user-centred design process and
practical implications on how to maintain the joint work of academic and industrial practitioners and, therefore, avoid the barriers of academia-industry collaboration. This contribution is explicitly described in Section 4.3.7.

Secondly, based on the expert involvement in the design and development process of experimental XR software, I provide practical knowledge in the form of design guidelines or implications to support several activities related to the adoption of XR. In detail, my findings would assist in designing AR-based in-field guidance and safety warnings, VR tools for industrial tasks and collaboration, and finally, in using the technologies smartly and cost-efficiently. The research data was extracted based on the involvement of domain experts, which ensures the validity and further generalisability of the results to other industrial contexts and domains. Therefore, the delivered practical knowledge would positively impact the adoption of XR by industries and provide further discussions and findings for other sectors. These contributions are explicitly described in Section 4.2.4 and Section 4.3.6.

Lastly, the major contribution of this work lies beyond the specific attributes of the developed XR experimental software, collaboration methodology or design guidelines, derived from expert evaluations. By answering the raised research question, I discuss how the application of XR would shape the field of industrial maintenance in the future and how industrial experts perceive the upcoming changes. These insights are shown in sections 5.1 and 5.2. Furthermore, by combining above-mentioned contributions into a foundation, my work delivers a holistic vision for XR integration and strategy on how to approach the design and adoption of XR technologies in the industrial context. The strategy is shown in Section 5.3.

1.5 Structure of the Thesis
This work is an article-based thesis, comprising five original publications. Nevertheless, with this work I provide a wider overview and additional data, which was not included in the publications. Therefore, the dissertation contains an extended and detailed description of the case studies.

The dissertation is structured as follows: first, I introduce the relevant theory and related work, divided into two chapters: one is technology-oriented (Technologies & Industrial maintenance) and the second one is human-oriented (Humans, Work and Collaboration). Next, I describe the case studies, starting from the general introduction and methodology, then going into each case study, separately describing the experimental software design and development, user study composition, and
presenting outcomes and contributions. The case study chapter is concluded by an overall summary. Finally, I provide answers to the stated research questions in Discussion chapter and summarize the work and contributions, outlining the future work directions.
The constant development of technology has a direct effect on society and industry, determining the ways humankind live and work (Ciffolilli et al., 2018). “The advance of technology is based on making it fit in so that you don’t really even notice it, so it’s part of everyday life.” Bill Gates, Co-founder of Microsoft Industry, which in a general meaning refers to a part of the economic system that produces material goods on a large scale, is a main driving force for economic and social development (Zizic et al., 2022). In over three centuries, we have observed how industrialisation processes are able to change the norms of society and work culture. A brief overview of industrialisation history demonstrates how the world was shaped by technological development. Starting with the 1st Industrial Revolution at the end of the 18th century, when people learned to mechanize industrial production with the help of water and steam power, going through the 2nd Industrial Revolution at the end of the 19th century, where the power of electricity was applied to shift towards mass production of goods and till the second half of the 20th century, when the 3rd Industrial Revolution, driven by nuclear energy, brought the rise of electronics and telecommunications, influencing in overall digitalisation and automation of industrial processes (Ciffolilli et al., 2018; Rüßmann et al., 2016; Xu et al., 2021). As an outcome, in about 300 years of industrialisation, the world
2 Technologies & Industrial Maintenance

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“The advance of technology is based on making it fit in so that you don’t really even notice it, so it’s part of everyday life.”

Bill Gates, Co-founder of Microsoft

Industry, which in a general meaning refers to a part of the economic system that produces material goods on a large scale, is a main driving force for economic and social development (Zizic et al., 2022). In over three centuries, we have observed how industrialisation processes are able to change the norms of society and work culture. A brief overview of industrialisation history demonstrates how the world was shaped by technological development. Starting with the 1st Industrial Revolution at the end of the 18th century, when people learned to mechanize industrial production with the help of water and steam power, going thought the 2nd Industrial Revolution at the end of the 19th century, where the power of electricity was applied to shift towards mass production of goods and till the second half of the 20th century, when the 3rd Industrial Revolution, driven by nuclear energy, brought the rise of electronics and telecommunications, influencing in overall digitalisation and automation of industrial processes (Ciffolilli et al., 2018; Rüßmann et al., 2016; Xu et al., 2021). As an outcome, in about 300 years of industrialisation, the world
has changed dramatically, leaving the agriculture-based society on the pages of history books.

### 2.1 Industry 4.0 in a Nutshell

Currently, humankind lives in the era of the 4th Industrial Revolution (also referred as Industry 4.0), boosted by the spread and worldwide immediate access to internet technology through personal computers and smartphones. This transition is further enforced by the concepts of pervasive and ubiquitous computing, enabling the context-aware and invisible integration of advanced digital technologies into various aspects of our daily lives, including industrial contexts. Pervasive and ubiquitous computing are related concepts that expand the traditional model of human-computer interaction towards a paradigm, where intelligent devices and information processing are transparently blended into living and working environments and everyday activities, creating seamless and all-pervasive experiences (Zhao et al., 2011).

![Figure 2. Pervasive interaction illustration (generated by DALL’E)](image)

**Industry 4.0**, firstly presented in 2011 by a group of German research, business and political representatives (Vogel-Heuser et al., 2016; Xu et al., 2021), is now the major factor to reshape the industrial and business world of tomorrow to an unknown magnitude, aiming at mass production, intelligent networking of machines and overall technology-driven optimisation and adaptability. The key element of Industry 4.0 is the transition from traditional centralized production systems (CPs) to decentralized Cyber-Physical Production systems (CPPs)(Rüßmann et al., 2016), virtualisation and digitalisation of industrial operations (Zizic et al., 2022). This way, the centralized decision making and control, typically made by human operators or management teams, would be replaced with a decentralized, interconnected, and data-driven process, which would promote flexibility, efficient use of resources, fast response to changes, and, therefore, enhance the competitiveness of industries (Henning et al., 2013; Vogel-Heuser et al., 2016). This transition is based on the expansion of the Cyber Physical Systems (CPS) concept – an integration of physical and virtual systems for intelligent control, monitoring and coordination.
(Monostori et al., 2016) - to suit the needs of the manufacturing sector, therefore, providing real-time feedback and supporting data-driven decision-making. Data-driven paradigm of Industry 4.0 reflects in utilizing data for value creation, established on technologies (for data generation, transmission, processing, and storage), and in value-creating technologies (e.g., data applications) (Orsolín Klingenberg et al., n.d.). The following value drivers of Industry 4.0 were defined: Resources/processes, Asset utilisation, Labour, Inventories, Quality, Supply/demand match, Time to market and Service/aftersales. (Industry 4.0 How to navigate digitization of the manufacturing sector, 2015). Each driver, representing an area of significant impact on manufacturing performance, can be addressed and improved by Industry 4.0 interventions. To accommodate this, other key components of Industry 4.0 include (Henning et al., 2013; Michael Rüßmann et al., 2015; Oztemel et al., 2020; Peres et al., 2020; Zizic et al., 2022):

- **Internet of Things (IoT) and Internet of Services (IoS)**, which facilitates real-time data generation, collection, and transmission by enabling the interconnectivity and communication among physical smart devices (sensors, actuators, mobile phones, etc), while providing access to data and web-based services for the manufacturers, customers, and end-users.

- **Big Data and Analytics**, which enforces IoT and provides a critical function of collecting, processing, filtering, and analysing of enormous quantities of diverse data generated by production processes.

- **Cloud Computing** would ensure the success of data management and data storage in a safe and efficient to support the operations of IoT and handle Big Data. Additionally, it would grant fast and equal access to programs, applications, services, system updates, and other critical materials at any given time while providing useful insights in the form of reports, advancing the work environment and overall efficiency.

- **Cybersecurity** or a set of policies, tools, and security concepts to ensure the protection of cyber environments and systems, data, and other organisational assets.

- **Artificial Intelligence (AI)**, which adds an intelligence factor and allows the establishment of smarter production processes via the capability to process and analyse complex and non-linear datasets in real-time, thus, enabling predictive maintenance and enhancing real-time process optimisation, decision-making, and quality control.

- **Advanced automation**, robotics, and enhanced human-machine collaboration. Powered by AI and IoT, robots are becoming more intelligent, flexible, and autonomous, which offers utility beyond teleoperations. Robots will become more dominant, being able to
independently operate in complex assignments, detect flaws in manufacturing processes, and make corrections to ensure the smoothness of industrial operations. Additionally, as robots are learning to cooperate and interact with humans and each other, they will become a part of the labour working side-by-side with human operators, assisting, providing relevant information, and ensuring the safety of operations.

- **Augmented and virtual reality**, due to the potential to blur the borders of real and virtual, is reviewed as the core of Industry 4.0 operations with a wide scope of application scenarios. AR is mainly seen as a tool to establish smart manufacturing functionality and enhance worker’s capabilities. VR and simulation, which are becoming more comprehensive and cost-efficient, would advance decision making and support the design of products and production systems. Together, the application of AR and VR would shift the nature of industrial tasks, increase the speed of processes, and minimize the corresponding number of errors and mistakes.

The application of above-mentioned technologies will also have a major effect on the development of new socio-technical infrastructures, resulting in a change of current human-technology and human-environment interactions at the workplace (Henning et al., 2013). Despite Industry 4.0 is hardly can be considered as “human-centric approach”(Xu et al., 2021), it aims to transform work organisation and work-and-life balance by empowering diverse professional and career development, upskilling and life-long learning (Henning et al., 2013).

“They will be machines that adapt to the needs of human beings and not vice versa. Smart industrial assistance systems with multimodal user interfaces will bring digital learning technologies directly into the workplace”

Wolfgang Wahlster, CEO of the German Research Center for Artificial Intelligence

In overall, the vision of future labour is based on minimizing human workload and routine via assistive technologies and providing more options for creativity and personal development, thus highlighting the role of human work in the innovation processes.

Following the hype of this transition, the latest economy, business, and governmental policies in European Union are highly interlaced with the concepts of Industry 4.0, aiming to redesign and transform the existing economical and socio-technical systems. As follows, many countries have already started to coordinate research activities and provide funding to support Industry 4.0 interventions, with Germany being a solo leader, followed by Spain, Italy, and the United Kingdom, together taking over 50% of cases. Finland, while representing 2.16% of participation, yet possesses
no significant capacity and considered a laggard in the field of Industry 4.0. (Ciffolilli et al., 2018)

2.2 Transition to Industry 5.0 and Society 5.0

Despite the potential of Industry 4.0 interventions for economic development and growth, a strong criticism from technic, economic, and social perspectives has emerged in the academic and industrial society. In particular, concerns were raised regarding the aspects of ethical and legal considerations, data privacy and cybersecurity, complexity, and costs of implementation as well as potential job losses, skill gaps, and resistance to change (Aoun et al., 2021; Mourtzis et al., 2022; Sony, 2020; Sony et al., n.d.). Most importantly, Industry 4.0 is a profit-driven paradigm, which focuses on manufacturing, and consequently, leads to business and industrial transformation, impacting society as an aftereffect, not as a core element. In the light of the current global crisis and the need for responsible innovation and cooperation to resolve it, a purely profit-oriented approach cannot be reasoned in line with the Agenda for Sustainable Development (Transforming our world: the 2030 Agenda for Sustainable Development | Department of Economic and Social Affairs, n.d.).

[Figure 3. Industry 5.0 core values (Breque et al., 2021)]

**Industry 5.0**, a paradigm, which originated as an extension of Industry 4.0, addresses the concerns mentioned above and highlights the importance of social and environmental needs for value creation via novel technologies (Müller, 2020). As follows, Industry 5.0, using industry as a driver to achieve societal goals, aims to create more sustainable, efficient, and flexible production systems, delivering mutual benefits for the industry,
its workers, and, most importantly, the society. This proposition is based on three core elements: human-centricity, sustainability, and resilience (Breque et al., 2021), explained in Figure 3.

Additionally, a related concept - Society 5.0 – which commenced in Japan in 2016, aims to address global challenges, such as inequality, injustice, poverty, and climate change, based on the blending of physical and virtual spaces with the help of ICT technologies (Breque et al., 2021; Harayama, 2017). This vision depicts “a super smart society” of the future, where people live in comfort and receive high-quality services, based on defined needs and with respect to their differences in age, sex, region, or language. The transformation towards Society 5.0 is led by a scientific and technological co-creation and innovation process, based on the multidisciplinary collaboration of industry and businesses, academia, government, and other related ministries and stakeholders (Harayama, 2017).

Industry 5.0 and Society 5.0 are value-driven concepts (Harayama, 2017; Xu et al., 2021), which review novel technology from the perspective of how it can positively affect everyone involved in the economic system: not limiting to industrial workers, consumers, investors, and other stakeholders, but also including the environment and the society (Breque et al., 2021). It aims to promote collaboration and co-creation to jointly create a sustainable and resilient industrial infrastructure linked to societal systems (such as economy, education, and health). To achieve it, the focus is set on the flexibility of production processes with respect towards the planet’s limitations, while placing the worker’s well-being in the centre of all production processes. (Breque et al., 2021; Mourtzis et al., 2022)

Industry 5.0, therefore, is expected to blend the accuracy and productivity of machines with creative thinking and proactive decision-making of humans (Maddikunta et al., 2022), envisioning a safe and efficient collaboration of humans and machines or robots at a workplace (Mourtzis et al., 2022; Zizic et al., 2022). To balance the human and artificial workforce, special attention should be paid to developing the skillset, knowledge, and ability to support humans in cooperation with machines while educating machines on how to cooperate and work side-by-side with humans (Breque et al., 2021). Technologies also can aid in the development of motivating and rewarding working environments to promote wellbeing at work (Lu et al., 2022). However, from the human-centred perspective, the aspects of technology acceptance and trust in technology are central for smooth technology integration. Human-centricity and mass personalisation can be truly achieved by emphasizing and establishing the role of the individual in technology development (Lu et al., 2022; Zizic et al., 2022), for instance in practical meaning it would
refer to directly involving employees in the design and development of technologies from the earliest stages of design (Orso et al., 2022).

The technology drivers of Industry 5.0 are similar to Industry 4.0, extended by mass integration and use of Artificial Intelligence and xReality (VR, AR, MR, simulation, etc), Co-robots and Wearables, Edge Computing, 6G and Blockchain technologies, Bio- inspired technologies, Energy efficiency, renewables, storage, and autonomy-related technologies and other (Breque et al., 2021; Maddikunta et al., 2022; Müller, 2020; Zizic et al., 2022). Some examples of application cases of Industry 5.0 technologies, driven by core values would be reflected in Intelligent Healthcare System, Smart Education, Disaster Management models, Supply Chain Management, Cloud Manufacturing and Smart Manufacturing/Production (Maddikunta et al., 2022).

2.3 Industrial Maintenance

Industrial maintenance is a set of technical and administrative actions to preserve, retain, repair, or simply keep in a good working condition industrial facilities, equipment, and machinery (Pradhan et al., 2006). It consists of activities such as inspecting, repairing, replacing, and upgrading components to prevent equipment failure, maintain production efficiency, and extend the overall lifespan of the equipment. Organisation of maintenance is a complicated activity, which refers to the management process of arranging resources (people, materials, technology, etc.) together, which consists of planning, organizing, implementing, and controlling phases (Haroun et al., 2009).

Maintenance operations can be generally categorized into corrective and preventive maintenance. Corrective maintenance occurs as a response to a problem or failure of the equipment, e.g., repairing activity; the main goal is to recover from the failure and return the equipment to the working condition. Preventive maintenance, in turn, aims to prevent failure via routine inspections, cleaning, and adjustments to equipment (Pradhan et al., 2006). Preventive maintenance may be further subcategorized into 1) predetermined maintenance, which follows the manufacturer’s recommendation to set the maintenance schedule, 2) condition-based maintenance, which relies on equipment monitoring to determine when maintenance is required and 3) predictive maintenance, which relies on data analysis and technology to anticipate equipment failure before it occurs (Legát et al., 2017).

Through the years, as technology develops, the field of Industrial Maintenance has gone through significant changes in activities and management practices. Maintenance 1.0, representing Mechanical Era, included repair and replacement of the mechanical components once they
fail, relying on corrective maintenance management. In the Electrical Era, Maintenance 2.0 evolved into maintenance and repair of electrical equipment, introducing the preventive maintenance strategy. Maintenance 3.0 originated in Computerized Era, in which maintenance computers were taken into use to achieve more efficient maintenance operations, introducing condition-based maintenance (Rødseth et al., 2017). As Industry 4.0 intervention empowers in industry, the field of maintenance has gone thought a massive transformation towards smart and digital Maintenance 4.0. The integration of IoT, Big Data and other technologies supported a major shift from corrective to predictive maintenance (Rødseth et al., 2017). This shift has a proven a beneficial effect, for instance, up to 70% reduction in equipment failures and a 12% decrease in repair time (World Economic Forum, 2019), whereas data-driven predictive maintenance is considered a fundamental element to positively affect some of the core value drivers of Industry 4.0, e.g., asset utilisation and service/after-sales (Industry 4.0 How to navigate digitization of the manufacturing sector, 2015). Maintenance 5.0 is the latest evolution of maintenance management, empowered by AI and AR technologies. Pursuing the value of Industry 5.0, it targets the overall increase in efficiency and effectiveness of industrial maintenance processes by emphasising the role of the human operator in the loop.

In overall, the application of novel technologies to the field of maintenance in line with Industry 4.0 and Industry 5.0 is expected to lead to a critical change in maintenance and human resource management. For instance, it can improve failure prediction, scheduling, and optimisation of service procedures while enhancing the ways of working for a human operator. This, in turn, would lead to changes in maintenance policies and regulations on organisational and governmental levels, which are required to address the digitalisation and the use of AI in the field. The integration of technologies would also change the role of the human operator, the required skillset, and the nature of the maintenance job (Silvestri et al., 2020; van Oudenhoven et al., 2022; Werbi et al., 2023). However, the exact spectrum of changes in the field can be only speculated nowadays; a more concrete picture would be clear after years of implementing and iterating the technologies.

Reliable and efficient maintenance plays a crucial role in the success of companies in large machinery industries. In addition, maintenance costs may significantly affect the company’s profitability and become a source of additional revenue (Haroun et al., 2009). The selection of the maintenance strategy, scheduling of maintenance operations, and maintenance technicians’ skills and expertise have a direct effect on the quality of maintenance services, whereas poor maintenance may influence in a larger number of breakages and failures, waste of resources and even shorter product lifespan (Nowakowski et al., 2019).
As an outcome, industrial maintenance as a research topic has gained a certain interest among engineering academic circles, whereas industrial companies strive to reach higher levels of maintenance effectiveness and performance while minimizing associated costs (Swanson, 2001). Considering the novel challenges in the field, such as 1) increased complexity of equipment and systems under maintenance and, correspondingly, increased duration time of maintenance tasks, 2) global scatter of equipment and human expertise and 3) shorter training and, consequently, lack of experience (Fernández del Amo et al., 2018), one way to achieve high-quality of maintenance service is to provide a better means of support to the maintenance technicians (Siltanen et al., 2020). One way to address it is through the lens of technical documentation.

Technical Documentation
During the Maintenance 1.0 era and the domination of corrective maintenance, workers tend to rely on their own skills, knowledge, and expertise to repair a machinery. With the evolution of maintenance and the related increase in complexity and variety of maintenance activities, the role of technical documentation became prevalent.

Technical documentation refers to the means of providing information, usually in a written form, about a product, system, or process (e.g., descriptions on how to install, operate, or maintain it). According to (Johnson-sheehan, n.d.), technical documentation can be categorised as 1) instructions (e.g., step-by-step description of how to perform a specific task), 2) specifications (also called “specs”, to provide a detailed overview of a process, such as product assembly) and 3) procedures / protocols, written to ensure quality and consistency of a specific process.

In the field of Industrial Maintenance, technical documentation is a primary element to support the inspection, troubleshooting, maintenance, and repair of complex systems and equipment. It delivers educational information in the form of step-by-step instructions, specifications, checklists, schematic illustrations, and pictures. As a result, technical documentation ensures an accuracy and safety of a maintenance task execution, increases the reliability of equipment, and ensures quality control. This, in turn, positively affects the performance of the worker and the overall quality of the provided maintenance services while decreasing associated costs (Mead, 1998; Siltanen et al., 2020).

The process of technical documentation creation, which is defined by the requirements and characteristics of the reader and the task under description (Johnson-sheehan, n.d.), may be complex and requires the contribution of several experts/ workers to the process. Systematic and consistent management of the documentation creation process is critical for successful outcomes (Mead, 1998). The process itself can be divided into the following six phases (Technical Documentation in Industrial
Environment - Its Importance, Challenges, Writing process, Tools, and Technologies, n.d.):

1) Analysis of the requirements: e.g., identifying the requirements for the document and target audience, specifying the complexity level and language style, studying any available input materials, verification with domain experts or other stakeholders,

2) Design, including drafting templates, formatting, and estimating the needs for the content,

3) Development of textual content and illustrations,

4) Technical review of the created document for relevancy, accuracy, and logic

5) Proofreading to check the grammar, information presentation, formatting, and other aspects,

6) Publishing, which is based on the requirements (e.g., for printing or electronically) for further distribution

Traditionally, technical documentation consisted of textual instructions and black-and-white illustrations and was conveyed through paper and printed electronic materials (Siltanen et al., 2020; Stock et al., 2005). More recently, it became possible to use online mediums to access technical documentation, such as web-based portals and online services. This, in turn, provided more freedom for information visualisation and influenced the documentation to become more visual (Gattullo et al., 2022). Providing technical documentation online may have certain advantages over the traditional paper-based format, such as support for quick updates and revisions and access to it from anywhere via smartphones or other handheld devices. However, due to the nature of maintenance work (hands-busy), novel ways of delivering technical documentation to the field are necessary. (Heinonen et al., 2021; Siltanen et al., 2020; Stock et al., 2005) This can be addressed via novel immersive XR technologies.

2.4 xREALITY (XR)

Virtual Reality (VR) and Augmented Reality (AR) technologies are widely known in academia and industry as technologies, which are able to blur the border between real and virtual, enhance the reality, or fully replace it by means of computer-generated data. Despite the technologies have certain differences, they all possess one common characteristic: providing the means to expand the possibilities of the real world and delivering an endless spectrum of opportunities to transform and enhance human experiences in all domains of human vital activities. xReality promotes and advances the use of multimodal interaction - interaction with a digital system via different modes of communication (by stimulating different
human senses), such as speech, touch, gaze, gestures and even smell. This provides the means for more natural, intuitive, and efficient all-pervasive interaction in comparison to traditional computer and smartphone interfaces.

“The believability of virtuality is oft superior to the unrealness of reality”

– Vineet Raj Kapoor

The first mentions of VR and AR technologies are dated in the middle of the 1900s, however, through years this topic caught more attention, prevailing in military and academic research (Cipresso et al., 2018; Liu et al., 2018) and providing concrete definitions of technology as well as variations of end-devices and use cases. In 1994, Milgram and Kishino introduced the virtuality continuum (Milgram et al., 1994), which connects and represents the technology transition from completely real to completely virtual environments. In addition to AR and VR, which are situated on the extreme sides of the continuum, the article introduced Augmented Virtuality (AV) (e.g., the synchronisation of a virtual world and real objects) and united AR and AV to the term of Mixed Reality (MR): everything that comprises the fusing of real and virtual worlds. (Milgram et al., 1994; Speicher et al., 2019)

![The Virtuality Continuum](image)

**Figure 4. Reality-Virtuality Continuum**

**Defining xReality**

As the technology was developing, introducing new devices, interaction techniques, and application cases, a high number of related concepts (such as “Assistive Reality” (Raghavan et al., 2018), “Digital Reality” (Immersive technologies of the new digital reality | Deloitte Insights, n.d.), etc), definitions and reflections, coupled with a variety of devices, branding strategies and labels, were produced by academia and industry. This notion led to the absence of universally agreed definitions, the inconsistency in the way the terms are used in different fields, and, as a major flaw, resulted in a general misconception of the meaning behind the terms (Rauschnabel et al., 2022; Speicher et al., 2019). This emphasizes the need for a globally accepted framework (Rauschnabel et al., 2022), which is especially critical
once all modalities and human senses come to the scene of virtually advanced experience.

Despite AR and VR technologies have integral differences and should be considered as different experiences (Rauschnabel et al., 2022), the link between the technologies is becoming more obvious, which led to the creation of Extended Reality definition. According to (Raghavan et al., 2018), Extended Reality refers to all real and virtual combined environments and human-machine interactions powered by wearables and computer technology. This definition, promising to reduce the associated complexity, boomed as an umbrella term to describe AR, MR, and VR (Alcañiz et al., 2019; Chuah, 2019), especially in non-academic literature. Nevertheless, this definition was confronted by certain academic circles, since the word “extended” does not truly reflect the meaning of virtual reality, where experiences happen in a fully generated virtual environment. To avoid further dissonance, it was proposed to use XR or XReality, where X is a placeholder for “all” new reality formats (Rauschnabel et al., 2022): the presented framework separates VR from AR based on the importance of the physical environment on user experience and introduces the dimensions of “local presence” for AR and “telepresence” for VR, consequently.

This framework will be utilized in my dissertation to demonstrate the applicability of XR technologies (both AR and VR) in the field of Industrial Maintenance, whereas XR or xReality will be used as terms to define both AR and VR.
Virtual Reality

Virtual Reality (VR), also referred as virtual world or virtual environments (VEs), has received several definitions thought over the years, such as “an interactive, participatory environment that could sustain many remote users sharing a virtual place” and facilitate “immersive multisensory experience” (Gigante, 1993) or “real-time interactive graphics with three-dimensional models” which provides direct manipulation and a sense of immersion to the users (Bishop et al., 1992). In simple worlds, VR refers to computer-generated 3D worlds, which can facilitate reality-like experiences by affecting and replacing human sensory perception via synthetic cues. To do so, a VR system should consist of a set of input / output devices or displays (visual, auditory, haptic, and most recently, olfactory) and a tracking system, managed by a dynamic database for synchronisation and continuous rendering (Slater, 2009).

Based on the xReality framework, telepresence (“the degree to which a user feels present in the virtual rather than the physical environment”) (Rauschnabel et al., 2022) can be used as a decisive factor to classify VR experiences in a simplistic manner. As follows, the lower degree of telepresence would happen in Atomistic VR, where the completion of some task rather than a quality of the user experience is a primary goal. Holistic VR, on the contrary, emphasizes the realism and quality of virtual experience, almost identical to a real-world experience.

Experiences in VR

As summarized by (Cipresso et al., 2018), the major features that affect virtual experiences are: 1) immersion, 2) presence, and 3) interaction with a virtual environment. Immersion, or the feeling of being physically present in a virtual environment, directly depends on how well VR system isolates the user from the real world and simulates users’ senses via technological aspects (Slater, 2009). Various degrees of immersion affected the development of the following categorisation of VR systems (Cipresso et al., 2018), making it possible to compare the characteristics of different VR systems:

- **Non-immersive VR** (typically, a low-cost technological setup to access a virtual world via a 2D computer desktop and easy manipulation via keyboard and mouse);
- **Semi-immersive VR** (projection of a virtual world over a real environment, such as CAVE or Fish Tanks),
- **Fully immersive VR**, meaning all-pervasive and close to reality experience, usually based on a head-mounted display (HMD) usage.

Head-mounted display is the most popular device to enable virtual experience, firstly introduced by Ivan Sutherland back in 1965 (Sutherland, 1965), and nowadays being mass produced by multiple organisations.
As VR is supplemented with a human body (hands) in VR, grab and move virtual objects (Slater, 2009). The combination of visual, audio, and other cues enforces a sense of spatial awareness and makes it seem as if the user is physically present in the virtual world.

Figure 6. Virtual Reality users wearing HMDs (pictures generated by DALL’E)

**Presence** in VR is a similar concept, which originated from the concept of telepresence, “a sense of being there”, e.g., being in a different place than the physical body is located (Slater et al., 1997) or even “transportation of consciousness” into a virtual world (Sanchez-Vives et al., 2005). It is also argued that presence is characterized by the realism and correspondence of actions in VE, e.g., the sense of “doing” than “being (Sanchez-Vives et al., 2005; Zahorik et al., 1998), which is further affected by display parameters, realism of visual, sound, and haptic elements, virtual body representation and engagement (Sanchez-Vives et al., 2005). In general, the feeling of presence is affected not inclusively by the technical aspects of the system, but also is tightly connected to human perception processes and how the sensory stimuli presented by a virtual environment are interpreted by an individual (Doerner et al., 2022). In particular, expectations as well as personality and psychological differences affect reality judgment, realism of the experience, and the number of feelings and sensations (Baños et al., 2009) and should be studied to investigate the presence in VR. Additionally, *user preferences* were emphasized by (Jung et al., 2021) to be another important indicator to influence presence and overall experience in multisensory VR, especially critical for the business perspective.
Another critical characteristic of VR is the ability to immerse multiple remote users into a shared virtual space. Such VR systems are usually referred to as Collaborative Virtual Environments (CVEs) (Churchill et al., 1998). The distinctive feature is that CVEs accommodate the purpose of collaboration, and thus, should represent information in an appropriate manner and deliver a context for collaboration as well as communication tools (Churchill et al., 1998). As VR is supplemented with a human-to-human interaction, additional influencing factors are added to the scope of virtual experiences, such as a feeling of participation or co-presence, which refers to “being in the same place with others” and collaborating with real people. Another extended concept related to multiuser VR is social presence, referred as the perceived ability of the environment to connect people (Nowak, 2001), or simply “being there, engaged together” (Jung et al., 2021). Both characteristics are critical for a social virtual experience to achieve positive communication outcomes and depend on the immersive and contextual features of the system (Oh et al., 2018). Particularly, self-representation in VR via avatars and visual representation of others, have a direct impact on co-presence and social presence [8,35].

In collaborative settings, the appearance of the avatars (e.g., realism) and their functionality (e.g., facial expressions, head and hand gestures) was found to enhance the feeling of co-presence. On the opposite, another study reported that in competitive settings, the appearance of the avatars had no such effect, whereas the locomotion of the avatar had (Freiwald et al., 2021), which suggested that nature of the task in VR would define the correlation between visual representation in VR and the effects of co-presence.

It was further argued that the coherence of virtual environments, e.g., internal logic and consistency, including the realism of experience, also known as fidelity (D. J. Harris et al., 2020), has no direct positive effect on immersion or presence, and thus, can be treated as an independent dimension. Based on this notion, Jung and Linderman (Jung et al., 2021) proposed three characteristics: immersion, presence (including co-presence and social presence), and coherence to be the major components to evaluate the quality of virtual experiences, linking the system, context, and illusion.

In summary, despite a large body of theoretical knowledge on experiences in virtual reality, there is still a lack of practical knowledge on how to design and develop VR systems. Some UX guidelines for designing VR applications are present in the literature (Vi et al., 2019) and can be found over the web (Leap Into VR/AR Design | Toptal®, n.d.; Virtual Reality (VR) Design & User Experience | Adobe XD Ideas, n.d.). However, this knowledge is not sufficient to aid technology adoption, especially regarding designing industrial VR systems.
Augmented Reality
Augmented Reality was defined in the late 90s by Azuma et.al. (Azuma et al., 2001), as a system that in real environment and in real-time interactively combines and registers real and virtual objects. In contrast to VR, AR advances the reality by augmentation, whereas all interactions happen in a real context, thus providing a different nature of experience (Rauschnabel et al., 2022). To include virtual objects in a real environment, AR systems consist of a display (visual, auditive, etc) and a tracking device (e.g., camera) (Cipresso et al., 2018); the visualisation happens over a surface, or a designated location based on a geospatial data of the object and requires sufficient processing power for displaying computer-generated graphics and merging it with real environment (Carmigniani et al., 2011).

According to the xReality framework, local presence or “the degree to which a user experiences AR objects as being actually present in his or her own physical environment” (Rauschnabel et al., 2022) is a base factor to classify AR experiences. Thus, on the lower extreme of the local presence, AR is defined as an assisted reality, where the augmented objects are perceived as artificial elements, which provide some knowledge about the physical surroundings without merging with it. On the higher extreme, AR can be defined as a mixed reality, where physical and virtual merge into one matter.

AR-based experience
Nowadays, AR is a widely known technology, which has evolved from passive overlaying computer-generated information over a real context towards a more active interaction with virtual content, which blends with
real world settings (Ghazwani et al., 2020). Nowadays, AR is being mass used on handheld devices (e.g., smartphones and tablet devices), whereas more immersive AR-systems, based on projection, or AR headsets (also called Head-Up Displays (HUDs) or see-through displays, such as Microsoft HoloLens, Magic Leap, etc) are less explored. HUDs are seen as the most promising technology for AR-based interaction, which can change human-machine interaction in many scenarios, especially in an industrial context (Carmigniani et al., 2011; de Souza Cardoso et al., 2020; Devagiri et al., 2022).

Figure 8. Augmented Reality users wearing See-Through Displays (pictures generated by DALL'E)

In see through displays, virtual content can be augmented in front of the users’ eyes, which in turn provide seamless and natural “heads-up” interaction and free hands for other activities (Devagiri et al., 2022). However, several barriers restrict the development and mass adoption of “heads-up” AR displays, such as user acceptance of the technology, user - experience-related issues (lack of seamless and natural interactions and interfaces, ergonomics of AR-headsets), and content-related issues, development complexity and costs, and other technological and hardware limitations (e.g., limited field of view, low resolution of projected virtual content, poor and inaccurate tracking, low battery capacity and power capabilities) (Abhay S. Prajapati, 2019; Carmigniani et al., 2011; de Souza Cardoso et al., 2020; Ghazwani et al., 2020).

Despite the fundamental differences between AR and VR experiences, the quality of AR experiences can be measured based on the same criteria: via immersion, presence, and coherence components (Cipresso et al., 2018). Immersion in relation to AR-based experiences is re-conceptualized as a feel of being in a digitally enhanced environment (Dede, 2009) or, in general, the degree to which the user is emotionally and cognitively engaged in an activity or process (Weibel et al., 2010). Thus, the difference is that the experience quality evaluation would be directed towards interactions on the edge of virtual and real: how user expectation corresponds to actual experiences, how intuitive and logical these
experiences are, how user preferences are addressed, etc. In overall, the quality of AR-based user experience can be enhanced through the lens of the user specifics (passive vs. active), the user interface, and computer-generated content (Ghazwani et al., 2020).

2.5 INDUSTRIAL xREALITY: OPPORTUNITIES AND CHALLENGES

In the early 1990s, VR and AR technologies gained interest among industrial practitioners and started to be applied in industrial settings. Through years, the technologies have shown their potential and have been adopted in various industries and domains, such as but not limited to: construction and architecture (Lopez et al., 2022; Tea et al., 2021; Y. Zhang et al., 2020), automotive, aerospace and maritime (Clergeaud et al., 2017; Liu et al., 2018; Schwarz et al., 2020), manufacturing and maintenance (Guo et al., 2020; Siltanen et al., 2020; Webel et al., 2013), retail and fashion (Silva et al., 2018), healthcare and safety (Chen et al., 2021; Lopez et al., 2022), education and research (Suh et al., 2018), energy and environment management (Francisco et al., 2019; Suh et al., 2018), recreation and tourism (Chung et al., 2015).

**Figure 9.** Industrial XR use case (the pictures were generated by DALL’E)

Virtual reality, due to the ability to fully replace the real world with computer-generated content, has demonstrated its’ utility to facilitate a large variety of industrial operations and tasks. Simulation and modelling, known as one of the drivers to support planning, decision-making and boost innovation in line with Industry 4.0 (de Paula Ferreira et al., 2020), provide even more opportunities in VR. VR-based simulations are widely used in healthcare, aviation, military, manufacturing, and construction, where they are used to simulate operations, impossible or hard to replicate (Adriana Cárdenas-Robledo et al., 2022; Gao et al., 2019; Liu et al., 2018; Tea et al., 2021). For instance, they are used for flight, military and tele-operated simulations and training (Liu et al., 2018; Xie et al., 2021), construction site simulations (Murray et al., 2003; Zaker et al., 2018), or for smart factor assembly and maintenance operations(Cortés-Leal et al., 2022; Dornelles et al., 2022; Monetti et al., 2022). The major advantage of VR-based simulations is providing a highly immersive experience in a fully 
synthesized industrial environment, which are safe and controlled (Schwarz et al., 2020). This allows learning and practicing hazardous tasks or performing complex operations without being exposed to risks and dangers, which positively affects workers overall occupational safety, and reducing the risk of accidents and injuries (Ayala García et al., 2016; Gao et al., 2019; Shaw et al., 2019). Another outstanding benefit comes from the fact that such tasks and scenarios would be difficult, expensive, or even impossible to perform in the real world, making VR so desired and required technology.

Another widely known application case of VR in industrial settings is to aid the design process for complex product development and associated services, where the usefulness of VR is definite. Multiple industrial fields have been experimenting and adopting VR in various stages of product design and development over the last decades (Berni et al., 2020; Kovář et al., 2016; Maher, 2011; Wolfartsberger, 2019; Wolfartsberger et al., 2020; Zaker et al., 2018), demonstrating that VR is a powerful production tool to support and bring benefits throughout the whole production lifecycle (Berni et al., 2020). The application scenarios include, but are not limited to: product management, 3D modelling and virtual prototyping, conceptualisation and co-design activities, immersive product testing and evaluation, manufacturing process review, and collaborative design review (Berni et al., 2020; Guo et al., 2020; Schina et al., 2016). In the early design phases, VR enhances the sense of scale because of the simulated context and allows natural interaction with virtual prototypes in a 1:1 scale, which helps to identify critical design flaws that are typically overlooked by traditional computer tools (Guo et al., 2020). Additionally, the use of VR for conceptualisation and design in collaboration has proven to enhance decision-making, communication, and knowledge transfer among multidisciplinary teams (Berg et al., 2017; Wolfartsberger, 2019; Wolfartsberger et al., 2020). Furthermore, collaborative the design reviews enhance design for maintainability, which ultimately leads to improved design optimisation and decreased overall costs (Di Gironimo et al., 2013; Stapelberg, 2016). In summary, the use of VR, when applied to support product development, potentially optimizes all industrial activities under the scope of development, decreases the duration and costs of it and minimizes the number of design errors (Berg et al., 2017; Germán Frank et al., 2019; Stapelberg, 2016).

**Augmented reality**, due to the possibility to blend computer-generated content over realistic surroundings, has addressed industrial challenges from another direction. AR is able to deliver context-sensitive data to industrial hazardous environments and, thus, enhance situational awareness, which reflects in the major application cases. As follows, AR is primarily used to address the tasks of manufacturing, design and service operations, and training as well in marketing and sales; the scenarios
include, but not limited to (de Souza Cardoso et al., 2020; Nee et al., 2012; Reljić et al., 2021): assembly and maintenance work instructions, robot programming and operations, process monitoring and simulation, training, ergonomics and safety, quality inspections and assurance, and many other.

In manufacturing and Smart Factory environments, workers can use AR to see real-time information about machine status, production line efficiency, and quality control, which is beneficial for monitoring and decision-making (Damiani et al., 2018; Reljić et al., 2021). AR is especially valuable for assembly, maintenance, and repair tasks, as it aids workers with multimodal instructions (e.g., in the form of text, pictures, animations, sound and video), which are more intuitive and informative when compared to traditional paper-based manuals (Reljić et al., 2021; Siltanen et al., 2020). This, in turn, enhances the overall workers’ performance in the field, as it removes the need to memorize instructions or check them on the paper, which reduces the number of possible process errors and increases the speed, accuracy and effectiveness of workers (Devagiri et al., 2022; Fraga-Lamas et al., 2018; Jetter et al., 2018). Studies also demonstrated that AR assistance increases the efficiency of workers by reducing mental and physical workload (e.g., minimizing head and neck movements) (Henderson et al., 2011). Additionally, AR enables remote support and assistance, connecting technicians in the field with experts from wherever in the world, thus reducing the time and cost of operations (de Souza Cardoso et al., 2020).

Similar to VR, AR can be applied to provide immersive and interactive training experiences that would simulate real-world scenarios. However, opposite to VR, training tasks can be practiced based on real equipment. Similarly, AR was found to be useful for design and sales purposes, since it can augment virtual prototypes or 3D CAD models, which can be valuable on construction sites or customer presentations (Manuel et al., 2020).

For many years, augmented and virtual realities have been applied and studied separately, as independent from each other technologies. As the capabilities of technologies advanced while decreasing associated costs, delivering a variety of devices and software to experiment with, new forms of experience on the border of virtual and real were identified, as well as a mixture of new definitions originated. The term XR, mistakenly connected with “extended reality” (Rauschnabel et al., 2022), became to be mass used to achieve unity of opinion and define any experience enhanced by computer-generated content. Especially XR has become a hype word in industry.

Through years of investigating technologies, VR and AR have both proven to deliver certain benefits within a single process, domain or industry.
Coupled with the rapid digitalisation of industrial artefacts, which enables efficient reutilisation of organisational resources, the link between AR and VR is becoming more prominent. For instance, training and learning activities were heavily explored in both VR and AR in many domains. The findings demonstrated that VR cannot fully replace hands-on training activities in real settings and should be used for the initial learning module. This suggests that the training materials from VR can be reutilized (with minor modifications) for AR-based training as a natural continuation of the training process, whereas finally, the same materials can be further used in the field to support technicians in their work routine. The same applies to design activities: 3D models can be iteratively created and visualized in both AR and VR depending on the design stage and needs of the related task: from early prototype development to review and sales-related activities. These examples illustrate that XR would highly benefit from reutilisation of materials from one application case to another within an organisation or domain. These aspects highlight the need and value of exploring and adopting both technologies in an industrial context simultaneously, under the topic of xReality or XR.

In overall, the body of research on industrial XR technology is already overwhelmingly complex and extensive, building on the foundations of different fields and domains. The application of XR technology to address industrial challenges demonstrates a large variety of application scenarios and tasks, where it offers advantages over the possibilities of the real world. As follows, XR showed utility for product design and development activities (Berni et al., 2020; Guo et al., 2018; Venturi et al., 2006), global and multidisciplinary collaboration activities (Aufegger et al., 2022; Berg et al., 2017; Maher, 2011; Wolfartsberger, 2019), training and learning activities (Leyer et al., 2021; Shaw et al., 2019; Tea et al., 2021; Xie et al., 2021), in-field support and assistance (Barthelmey et al., 2016; Kolesnikow et al., 2013; Siltanen et al., 2020), and many other. To get a systemized understanding of the current state-of-art of XR technologies, the taxonomy for XR approach in industry 4.0 (shown on the Figure 10), has been proposed by Cárdenas-Robledo et.al (Adriana Cárdenas-Robledo et al., 2022). Their article depicted ten categories, including 68 categories, to describe XR systems.

Mentioned above opportunities and advantages provide a stable foundation to assume that XR has the power to transform and shape the future work operations in line with Industry 4.0 and Industry 5.0 interventions. And it seems only like a beginning of the success story of XR technology. According to the EU’s VR and AR Industrial Coalition strategic paper (Vigkos et al., 2022), the European XR market was estimated around 7,1 billion euros in 2021 (9,6 billion including non-EU countries), with an increase of 26% from the previous year. Furthermore, market forecasts suggest that the XR industry has the potential to grow
significantly at both the European and global levels in the nearest future. On the EU’s market, the growth level is expected to rise up to 37% by 2026, creating employment for 440 000 to 860 000 people. On the global market, XR is expected to boom with a projected value of up to 766 billion euros in 2025 and to contribute to the global economy around 1,3 trillion euros by 2030.

Despite the hype around XR, its potential to transform existing work processes, and the extremely positive forecast for growth, the reality shows a slightly different picture. Currently, XR is not widely adopted by industrial organisations, whereas only several organisations use VR at the workplace in their daily work routines (Lopez et al., 2022; Y. Zhang et al., 2020). The existing body of research, which contributes to theoretical concepts, validation, and technical advancements towards the overall innovation drive, does not sufficiently approach the lack of VR adoption in occupational settings (Lopez et al., 2022). Among the major barriers towards XR adoption, the following were identified (Lopez et al., 2022; Manuel et al., 2020; Vigkos et al., 2022; Y. Zhang et al., 2020):

- **Technology-related barriers** are still the major stopping factor of XR adoption in industry. Despite technology is progressing in a geometric progression, it is still not there to deliver highly immersive experiences that would address the needs of the industry in a sufficient and comprehensive manner. For instance, content development, such as creating high-quality simulations or immersive virtual environments, is still a complex resource-inefficient and time-consuming task, complicated by a lack of commonly accepted and tested interactions and clear user interfaces for XR. Another limiting barrier is the absence of shared infrastructure, ecosystem fragmentation, and lack of interoperability between hardware and software, which limits the development, progress, and
reutilisation of resources and data. Similarly, the scalability and accessibility of the XR hardware is limited, which minimises the group of potential users of the technology. Additionally, XR equipment lacks ergonomics and comfort. Coupled with the need for high-quality network connection and other issues (e.g., cabling, tracking, no resistance to dust and water, etc.), most of XR hardware is not applicable for use in realistic hazardous contexts and requires additional help with installation and usage. In summary, the state-of-the-art technology currently doing not correspond to the needs of the industry, cannot accommodate the use of XR on the needed scale, and would require years of progress to reach a desired point.

- **Financial constraints** are usually referred to as the high cost of XR hardware, software, and other required components (e.g., powerful PCs, physical spacious space, safety items, disinfection, etc.), required to install XR systems and use them in the work environment. However, XR-related expenses may include resources needed for internal research, design, and development activities in addition to establishing new work positions and departments (e.g., a team of skilled professionals to maintain and management of the XR systems and provide support for other employees). Coupled with a lack of public and private financing, opportunities to cover high costs, as well as complex procedures to get external support, minimise the desire and opportunities for positive decisions regarding technology adoption.

- **Legal barriers** also exist and slow down the adoption of XR. Despite the desire and governmental attempts to embed the rule of law into virtual worlds to achieve user safety and digital security, there is still a lack of governmental frameworks, policies, and structures to enable it. The collection and processing of significant volumes of personal data, such as biometric and cognitive data, presents an additional layer of complexity in ensuring compliance with personal data and privacy laws and regulations. Similarly, another concern is raised around the topic of intellectual data protection and copyright, which is not limited to XR technologies alone, but also covers blockchain and artificial intelligence technologies.

- **Finally, social factors** play an important role in XR adoption, which covers problems with the development of skills and expertise in the workforce, the lack of educational opportunities and awareness, the spread of the technological impact on organisations and society, as well as individual
perceptions, misconceptions, and diffuse attitudes towards technology.

On the one hand, there is a workforce and skill shortage in overall; the number of experts in the field is not sufficient to achieve rapid technology development. In the EU, for instance, one of the recognized barriers is brain drain to US and Asian markets, which slows down the development of XR-related infrastructure over Europe. Similarly, there is an absence of XR-related learning opportunities and skills development programs in educational organisations and companies, which result in a complexity in accessing skilled graduates and the workforce. Furthermore, there is an inaccurate perception of XR technology: the general public does not understand the value of using the technology and perceives it as a replacement technology for humans, which may lead to job losses. Coupled with the instability of technology for the mass public and the lack of time to explore it, there are certain issues with technology acceptance and the resulting resistance to adopt them.

In summary, the adoption of XR technology in industry faces unique challenges in terms of technology feasibility and human resources challenges (Manuel et al., 2020). Therefore, to achieve the widespread use of XR technology, it is a need to enhance digital literacy among future developers and users as well as to raise awareness of potential business cases as well as cover possible social influence (Vigkos et al., 2022).

**xReality for Industrial Maintenance and Technical Documentation**

Narrowing to the field of Industrial Maintenance, xReality has a lot to offer to optimize and advance its operations (Silvestri et al., 2020). The transition to Industry 4.0 ideology, which resulted in the deployment of new technologies, processes, and structures, has also affected the field of industrial maintenance (Silvestri et al., 2020). As follows, Industrial maintenance is the first largest application field for AR (Reljić et al., 2021) and the second largest application field for VR (Guo et al., 2020). The use in the maintenance context is one of the critical issues to target Maintenance 4.0 concept, together with Operator 4.0 concept (Romero, Stahre, et al., 2016), data-driven decision making and cyber security in maintenance as well as maintenance system architecture (Werbi et al., 2023). Due to perceived advantages, a large body of research contributes to this topic (de Souza Cardoso et al., 2020; Fiorentino et al., 2014; Guo et al., 2020; Palmarini et al., 2018; Reljić et al., 2021; Werbi et al., 2023), while many industrial organisations already exploring and adopting the technologies in use. KONE Corporation, for instance, has already invested into the exploration of AR-based in-field guidance and VR-based training, among other opportunities.

According to (Werbi et al., 2023), the main application cases for xReality in the context of industrial maintenance are:
(1) VR-based and AR-based training, which enables knowledge transfer and enhanced learning.

(2) Design and prototyping activities in the product or process development lifecycle.

(3) Collaborative virtual environments (CVEs) for communication and knowledge sharing, decision-making, as well as manufacturing and maintenance process support.

(4) Design of the AR/VR system itself.

According to other studies (de Souza Cardoso et al., 2020; Palmarini et al., 2018; Reljić et al., 2021), another dominant application case of xReality is:

(5) AR-based in-field guidance.

**Augmented Reality**, currently being a leading technology of Industry 4.0 (Silvestri et al., 2020), can dramatically transform in-field operations by providing guidance and step-by-step instructions for the technicians, as well as increasing the quality of interactive training sessions. These approaches possess several benefits over traditional operations (optimisation of processes in general and advancing human capabilities (Jetter et al., 2018)), discussed in the previous section.

In-field AR guidance has been applied to support the following maintenance operations: assembly/disassembly, repair, inspection, diagnosis and training (Palmarini et al., 2018) and has been evaluated on several devices – for handheld devices (smartphones and tablets) to more immersive options (large screens, projectors, see-thought displays, or smart glasses and other wearables) (Borro et al., 2021; Fiorentino et al., 2014; Palmarini et al., 2018; Reljić et al., 2021). Although smartphones and tablet-based interfaces are widely accessible, inexpensive, and easy to use, they already can be now used in the field to get help and guidance in a more visual and clear form than traditional paper-based documentation (Di Gironimo et al., 2013; Reljić et al., 2021), based on the availability of multimedia assets (Gattullo et al., 2022). However, the use of handheld devices is not optimal – as it keeps the hand busy and, therefore, cannot provide smooth support and heads-up interaction during the whole process of maintenance work. Therefore, the use of see-through displays and smart glasses is more promising in this context (Funk et al., 2016; Siltanen et al., 2020). The same applies to AR-based trainings, which not only boost learning and skill acquisition, but also positively affect occupational safety (Gavish et al., 2015; Henderson et al., 2011; Tatić et al., 2017).
Nevertheless, the adoption of AR smart glasses in the field is slowed down by many factors: the immaturity of technology in general (limited battery capacity, picture resolution and field-of-view, tracking inaccuracy, etc.), fragmentation among software and hardware, lack of authoring tools, complex content creation and management and, finally, risks associated with testing in hazardous industrial environments (Abhay S. Prajapati, 2019; Fernández del Amo et al., 2018; Gimeno et al., 2013; Loizeau et al., 2021; Manuel et al., 2020; Siltanen et al., 2020). Additionally, the process of AR application development itself is complex and expensive: it consists of multiple steps (Loizeau et al., 2021), which requires human resources, time, and domain knowledge.

![Figure 11. AR application development process (Loizeau et al., 2021)](image)

In particular, content creation for AR systems is complicated, since it should be developed based on the transfer of knowledge from domain experts to designers and developers (Gimeno et al., 2013), not to mention other challenges, such as limited availability of digital data, suitable for AR content, its further visualisation in see-thought displays and interactions with it (Fernández del Amo et al., 2018). For example, technical documentation, the main source of content for AR-based maintenance instructions, only recently is it becoming more visual (Scurati et al., 2018), making a step from including only textual description and black-and-white illustrations (Stock et al., 2005). However, this transformation is obscured due to the lack of guidelines on how to convert existing formats into visual manuals (Gattullo et al., 2019). On the other side, the redesign of technical documentation may not only boost the AR-adoption in the field, but also enhance organisational operations under the Industry 4.0 intervention. For instance, technical documentation as a service approach (Barthelmey et al., 2016), would not only enhance maintenance task execution, but also enrich the content of documentation with operational details and include more groups of employees to contribute to the improvement of documentation and engineering.

To conclude, the challenges of AR system design and development in industrial settings, despite the potential, are hidden much deeper than being purely technological. Partly, the challenges are rooted in the way industries have been operating during previous years, as well as the lack of infrastructure, methods, and tools to support technology development and adoption. Similarly, this topic is interlaced with the concept of digital work management, which together with predictive maintenance are two major domains towards successful maintenance-tech transformation (Decaix et al., 2021).
**Virtual reality** in the context of Industrial Maintenance is mostly applied to facilitate pre-job training and communication between in-field and remote maintenance technicians (Guo et al., 2020). VR-based training, in addition to the potential benefits of immersive learning discussed in the previous section, helps organisations reduce training costs and travel time by integrating training activities into the digital work environment globally and equally (Ayala García et al., 2016).

Furthermore, VR-based communication and collaboration, apart from the direct application scenario (e.g., to advance the contextual understanding of the remote expert during the maintenance task), have many indirect effects for maintenance. When VR is applied for the entire product lifecycle, being a powerful production tool, it supports the collaboration of different multidisciplinary experts (Tea et al., 2021; Wolfartsberger, 2019; Wolfartsberger et al., 2020). This, in turn, positively affects various design activities, from conceptualisation to reviews, enhancing the design for maintainability, and optimising the outgoing maintenance operations (Guo et al., 2018, 2020). The safety perspective is one of the critical beneficial factors of VR in this context: not only does VR provide an opportunity to efficiently spread occupational safety education in a simulated context to various industrial groups, but it also minimises the need to visit hazardous industrial environments (Chen et al., 2021; Gao et al., 2019).

VR was also applied to aid other maintenance processes: for instance, for the planning of the maintenance procedure, maintenance procedure analysis, and creation of multimedia materials to replace paper guides (Di Gironimo et al., 2013; Guo et al., 2020; Werbi et al., 2023). Computer-based tools, supported by VR, have also been proposed as an authoring tool for technical documentation (Stock et al., 2005). Furthermore, VR was used to evaluate the usability and user experience of AR-based systems, showing both the potential and limitations of this approach compared to a realistic AR-evaluation scenario (Lacoche et al., 2022).

However, these topics gained less attention from the research community, resulting in the lack of concrete theoretical and practical knowledge, methodologies, design guidelines, or implications in this regard.
Humans, Work and Collaboration

One of the most popular approaches to define humans is through the lens of social science: humans are inherently social creatures, whereas social interactions play a crucial role in shaping human experiences and behaviours. A group of individuals, involved in social interactions form a society, whereas life in society serves as a function to adopt to the world (Kingsley Davis, 1949).

"Individually we are one drop; but together we are an ocean." – Ryunosuke Satoro

Figure 12. How work contributes to the satisfaction of human needs (Jeanne M. Brett et al., 2002)

Work, being an integral aspect of modern society, influences the formation and evolution of social interactions and relationships. Not only helps to form and enhance social interaction skills based on daily interactions at
3 Humans, Work And Collaboration

One of the most popular approaches to define humans is through the lens of social science: humans are inherently social creatures, whereas social interactions play a crucial role in shaping human experiences and behaviours. A group of individuals, involved in social interactions form a society, whereas life in society serves as a function to adopt to the world around (Kingsley Davis, 1949).

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Figure 12. How work contributes to the satisfaction of human needs (Jeanne M. Brett et al., 2002)

Work, being an integral aspect of modern society, influences the formation and evolution of social interactions and relationships. Not only helps to form and enhance social interaction skills based on daily interactions at
work, but also supports the establishment of personal bonds and social networks outside the work environment, contributing to overall human well-being. Therefore, work is a critical element of human life in the industrialised world, which contributes to the satisfaction of human needs at the levels of the Maslow’s hierarchy.

As the industrialisation process evolves, it reflects on the nature of work tasks and, correspondingly, on social interactions at work. As follows, each evolution wave brought new work-related challenges, conditions, and novel technologies and tools, which directly affected the way workers interacted and collaborated.

**Figure 13. The Revolution of Workers thought the Industrial Revolution**

During the Mechanical Era, manual labour dominated, and workers (also referred to as Worker 1.0 or Operator 1.0 in the industrial context) usually performed manual work, consisting of repetitive tasks, and mostly supported by hand tools. They worked physically close to each other and were involved in face-to-face interactions and limited collaboration activities. Worker 2.0, or Operator 2.0 from Electrical Era performed still manual, but more specialised tasks, supported by machinery. As the work focus was shifted towards completing more complex tasks than previously, it required more work-related interaction between specialists and led to increased collaboration activities and the formation of manager-employee relationships. (Cortés-Leal et al., 2022; Frey et al., 2017; Romero, Bernus et al., 2016) In Computerized Era, computers and other digital tools became an essential part of the work environment, which opens the possibilities of digital cooperation, including technology-supported communication and information sharing. Worker 3.0 was required to have basic computer skills and was expected to be able to perform work tasks using digital means. (Cortés-Leal et al., 2022; Frey et al., 2017) The nature of work has evolved from being solitary to being cooperative: from 20% of team-based work in 1980 up to 80% in 2010 (Hollenbeck et al., 2012). Operator 3.0, in turn, became responsible for ‘cooperating with machines’, control and monitoring of automated equipment, which lays the foundation of human-robot collaboration (Romero, Bernus, et al., 2016).

In the 21st century, the focus has shifted toward automation, collaboration, and continuous learning. A typical day of **Worker 4.0** might consist of
individual and team-based tasks, including a mix of in-person and virtual interactions. Therefore, workers are expected to have advanced computer skills and know how to use various digital tools to perform their work tasks. Social interactions at work became more flexible, with a focus on collaboration and communication over distances. Especially after the social isolation of the COVID-19 pandemic, there was a mass adoption of technologies to support work processes and remote ways of working in general. Additionally, many organisations focus on increasing worker satisfaction and productivity through enhancing work-life balance, employee development, and work conditions, resulting in overall changes in work culture and global workforce diversity. (Calvetti et al., 2020; Frey et al., 2017; How COVID-19 is Affecting Industry 4.0 and Innovation - IEEE Transmitter, n.d.; York et al., 2014). Operator 4.0 is now a smart and skilled worker who not only actively collaborates with machines and robots, but also is aided by them (Dornelles et al., 2022; Romero, Bernus, et al., 2016).

As we are heading towards Society 5.0 and Industry 5.0, which aims to personalise decision making and empower workers to take on more creative and leadership-orientated roles within the organisation, the characteristic of a workforce is expected to again transform. Therefore, Worker 5.0 and Operator 5.0 are seen as individuals who use their cognitive skills and social leadership to improve organisational well-being and add value to the company through the use of intelligent devices (Cortés-Leal et al., 2022). This includes the ability to rapidly adapt to new technologies and changing job requirements. As for repetitive tasks, it would be done by machines and robots, which places workers in the centre of operations, promoting social responsibility and ensuring business resilience (Adel, 2022; Cortés-Leal et al., 2022). Social interactions are expected to become more fluid and less tied to physical location, allowing for increased flexibility, collaboration, and communication across geographical borders, relying on digital tools and platforms.

In this chapter, I provide an overview of relevant theories and related work from the human perspective, starting from the most popular work philosophies, such as Lean and Agile, and going into teamwork and collaboration topics. I also cover the aspects of technology-supported collaboration and collaboration, in XR, asymmetry of collaboration and related technology acceptance and adoption models. Finally, I introduce the collaboration and further narrow the context for the case studies, reflecting on the KONE work processes based on the knowledge I gained from collaboration with KONE’s R&D team and other focus groups.

### 3.1 Industrial Management Philosophy and Work Processes

In the 21st century, industries operate in a rapidly changing and complex business environment. Digitalisation and globalisation, brought by the
latest industrial revolution, coupled with increasing competition on the market, have transformed the way that industries are structured and operate.

The structure and organisation of industrial processes has a massive effect on the overall productivity and effectiveness of industrial operations, increasing revenue and overall competitiveness. A well-known case by Henry Ford from the early 1900s has demonstrated how mass production outperformed craft production in the auto industry, whereas the focus on maintainability and ease of repair promoted a wide use of American cars globally – by the 1930s, 90% of cars were manufactured in America. Despite impressive results, mass production caused separation of labour and other workforce-related problems, not to mention issues with quality and high costs to overcome defects and flaws occur during the production (J. Womack et al., 2007).

The solution to this problem came from Japan, where Toyota engineers presented a novel organisational value-driven strategy, called the Toyota Production System, which promotes continuous improvement of operations and respect for customers and employees. As follows, employee well-being was prioritized from a long-term perspective, offering development programmes and support (Liker, 2021; J. Womack et al., 2007). This move laid the foundation of the work philosophy, which is nowadays known as Lean manufacturing or Lean thinking.

Lean Thinking and Agile Process

Lean and Agile have been two dominant manufacturing paradigms over the past years due to their positive impact on flexibility of operations, adaptability, and cost-effectiveness (Ding et al., 2021; Raji et al., 2021).

Lean thinking was first introduced by James Womack and Daniel Jones in 1996. Lean philosophy is focused on two simple rules: maximising value and minimising waste in all aspects of a business, from design and production to delivery and customer service (J. P. Womack et al., 1997). Waste in this sense is related to any human action that requires resources and delivers no end value (J. Womack et al., 2007). The following eight types of waste can be minimised to positively affect value creation and optimise any industrial process: transportation, inventory, people motion, waiting and underutilisation, overprocessing and overproduction, product defects, and finally, goods and services that do not meet the customer’s needs (J. Womack et al., 2007; J. P. Womack et al., 1997). This can be achieved by implementing the Lean Principle (Figure 14, left) in manufacturing. Lean thinking has been widely adopted to other processes, for instance in the Lean Start-up (Ries, 2011) and also applied to many industrial operations, from manufacturing, management, monitoring processes, and product design (Dallasega et al., 2020; Huang et al., 2022; Komkowski et al., 2022) to educating the workforce (Gamlin et al., 2014; Wang et al., 2020).
Figure 14. Lean Thinking Principles (J. P. Womack et al., 1997) and Agile process, author’s interpretation

Agile methodology, originating from software engineering and based on the Agile Software Development (Manifesto for Agile Software Development, n.d.), has also spread vastly across industrial activities (Ding et al., 2021; Scheuermann et al., 2015). Agile philosophy is similarly beneficial as Lean thinking. It covers a slightly different perspective and aims at rapid adaptation as a response to change and value creation based on the iterative nature of the work and the multidisciplinary collaboration of various stakeholders (Hoda et al., 2018; Martin, n.d.). Agile core values are defined as follows (Manifesto for Agile Software Development, n.d.):

- respond to change rather than pursue the planned process,
- focus on individuals and interactions rather than processes and tools,
- prioritize close collaboration with customers and users above contact negotiation,
- focus on delivering working software rather than comprehensive documentation

Thought the years, Agile gained many reflections and adoptions of various processes and integrations with other beneficial strategies (Ding et al., 2021; Scheuermann et al., 2015; Yli-Ojanperä et al., 2019). Relevant to the field of HCI, Agile can be seamlessly integrated with user-centred design practices (Fox et al., 2008), as depicted in Figure 14, right.

The integration of Lean and Agile methodologies enhances industrial operations in line with Industry 4.0 integration and helps organisations remain competitive in a rapidly changing business landscape. It establishes a culture of continuous improvement for industrial operations, allowing faster response times to changing customers’ needs, improving product quality, and increasing efficiency (Ding et al., 2021; Yli-Ojanperä
In turn, the key technologies of Industry 4.0, including xReality, promote, improve, and empower the appliance of Lean and Agile methodologies in a variety of ways (Buń et al., 2019; Dallasega et al., 2020; Gamlin et al., 2014; Raji et al., 2021), emphasising the need for the adoption of xReality in industrial context.

**Teamwork Effectiveness**

The changes in work organisation in the last century led to an increased emphasis on collaboration and teamwork, whereas teams are becoming more cross-functional and interdisciplinary. Additionally, during the last years, remote work and globally scattered virtual teams have become more widespread, which creates own advantages and barriers. (Delgado Piña et al., 2008; Maznevski et al., 2000)

Various types of teams were identified to guide team research, differentiating on team composition and dynamics, task complexity, and the skills required to accomplish it as well as team management. For instance, in 1997, Cohen and Bailey presented the following four types of teams: traditional work teams (e.g., most typical teams involved in continuous tasks and responsibilities related to the production of goods or provision of services), project teams (e.g., time-limited teams focused on a single time output), parallel teams (people from diverse areas, pulled together for problem-solving or improvements) and management teams (e.g., coordinating group of people who are responsible for overall performance (Cohen et al., 1997). With the spread of computer technology in the work environment, more forms of teams originated – such as global virtual team, which is formed by a group of people, who work and reside in different countries, mainly uses technology-based communication and is responsible for decision-making and task implementation related to the organisation’s global strategy. Their teamwork activity can be reviewed as a collection of social interaction events, which follow a repetitive temporal sequence, influencing their decision-making process. (Maznevski et al., 2000). Further, in 2012, the dimensional scaling of teams (e.g., skill differentiation, authority differentiation, and temporal stability) was proposed for team classification (Hollenbeck et al., 2012).

Team performance, which is one of the key issues in team research, is a composition of many variables (such as environmental factors, design factors, internal and external group processes, and psychosocial traits (Cohen et al., 1997)), and is greatly influenced by team characteristics. Despite initially team performance and productivity being assessed based on objective measures (Shea et al., 1987), acknowledging other factors, such as attitudinal (such as job satisfaction and trust) and behaviour outcomes (such as absenteeism, turnover or safety) (Cohen et al., 1997) to be more comprehensive approach in modern settings. However, the importance of the outcomes would still vary with the team type, tasks, or
values associated with the team (Delgado Piña et al., 2008). Further, in relation to virtual teams, which can be also multinational, cultural composition becomes a significant structural characteristic to affect effectiveness together with the technology used for communication and organisational social systems (Maznevski et al., 2000).

3.2 Collaboration in a Nutshell

Building on the need for revolutionary novel solutions to address the appearing environmental problems, collaboration was brought as a value system to replace a competitive one in the second half of the 20th century. Currently, collaboration is seen not only as a cooperative problem-solving technique, but holistically as an approach to drive innovation and change in the social context (Horváth, 2012), which has also been reflected in a work context.

Collaboration simply can be defined as a process where individuals, a group of individuals or organisations work together to achieve a common goal (Moniz, 2007). In a formal sense, collaboration is defined as a process (Gray et al., 2016; Thomson Ann Marie, 2001):

- that involves shared norms and mutually advantageous interactions,
- where autonomous actors engage in formal and informal discussions,
- where rules and structures are created to regulate actors' relationships and decision-making on the matters that bring them together.

Collaboration is often mistakenly used as an alternative to words “cooperation”, “coordination” and even “communication”, so-called C-Three (Kling, 1991; McNamara, 2012). However, these concepts, even being similar, possess differences from the perspective of integration and interaction of actors, as shown in Picture 15.

![Diagram of interaction and integration of actors](image)

**Figure 15.** Diagram of interaction and integration of actors (Nof, 2010; Zhong et al., 2015)
Communication is the easiest form of interaction between actors to exchange information and ideas. Therefore, communication can be seen as a tool to develop shared understanding, agree on goals, and find resolution. Coordination combines communication and information exchange to achieve harmony of working to achieve mutual benefits; however, it is characterised by the alignment of activities and complementary goals rather than shared goals and efforts. Cooperation happens based on the coordination of actors coupled with a resource-sharing function, which enables compatible goals and some level of established shared practices. Collaboration, in turn, involves both functions and builds on information, resource and responsibility sharing, which help to establish common activities to reach the goal (Nof, 2010; Zhong et al., 2015).

By the scope of collaboration, activity and involved parties, collaboration can be reviewed from the following levels: interorganisational (between different organisations), intraorganizational (within an organisation) and interpersonal (between individuals). Collaboration, taking different forms, can be further classified based on: Design, Formality of the agreement, Organisational Autonomy, Key personnel, Information sharing, Decision making, Resolution of issues, Resource allocation, System thinking and Trust (McNamara, 2012). Despite the composition and participants, all collaboration processes are considered inherently complex in nature and hard to maintain (Cohen et al., 1997; Patel et al., 2012); whereas time and energy of the actors were argued to be the critical resources of collaboration (Thomson et al., 2006). As follows, the drivers influencing factors and barriers of collaboration would be different based on the collaboration settings. For instance, Patel et al., presented the following seven factors of collaborative work (Patel et al., 2012):

- **Context**, or the types of individuals and teams who are collaborating, such as culture, environment, business, climate, and organisational structure.
- **Teams**, or a group of people participating in a shared task, their characteristics (e.g., roles, relationships, shared awareness and knowledge, common ground, group processes, composition), and their work settings (co-located, distributed in time and space).
- **Individuals** and individual performance, which is based on skills, psychological, and cognitive factors (e.g., needs, perceptions, preferences, values, biases, motivations, working style, and behaviour) as well as overall physical and mental wellbeing.
- **Tasks**, which teams or individuals are supposed to perform in collaboration, including a type, structure and demands.
- **Support** or management components to aid the collaboration process between teams or individuals (such as tools, networks,
resources, training, team building, knowledge, and error management).
- **Interaction Process** or procedural elements of collaboration, such as learning, coordination, communication, and decision-making.
- **Overarching factors** are other relevant factors to influence the collaboration, such as trust, conflict, experience, goals, incentives, constrains, management, performance, and time.

In the modern work environment, technology has a large role in facilitating collaboration activities between individuals, which lied in the foundation of new multidisciplinary field of research – Computer Supported Collaborative Work (CSCW), described in the next section. Furthermore, as technology is becoming smart and intelligent, it is becoming a similarly important collaboration actor. This led to the development of new collaboration concepts: in addition to traditional human-to-human collaboration, the concepts of human-to-system, system-to-human, and system-system originated. The difference between the human-system and system-human collaboration is explained by the autonomy, decision-making ability, and proactivity of collaborators (Horváth, 2012). System-to-system collaboration refers to already mentioned concept of CPS (and the main Industry 4.0 driver) – which enables complex collaboration of geographically distributed physical and virtual systems for intelligent control, monitoring and coordination (Monostori et al., 2016).

### 3.3 Technology-Supported Collaboration

The CSCW field of research originated since the creation of distributed systems – a system that is composed of multiple physically separated autonomous computers or devices that are interconnected to communicate and coordinate with each other (Van Steen et al., 2017). The CSCW field integrates the topics of “collaborative work” and “information systems” (Moniz, 2007) with a goal to inform the design of technology-supported work practices and enhance collaboration, building on social and cultural factors. Through years, the field delivered a variety of frameworks, environments, tools, and techniques to clarify the nature of technology-supported collaboration and to support the implementation of cooperative work (Reddy et al., 2004).

![Figure 16. Examples of Technology-supported collaboration; photos are taken from Canva](image)
In the early 90s, the term *groupware* was introduced, defined as a computer-based system, which provides a shared environment interface to support the accomplishment of common tasks or goals for a group of people (Ellis et al., 1991). The definition provides two critical dimensions for collaborative computer-based systems: a *common task* and *shared environment*. Further, the time space taxonomy of a groupware was presented, classifying collaboration as follows: co-located vs. distributed or remote, as well as synchronous vs. asynchronous. This classification, shown in Figure 17, provides a variation of collaborative work practices and how technology can aid these different scenarios (Bullinger-Hoffmann et al., 2021).

![Figure 17. Time and Space taxonomy of a groupware (Borghoff et al., 2000; Bullinger-Hoffmann et al., 2021; Ellis et al., 1991)](image)

As collaboration is transforming from a problem-solving activity towards a more systematic way to overcome resource and expertise limitations, smart technology offers a better way to address it by delivering new tools, systems, and infrastructure for collaboration (Horváth, 2012). Despite the perceived benefits of technology-supported collaboration (such as increased communication and productivity of collaborators, flexibility of methods, and support for creativity (Ross, 2015)) and a belief that collaboration practices should even more be supported by technological means (Horváth, 2012), special attention should be paid to the potential effects of technology on humans, their interactions and work processes (Ellis et al., 1991).
The design of a collaborative system has a direct influence on the efficiency of the collaboration process (X. Zhang et al., 2011): for instance, poor design may not only decrease team performance, but also affect team dynamics and relations, such as interpersonal trust building (Choi et al., 2019). As follows, developing, designing, and adopting software to support collaboration in a work context is not a straightforward task, which should be based on multiple considerations: theories, such as collaboration theory (Colbry et al., 2014) and technology acceptance model (Davis, 1989), work practices, tasks and related requirements, group dynamics, computer-mediated communication, and user-centred software design (Stahl, n.d.).

Collaboration with XR

As remote work is becoming a new normal, humans tend to rely on technology more often for work and collaboration purposes. Especially, due to restrictions on social gathering during the Covid-19 pandemic, the collaboration in xReality has gained extreme interest among academics and industrial practitioners as an alternative to face-to-face meetings. Through previous years, a wide range of commercial-based and research software originated on the market (Schäfer et al., 2021; Tea et al., 2021), where 37.8% of solutions are VR-based (24 commercial and 7 research systems), 20.7% are AR-based (Video-See-through, or Optical-See-through or a combination) and 41.5% are Mixed Reality – based (e.g., the mix of AR and VR or interaction of real world objects with AR or VR) (Schäfer et al., 2021). The mentioned collaborations in MR I refer to the asymmetric collaboration described in the next section.

VR is the leading XR technology to facilitate collaboration in industrial settings, which has been applied in the following use cases: virtual meetings, co-design activities, and remote expert support (Schäfer et al., 2021) with a goal to facilitate the communication of multidisciplinary teams, for instance, designers, engineers, and assembly operators (Gugenheimer et al., 2017; Maher, 2011; Wolfartsberger, 2019). The rise of Collaborative Virtual Environments (CVEs) or “distributed virtual environments” (Churchill et al., 1998) happened in the early 2000s, originated by the possibility to run VR applications on desktop computers.
and over the internet, whereas by the early 2010s it was already practiced in a more immersive manner via HMDs. The application of VR technology for collaboration purposes expands the existing time and space groupware taxonomy, making it possible to imitate face-to-face interaction for distributed team members or changing the nature of coordination for asynchronous work activities (Figure 19). 

As follows, the use of CVEs is considered a better alternative to traditional video conferencing tools in an industrial context, as it improves the collaboration process across distances and enhances the quality of interpersonal interactions among global teams (Narasimha et al., 2019; Wolfartsberger et al., 2020). This is achieved by the fact that in CVEs, employees from different teams and dispersed locations are immersed into a shared virtual workspace and can interact naturally with the environment and each other (Aufegger et al., 2022; Wolfartsberger et al., 2020). As a result, multiuser VR enhances the quality of discussion by providing a shared context, awareness of others, as well as clear, rich, and open communication, including verbal and non-verbal communication queues (Abbas et al., 2019; Du et al., 2017). In support of this, the pilot study by Steinicke et al., (Steinicke et al., 2020), demonstrated that, despite video-conferencing collaboration is still evaluated as the most usable solution, immersive VR experience gives a better result on social and spatial presence, involvement, and experienced realism. Another example demonstrated how collaboration in VR advanced the sense of team engagement and positively affected decision-making (Berg et al., 2017).
The design of XR collaborative system should correspond to the needs of the target users and address the requirements of the collaborative task, as any other technological system designed to aid collaboration processes (X. Zhang et al., 2011). In order to ensure productivity in VR, which is a rather versatile concept, perceived by the quality and efficiency of work (Kim et al., 2019), the system design should address the physical, environmental, cognitive, and behavioural needs of the users (Aufegger et al., 2022). This can be further achieved by focusing on so-called “pillars of remote collaboration”: 1) environment (which stimulates sensory perception and affects spatial presence and coherence), 2) interactions (ways to manipulate the environment and interact with others, such as shared object manipulation, hand gestures, facial expressions, drawing and others) and 3) avatars, a visual representation of an individual in VR, which can be in various styles (e.g., cartoon, realistic, full body, upper body, hand, and hands only) (Schäfer et al., 2021). The visual appearance and behaviour patterns of the avatar have a great impact on collaboration in XR (Boberg et al., 2008; Kurzweg et al., 2021; Wu et al., 2021). For instance, expressive avatars may have a positive impact on social presence and interpersonal attraction, making virtual communication to be more similar to realistic face-to-face communication (Wu et al., 2021). Furthermore, avatar behaviour during the meeting helps to determine how attentive the individual is and has a significant impact on perceived social richness and mood, self-assessed mood, and social realism (Kurzweg et al., 2021).

Asymmetric Collaboration

Asymmetry in technology-supported collaboration is a comparably fresh direction of research, branching from VR-based collaboration. As the focus of VR research has shifted from single-user experiences towards multiuser experience and social interactions in VR (Lee et al., 2019), novel forms and challenges of collaboration within VR systems were discovered. Asymmetric VR refers to the differences of user experience during the collaboration, which occurs among devices with different levels of control and immersion (Kaitlyn Michelle Ouverson et al., 2021), for instance, between a user wearing HMD and a desktop VR user. The focus of asymmetric VR research addresses the perspective and experiences of non-HMD users.

The initial mention of “asymmetry” can be found in studies on virtual telepresence and telecollaboration, where a real environment is virtually recreated, so remote participants can use VR to access it and interact with people in it, thus, creating the effect of asymmetry (Steed Anthony et al., 2012). Asymmetry was also identified in media spaces, differentiating in the six following forms: place, fidelity, participation, media, engagement, and benefit (Voida et al., 2008). Similarly, this concept originated in game studies, going from defining asymmetry levels in multiplayer games (such as asymmetry of ability, challenges, interface, information, and others) (J.
Harris et al., 2016) towards leveraging asymmetry in VR games, which promised to lower VR isolation and explore engagement and participation of non-HMD players (Rogers et al., 2021).

Initially, asymmetry was investigated in co-located settings (Grandi et al., 2019; Kaitlyn M. Ouverson et al., 2021; Pumsomboon et al., n.d.), while asymmetry in distributed settings was seen as a cross-platform multiuser VR experience. The Composite framework for Asymmetric VR (CAVR), presented by Ouverson and Gilbert (Kaitlyn M. Ouverson et al., 2021), describes how asymmetry occurs in co-located settings and how it influences group dynamics via technology-related and interpersonal experience-related dimensions of asymmetry: spatial copresence, transportation, informational richness, team interdependence, and balance of power. Enhancing the presence and immersion of non-HMD users was attempted to be solved by adding extra devices to the collaboration. For instance, floor projection and mobile displays combined with positional tracking showed a positive impact on non-HMD users’ enjoyment, sense of presence, and social interactions (Gugenheimer et al., 2017). Another example demonstrated that an external tablet, which is used for interaction with a virtual environment and allows drawing over it, improved communication quality among the two asymmetric user groups and had a positive impact over task completion time and error rate (Kumaravel et al., 2020). Additionally, it was argued that experience and presence in asymmetric VR are driven not only by technological set-up, but also by the roles and tasks of the collaborators (Lee et al., 2019).

Asymmetry, which was seen as a challenge to overcome in co-located settings, can deliver a certain value in distributed settings ( Voida et al., 2008). The collaboration case between industrial engineers, based on a video stream from VR environment to a meeting room, verified the potential of utilizing several spaces for industrial collaboration instead of a single medium with rich interactions (Clergeaud et al., 2017). As follows, when some user groups have no access to HMDs, they can still participate in VR collaboration via asymmetry. The asymmetry can be categorized based on the scope of non-HMD users’ interaction: low asymmetry, when there is a direct control over the virtual environment, medium asymmetry, when there is an indirect control, such as digital communication and high asymmetry, e.g., no control over the environment and communication, limited to verbal (Thomsen et al., 2019).

Distributed Asymmetric VR has the potential to positively affect the flexibility, accessibility, and scalability of VR technology and allow wider circles of users to participate in collaboration activities, sacrificing the immersion of these groups. However, there is a lack of academic knowledge on how asymmetry in distributed settings might occur and how it would affect collaboration in general team dynamics and effectiveness.
3.4 ACADEMIA-INDUSTRY COLLABORATION

Over the past decade, there has been an increase in the popularity of interorganisational multidisciplinary collaboration and project-based work (Lundström, n.d.), which is becoming a common practice in line with Industry 4.0 and Industry 5.0 interventions. Multidisciplinary collaboration covers any form of joint work between people from different fields, disciplines, and backgrounds. The major advantage of such collaboration is a collective strength towards achieving better outcomes by fusing diverse perspectives, skills, expertise, and experiences. The concept of Society 5.0 stresses the important of collaboration among multiple stakeholders (e.g., government, industry, academia, and other ministries) for value creation and “systematisation” of platforms and services (Harayama, 2017). Multidisciplinary and diverse approach towards collaborative problem-solving is, therefore, viewed as a modern, flexible, and more effective way of working compared to traditional organisational structures.

One of the bright examples that have the potential to drive value creation and boost innovation is academy-industry collaboration (Ankrah et al., 2015; Barnes et al., 2002; Garoussi et al., 2016). This form of interorganisational collaboration enables experience and knowledge sharing between academia and industry to address the relevance of R&D actions (Ankrah et al., 2015; Siegel et al., 2003). This may be achieved by defining academic research goals based on actual industrial needs, while utilizing established and verified research methods to arrange user studies, experiments or simply collect data from domain experts and target users. Such collaboration delivers multiple mutual economic, institutional, and social benefits (Ankrah et al., 2015). From an economical perspective, for academia, collaborating with industry may bring additional business opportunities, funding options, and other sources of revenue. For industry, it brings the potential to develop new and improve existing products or processes as well as generate patents, prototypes, and other intellectual property rights, which can contribute to the competitiveness of the company and advance revenues. Additionally, by working with academic institutions, businesses and industries can access cost-effective research or receive public grants to fund research and development efforts, which may not be feasible to conduct in-house.

From the institutional perspective, academia gets access to practical challenges, new ideas, and cutting-edge technology for students and facilities, which, in turn, enhances the curriculum (under the influence of companies) and delivers training and employment opportunities, contributing to the quality of education in general. It also advances research activities and stimulates technological advancement by providing access to users with domain knowledge and environments for testing, experimentation, and gathering feedback on research ideas, concepts, and
results. For industries, such collaboration gives the opportunity to improve innovative capacity and stay up to date with the latest technological developments. Academia offers access to new knowledge and innovative technologies, as well as multidisciplinary research expertise and infrastructure, which helps to accelerate the commercialisation of innovation, product testing, and time-to-market. The joint outcomes can be published in both academic and industrial forums to increase interest towards the research topic and initiate future discussion and action points around it. Finally, social benefits are related to advanced reputation, recognizability, visibility, and trust towards both academia and industry, which may lead towards expanding collaboration circles and becoming a more stable community member.

Despite academia-industry collaboration has a large positive impact for the collaborating actors and contributes to local and regional economic development and growth (Ankrah et al., 2015), it is not yet as widely practiced due to collaboration barriers (Bruneel et al., 2010; Garousi et al., 2016). The barriers can be split into 1) orientation-related (e.g., dissimilarity of objectives, perspectives, working methods, operating modes, and time horizons) and 2) transaction-related barriers (differences in knowledge property and administration) (Bruneel et al., 2010; Sandberg et al., 2011; Siegel et al., 2003). In other words, academics and industry professionals face challenges when collaborating due to their differing priorities and perspectives: while academics may focus on long-term research goals and work on theoretical and abstract levels for a longer period of time, industries prioritize practical and short-term goals with rapid deadlines. This can lead to misunderstandings, unrealistic expectations, and even mistrust between the two parties. Other challenges that can arise during collaboration include a lack of relevancy, experience, and skills required to support the process, minimal commitment and interest, inflexibility, and managerial and organisational issues. (Ankrah et al., 2015; Bruneel et al., 2010; Garousi et al., 2016)

To minimize the gap between academic and industrial parties and synchronize their joint work, different methods and theoretical models have been proposed (Garousi et al., 2016, 2020), building on agile (Sandberg et al., 2011) and action research (Petersen et al., 2014) practices. For instance, Certus model (Marijan et al., 2020), draws 7 phases to perform in academy-industry collaboration, emphasizing knowledge co-creation and continuous communication and goal development throughout the collaboration process.

3.5 Technology Acceptance and Adoption
The desire to use and adopt XR technologies in an industrial context is driven by an overall hype, created by both justified academic findings and
business-enforced speculations, promising endless benefits. Despite novel technologies are capable of enhancing and facilitating work processes on the individual or group level, and, thus, increasing the efficiency and competitiveness of organisations, in general, technologies cannot be simply put into use. The technology primarily should be accepted and willingly used by the employees to realize the benefits. Therefore, technology acceptance and the opposite to it, technology resistance, are two critical aspects to be considered for technology adoption, referring to the process when novel technologies become widely used by the workforce. In case employees do not accept or feel comfortable with the newly introduced technology, they would show certain levels of resistance towards it, would not use it effectively, or even would not use it at all. This would reflect in decreased productivity and potential business losses. Therefore, an understanding of how employees perceive the technology in the context of their work can inform software developers and designers on how to improve their user experience to overcome technology resistance and, in turn, boost technology adoption.

One of the most influential theories in this regard is Technology acceptance model (TAM) introduced by Davis in 1989 (Davis, 1989). The theory was developed to describe why people adopt technologies (e.g., computers and information systems) at the workplace. It concluded with two major influencing factors for technology adoption: perceived usefulness (e.g., how it would affect the performance of a worker) and perceived ease of use (e.g., to what extent it would be effortless to use it). A further study also reviewed both extrinsic and intrinsic motivation in the context of technology acceptance and found a positive interaction between the dimensions of usefulness and enjoyment, linking a factor of enjoyment to technology adoption (Davis et al., 1992). Another extension of TAM was presented by Venkatesh et al. in 2003, reviewing technology acceptance among employees and concluding with the Unified theory of acceptance and use of the technology model. The model suggests that the user’s intention to adopt a technology, in addition to performance and effort expectations, is also determined by the factor of social influence, which drives behaviour intentions and facilitates conditions for technology adoption.

Through years, the theories have been widely applied to evaluate the acceptance of xReality technologies, which provide new insights and factors to consider. For instance, it was argued that instead of focusing on usefulness per se, it is critical to evaluate the utilitarian value of a specific technology in a specific context (Rauschnabel, 2018) as well as personal factors (such as readiness for technology), situational factors and stimulus factors should be considered (Chung et al., 2015).

The mentioned theories review technology acceptance on an individual level, whereas regarding technology adoption in organisations, the
individual level is not sufficient to cover the matter. A useful theory for technology adoption from the perspective of organisations was presented in 1990 by Tornatzky and Fleischer (Tornatzky et al., 1990). The Technology-organisation-environment framework identified three contextual factors to influence the technological innovation process in firms: technological (existing and emerging technologies used by the organisation), organisational (characteristics, such as size, management, human resources, etc) and environmental (business environment, stakeholders, competitors, etc). Nevertheless, the body of research on XR-technology acceptance from an organisational perspective is not fully formed and requires further investigation (Chuah, 2019).

Figure 20. Factors related to the XR technology acceptance and adoption (Chuah, 2019)

To minimize the fragmentation of research in terms of XR technology acceptance and adoption, Chuah in 2018 addressed this topic from multiple perspectives and theories. As an outcome, the major influencing factors were summarised into individual-level factors and organisation-level factors (Chuah, 2019). The factors shown in Figure 20, can be used to evaluate the perceptions of both individual and professional users towards XR devices and should be acknowledged before adopting the technology.

3.6 PIPELINE OF MAINTENANCE METHOD AND TECHNICAL DOCUMENTATION CREATION AT KONE

As any other large manufacturer and service provider, KONE has a complicated work organisation, which involves multiple departments in a common loop. Since the focus of this work is the pipeline of Maintenance Method and Technical Documentation creation, I will provide only a brief overview of the preceding and follow-up company’s activities.
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Currently, the maintenance method and technical documentation creation at KONE is based on the general documentation process. Maintenance documentation is generated or updated in tight collaboration between two departments, the Maintenance Development Department (MDD) and the Technical Documentation Department (TDD). The departments are composed of multidisciplinary globally scattered teams, situated in different geographical locations and operating in different time zones. The process of work is iterative in nature and mostly remote; complicated with tight schedules and deadlines to fit in the project timeframe. The communication of departments happens via chatting (e.g., in Microsoft Teams), writing emails and, less often due to time difference, via Teams video calls.

Firstly, subject matter experts from MDD design the maintenance methods and outline instructions for performing certain tasks with the released equipment. They often have no access to the equipment; therefore, their work is typically based on using 2D images or 3D models on a computer screen, which provides no contextual information and might lead to misunderstanding or size and scales. This can result in a lack of spatial and contextual awareness, which may lead to a situation when a designed...
maintenance method is difficult or impossible to execute in reality, for instance, due to the inability to access some parts of the equipment or use the necessary tools due to lack of physical space. To create an outline of the maintenance method, which is further passed to TDD department, subject matter experts use paper notes, images, and markups in existing instructions. This, in turn, may lead to human factor errors, such as issues with interpretation and understanding.

The technical writers and illustrators from TDD department start with analysing the product and the provided outline, based on which they create a draft instruction. Similarly, they rarely have a chance to see the equipment in a realistic context to support their work tasks, which might cause misunderstandings and complications in illustrations. The draft is then reviewed by the MDD; often the draft is iterated with feedback and changes. Communication issues associated with lack of face-to-face communication and cultural barriers, absence of details, and difficulties with interpreting information or hand-drawn sketches may increase the number of iterations. Once the draft is ready, the technical documentation should go through approval before it can be officially released and used in further company activities, such as training or field operations.

Based on the described process, the following major challenges of multidepartment collaboration were identified:

1. **The lack of access to real equipment and industrial context.** In some situations, the access can be arranged, but it would require additional resources, such as travelling expenses, safety training, and procedures (in order to be allowed to visit a hazardous context) as well as the time of the employees. However, in some cases the access to physical equipment or realistic context is not possible.

2. **Communication barriers of globally scattered teams.** The complexity of the shared task is already determined by the complexity of the equipment, whereas traditional channels of communication, geographical barriers, and cultural differences deliver extra challenges for their teamwork and collaboration, resulting in extra costs for the project.

3. **Complexity and cost of digital content development.** The experts tend to rely on traditional pen and paper or pdf files to support their work activities. In general, they lack in visual assets or resource-efficient ways to generate these assets, which can be used to support their communication or as even as elements of technical documentation.
4 Case Studies

This chapter details two case studies, being the base for the dissertation:

I. Utilizing VR for user-centric AR content development and evaluation, and
II. Utilizing VR for maintenance method and technical documentation creation.

First, I will briefly describe the main flow of the case studies and their interconnection, followed by a brief description of the methodology. Then, I describe the objectives, methodology, and outcomes of them separately. The case studies were performed in sequence; the first case study occurred in 2018-2019 as a part of Dynavis project and led to the second one as a natural continuation of the research activity. The second case study consisted of three iterations and occurred in 2020-2022 as a part of HUMOR project. All mentioned research activities were performed in equal collaboration between academic researchers from PIRG research group at Tampere University, and industrial researchers from KONE Corporation. The timeline of the research activity is shown in Figure 22.

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3 HUMOR project, https://humanoptimizedxr.org/wp/
4 https://research.tuni.fi/pirg/
Figure 22. Timeline of research activities

The color-coded blocks demonstrate four separate user studies, which elicit data for one or more publications. All four user studies were based on realistic industrial scenarios and involved domain experts as participants. In all four studies, the expert participants experienced VR system in single-user or multi-user mode. Table 3 provides more details of the user studies.

<table>
<thead>
<tr>
<th>#</th>
<th>Scenario</th>
<th>Nature of interactions</th>
<th>Publication</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AR-content development and evaluation in VR</td>
<td>Single-user VR, No collaboration</td>
<td>I</td>
</tr>
<tr>
<td>2</td>
<td>Maintenance method and Documentation creation in VR</td>
<td>Single-user VR, Asynchronous collaboration</td>
<td>II, III</td>
</tr>
<tr>
<td>3</td>
<td>Collaborative maintenance method and documentation creation in VR</td>
<td>Multi-user VR, Asymmetric synchronous collaboration</td>
<td>IV</td>
</tr>
<tr>
<td>4</td>
<td>Technical Documentation review in VR</td>
<td>Multi-user VR, Synchronous collaboration</td>
<td>V</td>
</tr>
</tbody>
</table>

Table 3. User Studies in brief

Despite being different case studies, they are linked together into a common workflow. AR may improve the work efficiency and occupational safety of technicians working in the field by delivering context-sensitive guidance, instructions, and safety warnings. However, it is still an immature technology to be fully integrated into work processes. Many factors have to be developed to reach the desired state-of-art, such as hardware ergonomics and multimodal interaction, tracking, quality of visual representation, etc. Another critical barrier towards AR integration in the industry is the risks associated with prototyping and testing in dangerous contexts. Coupled with mistrust and fears that the technology might be faulty, the use of AR is not yet accepted by industrial workers.

This is where VR offers a solution. As VR can facilitate realistic experiences in simulated environments, it allows to design and evaluate
AR-solutions in a safe and controlled way. Due to flexibility the VR offers, various parameters of a prototyped AR-solution can be rapidly changed, would it be the technical parameters of AR hardware, such as field of view, or the visual elements of the AR application, such as the design of multimodal warning or font size of visual instructions. VR, additionally, allows to collect objective metrics, such as user head and hand movements and gaze data, which can be analysed to better understand the users’ needs and guide design decisions.

Therefore, interactive and functional virtual environments may partly boost the adoption of AR-solutions, and not only: the same environments can be reused to facilitate other industrial workflows, for instance, maintenance method and technical documentation creation. The traditional process of maintenance method and related technical documentation creation is not optimal – it involves multiple global departments and depends on technology-supported remote collaboration practices, such as shared online documents and communication via video calls, chatting and emailing. What is more, often experts have no or limited access to the physical equipment, they are supposed to provide maintenance and documentation for which, coupled with the challenges of remote collaboration, may lead to errors and misinterpretations. Even small errors may lead to significant costs and recovery time. Hence, the ability to access virtual shared working spaces and virtual equipment and to collaborate with colleges from abroad may potentially reshape and advance industrial work processes, contributing to overall’s company performance and sustainability.

When linking both case studies with a perspective of future technology advancements, it becomes evident that the existing industrial workflow, relevant to industrial maintenance, may be reconsidered to be more optimal. With a shift towards Industry 4.0 and Industry 5.0 practices and the rapid digitalisation of design artefacts in the form of 3D CAD models, it becomes easier to integrate work processes and materials in VR. If so, product design and development processes and service-related processes could be performed in parallel, before the development of physical prototypes, increasing the design for maintainability and reducing the waste of time and resources.

4.1 INTRODUCING THE RESEARCH METHODOLOGY

Both case studies were based on Action Design Research and performed in a tight collaboration between academia and industry. Through the research work, we followed the principles of user-centred design and conducted explanatory user studies with domain experts. To collect the data, a Mixed-Methods Research design was utilized, thus building on the analysis of qualitative and quantitative data.
<table>
<thead>
<tr>
<th>Research Activity</th>
<th>Phase</th>
<th>N</th>
<th>Data Collection Methods</th>
</tr>
</thead>
</table>
| **Case study #1** | Participatory Design session for AR-based in-field guidance and safety-warnings | 4 | • “Think-aloud”,  
• Free-form software exploration,  
• Observation form |
| **Evaluation 1: Usability and Effectiveness of AR in-field guidance and safety warnings** | 5 | • “Think-aloud” protocol  
• Scenario-based software exploration  
• Semi-structured interview  
• Online survey  
• Objective metrics from VR |
| **Evaluation 2: Efficiency of context-aware safety warnings** | 4 | • “Think-aloud” protocol  
• Scenario-based software exploration  
• Semi-structured interview  
• Online survey  
• Paper-based survey  
• Objective metrics in VR  
• Gaze data collection |
| Employee’s perception of AR, VR, and gaze data for the company needs | 12 | • Video-based online survey |
| **Case Study #2 (COVE-VR System development and validation)** | COVE-VR design and development process | - | • Kick-off meeting & Ideation  
• Maintenance Journey Workshop  
• Survey on feature prioritisation  
• Online Demo Sessions |
| | COVE-VR Design Validation | 18 | • Video-based online survey |
| **Case study #2 (Scenario-based evaluations)** | Evaluation 1: Asynchronous collaboration in VR | 7 | • “Think-aloud”  
• Scenario-based software exploration  
• Semi-structured expert interview  
• Pre- and post- online survey  
• Observations by researchers  
• Objective metrics from VR |
| | Evaluation 2: Synchronous collaboration with asymmetric set-up (VR – MS Teams) | 20 |
| | Evaluation 3: Synchronous collaboration in VR | 9 |

**Table 4. Research activities and Data collection methods**

Qualitative data is a core element to address the study research questions, since it helps to better understand the industrial needs, users, and the
application of technology in the industrial context, while quantitative data is as a supportive element. Table 4 provides a detailed overview of the performed research activities in line with the case studies. It demonstrates the phases of the case studies, the number of experts participated, and the data collection methods utilized. Furthermore, I describe the method of data collection and analysis used in this dissertation to elicit knowledge in the industrial context and reasoning behind the selection of the methods:

**Critical literature review and analysis.** A critical analysis of existing academic, industrial work as well as state-of-art was performed to clarify the direction and scope of the research activity as well as to identify possible design solutions. The analysis was performed based on multifield exploration (HCI, CSCW, and Technical Communication fields) to gather a diverse perspective on the subject. A concise literature review was performed prior to every case study at the initial phase of the research, thus linking the identified industrial challenges to existing gaps and the academic bank of knowledge. In addition, the academic literature was explored on-the-go of the project and was used as a supportive factor to establish research methodology and processes, adopted from verified by academy methods.

**User-centred design and development processes in collaboration with the industrial partner.** The initial agenda of the project work to tightly cooperate with the industrial corporation and base the research activities on realistic and actual challenges delivered by the industrial partners. This cooperation was arranged through a series of workshops and other collaborative means of knowledge gathering and sharing, such as meetings, presentations, company demonstrations, and focus groups. These methods helped to define the real problems and challenges and how to solve these, extracting the data from different perspectives: R&D team, young specialists, experts, and company management representatives with decision-making power.

*User-Centred Design* is a well-established design process in the field of HCI. Firstly introduced by Donald Norman in the 1980s (Norman et al., n.d.), this design philosophy is based on the direct involvement of the end-users in the design process, so they can affect the final outcome. Norman’s work highlighted the need to investigate users’ needs, desires, and intended use cases of the product and the context of use as the base of every design activity, thus ensuring the success and user acceptance of the product (Preece et al., 2002). A variety of methods to engage the users in different stages of the design process were further provided by the research community to understand the needs, preferences, behaviours, and other aspects essential to inform the design of the future product.

*Focus Groups*, a technique which has been initially utilized in social research to study ideas within a group of people (Morgan, 2012), refers to
a moderated (by a researcher) group discussion, focusing on a concrete topic of interest. This method should not substitute the traditional qualitative data collection methods – e.g., individual interviews and user observation, however, may deliver several benefits in comparison. Similar to observations, it allows to gather data based on the group interaction, but this interaction can be also directed towards the research agenda, making the data more focused on the subject of interest. In addition, this method is more resource efficient when compared to individual interviews (Morgan, 2012). Therefore, focus group was a beneficial method to address the needs of this study, since it allows to gather a concentrated set of data in a time-efficient manner. This method was mostly used to discuss and find a solution to a concrete topic.

Workshops, widely known as a method to engage diverse groups of stakeholders in an interactive session, which combines elements of qualitative research, brainstorming, and problem solving, was firstly introduced in 1948 as a method for creative problem solving in a group (Osborn, 1948). Workshops can be subdivided into three categories: “workshops as a means” to achieve a certain goal or to gain new knowledge, practices, or competences, “workshop as a practice” to create something together (e.g., process or design), and “workshop as a research methodology” to accomplish a research agenda (Ørngreen et al., 2017). In the study, workshops were utilized to facilitate the exchange of specific-to-domain knowledge among several stakeholder groups and discuss their issues and requirements with a purpose to proceed with the research purpose. In contrast to focus groups, workshops were conducted as longer sessions with a larger number of participants and explored the topic in a less concrete manner.

Participatory Design is a well-established approach to bring target users directly into the design process, also referred as co-design or co-creation. It originated as a democratic process, which is based on the idea that all stakeholders and, in particular, users should have an equal input to design of the product, system or service they are intended to use (Muller et al., 1993). In our case, we relied on participatory design sessions to co-create with the company’s employees and, thus, not only give them a sense of ownership over the technology they will be using, but also to ensure that the final design corresponds to their needs and tasks. This was achieved on different levels, including discussions on abstract levels (e.g., “How can you use VR for X tasks? How would you imagine the interaction?”) and redesigning based on interaction in VR (e.g., “How the interaction can be improved?”).

When meetings face-to-face were not possible due to the COVID-19 restrictions, we heavily relied on Online Demonstrations or recorded videos as a method to communicate ideas and collect feedback from various
groups during the development process. Demonstrations included a video stream from the VR environment from the perspective of the user and voice explanations of interactions, which was shared over a Teams meeting; the meeting attendees asked questions, proposed, and discussed design improvements for future work. Recorded videos from a VR environment were also used as a part of offline data collection methods, e.g., surveys.

**Iterative user study with experts.** In overall, the case studies were structured based on the principles of Lean and Agile work philosophies, emphasizing value creation and waste reduction via the iterative nature of work with the direct involvement of various stakeholder groups (*Manifesto for Agile Software Development*, n.d.; Ries, 2011; J. Womack et al., 2007). By integrating iterative cycles of ideations, co-design, and evaluation, we ensured the relevance of designed solutions from both organisational and workers’ perspectives and continuous improvement of the quality of the designed software based on target users’ feedback (Hartson et al., 2018; Ries, 2011). Therefore, the design solution, created with the help of existing academic knowledge and the involvement of different industrial focus groups, were further iteratively tested with the direct involvement of the users and other stakeholders via user studies, interviews, observations, and online surveys. For the user studies, the mixed research methods with a focus on qualitative findings were utilized as the means to gather research data. The qualitative data was prioritized over quantitative, since it delivers more in-depth insights and richer understanding regarding the application of novel technologies in the industrial context, while supporting the explorative nature of the work and providing flexibility to uncover new variables and influencing factors (Hartson et al., 2018).

*Observations* – defined as “the systematic description of events, behaviours, and artifacts in the social setting” (Marshall et al., 1989, p. 79), is known as one of the core elements of user research to collect qualitative data. It allows to precisely investigate users’ feelings, verbal / non-verbal cues, and their interactions with the technology and each other to better understand their needs and experiences when performing some tasks individually or in collaboration. In order to systematically collect data, we created and utilized observation forms (filled by the researchers) in most of the studies, which defines the scope of observed actions and helps to categorize the recorded data. To avoid the limitations of the method, such as individual biases and validity of results, whenever applicable, more than one observer was present for the study duration, whereas think-aloud protocol was used to identify the reasoning behind users’ behaviour, which helped to avoid personal interpretations.
Think aloud method – a concept, firstly introduced within the field of psychology, which refers to the use of verbal reports as a data source (Ericsson et al., 1984), is generally utilized to understand what a user thinks when performing some tasks. To verbalize thoughts, study participants are asked to report spontaneously and freely everything that crosses their mind during the procedure, would it be a positive or negative flow of thoughts. This scientific method usually helps to gather a more detailed picture of the user experience and spot misconceptions, since it discloses and helps to keep a record of factors that might be forgotten after the procedure and would not be covered, for example, during the interview. The method was utilized in every user study to support and enrich observations with data in verbal format.

Interview is another core method to gather qualitative data, which was the essential element of every user study. Interview, which traditionally was seen as a face-to-face dialog between two persons, has evolved as a method and adopted many forms and mediums, including technology supported tools. To gather the best possible qualitative data, a set of semi-structured interview (Brinkmann, 2020) frames were designed for each user study, which was adjusted as needed based on the conversation flow. Both individual and group interviews were conducted to gather expert opinion on the topic of the study, depending on the user study composition and available time.

Surveys, mostly in online form, were utilized to gather both qualitative and quantitative data, since it is a resource-efficient and flexible method to gather comprehensive datasets from a larger number of experts (Jones et al., 2013). For example, we have relied on surveys not only during user studies, but also during other phases of the research, when the involvement of larger expert groups was required, or when it was not possible to arrange face-to-face meeting sessions. The collection of both data types helped to get a complete perspective over the research topic: while quantitative data provides a general overview and validation of the research matters, qualitative provides a detailed explanation and reasons behind the identified trends. As follows, we utilized surveys to gather perceptions of technology acceptance and usefulness, to validate design decisions or to get priorities for feature development. In case the data collection via surveys included no other means of contact with the experts, we utilized visual content (such as 360 videos, videos with voice explanations, pictures, and graphics) to provide the best possible understanding of the subject.

During the user studies, we have utilized both validated surveys and self-designed set of questions, answered on a 5-point and, more often, on 7-point Likert scale, since it minimizes a central tendency bias while
allowing more dispersion and sensitivity of the answers. The list of thematic set of statements is shown below:

- To evaluate the usability and usefulness of the developed experimental software, validated System Usability Scale (SUS) (Brooke, 1995) and SUXES questionnaires (Turunen et al., 2009) were utilized. Both questionnaires are a commonly used quantitative method for software testing, since they directly demonstrate specific areas for improvement and are relatively fast to fill in. SUS was used in the first case study to rapidly collect experts’ usability and user satisfaction with the designed VR software for AR evaluation. The SUXES was further selected for the second case study as a better alternative, since it helped to gather exerts’ expectations and experiences regarding the VR platform and to track how they would change through all three iterations.

- To measure immersion and presence in VR, the adopted Presence Questionnaire (Witmer et al., 1998) and used it in both case studies. The questionnaire was selected due to the proved validity, reliability, and suitability of the questionnaire to measure presence in industrial VEs. The questionnaire was significantly shortened (from original 32 statements up to 10) due to time constraints to increase time efficiency and enhance the respondent’s engagement. Ten selected statements were sufficient to investigate the matter of presence in relation to the study goals.

- In both case studies, we also utilized self-designed set of questionnaires to collect data. Some pieces of data were required by the industrial partner, whereas for some aspects of interest, there were no validated surveys identified. Therefore, the following self-designed set of statements were utilized:

  o In the first case study, four additional sets of statements were utilized: 1) four statements to evaluate system effectiveness, 2) seven statements to evaluate the AR guidance tool (e.g., Documentation Panel), 3) eight statements to evaluate safety-related aspects, and 4) seven VR-related statements. Moreover, we have designed and utilized paper-based survey to compare the design of safety warnings in the last iteration.

  o In the second case study, additional sets of statements were designed as follows: 1) 12 statements to measure the perception of VR technology in the context of work, 2) eight statements to evaluate the design of virtual tools,
and 3) five COVID-related statements to collect information on how the pandemic had changed working activities, 4) 14 statements on collaboration aspects and 5) six statements to assess the value of technical documentation reviews in VR. Some of the statements in the second case study were borrowed from the first case study.

Objective data was also collected during the user studies. For instance, to investigate the design of AR-based in-field guidance and safety warnings during the first case study, gaze data was utilised. Gaze data collection method is becoming more popular for XR engineering, since it helps to assess the allocation of users’ visual attention (e.g., in the form of heatmaps and scan paths) and, thus, provide additional insights for user interface and interaction evaluation (Maurus et al., 2014; Pliumsomboon et al., 2017; Stellmach et al., 2010). Other objective metrics were logged by the experimental software, such as user actions (user movements via the position of HMD and controllers, controller clicks), system behaviour (e.g., crushes and bugs) and session time. This data was used as a supportive factor on provide more clarity to the user experience in VR.

The analysis of observation forms and interviews were performed by industrial researchers, using thematic data analysis (Harton et al., 2018). The respondents’ quotes from the user study and interviews were categorized by theme with affinity diagrams using excel as a tool. This approach was utilized, since it simplifies the analysis of large qualitative datasets within the collaboration of two actors, providing flexibility and user-centricity when identifying patterns in user experience and themes to support the advancement of the designed software (Clarke et al., 2016; Hartson et al., 2018). The survey results were analysed by academic researchers using descriptive statistics due to the small sample size. The results were further visualized for further presentation and discussion.

The objective data, including gaze data, was analysed by my academic colleagues with the help of programming skills and, therefore, is not included in the scope of my work. I will, however, include some gaze data results, which are presented in Publication I.

4.2 Case Study 1: VR for AR Content Development & Evaluation
In the first case study, the possibilities and limitations of Virtual Reality and gaze tracking technologies were investigated to address the challenges of design, prototyping, and evaluation of industrial AR applications. This case was referred as “AR within VR approach”. Virtual reality, in this application case, provides an opportunity to test design decisions in a safe and controlled environment, which replicates the actual
industrial context and provides natural interactions with the environment and virtual objects (e.g., virtual prototypes and 3D CAD models of machinery). The focus was to explore how experts perceive the practicalities and challenges of AR within VR approach as well as to identify characteristics that might affect and limit the use of VR technology for elevator industry development.

Another study goal was to investigate and gather practical knowledge on how to design AR in-field guidance systems that would assist technicians in their work tasks. Considering the high risk for a design mistake in hazardous industrial contexts, there is a need to identify the most accurate, context-relevant, and safe ways to augment instructions on how to accomplish a maintenance task. Another critical aspect is to ensure safety and consider the design of multimodal safety warnings and the representation of other information.

Therefore, the objectives of the case study were to:

1. Design and develop VR-system which would function as an environment to evaluate AR-prototypes in a simulated industrial context (elevator shaft)
2. Design and develop AR in-field guidance within VR
   - Simulate an interactive maintenance work process (a sequence of maintenance tasks based on technical documentation)
   - Design ways to extract and visualize in-field guidance instructions from existing technical documentation
   - Design and experiment with multimodal safety warnings as a part of the in-field guidance
3. Evaluate the designed AR-software and draw practical implications and design suggestions for AR in-field guidance systems
4. Evaluate the designed VR-system, identify the limitations and potential application scenarios
5. Collect gaze data and evaluate its usefulness for AR-prototyping and other possible scenarios

The flow of the case study is shown in Figure 23. To achieve the study objectives, we designed XRSafetyKit - a VR software, which replicates a real elevator shaft based on a 3D CAD model provided by KONE and simulates AR-glasses field-of-view overlay over the virtual environment. Within VR, we also developed AR in-field guidance for a single maintenance task and investigated how to design safety warnings. The system design is described in section 4.2.1.
We further conducted an iterative user study with domain experts, which consisted of a pilot and 2 evaluation rounds; each iteration contributed to changes and improvements to the system functionality and expanded our understanding of design solutions. The user study is described in section 4.2.2.

Based on the collected data analysis and visualisations, we made an online survey to extract an expert perspective on the AR within VR approach and the perceived benefits of gaze data analysis and visualisations. The survey is described in detail in Section 4.2.3. The outcomes and contributions of the first case study are presented in Section 4.2.4. The mentioned above research activities contributed to Publication 1.

**XR Safety Kit: system description**

The XR Safety Kit system was deployed in Unity, following close-to-industry iterative development practices. This section illustrates the final design of the system.

The virtual environment was created from a real 3D CAD model, which was simplified and reduced due to optimisation concerns. The environment was also equipped with all relevant tools and maintenance components (also 3D CAD models), which would be required to accomplish the “Remove and Replace Tension Weight” maintenance task in VR. The environment and virtual components are shown in Figure 24.

As a result, technicians can complete a realistic sequence of tasks of removing and replacing tension weights with interactive virtual objects – the same sequence of tasks would be useful, for example, for a VR training scenario.
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To enable the means of **simulating AR within VR**, the system visualises AR-software content as an overlay over the virtual environment—a rectangular area centred to the user’s eye position, as shown in Figure 25. The benefit of such feature comes with a possibility to rapidly change field of view (FoV) dimensions and test how different AR glasses would visualise AR-content without purchasing the hardware. For the user studies, the following parameters were used: a horizontal FoV of 40° and a vertical FoV of 27.5°, which was roughly equivalent to the Magic Leap One headset. To increase visual comfort, edges of the AR field of view are feathered, thus making the usable FoV to be slightly less than 40°x27.5° (feathering distance 12% horizontal, 3% vertical).

The designed AR solution, aimed to prioritize the occupational safety of in-field workers, consisted of two components:

1. **in-field guidance**, which visualises maintenance instructions, exported from technical documentation in XML-format,
2. **Multimodal safety warnings** about work-related hazards

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**Figure 24.** XR Safety Kit screenshot with explanations
In-field guidance component was implemented in the form of Documentation Panel tool, shown in Figure 25 (DocPanel for short) – a tangible element of the virtual environment, which can be freely moved in the environment and centered to the eye position. The DocPanel visualizes maintenance instructions, extracted from the actual technical documentation manual in XML format. It parses the instructions based on sections and visualizes the content with the following three structural components: 1) heading of the maintenance step, 2) general instructions for the maintenance step, and 3) a picture with visual explanations, if exists. To increase the effects of guidance, the components relevant to the current maintenance task are highlighted.

The user of the system can control the DocPanel with the VR controller. To navigate in the maintenance task steps back and forward, the user can click the right/left sides of the touchpad. Furthermore, the panel is moved when the user is touching it with a controller and holding a trigger, once the trigger is released, the DocPanel would stay attached to the position in the orientation the user prefers. Additionally, by pressing a single button on the controller, the DocPanel is centered to the user’s eye position, allowing to quickly get the relevant information without searching for the panel in the virtual environment.

The safety warnings are visualized over a virtual environment when the user’s action or maintenance task itself causes risk to the in-field worker. Three multimodal safety warnings were implemented, as shown in Table 5.

**Figure 25. AR within VR simulation in XR Safety Kit**
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<table>
<thead>
<tr>
<th>Warning Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Animated Safety Warning</td>
<td>✓ Uses an animated picture to explain the danger</td>
</tr>
<tr>
<td></td>
<td>✓ Appears when the user’s hand interferes with a risky area</td>
</tr>
<tr>
<td></td>
<td>✓ Picture stays for 1 second in a risky area after the user move the hand away</td>
</tr>
<tr>
<td>Textual Notification</td>
<td>✓ Uses text and an image to explain the risk</td>
</tr>
<tr>
<td></td>
<td>✓ Augments under the object when the relevant task should be held</td>
</tr>
<tr>
<td></td>
<td>✓ Stays under the object during the whole task</td>
</tr>
<tr>
<td>Audio and Visual Warning</td>
<td>✓ Uses an image to notify about the danger and voice to explain it</td>
</tr>
<tr>
<td></td>
<td>✓ Uses a red arrow to point at the danger if the picture is not in the user’s FoV</td>
</tr>
</tbody>
</table>

Table 5. Multimodal safety warnings description

Iterative User Study

To address the objective of the case study, we conducted three development user iterations of the XR Safety Kit system, focusing on both aspects of AR (e.g., the usability and efficiency of guidance and safety functionality) and VR (as a tool to support various industrial tasks and potentially facilitate multidisciplinary collaboration).

In the first iteration, we conducted a pilot with 4 experts; the agenda was to pursue free-form exploration of the system and facilitate co-design and co-creation process. At this stage, the system consisted of a realistic virtual shaft environment, components under maintenance, and the DocPanel. To gather a systematic understanding of the user experience process in VR, the experts were asked to follow think-aloud protocol while using the software and answered to three interview questions about the system design. Additional details were collected via observation forms. Based on the results of the first iteration, the prototype was enhanced with a complete sequence of the “Remove and Replace Tension Weight” maintenance task, required for the tasks tools (e.g., pliers and screwdriver) and one safety warning of an electric shock. The piloting also helped to advance the design of the DocPanel tool: how the content (textual instructions and illustrations) should be visualised, what are the visual characteristics (e.g., font size and colour) and what are the interactions.

In the second iteration, we conducted the first evaluation of the system with five experts with different roles: Method Developer, Senior Maintenance
Specialist, Installation Specialist, Reliability Specialist, Information Architect. The majority of the participants were familiar with XR technology: four of them have experienced AR and VR at least a couple of times before the experiment, and one had heard about it.

The goal of this evaluation round was to investigate the effectiveness, usability, and user satisfaction of the in-field AR guidance, evaluate the safety warning (including how experts evaluate the safety of using AR in the field) and assess the usefulness of the virtual environment. The evaluation was held in the premises of the industrial partner (meeting room). The research data was collected via an online survey, a semi-structured interview, and objective metrics logged on the experimental software. The online survey consisted of 42 statements on a 7-point Likert scale and two checkbox questions, collecting 1) background information, 2) perceived effectiveness of the system, 3) usability and user satisfaction (SUS-questionnaire), 4) Documentation Panel evaluation, 5) Safety aspects, and 6) VR-related aspects. The procedure went as shown in Figure 26. The participants were introduced to the concept of AR-based in-field guidance tool and the reasons to evaluate it within VR.

**Figure 26.** Procedure flow of the user study

Before the actual task, all participants got familiar with the VR environment and learned to use the controllers in a training session, based on a list of tasks which navigated through basic functionality, such as teleporting, interacting with virtual objects, and moving and controlling the DocPanel, as shown in Figure 27.

**Figure 27.** Training screens
A scenario to support the task was also provided to the participants, based on their role. Scenario for the maintenance workers was the following: “Please, imagine that you have your ordinary working day. One of today’s tasks is to Remove & replace the tension weight. You have been given new equipment that will support you in your task step-by-step. You should perform the task according to the instructions from the system.” For experts who do not perform maintenance as their daily routine, we asked them to imagine that instead of their ordinary work, they have to perform the maintenance task. The procedure finished when participants filled in the survey and answered to the interview questions.

This evaluation showed an extremely positive perception of novel technologies among industrial practitioners and resulted in several system changes before the next iteration: 1) increased effect of guidance (e.g., highlighting components and objects to interact with), 2) three types of multimodal safety warnings, 3) additional auditive feedback for maintenance task progress, and 4) advanced and more accurate system logging of 3D objects and gaze tracking data.

In the third iteration, the focus was on the safety aspect and efficiency of designed safety warnings – we aimed to understand and evaluate the principles of visualising different levels of safety-related information and define what modalities should be used. The evaluation was performed at the premises of the industrial partner with four experts: Senior Specialist in Maintenance Methods, Senior Field Trainer, Senior Information Designer and Maintenance Development Manager. For this iteration, the participants were less familiar with XR technology: half of them have used VR and AR for a couple of times, one has heard about it, and one had no previous knowledge or experience. The user study procedure and data collection methods were similar to the previous iteration. In addition, paper-based surveys, and more advanced logs of gaze data to evaluate multimodal safety warnings were utilized. The full list of survey statements and interview questions for both iterations are shown in the Appendix, Section 7.1.
Results

This section represents the results of the iterative user study, presenting the combined data from questionnaires and interviews. In overall, all three iterations indicated the relevance of the research topic and the positive perception of using AR-based systems to support in-field workers. The participants (of the second and third iterations) have finished the maintenance task in VR successfully, showing the interest in and eagerness to utilize innovative technologies in their work routine. In the second iteration, experts evaluated system effectiveness and usability somewhat positive, while in the third iteration, the majority of experts believed that AR-based guidance would make their work faster, safer, easier, and more efficient. The results also demonstrated that the support of a technical person would be beneficial to integrate the system into the company’s processes and educate technicians on how to use it. The increase of experts’ perception between the iterations indicated that the final design of the system was significantly enhanced in terms of quality and performance, correspondingly addressing the needs of target users.

The Documentation Panel – a tool to visualise maintenance instructions based on existing documents in XML-format – and its functionality were also evaluated positively. The main benefit of this was seen in easier access to information; one of the participants commented: “The system would affect the working process in a positive way, because the maintenance workers can have the instructions right away.” (P1). The panel was found to be useful for maintenance work and easy to use. The information representation on the panel was appreciated in general: the instructions were found easy to read, while one participant commented that: “It’s much better compared to paper instructions, what we have today” (P2). The need for further improvements of the design was also identified – for instance, some participants mentioned the need for zooming in the panel, and some pointed out for the need for a better navigation in the documentation (e.g., interactive table of content), especially for more complex maintenance tasks, which include several modules.

The analysis of gaze data demonstrated that the participants were able to read the instructions without directly facing the DocPanel with on average a 7.45 degree gaze vector angle, while the interquartile range illustrated the variability in gaze angle when reading the instructions (Q3–Q1 = 4.73°). Gaze data also illustrated the preferred position of the DocPanel in relation to the participant’s head: they placed it in front or to the left of the work area, below their head position, so the instructions are visible without turning one’s head.

The results of safety-related statements were also significantly improved at the third iteration – all participants felt safe when using the system and believed that context-sensitive safety warnings would help to identify
dangerous places and prevent accidents in a working environment. One participant commented: “I liked it in a way that it really wakes you up. If I don’t immediately see or recognize it, then the voice … it’s like a waking up call” (P3). In the third iteration, the paper-based surveys demonstrated the diversity of opinions regarding preferred visualisation methods and modalities. For every designed warning, the participants preferred different visualisation modalities or suggested own approaches, e.g., one participant suggested using the combination of text, voice, and blinking light to attract attention to the dangerous area, while another commented that only a visual warning in the form of a static picture would be sufficient to acknowledge the danger.

Furthermore, with the help of gaze data analysis, the number of gaze fixations for two types of warnings were calculated: (1) animated safety warning and (2) textual notification. The animated safety warning was directly glanced 4 out of the 22 times it was shown in total (min = 1, max = 9 per session), demonstrating that 2 out of 4 participants did not fixate their gaze on the warning and indicating that this warning design was unsuccessful in informing the participants about the dangerous area. On the other hand, this piece of data cannot help in determining if the warning was noticed from a side view. Further, the textual safety notification was directly glanced 7 times out of the 8 times it was shown, which indicates that this type of warning was mostly successful in alerting the participants about the danger associated with the task.

Lastly, industrial experts expressed an extremely positive evaluation towards the utilisation of Virtual Environments for company needs. The participants confirmed that VR technology coupled with gaze data tracking would be helpful to address their work tasks and ideated many the application scenarios, commenting that it “would be useful for testing new maintenance methods” (P4), “would be a good way to test out documentation” (P5), and “can be used for risk assessing” (P1). The majority agreed that VE is a practical approach to simulate elevator maintenance tasks and that they would like to use VR to learn new maintenance methods. It was also mentioned that training in VR would be especially useful for unexperienced maintenance workers, commenting that “It’s much more powerful way to make people really remember” (P4) and “the huge benefit is it is a safe environment to practice instead of going to the field area” (P1). Finally, the participants mentioned that they felt motivated by the VE to do their work.

In summary, the results of the iterative user study demonstrated that the xR Safety Kit framework is a viable and promising innovation for the industrial context, while industrial employees showed high intrinsic motivation and eagerness to work with both AR and VR technologies in their daily routines.
Gaze data and Expert Survey
Once the data from the iterative user study was analysed, we performed the last activity to evaluate the usefulness of VR environment and gaze tracking from the perspective of the company’s managers and seniors. Due to their busy schedule, we concluded to collect data via the video-based online survey. The survey consisted of four thematic parts and a background section; it collected responses in the form of statements on a 5-point Likert scale and open-ended questions. The survey gained the perception about the XR technologies in the context of industrial maintenance on the following topics:

(1) AR simulation within VR (10 statements + 3 open-ended questions)
(2) XR & Industrial Training (7 statements)
(3) XR & Technical Documentation (5 statements + 1 open-ended question)
(4) Gaze tracking and analysis (8 statements + 6 open-ended questions)

In this section, I report a more detailed overview and results of the survey, which were only briefly mentioned in the Publication I.

Respondents. Thirteen experts have left their responses to the survey: one of them skipped some questions about the AR simulation within VR, and another had not completed the survey, leaving blank sections about the gaze data and background information. Therefore, I report the background information only for 12 respondents: they were aged from 37 to 59, with the average in 49,50; one of them was female and one preferred not to specify. They represent the following areas of expertise: Training (8), Safety (6), Technical Documentation (6), Maintenance (5), and XR use cases (5). In addition, one of them had expertise in the “development of a new component through the whole life cycle including installation and maintenance”, one mentioned “installation, work studies, all modernisation tasks except direct selling” and another added “fault finding and ride comfort”.

Most of the respondents had previous experience with XR technologies and can be referred as tech-savvy users: the majority (83,3 %) had used VR technology a couple of times at most, one (8,3%) had used VR technology a lot and one (8,3%) had heard about it. Similarly, most of them (75%) had used AR technologies a couple of times at most, two (16,67%) had used AR many times, and one (8,3%) had heard about it. Further, regarding the general interest towards technology, two respondents (16,67%) have marked that “I’m very interested in technology – I’m among the first ones to try out new devices and digital services” and the rest (83,33%) were “somewhat interested in technology – I’m glad to use devices and digital services as a part of my everyday life”.

Results
The survey results were mostly positive, and the experts also left many supportive comments and ideas on how XR technology can be used in the industry. Some of them also left comments positively evaluating the study itself, such as:

• R7: “Ground-breaking! Please keep also on practical cases (but remember to highlight that technologies are developing too!)”
• R9: “This study is very important from that point of view that maybe this way the awareness of AR and VR will increase in the whole industry”
• R10: “Interesting study and useful for future development ideas”

Figure 29. Survey results on the concept of AR simulation within VR
The evaluation of the concept of AR simulation within VR was mostly positive (Figure 29).
All responders agreed or strongly agreed that Virtual reality with AR simulation would be a practical environment to design and test AR-based solutions before implementation and that it would boost AR development processes in industrial settings. Furthermore, most of the experts found that VR with AR simulation would be a safe environment for AR content development and testing, which would help to select the right hardware, mitigate risks during the product development, and positively affect the speed of AR solution testing. The experts also commented on the role and benefits of VR technology in the field, highlighting the applicability at the earliest stages of design:
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![Figure 29. Survey results on the concept of AR simulation within VR](image)

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The experts also commented on the role and benefits of VR technology in the field, highlighting the applicability at the earliest stages of design:
• R9: “It is a safe and cost-efficient way to test AR solutions.”
• R13: “AR simulation in VR could be used to test radically different ideas without, for example, safety concerns or limitations in a real environment.”
• R2: “Combined with 3d modelling, this could be used to aid the design for installation and maintenance at the very initial concept stages of a design.”
• R3: “Probably useful but not sure if it is wise to totally rely on AR-VR in AR development. Could be handy in prototyping and piloting.”

Despite most of the experts agreed that AR simulation in VR would help to develop safer maintenance methods and solutions, the safety concerns about the use of VR were also mentioned by the participants:

• R4: “The other important issue in the safety point of view is the lack of activity of other senses like noise, heat or cold, weight, sharpness of material, risk of falling, etc. Naturally you can put warning and warning sounds, but these you can feel and recognise only in real practice cases. Naturally you can practice in theory, but reality is also needed.”
• R13: “If VR model is missing real world components or context, it can be a safety hazard.”
• R9: “In VR surroundings the main thing would be to ensure that using AR does not cause any new risks in the real world.”

Further, the majority of experts showed a positive perception of using VR and AR for training purposes (Figure 30).

![Survey results on XR-based training and AR-based guidance](image)

Figure 30. Survey results on XR-based training and AR-based guidance

All experts agreed that trainees would be more ready to perceive the traditional training if familiarized with VR simulations first and that
complementing the traditional training methods with AR technology would make the training more efficient overall. Furthermore, half of the experts showed strong agreement that utilizing both VR and AR technologies in training would increase the overall quality of the training. In addition, most of the experts believed that maintenance efficiency can be improved by utilizing AR technology for in-field guidance and by reutilizing the same instructions in VR training and in AR-guidance. Furthermore, all experts believed that it would be useful to visualize technical documentation in VR (Figure 31). Most of them (84.62%) agreed that using technical documentation in VR simulation would help to investigate if the documentation is useful, while testing it in VR simulation would help to improve it.

The expert also clarified that testing of Technical Documentation in VR can increase the quality of the documentation based on real-life insights and suggested to accomplish it at the piloting phase:

- **R10:** “During machine replacement VR exercise we noticed several updates needs for paper technical method instructions, it was really improving document quality compared to traditional subject matter expert checking review.”
- **R6:** “I think this can be good for piloting a document before testing in practice.”
- **R9:** “Main thing would be to test the content and make improvements before testing those in a real environment.”

On the contrary, experts showed concerns on running time studies (e.g., how much time it takes to perform a certain maintenance task, which is used for the planning of maintenance operations) in VR, one of the participants explained that “Time studies must be done in real life by persons who have a license to do it. Otherwise, you can print the working study on soft paper and use it...” (R4).
Finally, the section on gaze data (Figure 32), despite demonstrating somewhat positive evaluation of the topic by the majority, also showed a higher level of disagreement. As follows, the experts believed that it is important that gaze tracking helps to analyse where the user pays attention to in the VR environment and that tracking users’ movements and visual attention would be an efficient approach to determine the best suitable multimodal combinations and designs for safety warnings. The same was reflected in experts’ comments – one of them commented that gaze tracking is “a good method to analyse where a technician is really paying attention.” (R9) and “To see if which information is most looked at (useful).” (R13). Further, 75% agreed that visualisation about where the user has paid attention to in the VR environment would be a useful tool in training maintenance technicians. They further left supportive comments:

R3: “Could be obvious that analysing the spots where the gaze remains longer periods while the user thinks, are the most crucial ones which require training.”

R10: “To improve training content (warning tool, spare part locations). Picking tools must be fast and safety warnings always in the same locations, etc.”

R9: “Trainer can track the focus areas of a trainee and based on this information guide him/her better.”

Figure 32. Survey results on gaze tracking and data collection

Furthermore, the gaze data showing how much documentation is utilized during work and which parts of it draw the users’ attention was found useful by the majority. Using gaze tracking and gaze visualisation while testing maintenance methods in VR to improve maintenance guidance in the field was found to be helpful by roughly half of the experts. Nevertheless, the experts also pointed out the weak side of gaze data
collection and tracking, one of them also claimed that it is a “waste of time” (R4). For instance, real-time gaze tracking was evaluated not so positively, commenting their concerns as follows:

R10: “Potential might increase, but currently it is not the most important feature.”
R3: “Getting enough data to make meaningful decisions based on a large enough number of people could be challenge.”
R13: “Gaze tracking might be a tool, but it is limited to what is included in the VR model... real world has other places to look at, so I would be vary of the results, because they are so much VR model dependent.”

Outcomes and Contributions

As a result, the iterative user study and follow-up survey demonstrated a positive perception of utilizing XR technology in the work context. The AR-based in-field guidance was found to be a desired concept in overall, which would help maintenance technicians in their work tasks worldwide and ensure the proper use of documentation. It was found to be an efficient method for unexperienced maintenance workers in terms of assistance and learning as well as useful for experienced ones for presenting and learning new maintenance methods. The most relevant approach was seen in creating different levels of documentation complexity according to the needs and knowledge level of technicians.

On the other hand, the AR technology was seen as not yet mature to rely on it in the industrial hazardous context, such as an elevator shaft; many of the industrial experts would not like to wear AR glasses, which blocks their view of a working space. The experts pointed out that completely transparent glasses and extensive testing of functionality might solve the trust issue.

This emphasizes the main problem associated with AR-prototyping – hazards related to its development and testing in the industrial context. Therefore, the XRSafetyKit or AR simulation within VR, was found to be a suitable technology to facilitate AR-prototyping in a safe and efficient manner. The experts especially mentioned the possibility to rapidly change design solutions, such as visual or other multimodal elements of documentation and safety warnings. Gaze tracking was also seen as a valuable analytical tool to collect objective metrics for AR content testing in addition to subjective metrics, such as user preferences. Combining both metrics during the design phase, the design of AR solutions could be optimized to the context of use and user needs accordingly.

Design implications for AR-based in-field guidance

Based on the expert insights, I have formulized practical implications in the form of design suggestions regarding the AR-guidance:
**Design suggestion 1:** The existing Technical Documentation (in XML-format) should be redesigned into a new visual format, consisting of short text statements, pictures with colours, and animations/videos. While text-based instructions with black-and-white illustrations are suitable for paper format, the use of AR technology allows to go beyond classical standards and to use more advanced and visually appealing methods of information representation. It could include techniques to simplify the understanding of instructions by maintenance technicians, for instance, color-coding of steps or elements under maintenance (as shown in Figure 33), animations and gifs to demonstrate the rotation direction or angle, voice explanations, etc.

![Figure 33. How to make technical documentation more visual for AR content](image)

**Design suggestion 2:** The size of visual objects (for instance, the documentation panel and its’ content) should be optimized for the glasses’ field-of-view, as shown in Figure 34. This would ensure the instructions can be read at a glance and would avoid unnecessary head movements of technicians.

![Figure 34. Optimisation of content size for the AR-glasses field of view](image)

**Design suggestion 3:** The DocPanel (or any other means of presenting the maintenance task instructions) should keep the user informed about the specifics of the task, such as visualising the required tools and safety equipment for a task step and associated risks, as shown in Figure 35.

![Figure 35. Informing the user about the specifics of the maintenance task](image)

**Design implications for AR-based safety warning**

In addition, augmented multimodal warnings were found to be a demanded and useful safety approach to avoid risks in the context of elevator maintenance. All types of warnings were reported as necessary and suitable in terms of modalities and situation when they are used. The interview results showed that visual modality was preferred, while there was no clear identification that animated images were more beneficial than the static ones. Auditive modality (sound signals and voice explanation) was perceived positively as “a waking up call”, especially in situations when the dangerous area is in the glasses field-of-view.

Nevertheless, the use of sound and voice should be planned carefully, while devices for sound output should not block the outside environment sound and support communication between technicians working together. Vibro-tactile feedback was suggested as an additional modality for warning; however, it would require an extra wearable device (such as a wristband).
**Design suggestion 1:** The existing Technical Documentation (in XML format) should be redesigned into a new visual format, consisting of short text statements, pictures with colours, and animations/videos. While text-based instructions with black- and white-illustrations are suitable for paper format, the use of AR technology allows to go beyond classical standards and to use more advanced and visually appealing methods of information representation. It could include techniques to simplify the understanding of instructions by maintenance technicians, for instance, color-coding of steps or elements under maintenance (as shown in Figure 33), animations and gifs to demonstrate the rotation direction or angle, voice explanations, etc.

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**Figure 34.** Optimisation of content size for the AR-glasses field of view

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**Figure 35.** Informing the user about the specifics of the maintenance task

**Design suggestion 4:** The system should be intelligent to keep track of the context and differentiate between safe and non-safe zones, as shown in Figure 36. It should not allow placing digital objects (e.g., Documentation panel) over dangerous sports in the context, thus hiding it from the technicians’ eyes.

**Figure 36.** Visualisation method for safe and non-safe zones

**Design implications for AR-based safety warning**

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Based on the qualitative study findings, I provide the following practical implications, presented in the form of **safety-related design guidelines** for AR-systems:

**Design guideline 1:** Multiple levels of awareness are required to support all technicians with different experience levels. For beginners and unexperienced workers, it is recommended to include more details and attention grabbers, such as warning pictures, text, sound, voice, vibration, and even flashing, while for experienced workers would not require extensive notifications and might find them irrelevant, focusing on performance and productivity. Additionally, different levels of awareness might be considered for the same notification type for the 1st time and the following times. When AR-guidance would be used for in-field training purposes, interactive notifications (which can be closed or confirmed by a trainee) should be considered to advance the learning effect.

**Design guideline 2:** The safety status/indicator of the task should be visualised over the DocPanel (for example, green-yellow-red shape to indicate the level of hazard during the task, as shown in Figure 37)

![Figure 37](image)

**Figure 37.** Visualisation of the safety status of the maintenance task

**Design guideline 3:** The warnings’ visual design should be simple, self-explanatory and contain only relevant information, as shown in Figure 38.

![Figure 38](image)

**Figure 38.** Simplifying the design of safety warnings

**Design guideline 3:** When a user interferes with a dangerous area, the visual image should stay over the risky area for 2-3 seconds. In situations, where the danger is outside of the FoV, additional methods should be utilized to point towards the danger (clearly visible and big enough...
Based on the qualitative study findings, I provide the following practical implications, presented in the form of safety-related design guidelines for AR systems:

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**Design guideline 3:** The warnings' visual design should be simple, self-explanatory and contain only relevant information, as shown in Figure 38.

**Design guideline 4:** When working in a team, the system should be able to track everyone’s actions and report critical changes (for example, if one technician turns ON the electricity, the second one should be notified about it, as shown in Figure 39) as well as to support communication between the team members.

**Design guideline 5:** The system should be able to provide guidance during accidents (for example, in the case of a fire alarm, the system should stop all maintenance tasks and guide the worker to the safe exit, as shown in Figure 40).

**Indications of the potential of VR technology**
Apart from AR-related findings, the study opened many important insights regarding the VR technology. The experts from different departments showed interest and eagerness towards using VR as a part of their job; most of them mentioned that VR can address many of the existing process-oriented problems in their everyday routine. First of all, VR was seen as a promising tool to educate young technicians; the developed sequence of tasks was found sufficient to practice “remove and replace tension weight” in a safe environment. However, this method was
evaluated as a supportive activity prior the real hands-on training. Next, VR was seen as a supportive tool to design maintenance methods for newly created equipment. Experts have shared that in many cases, maintenance methods are developed based on their expertise and 2D pictures or 3D models of the equipment – they rarely have access to physical equipment, and even more rarely they can see it in a realistic context – which would require additional time and expenses for travelling.

Therefore, VR offers a cost-efficient way to see the 3D model in real-to-context virtual environment in 1-to-1 scale. The same applies to the process of technical documentation creation, which is usually designed based on the maintenance method draft provided by maintenance method designers. This process is further challenged due to the involvement of multinational departments, scattered over the globe and working in different time zones. Due the known potential of VR to provide a shared workspace for people working remotely in different cities and countries, industrial experts believed that the application of VR would bring advantages to their existing work routine. Furthermore, this study suggested that in order to arrange the AR-prototyping and evaluation within VR in a sustainable and efficient way, the design and creation of technical documentation in the first place should be reconsidered, whereas VR can provide a realistic context and natural means of creating content for these processes.

In summary, this case study demonstrated that VR could solve and advance several industrial use cases:

- **maintenance method, education and training; risk assessment training.**
- **elevator prototyping together with developing and prototyping maintenance methods for it,**
- **maintenance and safety documentation development and testing**

Moreover, this can be achieved by reutilizing a single VR platform by multiple departments. Therefore, as the main outcome, this case study led to the continuation of the research activity towards exploring the application of VR for maintenance method and technical documentation creation.

### 4.3 Case Study 2: VR for Maintenance Method and Technical Documentation Creation

In the second case study, we have explored how to design and develop industrial VR technology with a goal to facilitate the collaboration of multidisciplinary departments working in the pipeline of maintenance method and technical documentation creation. The preceding case study
partly observed the usefulness of simulated virtual environments and access to 3D CAD models in 1:1 scale for the needs of the maintenance development department. Further investigation led to shifting the focus of the study towards integrating multidepartment collaboration and work processes into VR. Therefore, this case study aimed to investigate and create generalisable knowledge on how to (1) support industrial collaboration in VR, (2) deliver a means of interacting with 3D models, and (3) design virtual tools for technical documentation and content creation.

Therefore, the objectives of the case study were to:

1. Perform the collaborative user-centred design and development process of a VR-based platform
   - Report methods of academia-industry collaboration

2. To facilitate collaboration and execution of industrial tasks within VR
   - Enable natural interaction with 3D Cad models and in-depth investigations (e.g., scaling, disassembling)
   - Enable effortless means of producing digital content as a result of virtual collaboration
   - Design for natural and efficient multiuser interactions and shared object manipulation

3. To evaluate the VR platform in multiple scenarios and set-ups to elicit practical suggestions and recommendations on how to design VR platform and further adopt them into working processes.

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**Case study 2:**
*Maintenance method and technical documentation creation in VR*

![Timeline of the second case study](image)

*Figure 41. Timeline of the second case study*
The flow of the second case study is shown in Figure 41. We performed user-centred development process of the COVE-VR platform in close cooperation between academic and industrial researchers and the involvement of domain experts thought out the process. The COVE-VR system final design is presented in section 4.3.1, followed by the development process in section 4.3.2.

Next, the COVE-VR platform was evaluated in three different set-ups and scenarios with industrial experts. The collaborative development process and some part of the first evaluation (asynchronous collaboration scenario) contributed to Publication II. The results of the first evaluation, focused on the design and functionality of virtual tools for content creation, are presented in Section 4.3.3 and in Publication III. The second evaluation of the case study (described in Section 4.3.4.) explored the role of asymmetry in multidepartment meetings and contributed to Publication IV. The final evaluation (described in Section 4.3.5.) contributed to the understanding of how to perform a collaborative technical documentation review in multiuser VR and contributed to Publication V. The outcomes and contribution of the second case study are summarised in Section 4.3.6, whereas Academy-Industry collaboration-related findings are presented in section 4.3.7.

COVE-VR: system description

The COVE-VR platform was designed to support industrial task execution by facilitating efficient asynchronous (single-user) and synchronous (multi-user) collaboration of multidisciplinary global departments. Additionally, the system design and functionality should allow easy and natural interaction with 3D CAD models (to serve the needs of maintenance method developers, technical documentation writers, and illustrators) as well as provide a means of creating digital content as a result of the collaboration. In simple words, the desired VR platform should allow individual work, similarly to working in a cloud – when a user can access the virtual space (in own time and pace) and all its’ content, create own digital content (e.g., comments, photos, etc) and save everything, so another person would be able to continue with their tasks – therefore facilitating and advancing asynchronous collaboration practices. As well, the platform should facilitate teamwork, when people from multiple locations would be able to work jointly and feel the presence of each other.

In this section, the COVE-VR platform is described with a focus on major functionality and interaction design; technical aspects of the system development are out of the scope of this dissertation. Two virtual environments and eight virtual tools were designed to address the needs of industrial workers. The environments include (1) a small workspace,
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The VR Lab replicates the elevator shaft and was designed based on the real 3D CAD model provided by KONE. Due to the relatively small size, it can be used by a small group of users simultaneously. This major advantage of this space is that it provides a realistic context, so industrial employees would be able to see the shaft and the components in it in 1:1 scale, therefore, reducing the need for travel.

The Showroom virtual space was designed with a goal to facilitate teamwork of larger groups: 1) to accommodate presentation and 2) investigation of 3D CAD models. Therefore, the space is equipped with the Disassembler—a virtual tool, which allows advanced manipulation of 3D models and disassembly/assembly of its components. The model can be opened via the wall menu from the list of available 3D models (visualised over the wall). Once opened, the model is placed on the pedestal, while the list of available models is replaced with a wall menu,
which allows to disassemble / assemble the selected model, scale it in size, and change the disassemble explosion distance and elevation. The Showroom also has a second-floor balcony to allow a bird view over the model.

Other functionality of the system is designed in the form of virtual tools and is available via the wrist menu – a circular menu, which appears over the user’s left wrist when the user is looking at it. The menu items can be selected by moving the finger over the controller’s touchpad and clicking on the needed item. In order to move from one space to another, the user would need to select the “teleportation icon” on the menu. As well, the menu allows to open virtual tools in any of the spaces. Eight virtual tools and their functionality are shown in Figure 43. The tools can be wrist attached or located in the virtual space. To close a wrist-attached tool, the user needs to click the menu icon once more; for the rest, the Delete tool is utilized.

Figure 43. Virtual tools of the COVE-VR platform

COVE-VR development process

The COVE-VR platform for industrial work and collaboration was created in a close-to-industry development process, based on the principles of user-centred design. In this section, I provide an extended description of the process, since not all details have been included in Publication II.

The goal of the activity was to include different industrial focus groups throughout the process, thus ensuring that the design and system features address the needs of the users. As a result, four groups, presented in Figure 44, participated in the system design, development, and evaluation.
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Figure 44. Focus groups of the second case study

Academic and industrial researchers equally participated in the collaborative design activity, having equal influence over the progress of work and design directions. The project would not be possible without involving both parties. The presence of industrial researchers ensured that research activity is tightened to industrial challenges and provided access to focus groups. Academic researchers, in turn, brought methodological knowledge to initiate and organize the user-centred development process and human resources for design and development, ensuring that system design would be based on the latest academic related work. The involvement of Managers and Team Leaders was critical to validate the relevance of the research direction for the organisation, while other company employees from the three departments (Technical Documentation, Learning and Development, Next Generation Maintenance) would help to gather specific to the domain knowledge and insights on how to design the system and methods to validate that the design corresponds to the user needs. The whole design, development, and evaluation process, demonstrated in Figure 45, was iterative in nature and was split into three phases, linked to the phases of user-centred design. The phases are detailed below.

Phase 1: Identify user requirements and context of use

All four groups participated in the first phase, “Identify user requirements and context of use”, which consisted of three steps and shown in Figure 46. This phase was focused on gathering a complete and shared understanding of industrial challenges to address and related needs of industrial workers, which would narrow down into a concrete development agenda.
As a first step, we conducted *Kick-Off Ideation* session, involving both focus groups, which helped to establish the core values of collaboration and ideate the possible direction of work. The session occurred in KONE premises and started with HUMOR project overview and goals, followed by three presentations of industrial managers, representing the perspective of their departments (*Technical Documentation, Learning and Development, Next Generation Maintenance*).

Next, the participants of the session were split into three teams to ideate and discuss potential research directions in frames of the major areas of interest: (1) VR simulation environment, (2) Gaze tracking and other data analytics possibilities within VR, (3) Technical Documentation & XR. Ideation activity was planned and moderated by industrial researchers.
The teams had a limited amount of time per ideation and were dynamically mixed among the three sessions to gather a diverse and multidisciplinary perspective on all three areas.

As an outcome, the concept of VR-platform to support the work and collaboration activities of multidisciplinary departments was created. The pipeline of maintenance method development and technical documentation creation was selected as a case study since the traditional process is vulnerable and error prone.

The second step, the Maintenance Documentation Journey workshop, was conducted to collect detailed information about work processes, related problems, and how the virtual environment can facilitate better practices. The workshop was held at KONE premises, while two additional participants from India joined remotely - communication was facilitated via a Teams video meeting. A separate USB-plugged camera and a separate speaker were used to improve the visual experience of remote participants and provide good audio quality (as shown in Figure 47).

![Figure 47. Pictures from the Maintenance Documentation Journey workshop](image)

In the first part of the workshop, the participants were presented with the maintenance documentation journey and asked to participate in the discussion about their work practises and important details. Furthermore, the participants were divided into three groups to discuss the limitations and pain points of the process and to ideate how VR can solve these. As a result, it was possible to illustrate the user’s personas based on their work responsibilities, as well as identify their main tasks that could be transferred into VR. Furthermore, the process of developing maintenance methods and documentation instructions was verified, and four VR-based scenarios were proposed to improve the overall process (Figure 48).

Based on the result of the workshop, a list of development features was created – all features corresponded to the needs of target users. Before actual implementation, the features were once more iterated with KONE employees in a Prioritisation Survey. This research activity was planned, carried out and analysed by industrial researchers.
Data collection was conducted as part of a video-based remote session, where, first, the features were presented and explained to the participants in the introduction session, to ensure that everyone has a full and similar understanding of the development features. Participants could also ask questions and clarifications. Next, a digital survey was shared with the participants, and they filled it in on their personal computers. The survey collected their responses to the question “How important you consider the following features in VR?” on a 5-scale Likert. The video connection continued until all participants have confirmed that the survey was completed. As a result, nine KONE employees have answered the survey questions: three were from Technical Documentation department, four from Next Generation Maintenance, and two from Learning and Development. The features were split into six categories: Tools, Notes, Environment, Integration, Timeline and Other. The result of the survey is shown in the Appendix, Section 7.2.

As an outcome, this functionality was decided to be delivered in the form of **virtual tools**, which we defined as virtually tangible elements of the virtual reality system, which may be used to aid the execution of an industrial task, such as manipulation of the virtual environment or the creation of digital content.

**Phase 2: Produce design solutions.**

Once the results of the prioritisation survey were analysed and the main functionality of the system was confirmed, we initiated Iterative Development Process. All four focus groups participated in this phase, as shown in Figure 49. Due to restrictions on social gatherings, all activities of this phase were carried out remotely. The virtual reality platform was designed by academic researchers in weekly and monthly development sprints. Initially, industrial and academic researchers have discussed the agenda for the next month, e.g., what features should be implemented (next month) and what are the most efficient interactions. Next, academic
Researchers (four developers, one UX and visual designer, and three senior researchers) conducted weekly design, development, and testing sessions.

**Figure 49. Second phase of the design and development lifecycle**

Most of them happened in online meetings when new features were explained by one of the developers with the help of streaming a video feed from VR to Teams. Therefore, the developer can demonstrate and explain the implementation, while others can observe the experience and provide feedback and design suggestions. In addition, all academic researchers had access to VR equipment at their homes and had a possibility to access the platform and experience the interactions on their own. Once a month we had online demo sessions to demonstrate the development progress and gather feedback from industrial focus groups.

Once the development of the system was finalized, we aimed to evaluate the usability and functionality of the VR system and gather subjective perceptions about the concept of documentation creation within VR and the design of virtual tools. Again, due to covid restrictions, traditional in-lab usability testing was impossible to perform. Therefore, we collected expert feedback on the usefulness of the system and design improvements through the Concept and Design Validation Survey. The survey demonstrated the main system’s functionality and how it can be used via 360-video clips of virtual environments and first-person video with a voice over explanation. It consisted of a variety of question types (e.g. statements answered on a 7-point Likert scale, single-choice open-ended, and rating questions) subdivided into six categories: 1) background information, 2) two sections to demonstrate and evaluate the virtual environments (VR Lab and Showroom), 3) six sections to evaluate the virtual tools, 4) a section on menu items prioritisation, and 5) overall system perception. The survey was open for one month; the link to the survey was shared among company employees from both focus groups by industrial researchers. In total, 38 industrial employees: 18 completed and 20 partial.

**Respondents.** Respondents (N = 18) have represented the following three departments: Maintenance Development Department (9), Technical Documentation Department (5) and Learning and Development.
Department (4). The respondents were aged 26 to 62 (M = 36.5); two of them were female. Six of the respondents marked their country of residence as Finland, four were from China, four from India, and the rest represented Australia, the Netherlands, Germany, and Malaysia. Most of the respondents had a higher education, such as a bachelor or master’s degree (14), while four had a high school or vocational school degree. Four of the respondents were already involved in the previous phase and responded to the prioritisation survey. Eleven respondents had previous experience with VR or AR technology; three of them have experienced existing company technologies, such as KONE installation training in VR, VR-based elevator component replacement activities, and AR for viewing documentation.

Survey results. The results demonstrated an extremely positive evaluation of the platform concept, and the experts left many supportive comments to describe how they see the benefits of using the VR system as part of their work routine. The main advantage of being able to immerse into the virtual environment was seen in enhanced understanding of context-sensitive information, while simplifying related creation activities and ensuring the accuracy of outcoming methods and documentation. One of the experts commented: “VR would enhance the accuracy of technical documentation as it helps the writer to get closer to the product than ever” (R1). In addition, many of the participants mentioned that access to VR would significantly reduce travel and would allow larger circles of industrial employees to get familiar with the context and equipment, saying: “Large equipment is often hard to see in real, especially with a group of people. VR will enable this, safely” (R3). Another massive advantage was seen in enhanced communication and the ability to globally collaborate with colleagues.

- **R1**: “VR provides transparency and clarity of information to be discussed across departments”
- **R2**: “Good for meetings and handling models. Installation and maintenance procedures can be discussed in a room with all the members and handling models directly. Videos can be recorded”
- **R3**: “Communication becomes faster because you can just show things”

All of the respondents left a positive evaluation of the Virtual Lab space and designed virtual tools – the majority found that the environment is realistic and agreed that the platform is useful for developing and evaluating maintenance methods and safety documentation.

In summary, the survey results indicated a great potential and desire of industrial employees to use VR for their work tasks and verified the relevance of the system design to their needs. As an outcome, we
concluded that the COVE-VR platform, with small modifications, was ready for user studies with target users.

**Phase 3: Evaluate Design Solutions**

In this phase, we performed three iterations of user studies, involving the actual target, the company’s employees, as shown in Figure 50. All three studies followed a similar procedure: the goals, objectives, and resulting methodology of the study were agreed between academic and industrial researchers. All three user studies were built based on industrial work tasks – to accommodate it, we designed scenarios and tasks to accomplish for the participants. All user studies were piloted with target users prior to actual user tests to identify weak or problematic spots – this helped to ensure the efficiency of smoothness of the procedure. Data collection methods were designed in close collaboration and multiple iterations. After the studies were performed, we analysed the data separately: academics were mainly responsible for analysing survey responses and objective metrics from the system, while industrial researchers performed the analysis of interview data. Additionally, we combined our findings in remote discussions, eliciting ideas for the next round.

![Phase 3: Evaluate design solutions](image)

**Figure 50.** Third phase of the design and development lifecycle

**User Study 1 - Asynchronous Collaboration**

The first user study was explorative in nature; it was conducted to evaluate the usefulness of virtual environment for collaboration processes among maintenance method developers and technical documentation writers, as well as to evaluate usability of the COVE-VR system in a single-user mode and the effectiveness of the designed virtual tools. The study was built based on the process on the identified pipeline and investigated asynchronous collaboration scenario between the departments, as shown in Figure 51.

The **main goal** was to identify the opportunities and limitations in facilitating work tasks of working in VR and to obtain expert feedback on VR technology as a supporting technology for industrial work processes. Additionally, we explored how industrial employees would use virtual environments to approach their work task and what kind of digital content they would be able to generate.
To address the goal of the study, study participants were selected to represent two groups: maintenance method developers and technical documentation writers. Study scenarios and evaluation tasks were designed based on a realistic work process and were slightly different for two groups: maintenance method developers performed their tasks from scratch and created digital content in VR without having any other materials, while technical documentation writers could see some “pre-created content” when entering the VR and performed their tasks based on it. However, the general workflow of study procedure and the maintenance task in use were the same: all the study participants worked with the disassembled RBO 3D CAD model and went through interactive battery replacement task. Overall, all participants visited two virtual spaces and used six virtual tools during the study procedure.

**User study procedure and tasks.** The study was carried out in the facilities of KONE; the procedure was moderated by a single industrial researcher due to pandemic restrictions and recorded and streamed on Microsoft Teams for observation. The user study started with a brief introduction to the practicalities of the study, consent signing, and filling out the background section of the questionnaire. Participants were encouraged to use the think-aloud protocol and freely express their emotions and opinions about the design and functionality. The participants then watched a demo video on the functionality of the system and filled out the questionnaire on their expectations. Next, the participants have gone through the scripted training process to ensure that they learn to use the controls and understand the basic functionality of the system. Once the participants confirmed that they feel confident using the VR platform, actual user study tasks were performed. Firstly, the participants performed a sequence of tasks in the Showroom VE and were further asked to teleport to the Lab VR. The detailed task script is shown in the Appendix, Section 7.2. After all study tasks were completed, participants filled out the questionnaire and answered the interview questions.
**Data Collection and Analysis.** The data was collected via observations, pre- and post-questionnaires, and a semi-structured interview, which were further analysed as described in section 4.1. In this iteration, the pre- and post-online survey collected responses on a 7-point Likert scale and consisted of six parts, shown below:

1. Background Data Collection
2. Expectations vs. Experiences – a validated SUXES questionnaire, which collects the expectations of the system before usage and after it (9 x 2 statements)
3. Presence and immersion in VR – statements based on PQ (10 statements)
4. Perception of VR technology in the context of work (12 statements)
5. Evaluation of virtual tools (8 statements x 6 tools)
6. COVID-related statements

**Participants.** Seven industrial experts participated in the first user study: four maintenance method developers and three technical documentation writers with 10 and 14 years of experience on average. They were aged 27 to 57 (M = 40); one of them was female and one preferred not to reveal the gender. Six of them hold a university degree or similar, and one graduated from a vocational school.

**Results.** The user study demonstrated that the COVE-VR platform efficiently supports the asynchronous collaboration of two departments. All experts have completed their tasks and generated useful digital content and notes for further internal communication. The overall reaction to the experience was positive; many of the experts supported the idea of using VR technology as a part of their work, and ideated many other use cases, demonstrated below.

- “App would be maybe useful for first draft, get familiar with the product.”
- “Very useful for trainings for planning department”
- “Helpful also in replacement, assessment, and other activities”
- “It would help me making documentation method validation”
- “You could take a picture of the component and the note the was written and share it via email for instance to have a different way of communication with designers and methods developers”
- “Currently I take a note in different places, a lot of rework. If I get to show what I meant in VR, I can do it only once. I think that is a good way to do it, and faster”
They also pointed out that synchronous collaboration in VR would be also beneficial for their tasks in many phases of the product and service development:

- “Kick up in VR at the first meeting so that the designers can explain what they design, and everyone can ask questions. This in major projects or something completely new”
- “I would prefer to use the tool in collaboration with others at the beginning of project and end of product”

However, a severe number of system errors and bugs were identified during this iteration. According to the SUXES results, the system was expected to be faster, more pleasant and natural to use than it was evaluated. On the other hand, COVE-VR was found to be clearer and easier to learn than expected, for some experts the VR experience in VR was effortless (“It is clear after a couple of minutes”). Experts with previous VR experiences commented that “It was more much easier to get used to the environment. At first strange but it gets quite comfortable” and “This was better experience than the others. The space was better”. However, some experts faced problems with basic interactions (for example, teleportation, object grab), commenting that the use of controls was not intuitive: “Too many options. Need time to learn them” or “I was struggling with the buttons” or “I spent too much time thinking what to press”. The results of the presence questionnaire suggested similar tendency. Despite the fact that a larger half of the participants quickly adjusted to being in a virtual environment, not all of them easily adjusted to the controls and, for most of them, the experiences in VR were not consistent with real-world experiences. Furthermore, some experts did not feel confident when moving or interacting with virtual objects and could not concentrate on the assigned activities because the concentration was gone to the control mechanisms.

Despite all issues, all the experts were engaged in the assigned virtual tasks and most of them felt immersed in virtual working spaces. In summary, the experts found the platform useful and would like to use it in the future.

Further, I describe the results on the four virtual tools: the Disassembler, the TextBox tool, the Camera tool and the Measure tool, because they are essential for the pipeline of maintenance method and technical documentation creation tasks. The tools received mostly positive feedback: “I think the tools were good (camera, notepad, showroom, measurement) I can do my work with those”. For example, the TextBox tool, with minor adjustment to interactivity, corresponds to the user’s needs, as all experts agreed that it would make collaboration faster and more efficient. The design of the tool was also evaluated as easy to understand. The experts especially liked the
possibility of recording notes with a voice while investigating the 3D model. The left supportive comments:

- “As a maintenance developer is good to have the 3D model and make a note.”
- “The voice thing is nice; you can make quick notes with that”
- “I am amazed, this is very good” (about speech input)

The Disassembler also received mostly positive evaluation, especially from the maintenance method developers: they were completely satisfied with the tool design and commented:

- “I see all the parts in the platform, that is good. [...] It is easy, I get all the information and I don’t need to go anywhere.”
- “It is something I think would be very useful for my daily work.”
- “I enjoyed looking at things from different angles, to explore things.”

Some negative responses were mostly made by the technical writers and illustrators, as they would require more functionality and data visualisation over disassembled 3D CAD models, such as labelling, component grouping, highlighting, and removing/hiding parts. They commented:

- “Part removal in the platform would be useful, having more control on what to explode”
- “Having identifiers for the components and 3d models: part numbers, and to which elevator the 3d models belong”
- “Xray feature would be good – pointing at a lid, for example and seeing through – transparency/semitransparency. You sometimes want to show something inside of something else without losing the context”

The usability of the wall menu was criticized – since it requires extra effort and movements to control the 3D model on the pedestal. Experts left their suggestions as follows: “Instead of having a giant menu on the wall in showroom, maybe something smaller closer to the pedestal would be more intuitive”.

Next, the Camera tool, although seen as an important tool for the work tasks, was evaluated negatively from the perspective of user interface elements and interactions. The multipurpose functionality of the camera (or switching between video and photo modes) was not obvious. In addition, the orientation in selfie mode, preliminary designed to facilitate video instruction with a person in a shot, was criticised by the technical writers and illustrators, who would use the camera to make snaps of the
3D model. The positioning of the camera, when opened, was seen as too close to the user, which required them to move it further before using it.

- “I didn’t like when I open the camera, the first image was attached to me and the first thing to come in my mind was to push the screen further away and the twist it a bit.”
- “The camera is showing a different angle of what I am looking at slightly illogical” (about selfie-mode)

The Measure tool received the least positive evaluation after experiencing it: the tool was not easy to operate – the majority of experts faced problems with grabbing the ned points. The accuracy of the measures was also questioned; especially technical writers requested as accurate measures as possible so they can be directly used in the documentation. They commented:

- “It is difficult to place the starting point because now it is giving an approximate measurement”
- “Maybe adding a snap command to make the measurement more precise and being able to place inside the components and measure”

They also wanted to automatically record the measurements when made, commenting: “Do I need write it down?” or “How to record this measurement?”

In summary, the tools corresponded to the needs of industrial employees but required further development.

User Study 2 - Synchronous (Asymmetric) Collaboration

The second user study was conducted to evaluate the usefulness of collaboration within the virtual environment between maintenance method developers and technical writers and illustrators in the “outline creation” phase. The idea to facilitate collaborative activity in VR prior to the actual outline and documentation draft creation originated from the first user study. The modified pipeline is shown in Figure 52. The study asymmetric set-up between VR platform and Microsoft Teams (currently used software for teamwork), was dictated by covid pandemic restrictions and related unavailability of VR hardware on the global market, for instance in India.

The goal of this user study was to investigate the benefits and limitations of asymmetry for industrial collaboration and to identify the differences in user experience among two user groups, which might affect the execution of collaborative industrial tasks.
The positioning of the camera, when opened, was seen as too close to the user, which required them to move it further before using it.

“I didn’t like when I open the camera, the first image was attached to me and the first thing to come in my mind was to push the screen further away and the twist it a bit.”

“The camera is showing a different angle of what I am looking at slightly illogical” (about selfie-mode)

The Measure tool received the least positive evaluation after experiencing it: the tool was not easy to operate – the majority of experts faced problems with grabbing the needed points. The accuracy of the measures was also questioned; especially technical writers requested as accurate measures as possible so they can be directly used in the documentation. They commented:

• “It is difficult to place the starting point because now it is giving an approximate measurement”
• “Maybe adding a snap command to make the measurement more precise and being able to place inside the components and measure”

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The goal of this user study was to investigate the benefits and limitations of asymmetry for industrial collaboration and to identify the differences in user experience among two user groups, which might affect the execution of collaborative industrial tasks.

To address the study goal, we conducted 5 remote user study sessions with total 20 expert-participants, representing maintenance method developers, technical documentation writers and illustrators. The user study sessions replicated the actual industrial tasks and were remote, meaning that all the participants were physically isolated from each other and collaborated via technology set-up.

The participants were split into two groups: (1) VR-participants and (2) Teams-participants. VR-participants were immersed in the COVE-VR platform wearing HMD, were able to interact with it and each other and perform their tasks directly in VR. Teams-participants were able to see the virtual environment from the perspective of one of the VR-participants via Teams desktop application, communicate, and give instructions verbally while performing their tasks outside of VR using their laptop tools. The asymmetric set-up is visualised in Figure 53.

Figure 52. User study scenario 2 shown on the pipeline of the maintenance method and technical documentation creation

Figure 53. Asymmetric Setup between the COVE-VR and Microsoft Teams

Setup and Procedure. The user study was conducted in the KONE premises and was moderated by industrial researchers. Three facilitators were present to provide guidance and technical assistance: the main facilitator for VR-participant 1, who also moderated the user study, the support facilitator for VR-participant 2 and the chat-facilitator, who
managed remote participants via Teams chat and tracked the competition of their tasks. The communication of the participants occurred via Teams audio connection; VR-participants could hear the meeting audio in their built-in microphones of VR headsets. Teams-participants could see the virtual environment from the perspective of VR-participant, as shown in Figure 54, left.

![Teams view](image)

**Figure 54.** Teams-participants’ view of the procedure and group interview

The user study procedure started from consent signing, introduction to the user study practicalities and watching the training video about the COVE-VR platform. Then, the participants filled in the pre-survey on their expectations and proceeded to the hands-on training process (for VR-participants); the Teams-participants followed the training and had a possibility to ask questions. Next, the user study collaborative task begun; the participants were asked to use think-aloud protocol and openly share their opinions and feelings about the process. After the task, they have filled in the post-questionnaire and answered the interview questions. The interview was performed remotely via Teams - all the participants were asked to switch on their cameras for more natural interaction, as shown on Figure 54, right.

**User study tasks.** All the user study tasks for VR-participants were shown in the COVE-VR in pre-created textboxes, as shown in Figure 55. The tasks were designed to mimic their work routine and make remote participants collaborate with each other. All participants had specific roles in the collaboration activity:

- **VR1:** takes test tasks
- **VR2:** point of view for the remote participants
- **T1:** note taking to document the test from start to finish
- **T2:** snapshots to document the test from start to finish

The tasks were divided into two parts: 1) “3D CAD model exploration in collaborative space”, which was performed in the Showroom, and 2) “Assembly/disassembly of a 3D CAD model”, performed in the VR Lab. The tasks are presented in the Appendix, Section 7.2.
Participants. Twenty Kone employees, aged 27 to 60 (average = 40), participated in this user study; 16 were male and 4 were female. Five of the experts have previously experienced COVE-VR in a single user. Ten of the experts represented the technical documentation department (TDD), eight represented the maintenance development department (MDD), and the rest were from the mechanical design department; on average, they had 5,5 years of experience in their field (min = 1; max = 22). The experts represented multinational departments: 11 of them were from Finland, six from India, two from China, and one from the USA. Regarding their educational background, 17 had a bachelor’s degree, 2 had a master’s degree, and one had graduated for a vocational school.

Data Collection and Analysis. Similarly to the first user study, the data was collected via pre-and post-online questionnaires, observations, and the semi-structured interview and analysed in the same manner. The questionnaires collected responses on a 7-point Likert scale and consisted of six parts:

1. Background Data Collection
2. Expectations vs. Experiences – a validated SUXES questionnaire, which collects the expectations of the system before usage and after it (9 x 2 statements)
3. Collaboration aspects (14 statements)
4. Presence and immersion in VR - Statements adopted from the validated Presence Questionnaire survey (10 Statements)
5. Perception of VR technology in the context of work (12 statements)

The interview (shown in Appendix, section 7.2) was designed by industrial researchers and consisted of five parts; some questions were designed specifically to cover the experiences of VR-participants, Teams-
participants, and the participants, who experienced COVE-VR for the second time.

Results. In general, the user study demonstrated a positive evaluation of using the VR platform to support global departments. The asymmetry between COVE-VR – Microsoft Teams was found to be useful for the company, even despite the inequality of control, interactivity, and immersion. Both user groups, VR-participants (VR#) and Teams-participants (T#) showed active participation in collaboration process, behaved according to their roles, and managed to finish all tasks successfully. The use of virtual reality as part of work processes was found to make industrial work easier by 85% of experts, safer by 75%, and faster by 70%.

Access to the virtual environment (even in an asymmetric way) coupled with verbal communication was seen as ‘a low-cost option’ (VR1) to improve the efficiency of collaborative processes and to increase spatial understanding, critical to accuracy and work performance in general.

- VR2: “It always takes time to build the prototype, so with just the 3D model we can have the experience in VR.”
- T1: “It is important that there is context for the component, not only the component floating in air. [...] with this kind of view it would be easier and easily understandable to begin the illustrations at the beginning (of the documentation process).”
- T2: “3D exploration for new products it would be easy to see how to assemble and disassemble. New elevators would be easier to experience.”

The results of the user study confirmed that collaboration in VR, overall, would save time and decrease the number of iterations in the projects. Experts expressed positive evaluation of the COVE-VR as a tool for global collaboration: Most believed that it facilitates a cooperative atmosphere, which would help establish agreement on the current goals and future action points, since the communication process was seen as easier in comparison to traditional communication methods. The main advantage of using VE was seen in reducing emailing, chatting, and providing textual explanations, thus minimizing the number of possible errors and misunderstandings between the team members.

- T3: “we can use virtual rooms to improve the communication and have high-efficient meetings”
- VR1: “Travelling is not always possible, hands-on real work in the shaft is not always possible, because the shaft is not available, so this is a low-cost option.”; “the communication with all the participants was quite natural, the only issue was that I didn’t know who was talking”
Therefore, the VR platform was desired to be integrated into the KONE processes and be used in project milestones. Participants suggested that “the milestones in the process should be aligned with the product workflow so then it aligns with the schedule of the product” (T3) and “in that way we can avoid email/chatting/something else and we can do it directly in VR. Aligning VR with the timeline/milestones of the product development process.” (VR3). The results of the SUXES survey also confirmed that most of the participants would like to use the system in the future. Furthermore, expectations for the functionality of the system were lower than the actual experiences: the VR-participants perceived the system to be slightly faster, clearer, and effortless. Both groups found it more useful after completing the study tasks. The moderate increase in the statement on learnability also verifies that the guided training session was efficient, and that the application was easy to learn. The survey on immersion and presence supported positive experiences in VR: most of the VR-participants quickly adjusted to being in the virtual environment, easily adjusted to the control device. Additionally, the majority reported that they felt immersed in the virtual environment, felt confident when moving or interacting with virtual objects, and were engaged in assigned activities. The results, however, showed that visual and auditive aspects of the system could be better designed to increase user experience in a virtual environment.

The user study also showed the need for further improvements to improve usability in general and communication among asymmetric user groups, since it was not easy to understand each other, for example, “sometimes it was difficult to see who was talking to who” (VR2). Furthermore, the experts wanted other means of interacting than voice and wanted “to have better tools for interaction” (VR1), such as pointers. The teams’ participants shared that “being able to control things was difficult” (T4) and wanted to have even partial control, suggesting the use of COVE-VR via non-immersive interface.

**User study 3 - Synchronous Collaboration**

The third user study was conducted to evaluate the usefulness of the COVE-VR for collaborative review of technical documentation. The novelty lies in incorporating risk assessment activities into the already established collaboration process between maintenance method developers and technical documentation writers and performing it in VR environment, as shown in Figure 56.

The purpose of this user study was to investigate the benefits and limitations of VR to address collaborative technical documentation review and risk assessment activities. To address the study goal, we conducted three remote user study sessions with nine expert participants in total; each session included a maintenance method developer, a technical documentation writer, and a risk assessment expert. The user study
sessions replicated actual industrial tasks and were remote, which means that all the participants were physically isolated from each other and collaborated through COVE-VR. Therefore, this user study explores synchronous collaboration scenario.

**Scenario 3: Collaborative Maintenance Documentation Review in VR**

![Diagram](image)

**Figure 56.** User study scenario 2 shown on the pipeline of the maintenance method and technical documentation creation

**User study procedure and tasks.** As in previous iterations, the user study was performed in the facilities of KONE. All participants were physically present in separate rooms and were supervised by industrial researchers: one main study facilitator, two assistants, and one in-site observer, as shown on Figure 58. The main study facilitator was moderating through Microsoft teams, giving instructions and addressing questions. The user study procedure was also recorded and streamed over Microsoft Teams for observations by an academic researcher (e.g., the author of the dissertation).

![Image](image)

**Figure 57.** The details of the third User Study

The procedure was the same as in the previous iterations: it started with consent form signing, study practicalities description, demo video, and filing in the pre-questionnaire. Next, the participants have gone through the training process, supervised and instructed by the facilitator in the same room, and completed the study tasks, detailed in the Appendix, Section 7.2. After all the tasks were completed, the participants filled out the final part of the questionnaire and moved to a conference room for a group interview. The interview was also streamed through Teams but was not recorded.
sessions replicated actual industrial tasks and were remote, which means that all the participants were physically isolated from each other and collaborated through COVE-VR. Therefore, this user study explores synchronous collaboration scenario.

Figure 56. User study scenario shown on the pipeline of the maintenance method and technical documentation creation.

User study procedure and tasks. As in previous iterations, the user study was performed in the facilities of KONE. All participants were physically present in separate rooms and were supervised by industrial researchers: one main study facilitator, two assistants, and one in-site observer, as shown on Figure 58. The main study facilitator was moderating through Microsoft teams, giving instructions and addressing questions. The user study procedure was also recorded and streamed over Microsoft Teams for observations by an academic researcher (e.g., the author of the dissertation).

Figure 57. Third User Study setup.

The details of the third User Study.

The procedure was the same as in the previous iterations: it started with consent form signing, study practicalities description, demo video, and filing in the pre-questionnaire. Next, the participants have gone through the training process, supervised and instructed by the facilitator in the same room, and completed the study tasks, detailed in the Appendix, Section 7.2. After all the tasks were completed, the participants filled out the final part of the questionnaire and moved to a conference room for a group interview. The interview was also streamed through Teams but was not recorded.

Figure 58. Third User Study setup.

Data Collection and Analysis. The user study data collected via observations, pre- and post-questionnaires and a semi-structured interview in a group and analysed in a similar manner. The observations were supported with the question: ‘How VR can benefit the collaborative documentation review and risk assessment department’ and included categories or ‘tags’, for example, general state of mind, problems / bugs / technical issues / misunderstandings, improvements, interesting comments, procedure comments. The interview covered general experience with the system, the use of COVE-VR for the collaborative review process and risk evaluation, and the assessment of the functionality. The pre- and post-online survey collected responses on a 7-point Likert scale and consisted of five parts:

1. Background Data Collection
2. Expectations vs. Experiences – a validated SUXES questionnaire that collects the expectations of the system before usage and after it (9 x 2 statements)
(3) Evaluation of reviews in VR (6 statements)
(4) Perception of VR technology in the context of work (12 statements)
(5) Evaluation of the virtual DocPanel tool (8 statements)

Participants. Nine industrial experts aged 34 to 64 years (M = 49) participated in the user study (two female and seven male). Participants were carefully recruited to have high domain-specific expertise from the three fields they represent: Their experience in their role was on average 9.5 years (minimum 2 and maximum 21 years). At the educational level, all participants had a university degree: six hold a bachelor’s degree and three hold a master’s degree. Four of them had already been included in the process of testing COVE-VR in earlier studies; two of them had participated in both previous iterations, while the other two were partly included in the first phases of the design and development process.

Results. In general, domain experts positively evaluated the use of VR technology for the review of technical documentation and risk assessment. According to the observations, two sessions were extremely successful and efficient: All participants were actively discussed the maintenance method in question, reviewed the documentation collaboratively, found few errors, and proposed several edits from a safety-related aspect. The third session was less efficient and took more time, while fewer discussions were held in a group. However, in all three sessions, the expert groups managed to complete the tasks given and used different virtual tools to help them, while their collaboration in VR was seen as “much more visual than the current process”. The majority agreed that collaborative review sessions in VR would positively affect overall company performance and knowledge transfer, accelerate project span, and help identify more design errors.

In addition, the review process in simulated virtual environments with access to virtual models was found to benefit the overall review process by providing a realistic context, which was previously impossible. Experts commented that such sessions in VR would be mostly useful for new project, e.g., in early product creation, documentation draft and pre-assessment, but also can be used for a final review. One of the participants commented that VR would help concentration on the review task when compared to meetings via traditional conferencing tools since in VR “you are forced to participate; you can’t read emails and so forth at the same time, but you have to concentrate on the task at hand”.

The system’s usability was evaluated lower than in previous iterations: despite the majority found the COVE-VR fast, pleasant, and clear, none of them selected positive extremes, while one participant provided mostly negative or neutral answers. On the positive side, all the participants still found the COVE-VR to be useful; the majority would like to use it in the
future. In this scenario, the user expectations were higher than the actual experiences, which demonstrates the need to advance the platform design and functionality further, supported by the experts’ commented that they would “need a bit more tools and advanced features”.

The DocPanel tool addressed the need to visualize technical documentation in XML-format and was positively evaluated: the experts found it useful for KONE’s review work process and believed that it would make the collaborative review process faster, easier and more efficient. However, the results also showed that the design of the tool requires improvements: for instance, experts suggested adding a table of content or navigation panel. The page numbers were asked to be replaced with a progress bar, which would clearly visualise the progress of the review process. In addition, some experts found the size of the DocPanel to be small and would like to scale it accordingly to their needs. Further, in case the documentation required edits, experts suggested adding a markup or annotation feature, which would work similarly to commenting feature in pdf.

In summary, the concept of reviewing technical documentation in conjunction with risk assessment in VR was found to be a good addition to traditional practises. Collaboration in VR was seen as a meaningful way to proceed with work tasks, especially accounting for future improvements to the system design and functionality. Interestingly, multiple participants suggested the use of an asymmetric approach for collaborative review, where some participants would follow the review process via a desktop interface. Adding so-called ‘silent members’ or “observers” to the collaborative process was seen to add extra benefits, such as increasing visibility of the environments (avatars tend to cover critical objects, such as 3D model or DocPanel) while allowing to use traditional methods of taking notes, annotating, and marking edits in the technical documentation PDF files, leaving out the need to develop this feature in VR. Alternatively, for small working space, the participants suggested an option to turn invisible but still join virtual environment in a headset – the list of participants with names and departments would be a beneficial addition for such a working mode.

Outcomes and Contribution
In this section, I summarize the outcomes and contributions of the second case study, combining the results of all three user studies, starting from the general evaluation of VR to aid the process of maintenance method and technical documentation creation, and going into detail on aspects such as user experience, collaboration, and perception of VR technology.

In summary, the functionality of the COVE-VR platform was steadily evaluated in three iterations and three scenarios, involving more than 28 experts from three departments: Maintenance Method, Technical
Documentation, and Risk Assessment (8 of them participated in multiple scenarios). The main result of the study lies in the expert-based verification of the usefulness and effectiveness of VR technology to support and enhance industrial collaboration in the maintenance method and technical documentation pipeline. The adoption of virtual reality technology in this context would shift the traditional ways of working and collaborating for global teams.

Based on experiences with COVE-VR, the experts verified the need, desire, and benefits of integrating VR technology to support their work tasks. The VR platform was seen as an additional tool to coordinate and manage projects from the beginning to the end, enabling access to critical materials and allowing the execution of a variety of industrial tasks in different phases by multiple departments and user groups. Therefore, the results of this case study confirmed the indications of the first case study. By facilitating collaboration among global teams of experts and granting access to simulated virtual environments, 3D models, and tools for content creation, VR is capable of addressing the challenges present in the pipeline of maintenance method and technical documentation creation. Based on expert insight, transferring some activities from traditional collaboration channels to virtual reality medium allows to advance, optimise, and accelerate work routine of the industrial employees. However, the selected work processes for transfer should be carefully tested to find the best possible usage scenarios.

Usability and efficiency of the COVE-VR platform
The usability and efficiency were positively evaluated in all three iterations: The weighted scores for expectations and experiences were positive or neutral, as shown in Figure 59.

Figure 59. Expectations and experiences with the COVE-VR system in all three iterations (4 = neither agree nor disagree; 5 = somewhat agree; 6 = agree; 7 = strongly agree)
The variance in user experience among the users was noticed – some faced zero complications with using the system and quickly adapted to the virtual environment and controllers, being “natural users”; while others faced several issues and required the help from the facilitators. In general, the results demonstrated that using the platform was not expected, and neither was found effortless. This factor should be seriously acknowledged when presenting a new technology for a wide use, especially for the work context – all users have different technological skills and, therefore, would require different levels of on-boarding and training with the system, especially when it comes to novel experiences in VR, devices, and user interface, which differ from traditional 2D interfaces. In contrast, the survey results showed that the platform was expected to be less clear and less easy to learn than experienced, indicating that the selected method of representing the VR platform, e.g., the on-boarding video and facilitated training sessions, worked well for most of the users. However, some would require more time to become confident users. Also, in all three iterations experts expected the system to be less error-free than experienced, which demonstrates the further need for usability testing and bug fixing.

When evaluating the differences in user expectations and experiences among iterations, few conclusions are possible. In the first user study, for instance, user expectations regarding the system (e.g., using the system is fast, pleasant, natural) were higher than the actual experiences; in the second user study, the scores overall were improved, whereas in the third user study user experiences corresponded to expectations, but dropped when compared to the second user study. This may be explained by differences in user groups and tasks. Initially, expectations towards a novel technology among industrial employees based on on-boarding video were high: They saw the usefulness, but they do not have to operate the controllers. The improvement in scores between the first two iterations happens because we identified many platform issues for the same user groups and tasks, and fixed it before the second iteration, raising the overall user experience. The drop in the third iteration might be due to a lack of user research prior to the study. Due to the explorative nature of the study and the lack of resources, we implemented an additional tool to visualise technical documentation in VR (the DocPanel), without any additional iterations to deeply investigate user needs and requirements for the review task.

**Perception of VR technology among industrial employees**

Similarly to the preceding case study, the findings of this case study demonstrated that the experts positively perceived the use and adoption of innovative technology as a part of their work; most of them were excited about the opportunities this technology brings and actively participated in co-creation of the platform. VR was seen as a tool to shape
existing work processes into novel technology-supported activities, which in turn deliver benefits to the process and may even “enhance innovation minds of employees”.

The results of the survey on the perception of VR technology in the context of work (Figure 60) support this finding and show that in all three iterations experts believed that the potential of VR technology can benefit company work processes and enhance department-to-department collaboration. All experts support the idea of transferring work processes into virtual environments, which would deliver certain positive effects to the employees and the work routine in general. Additionally, the majority agreed that the use of a VR system would make their work faster, safer, and easier.

![Figure 60. Perception of VR technology throughout the case study](image)

When comparing the results between iterations, a few observations can be made. The results of the first user study are less positive compared to the latter iterations: Most show slight agreement levels to many statements, as well as some ‘somewhat disagree’ statements. This may be partly explained by the fact that users’ expectations of system usability was not met, which, in turn, would decrease trust in technology. Furthermore, the results from second and third user studies tend to be more positive, with a higher weighted score: only 13% (four experts: one VR user and two Teams users from the second user study and on one Risk & Assessment expert from the third user study) selected negative responses. The majority would like to use the VR system to perform their tasks, feel enthusiastic about it, and think that VR may increase their motivation and
The pyramid of industrial VR needs: Practical guidelines for industrial VR deployment

Overall, the VR platform and virtual tools, co-created based on expert involvement, addressed the needs of industrial employees, and supported the execution of industrial tasks in VR. The involvement of target users in the studies provided in-depth information and added clarity to further improve the design of interaction and tools’ features. The design of the tools is generalisable to other industrial and business contexts, where generated in VR digital content would be valuable, such as customer presentations or product reviews.

Based on the first user study outcomes, I have formulated the design guidelines for the implementation of virtual tools to aid the earliest deployment of the VR platforms, which were published in the Article III. In this dissertation, I provide an extended version, building on the knowledge gained during further study iterations. As follows, I divide practical implication into three subcategories (Basic Usability, Human-Technology Interaction, and Industrial Collaboration in VR), building the pyramid of industrial VR deployment needs, as shown on Figure 61.

![Figure 61. The pyramid of industrial VR-deployment needs](image)

The base of the pyramid visualises **Basic Usability of VR** and includes the first three guidelines from the publication:

1. *Embedded guidance and help.* VR platforms can be seen as completely new graphical shells, which entirely differ from well-known 2D interfaces and desktop/smartphone environments. Even basic VR functionality, such as teleporting or grabbing virtual objects, might not be intuitive with the controllers and require training.
Advancing the general UX and making the VR system manipulation to be natural and seamless is the primary task of every designer; however, it might be complicated to provide equal support for every user. Therefore, I suggest considering on-boarding and training with VR functionality as an essential part already at the design phase. The VR platform should include very basic introductory step-by-step guidance of how to use the system, followed by more complex instructions for the specific functionality, e.g., virtual tools. The guidance and instructions should be linked to actual industrial tasks, which would help build the holistic understanding of how the VR system can be used to perform work tasks. The training process should be steadily facilitated by special personnel or, for instance, AI-powered monitoring of the user, and should be based on own user progress rather than other objective metrics, such as time. In addition, easy-to-access reminders and tips should be always available to the user to recover from possible issues.

(2) Design consistency and resemblance to the real world. To further enable an effortless learning curve and establish the logic of the user experience, all functionality and designed virtual tools should be based on the similar interaction pattern; for example, the tools should be opened, manipulated, and closed in the same manner. In the first case study, we observed some levels of confusion about how to operate with virtual tools. In particular, in COVE-VR, virtual tools, objects, and generated content can be removed with the Delete tool, whereas closing the Delete tool itself caused confusion, since it was closed via interacting with the wrist menu. This finding caused the further subdivision of virtual tools into 1) hand-attached and 2) virtual environment attached; both groups of tools followed the same interaction pattern to close it, which was explained during the training process.

Moreover, since the Delete tool was designed in a shape of hummer, some experts tend to smash objects to destroy them instead of pressing a button, as was initially designed. This happened due to the fact that in VR users expect a stronger consistency between real-world physical movements and events in the virtual world. Therefore, this metaphoric understanding should be used to enhance the experience, rather than to add additional confusion.

(3) Positioning and orientation of virtual tools. During the first user study, many of usability issues arise due to a wrong positioning of tools in a virtual environment. Due to an immersive sense of space in VR, the location of virtual tools or objects should be calculated based on the head position and opened in the user’s field of view at a
comfortable grabbing distance based on the position in relation to the head position. Otherwise, the user might get confused and even open multiple tools at once, thus taking extra processing power and time to clean up the space. This in turn would negatively influence the system performance and overall usability.

In addition to the design implications mentioned above, when deploying a VR-platform, I recommend stressing the aspects of Accessibility and Hybrid or Asymmetric usage of the system among devices with different immersion and control levels. Attention to these topics would help to avoid usability issues in the future and would allow a wider circle of users to use the platform, e.g., without the need to invest in expensive hardware. Additionally, it would help to ensure equality and diversity of the users as a base of the VR-platform operations. The use of Artificial Intelligence technology and Data Logging for further optimisation should also be considered in the early design phases when deploying an industrial VR platform. However, I may only acknowledge the importance of the topic, and due to the absence of AI in the study, I cannot provide any design implications from this perspective.

The second level of the pyramid is called the Human-Technology Interaction in VR, which refers to individual interactions between the user and the system. This pyramid layer was defined based on a single guideline:

(4) Constant feedback and transparency of operations, which refers to informing users about the system’s background processes of the system to avoid disorientation or confusion when fully immersed in a virtual environment. For instance, when the system requires time for uploading or processing large data files (e.g., converting complex 3D CAD models for further use in VR), it should provide a comprehensive feedback and keep the user informed about the progress of the task. Further, VR environment provides advanced capabilities to implement the use of multimodal feedback (specifically visual feedback supported by audio or haptic) to benefit the overall user experience and increase the situational awareness.

The published guideline only covers the single side of human-technology communication: the way the system communicates with the user. I further highlight the importance of the opposite direction of this communication. VR offers multiple ways in which the user may control the environment, operate virtual tools and objects, or enter the data. Therefore, Multimodal Interaction in overall as well as specific Interaction Techniques should be carefully investigated during the design and development process; their selection should be based on the needs and requirements of the users. Since no interaction experiments were performed in line with the case
study, I cannot provide any concrete guidelines related to the use of multimodality in the industrial context, but I state that industrial experts’ multiple times highlighted the desire to use voice interaction and gesture interaction in VR, which feels more natural.

I can also share lessons learned based on the insights of the study. For example, one of the topics that arose during the study is direct and indirect object manipulation in VR. In the COVE-VR, we have utilised the indirect object manipulation, e.g., the wall menu for the Disassembler functionality because of the simplicity of developing it. To configure the 3D model size or disassembly distance, users use a pointer to move the sliders on the wall menu, which is not as intuitive and accurate as experts would desire. By redesigning this process into the so-called direct object manipulation, e.g., changing the scale or distance with the help of controllers’ movements, it would be possible to add accuracy and smoothness to users’ action, thus positively affecting the interaction in VR.

In addition, this case study demonstrated the importance of text entry methods in VR. Although text entry via speech was working quite well to the common surprise of experts, it still lacks in preciseness and level of control. The virtual keyboard and the ability to edit texts may partly address this issue; however, this topic in general requires separate attention and further investigation, especially with in mind that text entry is one of the major tasks in a given industrial context.

Finally, when it comes to the interaction of human-technology, there is no unique way to satisfy the needs of all users. User preferences for interaction vary along with differences in personalities, culture, technological skills, and previous experiences. Therefore, I highlight the need for Customisation & Personalisation for the VR platform to achieve a truly great experience for all users. As follows, the system should provide alternatives for interactions and user interface appearance, which users would be able to tie to their own needs and preferences. For example, the most requested feature was to scale the size of the virtual tools, like the TextBox, Camera, or DocPanel tools.

The last level of the pyramid includes the aspects to consider when designing for Industrial Collaboration in VR. This level aroused from a single published guideline:

(5) Authorship and information property, which highlight the importance of establishing information hierarchy and authorship inside VR platform, similarly to the company-existing metrics. Based on the study insights, I recommend logging at least the author, date, and time of creation, and the order (if the content was created in a sequence) for any created digital content. These data should be further saved and available from any interface it is used in (for
example, when viewing the content from a desktop PC when reviewing it). Additionally, user groups and their rights for content manipulation (e.g., a right to create, edit, or delete) should be settled to enable efficient collaboration of industrial departments.

This guideline was created based on an asynchronous collaboration scenario, where users have not been immersed together in virtual space. The latter iterations, where the experts collaborated synchronously in VR or in asymmetry with Microsoft Teams, opened a wider perspective to this point. Therefore, the needs for Industrial Collaboration in VR can be further subdivided into technology aspects and human aspects.

The technology aspects expand on the above-mentioned guideline with the topics of Shared infrastructure, Data Management, and Data Flow among different devices. To support the desire of industrial employees of using VR as an additional tool for project-related milestones, a VR platform should be integrated into existing work platforms and provide a seamless transition from one output device to another. When a group of experts would need to jump in VR to discuss something, they should be able to open virtual working space in a similar way as they would open a Zoom meeting, for instance via a link. The same applies to the data flow – the experts should have a fluid data flow among the platforms and work devices, whereas file import, export and conversion should be optimised to extent possible.

Human aspects of collaboration in VR have not been in the focus of the study; therefore, I cannot provide any guidelines in this regard. However, we have observed increased interest towards the topics of Avatars, self-representation in VR, and Social Interactions. The feeling of being surrounded by colleagues and working together shoulder to shoulder was seen as an important aspect of the iterations. The experts requested more means to add familiarity and recognition to their colleagues, e.g., customisable, more realistic avatars or simply photos from Microsoft accounts. In addition, experts expressed the desire for richer social communication, such as pointing, gesturing, and expressing emotions.

**Asymmetric VR: Collaboration scenarios and guidelines to enhance asymmetry between VR and traditional conferencing tools**

One of the most intriguing study findings, e.g., the potential of asymmetric VR in industrial context, came from the need to adjust to the pandemic restrictions on social isolation and the unavailability of VR hardware for purchase. First, due to COVID-19, the collaborating team of academic and industrial researchers had to adopt remote ways of joint software development, which demonstrated the value of guided demo-sessions and streaming videos from a VR environment. This finding coupled with pandemic restrictions led to an idea of the asymmetry
between COVE-VR platform and Microsoft Teams as an exploratory user study setup.

As a result, the study demonstrated that the asymmetric use of virtual reality is a **practical and useful low-cost approach** to facilitate collaboration between global departments. It appeared that when it comes to the industrial collaboration processes, the benefits of VR technology may spread beyond the immersive interfaces. The access to a simulated virtual environment for some team members and the video stream from VR for other team members coupled the ability to verbally communicate was seen as a sufficient approach to enhance the communication among the global departments and as a better option when compared to the traditional collaboration process. Even limited and non-interactive access to virtual environment positively affects spatial understanding, thus, reducing the number of possible misunderstandings or mistakes and supporting decision-making. Such an approach also expands the number of employees who may participate in the collaborative work activities and includes the collaboration the employees without access to HMDs or other advanced technologies. Therefore, asymmetric VR provides the means to enhance the degree of participation in work activities and engagement levels, potentially increases workplace satisfaction levels. Overall, asymmetry advances teamwork and communication between industrial departments of different countries in several industrial scenarios, which, in turn, leads to increased scalability, accessibility, and overall cost reduction.

The following scenarios in the context of industrial maintenance would benefit from the application of asymmetric VR:

1. **Maintenance method development**: the asymmetry can be applied as feasible, for instance, to include to the task colleagues who have no access to VR equipment.

2. **Technical documentation design**: similarly, the asymmetry can be applied as feasible within documentation designers’ virtual teams or in collaboration with maintenance method development.

3. **Documentation review and risk assessment**: in the earliest and latest phases, where asymmetry can be applied to advance the review process in VR through access to desktop tools or in include more experts to the process.

4. **Global training**, where asymmetry can be applied to support knowledge transfer from experts to less experienced technicians or trainees. To facilitate this, an expert can be inside the VR and stream his or her point of view to learners, which then would be
able to get familiar with the industrial context and maintenance method process via any device from anywhere on the planet.

(5) **Virtual maintenance assessment**, where the asymmetry is reversed to facilitate expert evaluation of the maintenance method remotely.

The exploration of the asymmetric setup between COVE-VR and Microsoft Teams resulted in the guidelines on how to efficiently adopt distributed asymmetry between VR platforms and traditional conferencing tools. The guidelines support remote industrial collaboration in an asymmetric way from three perspectives: organisation, collaboration, and technology, as shown in Figure 62.

**Figure 62.** Guidelines on how to efficiently adopt asymmetry (published in article IV)

From an organisational perspective, to facilitate collaboration in distributed asymmetric settings, it is important (1) to **identify the use case and assign roles and tasks among collaborators**. A clear division of roles and tasks would enhance the collaboration process in asymmetric distributed settings by ensuring that each participant understands their own responsibilities and does not interfere with the responsibilities of other collaborators. Additionally, (2) it is essential to **present the value and limitations of VR software and asymmetry through customised training sessions**. This training should be tailored to the specific needs of different user groups: for instance, for VR-users, it would increase feelings of control, and reduce stress associated with using novel technology, while for non-
VR users, it would educate on how to overcome limitation of non-interactive use of VR and how to reach better communication with VR-users. Finally, to facilitate smooth adoption and accelerate the acceptance of new technology in a work context, (3) a Key VR user should be nominated and trained to provide support and guidance to other colleagues.

From a collaboration perspective, considering the limited capabilities of a setup and voice interaction being the only communication channel, (4) use of voice should be encouraged. This can be achieved by interoperating the ‘think-aloud’ method to the collaborative activity, thus increasing employees’ confidence, promoting open discussions, and allowing non-HMD users to provide more concrete instructions. This or another relevant method would improve the overall quality of communication, positively impact team interdependence, and support common goals achievements.

From a technology perspective, (5) visual fidelity of the collaboration should be enhanced to achieve a better spatial understanding of the virtual simulated context and the objects in it. One suggestion would be to provide a stable video stream from a virtual camera controlled by VR users to offer detailed observations for non-HMD users. Also, using graphics and animations to visualise VR users’ movements and interactions with virtual objects would improve visibility for both user groups. Finally, (6) supporting collaboration directly in VR would increase the overall user experience for both user groups. For instance, experts recommend using highlights, pointers, and teleportation trajectory, among other solutions, to improve transparency of actions, information richness, and collaboration process overall.

Academy-Industry collaboration framework

The case studies, which lied in a foundation of this dissertation work, were performed in equal collaboration between academic and industrial researchers. Through five years of collaboration with KONE, I obtained a clear picture of why such collaboration is not only a valuable activity to carry, but also an essential element to spark inspiration and drive innovation. Every collaboration case is unique and worth sharing, and therefore I am motivated to derive insights and share them with other academics and industrial practitioners. Therefore, this experience of collaboration between the academy and industry, which resulted in the achievement of extremely positive outcomes for both sides, is another contribution to my work. The contribution is presented in the form of 1) the process-oriented framework and 2) practical suggestions to support academic-industry collaboration.

The framework, shown in Figure 63, is aligned to the phases of user-centred design methodology and demonstrates how to organise joint
activities with different industrial groups. As COVID-19 exploded, most activities were performed remotely.

Figure 63. Academy-Industry collaboration framework

In line with the phase “Identify context of use and user requirements” for the COVE-VR platform development, we performed three activities. First, the Kick-off ideation meeting, which included all focus groups, helped establish the core values of the collaboration, and ideate possible direction of work. Additionally, the Maintenance Documentation Journey Workshop provided us with a full understanding of the work processes among distributed teams and the requirements of the user groups for the system, including their main pain points. It helped to define the scope of system functionality and visualise how industrial workers can use it. And finally, the survey on feature prioritisation helped to focus on the most desired and required functionality.

For the phase ‘Produce Design Solutions”, we arranged development process of the VR platform (managed only by academics), while feedback was collected via online demo sessions. To stay on a shared schedule, we agreed beforehand what functionality would be developed and set local deadlines, supported by scheduled monthly and weekly meetings with industrial researchers. The online demo sessions helped to rapidly verify design decisions and enhance the overall user experience. We also arranged larger demo sessions with company managers to demonstrate our progress and receive their feedback. Once the system design was finalised, due to restrictions on remote gatherings, we compiled a survey to get the first impressions on the system concept and design of the virtual tools from a larger group of target users. It helped to verify that we may proceed with user studies.

The COVE-VR was iteratively evaluated according to the identified scenarios. Every user study was carefully designed in collaboration and
piloted prior to actual evaluations. It helped to ensure that academic and industrial goals would be covered, prepare for remote procedure specifics, and identify possible flaws of the process. After the user studies were performed, we analysed the received data, made changes to the system, and continued the flow.

In overall, the scope of performed activities facilitated the application of research methods over real industrial application scenarios and helped to ensure the relevance of the designed solution from both organisation and employee perspectives. The performed collaboration was equal and delivered advantages to both sides, establishing trustful work environment and knowledge sharing among the parties. Next, the list of practical implications, formulised based on open discussion to enhance the communication and knowledge sharing between academia and industry:

- **Define roles, procedures, and industrial focus groups**: To achieve this, it is essential to involve not only academic and industrial researchers but also the management team and other employees in the collaboration process. Identifying relevant industrial focus groups prior to collaboration and keeping them involved through academic practise aids addressing organisational challenges and the lack of commitment. Additionally, agreeing on the roles and responsibilities of each party and establishing procedures can help overcome transaction-related barriers to collaboration.

- **Establish trust and shared understanding**: To overcome orientation-related barriers of collaboration, it is crucial to exchange and clarify each party’s goals and expectations for the collaboration. We recommend initiating the collaboration process with a kick-off meeting that includes all relevant focus groups to ensure that everyone’s perspective is communicated. Additionally, establishing shared goals, objectives, and timelines can help harmonise the pace of joint work and avoid misunderstandings. To promote trust and openness while avoiding transaction-related issues, we suggest utilising both official and unofficial channels of communication, such as email lists and Teams chats, as well as a shared storage option with equal access, like OneDrive.

- **Facilitate remote participation and iterative feedback**: We found success in sharing unfinished work to elicit feedback and apply modifications iteratively from the earliest phases. Remote knowledge and experience sharing can be facilitated through traditional conferencing tools, such as Teams, where development progress can be presented via videos or streaming from VR. To address the lack of interaction, accurate spoken descriptions of how the system is operating and open discussion can be used.
4.4 Summary

To summarise, the findings of both case studies verified that the adoption of AR and VR technologies in the field of Industrial Maintenance would deliver definite value and positive impact on industrial operations and workers. Furthermore, the studies demonstrated positive perception of technology adoption among industrial workers. Despite some level of mistrust in the technology, mostly due to currently limited technological capabilities, the experts expressed desire and enthusiasm towards using xReality in the future and actively contributed to the co-creation process. As an outcome of expert participation in the studies, it was possible to obtain specific to domain knowledge and insights on the technology application in an industrial context, which helped to formulate practical implications and design guidelines, which can be further generalisable for other industrial contexts.

Based on the study findings, it is possible to claim that XR technologies are highly advantageous in the industrial context overall. Due to increased flexibility, as computer-generated content advances or fully replaces the real environment, the traditional ways of working in industry can be shifted towards novel technology-supported operations, whereas the challenges present in industry can be resolved. Augmented reality can positively affect field operations by providing context-sensitive guidance for maintenance task and increasing occupational safety of workers. Virtual reality, in turn, can positively influence the office routine in product and service development through the facilitation of global collaboration, improving communication among multicultural colleagues while providing tools with extended functionality to support their tasks.

In addition, studies highlight the deep connection between AR and VR technologies and suggest the usefulness of a common virtual infrastructure with different output devices (e.g., HMDs or see-thought displays). As follows, a united platform, shared among different departments, can be used, and reutilised to facilitate many of industrial tasks.

Therefore, the study results highlight the potential of XR technologies to fully transform operations in the field, optimise the processes and increase wellbeing of the workers. This shift goes in line with the Industry 4.0 and Industry 5.0, which promise a deeper integration of technologies into human lives, placing humans in the centre of the loop. However, the integration of XR technologies is impossible in isolation and should occur in combination with other technologies of Industry 4.0.

Since this integration is a logical continuation of the industrial revolution, the primary responsibility of researchers and industrial practitioners is to ensure appropriate and smooth integration of technologies so that they
deliver the maximum value to industrial organisations and its workers. In the next chapter, I aim to provide a comprehensive description of how XR integration might impact the field of Industrial Maintenance in addition to the perception of the technologies among industrial employees. Building on this knowledge, I will summarise the design and adoption strategy of XR technologies in industrial settings.
5 Discussion

This dissertation explored the application of xReality technology to address the needs of industrial maintenance. The work and the resulting findings are based on two case studies carried out in close collaboration with KONE Oyj, the largest elevator manufacturer and service provider company in Finland. Collaboration with industry gave me a chance to epistemically investigate technologies in a realistic industrial context with actual target users (industrial experts with domain knowledge and experience). Meanwhile, the research agenda was not driven purely by academic vision but was influenced by industrial R&D experts based on the identified organisational needs and challenges present in the field of Industrial Maintenance.

This unique setup of human resources, knowledge sharing, and iterative collaboration process made it possible to obtain insights and knowledge, which are valid and generalisable for other industrial contexts. On the basis of the study data, supported by academic literature, it is possible to draw certain conclusions about the role of XR technologies for industrial development and provide a comprehensive answer to the stated research questions.

5.1 The impact of xReality to the field of Industrial Maintenance

Although it is hard to estimate the exact scope of changes, the impact of xReality technology on any industrial field is undeniable. XReality, bolstered by other emerging technologies, such as artificial intelligence (AI), the Internet of things (IoT), big data and cloud computing, advanced automation, and robotics, will leave a similarly large footprint on the way
people live and work, as the emergence of electricity did during the second industrial revolution.

As Industry 4.0 interventions are steadily being followed and implemented by leading industrial organisations, their experiences and insights will lie in the foundation of a larger knowledge resource, attracting others to join this competition race. As technologies are advancing, becoming more pervasive and ubiquitous, xReality is getting closer to becoming a part of everyday routine in a similar manner as nowadays humankind relies on the use of computers and smartphones.

In this section, I attempt to draw a holistic picture of how XR will impact the field of industrial maintenance, building on how both augmented reality (AR) and virtual reality (VR) will be applied. Therefore, this section answers the first research question of my dissertation:

**RQ1:** What is the potential impact of XR technologies on the field of Industrial Maintenance?

**Integration and Influence of Augmented Reality**

Today, technicians have access to a wider set of knowledge through their personal or corporate devices. In case of a complex maintenance procedure, they can rely on interactive and visual assets, embedded in technical documentation (Gattullo et al., 2022), accessing them via web portals or applications (Siltanen et al., 2020). Additionally, technicians may be in contact with more knowledgeable experts from all over the globe. The mentioned changes in the field already provide additional support to workers and allow them to perform maintenance operations faster and more efficiently.

Augmented reality, which is becoming an essential element of smart factories, is already accessible from hand-held devices. Even in this “not so optimal” form, it provides flexibility over traditional paper-based manuals and delivers value to technicians in the field. Augmented reality on head-worn devices makes technical documentation and its visual assets even more valuable by enhancing situational and contextual awareness and delivering a ‘heads-up’ interaction while freeing workers’ hands. With the expected advancements in technological capabilities and supported by the integration of cyber-physical systems (CPSs), IoT, AI, trackers, and sensors, head-worn AR devices, as well as other forms of multimodal AR (e.g., projection, advanced interactable display lighting, sound) will become an integral part of industrial environments and maintenance operations. So far, head-worn displays and smart glasses are not yet suitable for work in the field, due to limitations in battery capacity, image resolution, and field of view, coupled with uncertainties in user interactions. However, sooner or later, these barriers will be overcome, as the research community works towards solving them. Once head-worn AR devices become more
functional and user-friendly, they will spread in the industrial context and become an everyday normal. There are indications on the market to believe that in the future, special safety equipment will be designed and developed, for example, a helmet with an integrated AR see-thought display working in connection with other wearable devices (Bluetooth headphones, wristbands, gloves, etc.). Such equipment may become an obligatory safety equipment in smart factories and other industrial objects. Powered by CPSs and IoT, such helmets would be able to increase overall occupational safety, while constantly collecting data for further improvements in industrial operations.

However, the full potential would be hidden in case the format of technical documentation remains unchanged through years. Not all organisations have been investing in updating their technical documentation format, and, in most cases, technical documentation remains the same as twenty years ago, delivering instructions in the form of text and black-and-white illustrations. The findings from the first case study indicated that the current format of technical documentation is not suitable to support a rapid shift to AR-based devices, particularly smart glasses. To allow a fast shift towards using documentation in head-worn displays, technical documentation itself should be evolving together with technological development and become more visual and richer in modalities. Ideally, the format of documentation should support automatic adaptation for various end devices and use cases (e.g., training or in-field support)(Heinonen et al., 2021).

The shift towards technology-advanced equipment, supported by Industry 4.0 and Industry 5.0 ideas, similarly will influence the role of the human operator, moving towards Operator 5.0 or Worker 5.0. This, in turn, means that humans no longer would need to rely only on their own skills in the industrial context – many of their operations would be technology-supported and performed in collaboration with machines and robots. Therefore, this would lead to changes in educational systems and workforce skillset. For instance, maintenance technicians would be expected to use technology in the field and interact with it to make decisions and perform their tasks. This, in turn, would influence human-machine interaction and know-how to operate machines and read data to become critical skills.

In summary, augmented reality in combination with other emerging technologies will be fully and transparently integrated into industrial operations, leading to the dominance of pervasive and ubiquitous interaction in industrial environments and a changing the role of human operators.
The summary of AR impact:

- Wearable technology combined with AR-based equipment (smart glasses, helmets with integrated see-thought displays) will become an integral part of industrial environments and possibly a required safety equipment.
- Technical Documentation will be created in a more visual format to accommodate rapid use on different end devices and in various scenarios.
- Maintenance technicians and operators will have a different role, responsibilities and required skillset to perform tasks.

Integration and Influence of Virtual Reality

Virtual reality is also becoming a more required and desired technology in industrial settings, which is about to spread in office environments. Previous work has already explicitly verified the benefits of VR for product design and development purposes, which positively affects product quality and optimisation of the processes (Berg et al., 2017; Guo et al., 2020; Narasimha et al., 2019; Schina et al., 2016; Wolfartsberger, 2019). The second case study of this dissertation similarly showed the value of VR to facilitate service design processes and other tasks related to maintenance services. Specifically, VR can enhance the operations in the pipeline of maintenance methods and technical documentation creation, enabling a global collaboration between method developers, documentation writers, illustrators, and risk assessment experts. Furthermore, the use of VR potentially simplifies content authoring, thus enriching the format of technical documentation. Despite this evidence coming from the maintenance documentation case, this data is generalisable to any other industrial service-related activity among multidisciplinary and global departments or teams, where access to equipment or industrial context is limited, but required to enhance work outcomes.

As the first case study indicated and the second case study confirmed, the use of VR technology in line with service-related work processes possesses the following advantages:

(1) Providing access to a hazardous industrial context, which would be impossible or costly to visit in real life. This, in turn, positively affects the sustainability of industrial tasks, reducing the need to travel and to visit industrial sites, cutting associated costs for organisations. For industrial employees, who sometimes are forced to travel for long distances, the use of VR may promote overall well-being and increase work satisfaction, reducing unnecessary time spending and stress associated with travelling.
(2) Providing **access to virtual prototypes**, which are inaccessible in real life. This would benefit the design for maintainability and increase the accuracy and efficiency of the teams involved in service design around the product. Combined with an access to a simulated industrial context, it also enhances spatial understanding and contextual awareness, which reduces the chance for mistakes and misinterpretations, that are costly to recover from.

(3) **Enabling and enhancing collaboration on a global level.** Apart from providing a safe and resource-efficient way to experience virtual prototypes in a realistic industrial context, VR offers a shared working environment to accommodate the synchronous and asynchronous collaboration of global virtual teams. This, in turn, positively influences teamwork performance, diminishing communication barriers among virtual teams by increasing the quality of their social interactions. Teamwork performance, in particular, can be advanced by not only affecting aspects directly related to productivity (e.g., enhancing time management or increasing enjoyment from the task and, thus, overall work attitude (Kim et al., 2019)), but also advancing the attitudinal and behaviour dimensions of teamwork, such as trust, commitment of individuals and perceived safety (Cohen et al., 1997). The communication in VR is more beneficial in comparison to traditional video conferencing, due to the possibility to use non-verbal communication cues and spatial presence, which result in better knowledge transfer and decreased misunderstandings among team members. Furthermore, the use of virtual reality environments can positively influence the interaction process, type and structure of the task, and support – e.g., factors affecting collaboration (Patel et al., 2012). Increased co-presence and participation in VR, coupled with the mentioned above aspects would lead to the overall increase in the quality and optimisation of industrial collaboration practices.

(4) Easy and **effortless content generation within VR** is another benefit, which can simplify industrial operations. The flexibility of VR would allow to capture multimedia files, such as pictures, videos, and animations, that can be used for initial documentation draft or for communication purposes (e.g., within a team, with stakeholders and customers). Similar, VR offers advanced ways of text generation, which can be done simultaneously while interacting with 3D CAD models.

Based on the above-mentioned advantages, it is possible to claim that VR can be applied in an industrial context to facilitate many scenarios and use cases, the scope of which is not yet fully discovered. Collaboration in VR, especially for global teams, would increase team performance and raise the quality of joint work, delivering new methods, approaches, and tools
to complete industrial tasks. As follows, VR would lead to project optimisation and shorter project lifespan via minimizing iterations and communication barriers among virtual teams and departments on many levels. Not only it would simplify the processes within a work team (e.g., a group of people involved in a common task, such as technical documentation creation), but also would promote closer collaboration between multiple departments as well as project and management teams. Based on the expert insights, the linear project flow (where one phase delivers an item for the next phase) can become circular and agile (as shown in Figure 64).

**Figure 64.** Optimisation of industrial processes via the adoption of xReality

This transition would enforce multidisciplinary collaboration among experts from different disciplines and advance knowledge transfer. For example, it would allow method developers and technical writers to contribute to the product development before the product is released, while also including maintenance technicians in the loop. In addition, it would minimize process-related waste and promote human-centricity and value creation, integrating Lean and Agile vision deeply into the organisation structure. Further, VR environments, created for specific tasks (e.g., to support product and service design lifecycle), can be reutilized for other tasks such as AR- prototyping and testing, training and learning, and others, depending on organisational needs. Support of other technologies and a fluid data flow from one case to another would be required to accomplish it.

The expansion of VR in the industrial context would be also facilitated by the asymmetric usage scenarios. The second case study demonstrated that VR delivers benefits over traditional conferencing tools even when only half of the users are immersed in a virtual environment, whereas the rest of the team gets a video stream from VR. As follow, the contextual knowledge and spatial understanding required for an industrial task can
be also enhanced based on non-immersive experience. This suggests that collaboration and knowledge transfer can be advanced via atomistic VR, where task competition is prioritized over user experience. Furthermore, asymmetry can provide other advantages for working teams – e.g., role division and the possibility to use existing and well-operated desktop tools as a part of VR collaborative experience (e.g., leaving comments to PDF files).

In summary, virtual reality, supported by other emerging technologies of Industry 4.0, will be mass used in the office environment and will be a critical element of organisational digital infrastructure. It would promote sustainability and human-centricity by boosting multidisciplinary collaboration beyond geographical borders and delivering flexible means of content generation.

**The summary of VR impact:**
- VR will become heavily used in the office environment to support many of the industrial operations
- VR will be used as a production digital tool throughout the whole project lifecycle, merging the phases of product development and service design around the product
- VR will become a technology to advance the collaboration among global teams and multidisciplinary departments
- VR will become more scalable, expanding its use over asymmetric or non-immersive set-ups

**xReality for Product and Service Design Lifecycle**
To sum up, the integration of XR is an important element of industrial development and growth, which would change existing work operations and deliver new technology-supported processes for industrial organisations and their workers. XR will enable a smooth, multimodal, and all-pervasive interaction with intelligent technologies in many industrial contexts, from the office environment to hazardous on-site locations, such as an elevator shaft. As technology matures, apart from “yet traditional” usage of VR and AR, e.g., via head-worn displays, xReality would compose and blend other smart technolgies: wearables, robots, novel interactive displays, holograms, projections, haptic and audotove displays, etc. Nevertheless, this transformation will not happen in isolation from other emerging technologies. Alone, xReality cannot transform the scope of industrial operations, since the true benefit of it is based on merging it with other technologies and deeply integrating it into the organisational infrastructure together with AI and Big Data, IoT and cloud computing, wearables and social robots.
Since my study relates to the use of xReality in the context of industrial maintenance, I have explored the topic through the lens of product development and maintenance service design. As follows, based on study outcomes and insights from domain experts, I summarised how VR and AR technologies can be integrated throughout the whole design lifecycle: from product development to in-field assistance, as shown in Figure 65. Holistically, xReality can be used as a tool to support and transform industrial project execution, where AR and VR, being two end technologies of a single digital infrastructure, could be used based on the needs of a specific task.

![Figure 65. How AR and VR can be utilized throughout the product development lifecycle and related service design and maintenance service delivery](image)

Primarily in the phase of product development, VR can be used for early design decisions, collaboration with the stakeholders involved, visualisation of ideas, MVP-testing, and prototyping (Berg et al., 2017). Once the 3D CAD model is created, it would be possible to facilitate design sessions, design reviews, and rapid evaluation of the product in both a simulated and realistic context between virtual and face-to-face teams (Tea et al., 2021; Wolfartsberger, 2019; Zaker et al., 2018). At the same time, my work demonstrated that it would be possible to initiate the creation of a maintenance method and technical documentation drafting for the product and utilize insights from it before the product release. This loop would also include a technical documentation review, which can be done initially with virtual prototypes, and, later on, with real equipment. The same digital content can be further reused to accommodate training and learning activities. Despite my work has not covered this topic explicitly, industrial experts ideated many cases and scenarios within the scope of the training and learning department, where VR and AR can be utilized, such as certification and recertification, train the trainer approach, maintenance method updating among experienced technicians, not to
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Holistically, xReality can be used as a tool to support and transform industrial project execution, where AR and VR, being two end technologies of a single digital infrastructure, could be used based on the needs of a specific task.

As an outcome, the integration of XR would dramatically affect current ways of working, delivering new workflows and practices. This, in turn, would contribute to the development of new diversity-focused organisational policies, norms, and methods. XR promises (and requires) overall optimisation and transformation towards a digitally supported work infrastructure, supported also by the development of CPSs and IoT. The collaboration as a matter would reach a new level and become a base for all operations, whereas workers would get used to collaborate more within disciplines and geographical borders. Due to the deep integration of technologies, educational and work environments would be also shifted, relying more on technology-supported learning methods. Reducing unnecessary travelling and resource inefficiency would help to deeply establish Lean and Agile ideology, maximizing value creation and minimizing waste of production and human resources.

The summary of XR impact:

- The application of XR will have the power to transform the traditional ways of working both in the field and in office environments, enforcing pervasive and multimodal interaction with intelligent technologies
- Integration of XR with other emerging technologies will lead to workforce and organisational changes, creating new departments, positions, and skillset composition, establishing novel procedures, processes, and methods of working
- XR will help to promote and deeply integrate Lean and Agile ideologies into organisational culture and operations
- XR will speed up the Industry 4.0 interventions and further enforce the core values of Industry 5.0, such as sustainability and human-centricity

Finally, xReality in combination with other emerging technologies, would help to achieve the goals of Industry 4.0 and further support the core values of Industry 5.0. The integration of XR is one of the supportive elements to establish decentralized, interconnected, and data-driven industrial processes, which would enforce the efficient use of digital and human resources and increase the competitiveness on the market (Henning et al., 2013; Vogel-Heuser et al., 2016). Industry 5.0 values, in particular, sustainability and human-centricity, are also achieved via
xReality. First, it would ensure the centric role of human in industrial operations, delivering flexible and advanced methods to interact with industrial objects and robots, collect and visualise data, and support decision-making. To achieve this, personalisation and customisation of XR interfaces and interactions are critically important. Secondly, it enforces sustainability on various levels, reducing unnecessary travelling or time spending, optimizing procedures and tasks, and promoting re-using and re-utilizing of digital infrastructure, e.g., virtual environments, virtual tools and features.

5.2 THE PERCEPTION OF xREALITY AMONG INDUSTRIAL EMPLOYEES

The application of xReality in the industrial context is predicted to have a positive impact on industrial operations and to deliver multiple benefits on the organisational level. Therefore, the adoption of XR is strongly desired by leading industries in the field. In the previous section, I described how XR can be applied to support and transform work processes in the scope of product development and related service activities. However, this could not be fully performed without paying attention to the end users of XR systems: industrial workers. In this section, I will uncover major trends of how XR is perceived by industrial employees, based on the continuous involvement and communication with industrial experts throughout my work. Thus, this section addresses the second research question of my dissertation.

RQ2: How industrial experts perceive the use of Virtual Reality and related technologies in the context of their work?

Supporting previous studies in the industrial context (Berg et al., 2017; Narasimha et al., 2019; Schwarz et al., 2020; Wolfartsberger et al., 2020), my study verifies the trend of positive perception and strong interest towards using XR technologies in a work context among industrial employees. The use of xReality for service-related processes in industrial maintenance were found to “enhance innovation minds of employees” as well as deliver benefits to many of the industrial processes listed below:

1) The use of **AR in-field guidance** was seen as a potential approach to enhance maintenance operations. However, most of the technicians expressed unwillingness to use AR see-thought displays in a hazardous context and mistrust in the technology in general. It showed that, currently, industrial employees would rather rely on existing ways of using documentation in the field than fully rely on technology to guide them.

2) **AR prototyping and testing in VR** was seen as a “safe and cost-efficient way” to address the current challenges of AR development
and authoring, associated with the risks and costs of testing it in real environments. The main advantages were seen during the early design phases of guidance and safety warning. The idea of completely relying on technology for in-field AR evaluation was not appreciated, since it may possess additional risks, as the current VR state-of-art is lacking many important real-world aspects, e.g., lack of multimodality, and multisensory cues – physical barriers, weights, lighting and other.

3) **The use of AR and VR for training**, especially in a pipeline, where an initial training activity would be performed in virtual environments with virtual equipment, followed up by hands-on training with real equipment, supported by AR-based systems. Similar to the previous application cases, experts believed that VR technology, thought suitable for initial phases, should not be used to replace the traditional training procedure in realistic settings.

4) The use of **VR for maintenance method development and technical documentation creation** was seen as highly beneficial to support current practices. Similarly, experts do not see VR as a space to transfer all their tasks, but rather as a supportive tool to add accuracy to the design process and avoid errors. The collaboration in a shared workspace with colleagues from other teams and geographical locations was evaluated extremely positively and was seen as a better alternative to traditional conferencing tools.

5) As follows, the use of **VR in collaboration** with other departments within a project and other relevant stakeholders was found to be a desired and intriguing opportunity, which would simplify their communication and enhance mutual understanding.

Despite the overall positive evaluation of XR technologies and support for further research and development of these topics, the study demonstrated that industrial workers are not yet ready to adopt them on a full scale as Industry 4.0 interventions would require it. Especially this concerns AR-based solutions meant to be used in the field. Indeed, the experts believe that AR technology can make their work easier, faster, and more efficient in the distant future, but they have no intention to rush towards using these technologies before its safety and benefits are explicitly verified. In other words, if the organisation would provide AR glasses and require using it in the field, most of the technicians would resist this change. The mistrust mainly comes from the limited technological capabilities of AR devices and lack of infrastructure, resulting in zero utility of the current AR-based solutions coupled with poor user experience. This is especially relevant for experienced workers, as for them, traditional ways of working based on own skills, knowledge, and technical documentation would be
more preferred. In result, the perceived risks of AR-based guidance tools are higher than the perceived benefits.

The adoption of VR in the office environment, on the other hand, seems like a more positive case. Despite VR still lacks in many critical aspects, e.g., physical boundaries and natural multimodal interaction, the perceived benefits of using it are higher than the perceived risks and still not perfect user experience. However, to make a shift towards using VR on a daily basis, special attention should be placed on the smooth adoption of these technologies regarding individual factors, reactions, and psychological variables of the employees (e.g., individual-level factors of technology adoption (Chuah, 2019)). The facilitating conditions of technology adoption, meaning providing awareness on the benefits, risks, and support, should also be considered to minimize resistance towards the technology and ensure the acceptance of it.

5.3 Design and Adoption Strategy of xReality

Industrial and business organisations strive to maximize value creation and raise revenue via integrating novel technologies into industrial processes in line with Industry 4.0 interventions. Meanwhile, even industrial employees positively perceive the technology in overall and express curiosity with the opportunities it may deliver, they still show certain levels of mistrust and resistance to certain technologies and application cases. Coupled with yet limited technological capabilities and high costs, it might slow down the pace of XR adoption in the industry. In this section, I combine all the gathered theoretical and practical knowledge about industrial XR with an intention to deliver a human-centred strategy towards xReality design and adoption, answering the last question of my dissertation.

RQ3: How to design and adopt extended reality systems to address the needs of industrial workers and organisations?

Primarily, I claim that the design and adoption of the technology should be considered as a single process, which consists of multiple iterative phases, as shown in Figure 66. Looking at the popular and value-proven design and development methodologies (such as user-centred design, design thinking, product development lifecycle, or agile manifesto), all of them emphasize the cyclical and iterative nature of design and development tasks, with respect to the end users and focus on prior user research.
Design and Adoption Strategy for xReality

**Explore the opportunities**
WHY to adopt xReality in the industrial context?
Deliverables: 1) Business objectives to achieve via xReality and 2) verified use cases.

**Specify user requirements and context of use**
WHAT specifically should be designed and HOW to design it?
Deliverables: 1) Development plan, 2) Prioritized list of features and tools to develop, 3) Design artefact to assist the development, 4) Defined methods on how to engage focus groups.

**Evaluate design solutions**
CAN the software be already used in a work context and WHAT should be developed further?
Deliverables: 1) Features to develop further, 2) Working and tested software, 3) Perception of the workers towards the software, and 4) Adoption plan.

**Define the needs**
WHAT holistically should be designed designed to address the needs of the organization and the end users and HOW to address it?
Deliverables: 1) Concept of the xReality solution and specific application scenarios, 2) Roadmap of XR technology adoption, 3) Primary development requirements, including focus groups, resources and other, 4) Perception of technology among workers.

**Produce design solutions**
HOW to ensure that the design actually corresponds to the needs of the users and HOW it can be implemented into use?
Deliverables: 1) Working pieces of the software, 2) On-boarding and training materials for the implemented features, and 3) Evaluation plan.

**Facilitate conditions and introduce the technology**
HOW to ensure efficient technology adoption?
Deliverables: 1) Adoption plan iteration, 2) Measures of perception and technology acceptance among the workers, 3) Identification of problems and barriers to address them.

**Monitor and Advance**
HOW to extract the maximum value and reduce waste?
Deliverables: 1) Measured effects of XR integration, 2) Data and Ideas for further optimization.

**Figure 66. Design and Adoption Strategy for xReality**

In the industrial context, the utility of the technology is valued more than the plausibility and enjoyment of it, since the main aim of the technology would be to accomplish an industrial task, which would positively affect an overall industrial operation. Therefore, in industrial settings, the technology should not be adopted in case it delivers no end value or caters to non-existent user needs. Therefore, the XR technology adoption
considerations should be placed at the initial stage of the design activity, combined with a user study. Furthermore, the user study itself should include both an organisational and individual perspectives.

Therefore, the first step towards xReality technology adoption should be initiated from a research activity, questioning why the organisation should adopt the technology and why industrial workers would need the technology to be adopted in a work context.

**Step 1. Explore opportunities: WHY to adopt xReality in the industrial context?** Based on the existing body of knowledge on XR technology (both academic and industrial), it is critical to define the areas of opportunity for XR integration and the possible problems it can address from an organisational perspective. This would lie in the base for defining the Business Objectives that can be achieved via xReality implementation. As well, the built assumption on how XR can be applied can be represented in the form of Use Cases, which should be further discussed and verified by involving industrial workers and other stakeholders in this investigation.

**Deliverables:** 1) Business objectives to achieve via xReality and 2) verified use cases.

Once the need to adopt the technology is verified from the perspective of organisation and employees, it is possible to proceed with “traditional user studies”, which would help to deeply investigate the organisational and user needs for the system development. This phase would consist of two steps:

**Step 2. Define the needs: WHAT holistically should be designed to address the needs of the organisation and the end users and HOW to address it?** In this phase, it would be required to investigate identified use cases based on the principles of human-centred design (e.g., viability, desirability, and feasibility). This would include the exploration of how the three main aspects: worker, organisation, and technology itself, correspond to each other. The viability of the XR for the organisation can be accessed by analysing the potential risks and costs towards the perceived benefits. This would reflect in the identification of more concrete XR application scenarios and the way it might shift existing ways of working.

In overall, a technology adoption roadmap (including timeline, expected impact of the technologies in correspondence with business objectives, estimated budget, and resource requirements) should be created at this phase and iterated further. The possible short-term and long-term KPIs of technology adoption should be similarly defined and iterated in further phases. The feasibility of the identified scenarios should be verified from the technology perspective – what kind of existing organisational digital
infrastructure is ready for technology adoption, what would be further required (including the costs of the equipment in addition to human resources) and how feasible is the whole adoption roadmap for a given technology state-of-art.

Furthermore, it is important to acknowledge not only the most sophisticated ways of using XR, but review also non-immersive and asymmetric options, ideating how it can be further expanded towards all-pervasive XR. These processes should not be done in isolation by the R&D, but rather be based on stakeholder engagement and multidisciplinary collaboration among the working units, facilitated by the R&D. As well, this phase should be used to ideate and conceptualize the future xReality solution and estimate the needs for integration and development (e.g., identify focus groups and stakeholders to keep in the loop, define the required scope of technological updates in the current infrastructure, define the human resources required for the design and development, etc).

Finally, at this phase, it would be required to evaluate the perception and desirability of the technology by industrial workers (e.g., target users) to estimate the technology acceptance and define the possible resistance of the technology and reasons behind it. The perception metrics should be designed at this phase and used thought the whole design and adoption cycle.

**Deliverables:** 1) Concept of the xReality solution and specific application, scenarios, 2) Roadmap of XR technology adoption, 3) Primary development requirements, including focus groups, resources and others, 4) Perception of technology among workers.

**Step 3. Specify user requirements and context of use:** What specifically should be designed to address the needs of the organisation and the end users and how to design it? This phase reassembles traditional user-centred phases of user research, meant to study the user and the intended context of use. It is all about narrowing down and investigating user needs and requirements for the XR application. It should consist of iterative circles of data gathering from different focus groups, which would closely identify their current work tasks and methods and define users’ current pains and gains of work-related activities. The methods of data gathering should be based on organisational needs and resources, and may include interviews and focus groups, workshops, ideation rounds, contextual inquiry and observations, surveys, and prioritisation activities.

This would result in the creation of design artifacts, which may be used during the future development: such as user goals, personas, walk-throughs, scenarios, and sketches of interacting with XR in the context, user flow and user journey, MVPs and mock-ups, prototypes, and other means to visualize the future XR technology and tangle it to the user
needs. By working in collaboration with target users, designers, and developers, to would be possible to summarize the list of required features and come up with the development plan. The final ideas should be communicated and confirmed not only by the end users, but also by the people with decision-making power, e.g., to stay consistent within the company vision and business objectives.

**Deliverables:** 1) Finalized development plan, 2) Prioritized list of features and tools to develop, 3) Design artefact to assist the development, 4) Defined methods on how to engage focus groups during the development.

Once the scope of development activities is clarified and confirmed both from organisational and workers’ perspectives, it is possible to continue with the actual development.

**Step 4. Produce design solutions:** **HOW to ensure that the design actually corresponds to the needs of the users and HOW it can be implemented into use?** Each development flow would be unique and should be organized based on the organisation’s needs, previously utilized practices, defined timelines, and available resources. The development maybe as well outsources or consist of a process of adopting and integrating already existing platforms. However, it is crucial to consider the following aspects while the development: **constant user involvement and feedback collection, transparency, and iterative nature of the activity.** The development should not happen in isolation from the target users and other stakeholders; they should be included to the process as early as possible. Previously defined methods of engaging different focus groups should be practiced and iteratively enhanced on-the-go. When users are introduced to a new feature, their reactions, perception, and suggestions for improvements should be recorded. Any arisen issues and obstacles should be solved within collaboration.

Additionally, during the development, the aspects of how the users can adopt the system should be considered, integrating these matters in the development process, and thus, developing and enhancing training and on-boarding with the future system. The methods and scenarios of user evaluations should be created during the development process, including the procedure, tasks, and data collection methods. From the other side, the adoption should be reviewed from a technological perspective – the developed software should be compatible with existing organisational infrastructure, systems, and regulations, and scalable for larger numbers of users, data flow and potential future growth.

**Deliverables:** 1) Working pieces of the software, 2) On-boarding and training materials for the implemented features, and 3) Evaluation plan.
Step 5. Evaluate design solutions: CAN the xReality software be used for work purposes and WHAT should be developed further? Similarly, evaluation of the designed software would be different for every organisation and should be performed based on organisational resources and requirements. Nevertheless, it is critical to conduct evaluations with the actual target users, who possess the domain knowledge and can provide concrete comments and ideas on how to improve the design and tailor the software better for the designated industrial task. Even short and sweet evaluation with small sample groups would deliver a value. Piloting session prior the actual evaluations is highly recommended to prepare for the unexpected happening, to recover from possible errors and to advance the testing procedure and data collection methods.

In terms of data collection, it would be required to measure how workers perceive the technology before and after using it, what strength and weaknesses they can spot. Another critical aspect to evaluate is the perceived and objective safety of the developed solution and ensure that it would not create additional risks and hazards. Additionally, it would be required to collect data regarding the future adoption of the technology - e.g., what support and resources would be needed by different user groups, and communication strategy (how to present and initiate the use of the system for everyday routine). This would help to finalize the adoption plan with respect to the workers vision and desires.

Deliverables: 1) Features to develop further, 2) Working and tested software, 3) Perception of the workers towards the software, and 4) Adoption plan to the mass use, which helps to prepare for the next phase.

The phases four and five should be iterated until the designed software is seen as a value for the work context. In the opposite case, if the user requirements are not met, it would be required to jump to the previous phases and perform additional user studies. Despite it might be reviewed as resource- and time-consuming, coordinated work with target users would help to minimize the expenses on a long run and ensure that the developed solution would be smoothly adopted by the workers, instead of being not used due to technology resistance.

Step 6. Facilitate conditions and introduce the technology: HOW to ensure efficient technology adoption? By that phase, all previously collected data would help to establish the adoption plan, which would include user groups, their demographics, characteristics and perception towards technology, training, and support requirements, as well as communication strategy. As follows, the environment and conditions for the technology adoption should be prepared based on this data, including human resources (e.g., new, or trained personnel, who would be responsible for introducing the technology or providing support), materials to aid the adoption process (e.g., individual training and
learning materials, manuals, instructions and guidelines), hardware and software.

Once ready, the new technology should be presented to the user groups, communicating the benefits, expected changes to the work processes, as well as possible difficulties. The introduction of the technology should not be rushed, while the use of technology should not be forced. On the opposite, introduction should foster a culture of innovation and attract employees to experiment with software based on their own desire.

Training sessions, guided by trained professionals, should be further arranged to ensure smooth learning curve with the software. The training should be based on actual industrial tasks and scenarios, so the workers would understand the value themselves and experience the work process. Similarly, it would make sense to again measure worker’s satisfaction with and perception of the technology, and in case of negative responses, investigate the reasons behind it. Once the workers would receive the technology for personal use, they should have an opportunity to contact support team and get more help if needed. All support requests and other matters should be collected to get a clear picture of what might restrict full technology integration in a work context. Based on the pattern and identified issues, more training sessions may be arranged as well as more software updates and improvements identified.

Deliverables: 1) Adoption plan iteration, 2) Measures of perception and technology acceptance among the workers, 3) Identification of problems and barriers to address them.

Step 7. Monitor and Advance: HOW to extract the maximum value and reduce waste? The adoption process is not over once the technology is started to be utilized as a part of the work routine. It is critical to monitor its usage patterns and how it affects the overall organisational processes and structures. The previously identified long-term and short-term KPIs should be implemented into use and monitored. This should include both objective (percentage of completed training and learning modules, number of support cases, frequency and time spend in XR, generated content, project duration, etc) and subjective metrics (user perceptions and feedback, employee satisfaction, self-reported productivity).

The collected data should be further analysed to identify areas of improvement and inefficient processes to cut and enhance. Setting the focus on continuous development and advancement, the adopted XR software should be constantly reviewed for optimisation and enhancement, as well as the related methods, e.g., training and learning materials, on-boarding, etc.
Deliverables: 1) Measured effects of XR integration, 2) Data and Ideas for further optimisation.

In summary, the process of xReality technology design and adoption is not a straightforward task, where multiple factors should be considered and iteratively evaluated prior the mass adoption. This process would be different for different organisations., whereas the proposed strategy can be flexibly adjusted for the company needs. Nevertheless, it is possible to highlight the main principles as a set of golden rules, shown below.

**Eight golden rules for XR technology design and adoption:**

- Base design decision on the real needs and industrial challenges, not on the hype.
- Emphasize the role of research and analysis prior and during the adoption.
- Design involving users and other stakeholders in the loop.
- Design based on multidisciplinary collaboration (e.g., academy-industry collaboration).
- Collect data iteratively to systematically measure employee’s perception of technology.
- Test and evaluate as early as possible.
- Monitor the progress.
- Strive to innovate and continuously improve.

**5.4 LIMITATIONS AND FUTURE WORK**

This dissertation is based on the exploratory case studies, which investigate the matter of XR from multiple perspectives and research fields, contributing mainly to the Human-Computer interaction field and delivering insightful information on the fields of Technical Communication and CSCW. As follows, my research contributes to a wider perspective of XR-related knowledge in industrial context, rather than provides concentrated pieces of statistically verified information. Another limitation of my work is building the contributions based on a single company case. More details and important insights on the use of xReality in industrial settings might arise from investigating similar use cases in different domains. Nevertheless, I acknowledge that the conclusions I draw should be flexibly adopted to suit the needs of different organisations and contexts, and I ensured the generalisability of the provided insights by providing a more on-a-surface overview rather than precise details. Another limitation is that the experimental software was in reality never adopted to the mass use after the case studies were performed. This fact is not connected to the quality of the final product or research outputs, but rather is based on the organisational change within
the company. Therefore, the adoption strategy I proposed should be further developed and iterated based on realistic scenarios of XR adoption, especially the latter phases.

Another interesting future work direction is a deeper investigation of industrial collaborative XR platforms linked to social and workforce-related theories, focusing on human factors. Such studies might be aiming at productivity and efficiency in VR, teamwork and collaboration aspects, knowledge sharing and transfer, as well as other relevant concepts. For instance, I believe that the proposed pyramid of industrial VR needs (Section 4.3.6.3) should be further expanded in a similar way as the Maslow’s pyramid of needs: the development of XR should have higher hierarchical goals, covering also esteem and self-actualisation at work (in accordance with Maslow’s higher hierarchies). More studies may look into balancing the use of XR together with other technologies to accommodate efficient work processes and employee’s well-being.

The future research may also expand towards technology-oriented topics, exploring topics such as multimodal interaction and interaction techniques for collaboration, speech and gestural interaction and control in industrial XR systems, multimodal text-entry methods as well as methods of content generation beyond traditional. Furthermore, it would be critical to investigate data management and content flow in order to efficiently integrate the use of xReality with existing digital infrastructure and enable re-utilisation of digital resources, prioritizing data security and user privacy. XReality should be further studied in combination with other emerging technologies, such as AI and machine learning, IoT, 5G, blockchain and edge computing. Only based on multifield and multidisciplinary research it would be possible to unlock full potential of xReality, reach the desired state-of-art and enhance user experience to deliver an actual value to the industrial use cases.

Accordingly, driven by continuous advancements and rapid change in work methods, the proposed process-oriented model of academy-industry collaboration may be further iterated and enhanced, adding classification related to the various nature of collaboration among two parties.
6 Conclusion

In this dissertation, I explored the value and application cases of xReality technology to address industrial needs for development and challenges present in industry. The work is done on the context of Industrial Maintenance and is based on two case studies, performed in close collaboration with the leading elevator manufacturer and service provider, KONE Oyj. The goal of the dissertation was to accelerate the adoption of XR technologies in the field by delivering a holistic overview of advantages, challenges, and critical aspects, related to the adoption and integration of XR in a work environment. To approach this, I raised the following research questions:

(1) How do XR technologies potentially impact the field of Industrial Maintenance?

(2) How do industrial experts perceive the use of Virtual Reality and related technologies in the context of their work?

(3) How to design and adopt virtual reality systems to address the needs of industrial workers and organisations?

The first question of the dissertation covered a wider perspective of the topic, exploring how the adoption of xReality technologies in the field may shape and advance the existing ways of working and operating both in the field and office environments. Two other questions narrowed to the critical aspects related to the technology adoption, reviewing human factors involved and design and development of the technology itself.

To accurately explore the matter and deliver a generalized knowledge, all the data was collected based on involvement of domain experts in real industrial settings. The qualitative data was prioritized above quantitative
due to the study specifics and relatively small sample size of industrial participants. Through critical review of academic and industrial literature and iterative user studies, which were grounded on the actual challenges of the company, two VR-based experimental software were designed, developed, and evaluated. The first one, namely XR Safety Kit, helped to verify the need for AR-based in field-guidance and showed how VR coupled with gaze data can be utilized for the authoring and testing of AR systems. Moreover, expert insights from this case led to the continuation of research, presenting the idea of utilizing VR to advance the process of maintenance method and technical documentation creation. The second experimental software, called the COVE-VR platform, was designed to accomplish, and test this idea. The platform was designed to facilitate industrial collaboration of virtual global teams, involved in the pipeline of technical documentation creation, and evaluated in three scenarios, demonstrating the value of VR for this process.

As an outcome, my study showed how xReality is capable to enhance industrial processes in the field of Industrial maintenance. AR has a potential to transform in-field work and change the role of maintenance technicians, optimizing maintenance operations and making it more safe, efficient, and error-prone. VR, in turn, may highly advance industrial processes in an office environment, providing access to hazardous industrial context and a way to naturally interact with virtual machinery, unavailable otherwise. This would have a positive impact not only on the productivity of workers and the effectiveness of their collaboration, but also would lead to overall process optimisation, promoting sustainability and human-centricity.

In addition, my study demonstrated the strong link between AR and VR, which suggests that these technologies should be integrated simultaneously into the existing organisational digital infrastructure, rather than separately. Both technologies can deliver certain benefits to the product development and service design lifecycle, whereas digital materials can be re-utilized from one application case to another. Further, to deliver the actual value and reach all-pervasive interaction in work environments, xReality should be reviewed and adopted in combination with other emerging technologies, such as artificial intelligence and machine learning, internet of things and 5G, cloud computing, big data and cybersecurity, wearables, collaborative robots and other. Only implemented together, the technologies can deliver a massive change to a workforce and drive innovations to achieve the Industry 4.0 and Industry 5.0 vision. Similarly, only based on multidisciplinary collaboration, it would be possible to make world a better place for future generations and avoid environmental and economic collapse.

To this end, the main contribution of my dissertation include:
- **Design and Adoption strategy of xReality technologies** that can be used by organisations as a primary guiding plan. The strength of the presented strategy is the account for both organisational and individual perspectives and a set of procedures and guidelines to ensure that the final XR solution would correspond to the needs of the organisation and what is similarly important, workers or target users. The strategy is generic enough to be further tailored to other domains and application cases. However, it provides enough details and insights to aid the design, development, and adoption process within the organisation. In addition, I formulated eight golden rules for XR technology design and adoption to help stay focused on aspects what matter.

- **Academy-Industry collaboration procedural framework**, which is linked to the phases of user-centred design and can be used as a demonstration of how to arrange joint activities of software development among two parties. Supported by the list of practical implications to enhance the communication and knowledge sharing between academia and industry, the framework can be utilized to guide the collaborative work and ensure successful outcome for both sides of the collaboration.

- **Practical guidelines and implications to support the design of AR and VR software**, which can be directly applied in the context of Industrial Maintenance or be further iterated and advanced for other use cases. In particular, I deliver a pyramid of needs for the VR-software development as well as design considerations for the AR-based guidance and multimodal safety warnings.

- **Exploration of perceptions towards xReality among industrial employees**, which demonstrates the main desires and fears of industrial workers and helps to prioritize their perspective during the development. The set of survey statements on VR perception can be utilized by other organisations to assess the perceptions towards XR technologies within their organisation and systematically collect this data during the design and adoption process.

- **Exploration of asymmetric VR set-up in industrial settings**, which demonstrated that the value of VR in industrial context can be extracted even without delivering highly immersive experiences. The appliance of asymmetric VR would help to boost the spread of VR in industrial organisations, advance the accessibility, inclusiveness, and scalability of VR software, while reducing hardware costs. I have also provided practical guidelines and insights on how to enhance the quality of communication via asymmetric set-ups and ensure smooth integration of technology for rapid use.
In conclusion, my work has a high practical significance for not only fellow academic researchers, who work on similar topics, but also for industrial practitioners and organisations. The knowledge and insights I presented in this dissertation are grounded on theoretical body of research merged with industrial context of application. Having the opportunity to extract research data based on the collaboration with industry, I aimed to inspire and engage other parties to emphasize collaboration and co-creation. Inspired by the possibilities of xReality, I deliver the practical knowledge to aid and boost the adoption of xReality technologies in the field, so technologies may serve for the better of humanity and the world we live in. I am convinced that, if applied correctly, XR in combination with other innovative technologies have the power to positively affect the sustainability and optimisation of industrial processes, which in turn would positively influence the workforce and well-being of individual workers, bringing equality, diversity, accessibility, and decent work conditions for everyone.
In conclusion, my work has a high practical significance for not only fellow academic researchers, who work on similar topics, but also for industrial practitioners and organizations. The knowledge and insights I presented in this dissertation are grounded on a theoretical body of research merged with industrial context of application. Having the opportunity to extract research data based on the collaboration with industry, I aimed to inspire and engage other parties to emphasize collaboration and co-creation. Inspired by the possibilities of xReality, I deliver the practical knowledge to aid and boost the adoption of xReality technologies in the field, so technologies may serve for the better of humanity and the world we live in. I am convinced that, if applied correctly, XR in combination with other innovative technologies have the power to positively affect the sustainability and optimisation of industrial processes, which in turn would positively influence the workforce and well-being of individual workers, bringing equality, diversity, accessibility, and decent work conditions for everyone.


*Industry 4.0 How to navigate digitization of the manufacturing sector.* (2015).


Lundström, A. (n.d.). *Improving lives by interorganizational collaboration: A collaboration analysis on a social development project*.  


from a work system perspective. 


Appendix 7.1 CASE STUDY MATERIALS

Data collection forms

#1. background information
   1. Gender
   2. Education level
   3. Role at KONE
   4. Familiarity with elevator maintenance
   5. Years of experience in maintenance work
   6. Attitude towards technology and experience with VR and AR

#2. system effectiveness
   1. I believe this system can make my work faster
   2. I believe this system can make my work safer
   3. I believe this system can make my work easier
   4. I believe this system can make my work more efficient

#3. usability and user satisfaction
   1. I would like to use this system frequently in the work context
   2. I found the system unnecessarily complex
   3. I thought the system is easy to use
   4. I think that I would need the support of a technical person to be able to use this system
   5. I would imagine that most people would learn to use this system very quickly
   6. I felt very confident using the system
   7. The system seemed inconsistent to me
   8. I found the functions in this system to be well integrated
   9. I was not confused or lost while performing the
# Appendix

## 7.1 Case Study 1 Materials

### Data collection forms

<table>
<thead>
<tr>
<th>#</th>
<th>topic</th>
<th>statements</th>
</tr>
</thead>
</table>
| 1  | background information             | 1. Gender  
2. Education level  
3. Role at KONE  
4. Familiarity with elevator maintenance  
5. Years of experience in maintenance work  
6. Attitude towards technology and experience with VR and AR |
| 2  | system effectiveness               | 1. I believe this system can make my work faster  
2. I believe this system can make my work safer  
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| 3  | usability and user satisfaction    | 1. I would like to use this system frequently in the work context  
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7. The system seemed inconsistent to me  
8. I found the functions in this system to be well integrated  
9. I was not confused or lost while performing the |
<table>
<thead>
<tr>
<th>4 Documentation Panel</th>
<th>tasks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. I found the documentation panel useful for maintenance work</td>
<td></td>
</tr>
<tr>
<td>2. I had some problems with controlling the documentation panel</td>
<td></td>
</tr>
<tr>
<td>3. I found the documentation panel easy to use</td>
<td></td>
</tr>
<tr>
<td>4. I liked that I could move and place the documentation panel anywhere I want</td>
<td></td>
</tr>
<tr>
<td>5. I found the function to center the documentation panel in my field of view to be useful</td>
<td></td>
</tr>
<tr>
<td>6. Instructions in documentation panel were easy to read</td>
<td></td>
</tr>
<tr>
<td>7. I would like to zoom into the documentation panel</td>
<td></td>
</tr>
<tr>
<td>8. I would like to have a Table of content for a task in a separate panel</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>5 safety aspects</th>
<th>tasks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. I felt safe when using the system</td>
<td></td>
</tr>
<tr>
<td>2. I believe AR headset is safe to use in maintenance tasks context</td>
<td></td>
</tr>
<tr>
<td>3. The safety warnings that appeared in the application were self-explanatory and I understood the risk</td>
<td></td>
</tr>
<tr>
<td>4. The safety warning helped me to identify dangerous places in a working space</td>
<td></td>
</tr>
<tr>
<td>5. I believe safety warnings like this can prevent accidents in a working environment</td>
<td></td>
</tr>
<tr>
<td>6. I would like to be warned this way in a work context</td>
<td></td>
</tr>
<tr>
<td>7. The safety warning made me nervous/scared</td>
<td></td>
</tr>
<tr>
<td>8. The safety warnings were annoying</td>
<td></td>
</tr>
<tr>
<td>9. The safety warnings were distracting</td>
<td></td>
</tr>
<tr>
<td>10. I noticed the following warning signals when using this system (Warning symbol, sound, haptic feedback (checkboxes))</td>
<td></td>
</tr>
<tr>
<td>11. I would prefer following signals for a warning signal (Warning symbol, sound, haptic feedback (checkboxes))</td>
<td></td>
</tr>
<tr>
<td><strong>12. I would feel more secure at work with context-aware safety warnings</strong></td>
<td></td>
</tr>
<tr>
<td><strong>13. I would feel more confident at work with context-aware safety warnings</strong></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>6 VR-related questions</th>
<th>tasks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. The virtual environment felt real</td>
<td></td>
</tr>
<tr>
<td>2. My interaction with the virtual reality seemed natural</td>
<td></td>
</tr>
<tr>
<td>3. The way I did maintenance tasks in VR are similar to the way I do maintenance tasks in the real world</td>
<td></td>
</tr>
<tr>
<td>4. I would like to use this virtual environment to learn new maintenance methods</td>
<td></td>
</tr>
<tr>
<td>5. I believe this virtual environment would be useful for inexperienced maintenance workers</td>
<td></td>
</tr>
</tbody>
</table>
| 6. I could easily map the virtual reality objects to
1. I found the documentation panel useful for maintenance work
2. I had some problems with controlling the documentation panel
3. I found the documentation panel easy to use
4. I liked that I could move and place the documentation panel anywhere I want
5. I found the function to center the documentation panel in my field of view to be useful
6. Instructions in documentation panel were easy to read
7. I would like to zoom into the documentation panel
8. I would like to have a Table of content for a task in a separate panel

1. I felt safe when using the system
2. I believe AR headset is safe to use in maintenance tasks context
3. The safety warnings that appeared in the application were self-explanatory and I understood the risk
4. The safety warning helped me to identify dangerous places in a working space
5. I believe safety warnings like this can prevent accidents in a working environment
6. I would like to be warned this way in a work context
7. The safety warning made me nervous/scared
8. The safety warnings were annoying
9. The safety warnings were distracting
10. I noticed the following warning signals when using this system (Warning symbol, sound, haptic feedback (checkboxes))

11. I would prefer following signals for a warning signal (Warning symbol, sound, haptic feedback (checkboxes))
12. I would feel more secure at work with context-aware safety warnings
13. I would feel more confident at work with context-aware safety warnings

1. The virtual environment felt real
2. My interaction with the virtual reality seemed natural
3. The way I did maintenance tasks in VR are similar to the way I do maintenance tasks in the real world
4. I would like to use this virtual environment to learn new maintenance methods
5. I believe this virtual environment would be useful for inexperienced maintenance workers
6. I could easily map the virtual reality objects to objects in the real world
7. I would be able to repeat the actions I have done in VR in real working situations
8. I concentrated on the assigned tasks rather than on the VR devices themselves
9. I felt motivated by the virtual environment to do my work
10. I felt in control when performing the tasks
11. I think using a virtual environment is practical to simulate elevator maintenance tasks
12. I would like to use this system for learning in a work context

Interview questions

1. What was the positive points about your experience?
2. What was the negative points about your experience?
3. Have you noticed any issues that might affect the working process negatively/positively?
4. Would you like to use this system in real life (AR version)? What interaction would you prefer?
5. Do you prefer to be guided by the system? Why?
6. What do you think about safety warnings?
7. Do you have any suggestion on how we can improve the system? What other features you might think of?

Legend:

Grey statements were used only in Evaluation 1; **Bold statements were used only in Evaluation 2**
### 7.2 Case Study 2 Materials

#### Prioritization Survey

<table>
<thead>
<tr>
<th>Category</th>
<th>Features</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tools</strong></td>
<td>Possibility to record videos/animations</td>
<td>4,8</td>
</tr>
<tr>
<td></td>
<td>Mark &amp; highlight the components to work with</td>
<td>4,7</td>
</tr>
<tr>
<td></td>
<td>Possibility to take snapshots</td>
<td>4,6</td>
</tr>
<tr>
<td></td>
<td>Clipboard in VR to see snapshots/videos, explosion models</td>
<td>3,9</td>
</tr>
<tr>
<td></td>
<td>Possibility to create line drawings from a VR</td>
<td>3,6</td>
</tr>
<tr>
<td><strong>Notes</strong></td>
<td>Possibility to leave text notes to the environment</td>
<td>4,2</td>
</tr>
<tr>
<td></td>
<td>Possibility to leave verbal notes to the environment</td>
<td>3,8</td>
</tr>
<tr>
<td></td>
<td>Possibility to leave 3D drawing notes to the environment</td>
<td>2,9</td>
</tr>
<tr>
<td><strong>Environment</strong></td>
<td>Collaboration i.e. multiuser support in VR</td>
<td>4,4</td>
</tr>
<tr>
<td></td>
<td>Create library for fastening/loosening methods &amp; tools</td>
<td>4,3</td>
</tr>
<tr>
<td></td>
<td>Accurate positioning tool in VR, different 3D models and virtual objects snapping together fluently and not overlapping etc.</td>
<td>4,2</td>
</tr>
<tr>
<td></td>
<td>Automatically measure the space needed for tools</td>
<td>4,1</td>
</tr>
<tr>
<td></td>
<td>Possibility to create different versions for methods (e.g. for A/B testing for maintenance methods)</td>
<td>3,7</td>
</tr>
<tr>
<td><strong>Integration</strong></td>
<td>Possibility export snapshots and videos from VR</td>
<td>4,9</td>
</tr>
<tr>
<td></td>
<td>Easy way to replace/update 3D model when there are changes</td>
<td>4,4</td>
</tr>
<tr>
<td></td>
<td>Possibility to test/change a component in the system level elevator context (e.g. in CR)</td>
<td>4,1</td>
</tr>
<tr>
<td><strong>Timeline</strong></td>
<td>Navigation timeline in VR. Having TOC/Index/subtitles e.g. “Removing old”, “Installing new”</td>
<td>4,1</td>
</tr>
<tr>
<td></td>
<td>Possibility to edit Timeline/TOC/index for the recording</td>
<td>4,1</td>
</tr>
<tr>
<td></td>
<td>TOC/index would also act as a shortcut when creating the draft</td>
<td>3,4</td>
</tr>
<tr>
<td><strong>Other</strong></td>
<td>System level elevator/3D model/VR model available</td>
<td>4,3</td>
</tr>
<tr>
<td></td>
<td>Explosion model to explain the composition</td>
<td>3,9</td>
</tr>
<tr>
<td></td>
<td>Include weight, max load etc. information from CAD to VR</td>
<td>3,8</td>
</tr>
<tr>
<td>Category</td>
<td>Features</td>
<td>Mean</td>
</tr>
<tr>
<td>----------</td>
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</tr>
</tbody>
</table>

**Interview Questions**

**User Questions Study**

1 **Overall:**
- What is your overall experience?
- Please share your thoughts and emotions about the experience with the VR system.
- Do you find the VR system is useful for your work? Why/why not?
- What concerns do you have about of using this application for your daily work?
- Do you have any suggestions on how to enhance interactions with the system?
- Do you have any suggestions on how to enhance the system functionality in order to positively influence our work performance? Was there something missing in the application that you would like to have? Why?

To the **1st participant-group**:
- What maintenance development methods issues would you like the application to help you with?

To the **2nd participant-group**:
- Do you find the content (created in VR, e.g., texts, videos and pictures) useful for your work? Why/why not?
- What tech writing issues would you like the application to help you with?

**Collaboration-related:**
- How do you feel about the collaboration features?
  - What exactly was good about the collaboration features?
  - What exactly was bad about the collaboration features? /
    (showroom/elevator pit (environment))
- When would you prefer collaborating with your teammates using this application and when collaborating in-person? WHY?
- For which tasks/purpose (if needed)
- How do you imagine the collaboration between maintenance and tech writing teams working using this application?
- What kind of other functionality would be useful in your opinion to support department-to-department collaboration in VR?

2 **General:**
- Please share your thoughts and emotions about the experience with the application
- In which situations – use cases – would this type of
application can be used in your work?

• Where and how do you see benefit of the media created (videos, photos, text) in VR?

• What do you think about the department-to-department collaboration using this VR environment?

• If you think about lean and agile processes, where and how would you see this application could be used at KONE? Which of your job tasks would benefit from using this application?

• What do you think needs to change in the KONE processes/your daily job for this type of VR application to be implemented?

To remote users:

• What are your thoughts about participating remotely in a VR session? How we can improve it for you?
• What were the difficulties to interact with the VR users during the tasks to get the point of view you needed?
• How did you feel about communicating to the user who was the “eyes of VR” for you vs the other VR user?

To HMD users:

• What are your thoughts about having remote participants in the VR session?
• How do you compare the communication between the other VR user VS the communication with the remote users?
• How did you adjust the way you behave because the remote participants were seeing what you were seeing?

To previous users:

• How do you find the system changes? How do you compare the current to your previous experience with the application?

Closing questions:

• How do you feel about the roles all participants had assigned? How would you improve the collaboration/teamwork? In your opinion, Who needs to participate as a VR user and who as a no-vr user? Why? (how being vr or non-vr affected their opinion)
• What did you like in the application? What was difficult?
• What needs to be improved in the application?
• Other thoughts or opinions?

3 General feelings:

• How did you like working and collaborating in VR?
• How would you compare collaborating in VR and
User Study Tasks

User Study #1

In the Showroom, the maintenance method developers and technical documentation writers had the following tasks:
1. Place the RBO in the showroom
2. Explode the model and modify the explosion distance
3. Modify the elevation
4. Modify the scale of the model
5. Check the fuse locations
6. Take pictures of the fuses
7. Teleport to Lab

After the participants have teleported to the Lab VR, their instructions slightly differ. The maintenance method developers were
asked to “Use virtual tools to create digital materials, that would be helpful when designing maintenance methods”, accompanied with a list of more detailed instructions:

1. Measurement from wall to wall
2. Start a video of what you are removing
3. Take a picture of each of the steps

(Battery removal starts)

4. Remove the lid
5. Remove fixing
6. Remove batteries
7. Place back spare batteries / spare batteries will be in a different color
8. Make a note using the keyboard, for technical documentation users on the 3d model they need to work on
9. Make a voice note, how the fixing is attached?
10. Make a voice note, is there actually a cable that needs to be removed and how the cables are supposed to be wired?
11. Delete dummy note

The technical documentation writers were asked to “Use virtual tools to create digital materials, that would be helpful when designing documentation”, followed by a list of more detailed instructions:

1. Open the application with the comments from Method Development Department (same for all participants)
2. Check the notes
3. Take general measurements of the 3d model to work on
4. Make a note to ask for clarification for the maintenance - by voice

(Battery removal starts)

5. Remove the lid
6. Remove fixing
7. Remove batteries
8. Take several pictures of the components from different angles for each step for the instructions - 3 to 5 pictures
9. Delete one of the cameras
10. Open the created content on the PC - (After the test assets will be available in the same folder where the executable is)

User Study #2

The first part, namely “3D CAD model exploration in collaborative space” was performed in the Showroom which consisted of 5 following tasks:

(2) Open a 3D model, explode it and adjust the scale, distance and levitation (individual – VR2)
(3) Locate a component (batteries), find a good angle and take a screenshot (shared – VR1, T1, T2)

User Study #2

The first part, namely “3D CAD model exploration in collaborative space” was performed in the Showroom which consisted of 5 following tasks:

(2) Open a 3D model, explode it and adjust the scale, distance and levitation (individual – VR2)
(3) Locate a component (batteries), find a good angle and take a screenshot (shared – VR1, T1, T2)
• VR1 explores the model to locate the batteries
• T1 asks for the better view angle
• T2 takes the snapshot of battery location
(4) Take a photo to support the illustrators for the battery replacement task in outline rendering mode (shared – VR2, T2)
• VR1 takes one shot
• T2 asks for additional shots in a different angle
(5) Take a photo to support the illustrators for the battery replacement task using a regular camera mode (individual – VR1)
(6) Teleport to Lab VE (individual – VR1, VR2)
The second part, namely “Assembly/disassembly of a 3D CAD model” was performed in the VRLab and consisted of 5 following tasks:

(1) Take general measurements of the RBOMU component: width, height and length (individual – VR2)
(2) Take additional measurements (from the component to the wall) and record them via a screenshot (shared – VR2, T1,T2)
• T1 asks for additional measurements
• VR2 makes the measure
• T2 asks VR2 to stand still while she is taking the screenshot
(7) Document the battery replacement workflow via speech input (individual – VR1)
(8) Add a text note with the name of the component via virtual keyboard (individual – VR2)
(9) Delete the last text note on request (shared – VR2, T2)
• T2 requests to delete the note
• VR2 uses Delete tool to do it

User Study #3

(1) Teleport to virtual elevator shaft
(2) Technical Documentation writer task: open the DocPanel tool and find RBO-related documentation
(3) Maintenance Method Developer task: interact with the RBO model as needed
(4) Collaborative task: Review the documentation using virtual tools you as you need
   a. e.g., discuss, interact with the model, take notes, use the camera, use the measurement tool,
(5) Discuss the method, presented on the documentation – is there any risks involved, any modifications needed for the document?
(6) Teleport to Showroom to continue the exploration the RBO model for further discussions
Alisa Burova, John Mäkelä, Jaakko Hakulinen, Tuuli Keskinen, Hanna Heinonen, Sanni Siltanen, and Markku Turunen.


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ABSTRACT

Utilizing VR and Gaze Tracking to Develop AR Solutions

Alisa Burova, John Mäkelä, Jaakko Hakulinen, Tuuli Keskinen, Markku Turunen

Simulation is widely used in the development of Augmented reality (AR) solutions for industrial maintenance. However, the development of real AR solutions is challenging due to the uncertainty with respect to safety, guidance, and documentation usage. In this paper, we introduce an approach combining virtual reality (VR) and gaze tracking. We conduct a survey, utilizing actual gaze data from the evaluation to elicit comments from industry experts on the usefulness of simulation. We further conduct a simulated AR environment for field guidance and safety awareness features in augmented reality; Virtual reality (VR), Computer mediated multimodal data (MR), and Mixed Reality (MR) expands the continuum of classical possibilities of classical virtual prototyping, gaze tracking. Our results show the potential of using gaze data in the evaluation process with experts to post on servers or to redistribute to lists, requires prior specific permission and that copies bear this notice and the full citation on the first page. Copyrights for components of this work owned by others than ACM must be honored. Abstracting with credit is permitted. To copy otherwise, or republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee. Request permissions from Permissions@acm.org.

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Figure 1. Simulated AR industrial maintenance environment.

On one side, the concept of augmented reality; Virtual reality (VR), and Real world SR, has been studied due to shorter time and cost savings. On the other side, the possibility of uniting augmented reality; Virtual reality (VR), and Computer mediated multimodal data (MR) expands the continuum of classical possibilities of classical virtual prototyping, gaze tracking. The concept of using gaze tracking to increase the possibility to safely simulate operations and increase the flexibility of using technological environments for learning without actual implementation has been studied. Various studies have introduced simulated AR training approaches combining VR and gaze tracking. However, So far, these concepts have been studied including augmented reality; gaze tracking; safety and human factors. Virtual reality, simulated AR, and gaze tracking have been combined to study the possibility to safely simulate operations and increase the flexibility of using technological environments for learning. However, the development of real AR solutions is challenging due to the uncertainty with respect to safety, guidance, and documentation usage.

INTRODUCTION

Industrial maintenance is an area where information and/or a warning and training: Technical knowledge and human factors are important. On one side, the concept of augmented reality; Virtual reality (VR), and Real world SR, has been studied due to shorter time and cost savings. On the other side, the possibility of uniting augmented reality; Virtual reality (VR), and Computer mediated multimodal data (MR) expands the continuum of classical possibilities of classical virtual prototyping, gaze tracking. The concept of using gaze tracking to increase the possibility to safely simulate operations and increase the flexibility of using technological environments for learning without actual implementation has been studied. Various studies have introduced simulated AR training approaches combining VR and gaze tracking. However, So far, these concepts have been studied including augmented reality; gaze tracking; safety and human factors. Virtual reality, simulated AR, and gaze tracking have been combined to study the possibility to safely simulate operations and increase the flexibility of using technological environments for learning.
Utilizing VR and Gaze Tracking to Develop AR Solutions for Industrial Maintenance

Alisa Burova¹, John Mäkelä¹, Jaakko Hakulinen¹, Tuuli Keskinen¹, Hanna Heinonen², Sanni Siltanen², Markku Turunen¹

¹ Tampere University, Tampere, Finland
{alissa.burova, john.makela, jaakko.hakulinen, tuuli.keskinen, markku.turunen}@tuni.fi

² KONE Corporation, Hyvinkää, Finland
{hanna.heinonen, sanni.siltanen}@kone.com

Figure 1. Simulated AR safety warning as seen in the VR training environment.

ABSTRACT
Augmented reality (AR) presents a variety of possibilities for industrial maintenance. However, the development of real-world AR solutions has been limited due to the technological capabilities and uncertainty with respect to safety at deployment. We introduce the approach of using AR simulation in virtual reality (VR) coupled with gaze tracking to enable resource-efficient AR development. We tested in-field AR guidance and safety awareness features in an iterative development-evaluation process with experts from the elevator maintenance industry. We further conducted a survey, utilizing actual gaze data from the evaluation to elicit comments from industry experts on the usefulness of AR simulation and gaze tracking. Our results show the potential of AR within VR approach combined with gaze tracking. With this framework, AR solutions can be iteratively and safely tested without actual implementation, while gaze data provide advanced objective means to evaluate the designed AR content, documentation usage, and safety awareness.

Author Keywords
Industrial maintenance; virtual reality; virtual prototyping, augmented reality; gaze tracking; safety.

CSS Concepts
• Human-centered computing—User Studies; Mixed / augmented reality; Virtual reality

INTRODUCTION
Industrial maintenance is an area where information technology is taking an increasingly large role. The concept of the Mixed Reality (MR) continuum [23] expands the possibilities of classical practices via exposing the use of computer-mediated multimodal data both in an immersive virtual environment or as augmentations over the real world. On one side, virtual reality (VR), has proved to be a viable environment for learning and training [7] due to the flexibility [4] and realism of experience [12], in addition to the possibility to safely simulate dangerous operations and contexts [33]. On the other side, in-field guidance via augmented reality (AR) can improve speed, quality, and safety of work, resulting in decreased physical and mental workload for the technicians [13]. So far, these concepts have been studied separately despite the potential of uniting AR and VR under one comprehensive platform, including cost savings due to shorter development time, increased efficiency in training, and the possibility to integrate safety-related aspects deeper into organization’s culture and processes.
Benefits of AR, especially solutions based on see-through head-mounted displays (HMDs), come from immediate access to information in a context-sensitive manner during work. Moreover, AR can actively support safety by displaying warnings and other critical information when relevant. However, AR can also create safety risks if the information is displayed in an inappropriate manner, thus, distracting the user from noticing real-world hazards. Hence, industrial AR solutions should be reliable, flexible, and efficient since work tasks involve many risks and hazards. The development of industrial AR solutions should be iterative, with systematic testing, to identify the best strategies of information presentation and interaction for accessing the AR content. This includes media types, such as text, video, audio, pictures, and 3D models, and interactions like browsing, acknowledging messages, and searching for information. Errors in design may lead to dramatic consequences.

So far, there has been little focus on defining what kind of technical information should be displayed in AR applications and how [10, 37]. The development of AR solutions is often frozen in the proof-of-concept state and such solutions are rarely implemented in a real context due to hazards of real-life evaluations and technical limitations of see-through HMDs. As technology develops and becomes feasible for industrial maintenance, technical content must be fitted to the needs of the users, context, tasks, and devices. Considering the risks associated with testing in a real industrial context, an easy, resource-efficient, and safe way to test content and interactions is required to boost AR development further.

The flexibility of VR simulations makes them a feasible and efficient approach to address AR development issues [3, 29]. Within VR, potential AR concepts can be evaluated in a realistic simulated context, and aspects like information presentation, interaction techniques, and context-sensitive functionality can be tested in a safe environment. VR solutions can also simulate many of the limitations of AR technologies including field of view, tracking accuracy, and image contrast and color. Furthermore, VR prototyping can provide material, that can be used to elicit comments and opinions from domain experts, which is vital given the special characteristics related to the field of industrial maintenance. Finally, considering the digitalization of industrial design processes, prototyping in virtual environments (VE) can be done in a resource-efficient manner.

Furthermore, HMD-integrated gaze tracking provides extended analysis possibilities for the usage of the augmented content and other user behavior [2, 18]. Gaze tracking has proven itself as a valuable tool to analyze attention span [18] as well as to measure learning [5] and safety awareness [2]. In VR prototyping and training, gaze tracking can provide an understanding of how maintenance technicians perform their tasks, how they notice and utilize AR content, how the AR interface affects their performance with the task, and how it affects work safety.

We have explored the potential of VR technology coupled with gaze tracking for prototyping industrial AR solutions, focusing on how experts involved in the development process perceive the benefits and challenges of the approach in the industrial context. To enable this, we developed the xR Safety Kit framework, a multipurpose VR platform with AR simulation and gaze tracking to support AR prototyping and training. We also performed an iterative, industrial development-evaluation process with expert participants to demonstrate how AR features, in our case in-field guidance and safety warnings, may be evaluated in a resource-efficient manner with a small number of participants. In addition, the resulting materials, e.g., visualized gaze tracking data and recordings of the testing procedure, were utilized in an online survey to gather domain experts’ opinions on the framework and the use of AR, VR, and gaze tracking in industrial context.

Our results show the potential of utilizing VR coupled with gaze tracking for efficient industrial AR development. The xR Safety Kit is a flexible and safe framework for AR prototyping, which may be easily deployed by utilizing existing materials in industrial contexts. Using gaze tracking while testing provides valuable understanding, which cannot be gathered with traditional evaluation methods. We further framed design suggestions for documentation presentation and safety warnings for an in-field AR tool, which are generalizable for other hazardous industrial contexts of use. Moreover, we found positive attitudes toward, and the desire for, utilizing innovative technologies in the industry. Additionally, our results indicate that integrating industrial working processes into a virtual environment to enable collaboration of different departments would positively affect not only the employees’ motivation but also the overall company performance.

RELATED WORK
Three decades of work within the MR continuum in the industrial context have resulted in a set of prototypes, concepts, and evaluations indicating the benefits of utilizing AR and VR as assistive environments, including cognitive support, quality assurance, and training [7]. This chapter presents use cases and opportunities related to the use of AR, VR, and gaze tracking in the industrial context.

AR in Industrial Maintenance
The field of maintenance remains the second most popular application field of AR [6] due to the complex and dangerous nature of the work [21] combined with significant physical and cognitive requirements [13]. AR has been reviewed as a promising supporting technology [6] due to its possibility to enrich the real-world experience with computer-mediated data [23]. Early research [13] in the field demonstrated that effective AR assistance can reduce mental and physical workload by increasing the efficiency of workers and minimizing head and neck movements. Over the years,
augmented reality has been applied to industrial maintenance in various prototypes, which provide access to information, guidance in work procedures [13, 16, 27], and ways to record information [11]. Research by Platonov et al. [27] demonstrates a prototype of a monocular wide-angle camera AR setup with markerless tracking that was tested on BMW 7 series engine maintenance and showed robust and stable system behavior and successful task performance. An AR system for guiding technicians in aircraft maintenance, presented by Jo et al. [16], showed a decrease in preparation and repair time in comparison with implementing the task relying on paper-based manuals.

Nevertheless, existing research in maintenance-related AR has contributed to narrow use cases, thus, lacking in the generalization of content creation and adaptation [9]. The same applies to the field of technical communication, which conveys technical or specialized information and uses technology to communicate instructions [40]. Traditionally, technical information has been delivered on paper, as electronic prints, as embedded online help, or, more recently, through online portals or web services. However, very little has been done to create any guidelines for the use of new media and technologies, such as AR glasses, in technical communication [37]. A recent study [34] in an industrial setting demonstrated that existing, traditional technical documentation content does not work when viewed with AR glasses. The amount of text is generally too large, and the user is forced to scroll to find the needed information, which makes it difficult to comprehend the content. Furthermore, an adaptable delivery channel from the documentation system to the guidance application is required, as it is not feasible to tailor the content only for a specific device or task.

Other popular directions for industrial AR are in-field training [12, 39] and tele-assistance [24]. The main benefit of AR training over VR is the possibility to utilize virtual information overlaid on real equipment [12], enhancing the mapping between the training and the task [39]. The study by Gavish et al. [12] demonstrated a significant difference in performance, e.g., a reduced error rate for the participants trained with AR. Further, De Pace et al. [24] introduced two AR designs for collaborative MR tele-assistance where the trainer, being in VR, gives instructions to the trainee (in the form of abstract metaphors or as an avatar) working on real equipment with AR. AR is also seen as a viable tool to address safety in hazardous working environments through situation awareness and hazard identification. The benefits of AR in terms of safety have been shown in the field of construction [1, 19] and driving [31]. Yet, the potential of applying AR in maintenance to address the safety aspects is unexplored [6].

**VR as an Environment for AR Prototyping and Training**

Despite the benefits that AR technology can bring to industrial maintenance, the technology has not yet been widely applied in real-life contexts [10, 15]. The challenges of AR development have been divided into three areas: authoring (augmented content creation), context awareness (content adaptation to the environment), and interaction analysis (advancement of the interaction between the user and the system) [9]. One approach to address interaction analysis is prototyping AR solutions within a VR environment. This provides a safe and controlled way to test techniques and hardware with manipulation of factors such as field of view and image resolution [29]. For example, Alce et al. [3] introduced the Immersive Virtual AR method for prototyping wearable AR interaction and showed its potential in the industrial setting due to fast prototyping of several designs. Moreover, virtual prototyping benefits the existing industrial product development framework by enabling cooperative engineering in open and distributed environments with diverse data formats and content [30].

Considering rapidly increasing digitalization processes in the industry (the development of CAD models and structured technical documentation), establishing realistic VEs and data does not require extensive content production. Thus, integrating VR into the industrial development processes can actually reduce the development time and costs and increase the quality of operations [30] without additional efforts and resource usage. Further, AR prototyping in VR can be integrated into existing VR training environments, while testing could be performed together with the training of target users.

Training via VR brings significant value for the industry due to the extended adaptability and flexibility [4] with the possibility to provide standardized training worldwide for various skill levels within one system. Furthermore, in VR trainees can perform the practice tasks in a realistic manner (e.g., training physical memory or patterns of the task) without visiting the real environment. The use of VR in training ranges from non-immersive training platforms [4] to simulators [33] and HMD-based VR solutions [28]. For instance, Borsci et al. [38] found a significant increase in trainees’ acquisition of the procedural skills when training in a VE, meanwhile showing no significant difference between a fully immersive CAVE system and a simpler holographic 3D table. Further, Quevedo et al. [28] suggested a multi-layer scheme for the development of immersive, HMD-based, virtual training environments and demonstrated a comprehensive prototype that allows selecting different working environments and difficulties. In contrast, the study by Gavish et al. [12] showed no significant difference in performance between VR training and traditional training methods. They suggest that VR training may still be advantageous, and note, that the results are based on a small number of participants. All in all, there is still no clear understanding of how fully immersive training environments should be designed to benefit the training process.

**Gaze Tracking**

In addition to the information gap in terms of knowledge representation [9], there is also a gap regarding the integration of AR with other technologies and analytic tools [10], including gaze tracking. Gaze tracking is a traditional
tool in usability engineering and it is increasingly being applied to VR and AR [14, 26], as it is the most accurate method to investigate the allocation of visual attention. 3D gaze visualization has been studied by, for instance, Stellmach et al. [35] and Maurus et al. [22]. In particular, Stellmach et al. developed generalizations of existing 2D visualizations (heatmaps, scan paths, and timeline representations) into 3D space. Another motivation for increased gaze tracker adoption in HMDs is that it can facilitate foveated rendering for increased rendering performance in VR applications [25].

Gaze data have also been used to facilitate and measure learning. In 2002 [8], the gaze data of expert doctors were utilized to increase the performance of novice doctors in assessment strategies, while in 2012 [18] gaze data analysis demonstrated a significant difference in visual attention (gaze overlap) between expert and novice surgeons while watching a laparoscopic operation. This suggests that gaze data recordings are useful to gain insight into the learning of surgeon students. Other studies [5, 17] have utilized gaze data for user modelling, using classification models to predict high vs. low achievement based on gaze data, with a goal of providing online systems that could provide feedback also during the interaction, not only after the fact. Some studies have also used gaze tracking to improve safety, i.e., to measure the impact of safety warnings during driving [2] or to improve process safety while dealing with hazardous materials [32].

XR SAFETY KIT: SYSTEM DESCRIPTION

We designed the xR Safety Kit framework, a multipurpose VR system, which allows performing maintenance tasks in virtual environments (wearing an HMD and using hand controllers) for training as well as for AR content development and testing. The system was made with the Unity game engine and the existing 3D CAD model of an elevator shaft. The virtual elevator shaft contains equipment and tools relevant to the current task, as seen in Figure 2, top. The virtual objects detect collisions with tools, animate, and play sounds at appropriate moments to give information on the progress of the task. The system also stores the user’s gaze data, object positions, and task progress. User activities can be played back with gaze data visualizations (scan path and heatmap over the interaction environment).

The system assists the user in performing a maintenance task with instructions, extracted from existing XML-based maintenance instructions currently used by the technicians in paper format. As an exemplary task, the users of the system are to perform the Remove and Replace Tension Weight maintenance task in VR the same way they would do it in real-world settings: The users read the instructions, select and use the correct tool on the correct spot in the tension weight assembly and repeat these steps until they have completed the disassembly phase. After replacing the tension weight, the users perform the assembly, which consists of the same steps as the disassembly, in reverse order.

The distinctive feature of our VR-based system is the simulated AR mode. Simulating AR within the VR system has two major purposes: Firstly, it allows evaluating AR features, in-field guidance and safety awareness, in a safe and controlled environment. Second, it allows the testing of different hardware aspects of AR presentation. These include field of view (FoV), image quality, colors and transparency of objects, fonts of the AR display, and AR tracking precision. The system simulates AR glasses’ FoV by displaying AR content over a rectangular area. In our evaluations, we used a FoV of 40° horizontally and 27.5° vertically, centered to the user’s field of view, as it is in the range of the currently available commercial AR solutions. The edges of the FoV are feathered to avoid visual discomfort. Optical distortions that may be caused by AR glasses were not simulated.

To sum up, the system can be potentially used for several purposes: It enables 1) maintenance method training for unexperienced technicians in realistic, yet safe settings via step-by-step task guidance, and 2) risk identification, safety training and certification via gaze tracking, and user activity analysis. The logged data and the system can be further utilized for 3) maintenance methods development and testing, 4) documentation development and testing, and 5) AR content development and evaluation of, e.g., multimodal interaction techniques for in-field technologies and adaptation to the industrial context of use.

In-field Guidance: DocPanel Tool

As a metaphor to classic paper instructions, we created a documentation panel tool, the DocPanel, for step-by-step task guidance. The DocPanel visualizes instructions in the form of text, pictures, and animations over a white square (Figure 2, bottom). The user can move the panel in the 3D space and center it to eye-position. The panel position is parented to the user’s head location, but its orientation is
fixed to the world orientation. This allows the user to find the panel always in the same direction and supports information retrieval with a glance as the DocPanel can be located in a comfortable spot for each working position. In addition, when the user progresses with the maintenance task, the VR system highlights the tools and equipment that are required during the current step, as seen in Figure 2, bottom.

**Safety Awareness: Multimodal Safety Warnings**

We designed three *multimodal warning types* to inform the user about possible hazards in the elevator shaft context:

1. **Textual Safety Notification** is used to present task-related hazards, e.g., heavy equipment parts. It contains text and a static icon to explain the risk displayed over the relevant object at relevant steps during the task.

2. **Animated Safety Warning** is used to indicate environment-related risks and is shown in the form of an animated icon when the user is at risk to interfere with, e.g., by touching, dangerous elements. The icon remains visible for 1 second over the dangerous area after the user has moved their hand away. In case the area is out of the user’s FoV, the system plays an audible beep and displays a red arrow pointing toward the risk area. See Figure 1 for an example.

3. **Audio and Visual Safety Warning** utilizes both voice warning and an icon to warn of an environment-related risk when a visual icon alone is not enough to explain the danger. If the hazard is out of the user’s FoV, a red arrow and voice warning are used to communicate the danger.

**METHODOLOGY**

In order to investigate the feasibility of our system in terms of VR for training and AR within VR, we carried out three development-evaluation iteration rounds in a realistic industrial context with expert participants from an elevator company. Utilizing experts was vital in our industry-focused study, as the needs and challenges of systems designed for industrial maintenance are different from other systems. We also collected attitudes and thoughts from another set of experts with a survey utilizing, e.g., gaze data collected in the user evaluations. Next, we describe our evaluation and development activities.

**Iterative User Study**

The first iteration was carried out to verify the concept and collect ideas and requirements to proceed further with the system development. At this stage, the virtual environment represented the elevator shaft with equipment and the DocPanel tool; however, it did not support maintenance task guidance. Four expert participants explored the designed VE without defined instructions and afterward answered three interview questions. The collected data provided us with directions for design decisions on, e.g., the DocPanel tool interactions and font size, safety warning locations, and sizes and textures of 3D models.

The 2nd iteration was focused on investigating the usability and efficiency of the in-field AR guidance and warnings in general. Modified after the first iteration, the system now allowed users to proceed with a maintenance task fully, displaying a safety warning of electric shock hazard in the form of a static picture. The outcomes of this stage resulted in fixing minor usability issues, designing the highlight of maintenance tools and equipment parts to increase the effect of guidance, and the deployment of three types of safety warnings. In addition, the need for advanced logging of the 3D objects and gaze tracking was identified.

In the 3rd iteration, the system design corresponded to the description in the previous chapter. The focus of this evaluation iteration was on safety aspects: e.g., the evaluation of the designed safety warnings and further exploration of the DocPanel tool’s efficiency with gaze data.

Next, we provide a more detailed description of the second and third iterations’ evaluations, which were similar in methods and procedures.

**Participants**

Five male experts from the elevator company took part in the 2nd iteration evaluation and four male experts in the 3rd iteration. Two of the participants had no experience in elevator maintenance but were specialized in information architecture related to it. The rest had at least 2.5 years of elevator maintenance experience (M = 15) and at the time of the evaluation, some were working in the office on different positions (R&D, Reliability, Field Trainer, Method Development, etc.). Six of the participants had tried both AR and VR technologies before the evaluation, two had heard about them while one had no prior experience.

**Collected data**

We collected both objective and subjective data in the two latter iterations. Subjective data were collected via a digital questionnaire and a semi-structured interview. The questionnaire consisted of six parts: 1) background information, 2) system effectiveness, 3) usability and user satisfaction, 4) AR guidance tool, 5) safety aspects, and 6) VR-related questions. Due to the focus on safety, in the 3rd iteration, we utilized also paper questionnaires for each safety warning type. The interview questions were designed to gain deeper insight into the framework in the industrial context on the same aspects as the digital questionnaire.

Collected objective data consisted of gaze and user behavior data, i.e., the orientations and positions of the HMD, hand controllers, and virtual objects, and the use of buttons. Data on the DocPanel usage was collected during both iterations (n = 9), while data on safety warnings were gathered only from the 3rd iteration (n3 = 4). The eye tracker sampling rate was 120 Hz and behavior data were logged once per frame. The gaze vectors from the eye tracker were converted into gaze points by taking the normalized sum of the direction vectors from the left and right eye and performing a ray cast to the closest surface in the virtual world. Only samples marked valid for both eyes by the manufacturer’s software were included. The mean percentage of valid samples out of
all samples per user was 96.1% (min = 93.2%, max = 98.5%). Invalid samples may happen as a result of blinking or if the HMD moves too far on the user’s face, causing one or both eyes to go outside the detection window of the eye tracker. The gaze points were further processed into fixations using a sliding window of 200 ms [20]. By default, a new fixation was created if all the gaze points inside this window were a maximum of 10 cm away from the average for the window. However, if the distance from the potential new fixation to the previous fixation was under 5 cm, a fixation was not created. We consider it acceptable to use the fixed thresholds of 10cm and 5cm because the distance from the fixation points to the user is limited inside our elevator shaft model. These criteria for defining a fixation were also used for creating the scan path gaze visualizations for our domain expert survey.

Procedure
The evaluation sessions in both iterations took place in a spacious meeting room, in the premises of the company where the experts worked. We used HTC Vive HMD with an integrated Tobii 120Hz eye tracker and Vive controllers for the study. The view the participants saw via the HMD was mirrored on a screen, so the moderators could see the process and assist if needed. First, the moderator presented the study objectives and described the study shortly. Next, the participant practiced using the controllers and learned the functionalities in a training session. After that, the scenario was presented, gaze-tracking calibration was performed, and the participant started to perform the maintenance task following the guidance provided by the system. After completing the task, the participant filled in the online questionnaire about their experiences and answered the interview questions. The procedure was audio-recorded with the participant’s written consent.

Survey on AR, VR, and Gaze Tracking Feasibility
The main goal of the survey was to gather expert opinions on the usefulness of the AR within VR approach and gaze tracking in the context of industrial maintenance. The digital survey was created with an in-house tool; the link was shared with the experts in different departments of the elevator company. The survey consisted of three parts and included videos, open-ended questions, and altogether 29 statements answered on a 5-point Likert scale with extremes of Totally disagree (1) and Totally agree (5). An electronic consent to participate was collected at the beginning of the survey.

The survey firstly introduced the designed system’s functionality with a demo video and textual description as well as defined the terminology used in the statements. The first part of the survey collected data related to the AR simulation, training, in-field guidance, safety aspects, and technical documentation development. Prior to the questions, a video demonstrating the maintenance task in VR from the user’s point of view was shown. The second part of the survey collected data related to the potential of gaze tracking for the industry; a video with gaze tracking data visualizations was shown before the questions. The video used the scan path visualization of gaze data we implemented (similar to [36]) with arrows indicating the order of fixations. The final part of the survey gathered respondents’ background information including age, gender, areas of expertise, and previous experience with VR and AR technologies.

Respondents
Twelve experts (10 male, 2 female), aged from 37 to 59 (M = 49.5) filled in the survey. The respondents were proficient on at least, but not limited to, one of the following areas of expertise: 50% of the experts were proficient in Safety and/or Training, 41% in Maintenance and/or Technical Documentation, and 33% were proficient in XR use cases. Most of the respondents (83%) had used VR technology a couple of times at most before filling in the survey, one respondent had used it a lot, and one had only heard/read about it. Similarly, 75% of the participants had used AR technologies a couple of times at most; two participants (17%) had used them many times and one had heard/read about it. Ten participants (83%) reported that they were glad to use digital devices as a part of their daily life, while two (17%) considered themselves to be even among the first ones to try out new digital devices or services.

RESULTS
This chapter presents the results of our three-round iterative study, including participants’ performance and behavior metrics, and user experiences, followed by combined objective and subjective results on the DocPanel usage and safety warnings. Finally, we present the results from the expert survey on AR, VR, and gaze tracking feasibility.

Iterative User Study Results
The xR Safety Kit framework was perceived as a viable and promising innovation for the industrial context. The participants showed eagerness about the possibilities of working with both AR and VR technologies in their daily routines and further ideated on how such technologies could be integrated into the company’s processes. The participants pointed out that the VR environment coupled with gaze data “would be useful for testing new maintenance methods” (P1), “would be a good way to test out documentation” (P2), and “can be used for risk assessing” (P3).

All the participants in both iterations successfully finished the maintenance task. On average, the session (the overall time the participants were wearing HMD excluding training) took 13.1 minutes (min = 5.5; max = 20.8) during the 2nd iteration and 11.1 minutes (min = 7.5, max = 14.7) during the 3rd iteration. The participants spent 35.4% of the session reading instructions (min = 14.6%, max = 63.8%); the large variation is explained by the participants’ different backgrounds and different requirements for system assistance. As the logged data from the 3rd iteration were more detailed, we separately analyzed the time spent for disassembly and reassembly, excluding the equivalent first and last subtasks (3.6 minutes and 0.3 minutes on average,
respectivey), as some of the participants spent extra time observing the environment at the beginning of the session. The disassembly took on average 3.0 minutes ($\text{min} = 1.7, \text{max} = 5.8$), from which 27% of the time participants were reading instructions, while reassembly took on average 2.2 minutes ($\text{min} = 1.5, \text{max} = 2.8$), from which 19.3% of the time was reading instructions. The participants in the third iteration navigated backward in the DocPanel 8 times on average ($\text{min} = 3, \text{max} = 15$); the maximum number comes from a participant who browsed through all the steps in the DocPanel before starting the task.

Figure 3 represents the combined questionnaire results from the second and third iteration rounds. It illustrates the participants’ more positive experiences in the third iteration due to the usability improvements and system modifications made after the second iteration. All the participants ($n_2 = 5, n_3 = 4$) found the system to be easy to use ($\text{Mdn}_2 = 6; \text{Mdn}_3 = 5.5$ out of 7). Eight participants (89%) would like to use this system frequently in the work context ($\text{Mdn}_2 = 5; \text{Mdn}_3 = 6$) and felt confident while using it ($\text{Mdn}_2 = 5; \text{Mdn}_3 = 6$). Further, eight participants (89%) agreed that VR motivated them to perform the task ($\text{Mdn}_2 = 5; \text{Mdn}_3 = 6$) and, similarly, eight participants (89%) found it easy to map the VR objects to objects in the real world ($\text{Mdn}_2 = \text{Mdn}_3 = 6$). Besides, all of the participants showed a positive attitude toward the idea of utilizing VR for training purposes, saying, “It’s much more powerful way to make people really remember” (P4) and “the huge benefit is it is a safe environment to practice instead of going at the field area” (P1). In both iterations, the participants agreed that using a VE is a practical way to simulate elevator maintenance tasks ($\text{Mdn}_2 = 5; \text{Mdn}_3 = 6.5$) and this VE would be useful for inexperienced maintenance technicians ($\text{Mdn}_2 = 6; \text{Mdn}_3 = 6.5$).

In-field Guidance and DocPanel tool
The majority of the participants showed enthusiasm toward the idea of utilizing a head-mounted AR display for in-field assistance. One of them said, “The direction is very good. I support it 100%” (P5). The main advantage of this was seen in easier access to information (P3): “The system would affect the working process in a positive way, because the maintenance workers can have the instructions right away.” Also, the information presentation was appreciated (P6): “I liked these animations, it’s much better compared to paper instructions what we have today.” The DocPanel tool was found to be useful for the maintenance context ($\text{Mdn}_2 = \text{Mdn}_3 = 6$) and easy to use ($\text{Mdn}_2 = 5; \text{Mdn}_3 = 6$). The participants liked the functionality to move and place the panel anywhere in the 3D space ($\text{Mdn}_2 = 6; \text{Mdn}_3 = 7$) and center it to eye position ($\text{Mdn}_2 = 5; \text{Mdn}_3 = 6$). However, some of the participants demonstrated mistrust of the current state of the technology and fear of wearing an AR headset, which limits the visibility, in the context of an elevator shaft. Two participants (22%) disagreed that AR headsets are safe to use in maintenance task contexts.

The participants were able to read the instructions from the DocPanel without directly facing it: On average, the gaze vector angle relative to the HMD was over 7 degrees ($M = 7.45^\circ, Q1 = 4.14^\circ, Q3 = 8.87^\circ$), while the interquartile range ($Q3–Q1 = 4.73^\circ$) demonstrates the variability in gaze angle to HMD when reading the panel. Figure 4 illustrates how the participants chose to position the DocPanel relative to their head. The participants preferred to place the DocPanel in front or to the left of the work area, below their head position so the instructions could be seen without turning one’s head. A possible contributing factor is that the default position of the DocPanel was in the negative $x$-direction. We sampled 10,000 DocPanel positions from each participant (training phase excluded) for the histogram, spread evenly over the session. The color of each cell indicates how commonly the position was chosen for DocPanel placement.
Safety Warnings

Since the three warnings were added after the 2nd iteration, these results concern only the 3rd iteration round with four participants. All participants verified the need for in-field safety warnings. Two participants noticed all three warning types and two participants noticed two warnings: textual safety notification and audio and visual safety warning. All participants found the warnings to be self-explanatory, easy to understand (Mdn = 6), and helpful to identify dangerous places in the working space (Mdn = 6). One of the participants commented: “I liked it in a way that it really wakes you up. If I don’t immediately see or recognize it, then the voice ... it’s like a waking up call” (P4). Further, participants agreed that similar warnings can prevent accidents in a working environment (Mdn = 6) and would like to be warned this way in a work context (Mdn = 6.5).

None of the participants found the warnings to be annoying or destructive, commenting: “It was not annoying because it was there exactly where it should be” (P7).

Nevertheless, the preferences in visualization methods and modalities were diverse. For every designed warning the participants preferred different visualization approaches or modalities, e.g., one participant commented that only visual warning in the form of a static picture would be enough to inform about the dangerous area, while another suggested using text, voice, and blinking to attract attention.

We also calculated the number of fixations for textual safety notification (e.g., heavy object warning) and animated safety warning (electric shock warning). Visual attention patterns were not considered in the case of Audio and Visual Safety Warning, because the voice warning component alone was descriptive enough for the participants to understand its meaning. We consider the participants to have observed the warning if there was at least one fixation on the warning while it was shown to them.

The electric shock warning was observed 4 (min = 0, max = 3 per session) out of the 22 times it was shown in total (min = 1, max = 9 per session). 2 out of 4 participants did not observe the electric shock warnings at all, although it should be noted that the warning also got less frequently activated in the first place as a result of these participants’ behavior. This indicates that the electric shock warning was unsuccessful in deterring the participants from touching the area. This may be because the warning often appeared outside the simulated AR field of view as it was statically positioned to indicate the location of the dangerous area. To guide the user’s attention to warning icons placed outside the AR FoV, the system played a warning sound and displayed a small red arrow pointing in the direction of the warning icon whenever it was outside the simulated AR field of view. This sound, however, may have had the opposite effect of encouraging the participants to interact with the dangerous area, and the arrow may have been too small to strongly guide the user’s attention.

The heavy object warning was observed 7 times out of the 8 times it was shown in total (2 times per session). Based on the gaze data, it can, therefore, be argued that the larger heavy object warning with static icon and text was mostly successful in alerting the participants, while the smaller electric shock warning with an animated icon and sound was mostly unsuccessful.

Survey on AR, VR, and Gaze Tracking Feasibility

The survey filled by the 12 experts from the elevator industry verified the usefulness of gaze tracking, VR, and AR simulation within VR and pointed to related challenges. More than half of the respondents (67%) found the opportunity to analyze where the user pays attention in the VR environment to be important (Mdn = 4 out of 5). In addition, 75% of the respondents agreed that the visualizations produced from the users’ visual attention are useful in training (Mdn = 4) while analyzing gaze data visualizations by expert maintenance trainers could be utilized to improve also the traditional training methods (Mdn = 4). Tracking users’ movements and visual attention was found to be efficient to determine the best suitable multimodal combinations and designs for safety warnings (Mdn = 4; 67% totally or somewhat agreed) and the best locations and visualization techniques for visual safety warnings (Mdn = 4; 75% totally or somewhat agreed). One of the respondents
commented, that gaze tracking is useful to "check the optimal locations where to display information" (R1). Most of the respondents (83%) agreed that the possibility of gaze tracking to investigate how much the documentation is utilized during work and which parts of it draw the users' attention is important, while 17% somewhat disagreed. The respondents also verified that testing existing technical documentation in VR simulation would help to improve the documentation (Mdn = 4, 83% agreed); one of them commented that gaze tracking should also be used "to ensure that user does not skip any content when following instructions" (R2). However, 42% of the respondents somewhat or totally agreed, while 17% somewhat disagreed, that real-time gaze tracking and gaze visualizations would be beneficial for guiding maintenance technician trainees. One of the respondents shared their concern, saying "the person who is analyzing the gaze tracking must be extremely well trained so that he/she can understand which eye movement is unnecessary" (R3).

All the respondents perceived VR with AR simulation as a practical (Mdn = 5, n = 11) and safe (Mdn = 5) environment to design and test AR solutions, that may boost the development of AR solutions in industrial settings (Mdn = 4, n = 11). The respondents commented that AR simulations' "role and importance will increase in the future" (R4) as this environment "can be used to test radically different ideas without, for example, safety concerns or limitations by the real environment" (R1). Further, 55% totally agreed, and 36% somewhat agreed, that utilizing both AR and VR technologies in training would increase the overall quality of training (Mdn = 5, n = 11). All respondents totally or somewhat agreed that complementing traditional training methods with AR would make the training more efficient overall (Mdn = 4, n = 11). Meanwhile, 82% of the respondents totally or somewhat agreed that trainees would learn the maintenance tasks faster with VR simulation compared to the traditional training methods (Mdn = 4, n = 11) and 91% totally or somewhat agreed that trainees would be more ready to perceive the traditional training if familiarized with VR simulations first (Mdn = 4, n = 11). The respondents found VR with AR simulation to be a suitable environment to test various designs and multimodal combinations for in-field safety warnings (Mdn = 4, 92% agreed somewhat or totally). Moreover, they also found the environment to be suitable to determine the best safety warnings (Mdn = 4, 75% totally or somewhat agreed) and the best locations and visualization techniques for visual safety warnings (Mdn = 4, 83% totally or somewhat agreed).

**Summary of the results**

In summary, the results of both iterative studies and the survey showed a positive perception of, and eagerness in, utilizing AR/VR technologies and gaze tracking by the domain experts for multiple purposes. The AR within VR was found to be efficient and, most importantly, a safe approach for industrial AR prototyping, while HMD-integrated gaze tracking is seen as a viable analytic tool for AR content testing. Gaze data analysis also illustrates the strategies for identifying the value of the designed solution, e.g., the success of the DocPanel tool and the failure of the animated safety warning. Further, gaze tracking was found to be useful in the development of training procedures and technical documentation.

Finally, our results indicate the potential of utilizing a virtual environment for other companies’ processes to accommodate efficient collaboration and resource sharing between different departments.

**DISCUSSION**

In this study, we explored the capabilities of VR coupled with gaze data to address AR content development and testing. We deployed the xr Safety Kit framework and tested AR features (in-field guidance and safety warnings) in a realistic industrial evaluation process with experts from the elevator industry. In addition, we utilized resulting materials to elicit feedback from another group of domain experts on the use of such technologies in the industry.

Based on the collected expert opinions, we identified the need, desire, and benefits in utilizing AR, VR, and gaze data in the context of industrial maintenance. The industry requires well-designed assistive AR solutions, which reduce risks by providing guidance to technicians and increase safety awareness in hazardous working environments. All expert participants confirmed the necessity to replace the existing paper-based manuals with an AR-based solution that would not require any hand manipulations while performing the tasks. What is more, the industry requires flexible and safe ways to develop such solutions. While AR technology is currently unsuitable for the context, as wearing heavy head-mounted displays that limit the user’s view is unsafe, e.g., the authoring and interaction analysis of assistive AR tools for the industry can, and should, be done already now.

Our study demonstrates the relevance and success of utilizing VR with gaze tracking to prototype and evaluate AR content. The conducted iterative study shows an example of how the xr Safety Kit framework can be applied for safe, efficient, and fast industrial AR development with a small number of users. Integrated gaze tracking brings an advantage to gathering detailed and objective data for further analysis, which could not be gathered via traditional user study methods, such as interviews or questionnaires. For instance, gaze data helped us to identify that the designed animated safety warnings were unnoticeable by most of the participants. While subjective results indicated that animated safety warning was noticed by 50% of participants due to wrongly selected visualization technique (e.g., too small animation and arrow, improper placing), gaze data analysis exposed that the participants fixated their gaze at the warning in only 18% of cases, clearly demonstrating the failure in the design of the warning.

Similarly, gaze data were useful to evaluate the technical documentation presentation by providing information on
reading behavior and positioning in 3D space. We identified that the DocPanel tool is a good maintenance solution with comprehensive functionality. The participants utilized the option to place the information in the position they preferred, and analysis showed that this place is mostly to the left or in front of the working area and below head level. This enabled participants to glance at the instructions without much effort. Subjective feedback indicates that the participants found the design efficient and valuable. However, we identified the need to redesign the existing XML instructions to fit the AR visualization capabilities, e.g., emphasize the use of 2D and 3D schemas, pictures and animated instructions with appropriate color-coding to decrease reading time and minimize eye strain. To increase the assistive effectiveness, the DocPanel should also visualize the tools required for the task and related to the task dangers.

In addition, we have formulated suggestions related to the design for safety in the industrial context, which may be generalized for other use cases. We found that novice technicians require more attention grabbers and interaction with the warnings, while experienced technicians found the extensive notifications irrelevant, focusing on task performance and productivity. Hence, multiple levels of awareness are recommended to support technicians of different expertise, e.g., variations of modalities, visualization techniques, levels of instructiveness, times of displaying, and sizes of the warnings. Different levels of awareness may be also considered for communicating repeating risk. Further, the safety indicator (e.g., visualization of the level of associated risk) is another way to inform the users about possible dangers, related to the task or environment. It can either be visualized on the DocPanel or constantly displayed in the user’s field of view. Lastly, AR solutions for an industrial context should support cooperative work, e.g., by tracking the progress of two technicians working in separate spaces as well as integrated guidance in case of an emergency.

Our study demonstrates the usefulness and efficiency of AR development and testing within VR while utilizing gaze tracking. Such an approach was found to be suitable in the industrial context due to three main aspects: flexibility, safety, and advanced analytics. It allows quick and resource-efficient iterative development processes with both the target users (maintenance technicians) and other specialists involved in the decision-making and development process. In addition, our study uncovered the potential of utilizing the MR continuum to address other industrial processes and enable collaboration between different departments, which should be further explored.

Limitations and Future Work
A limitation of this study is the focus on elevator maintenance. The expert participants were sharing their opinions on the usefulness of the MR continuum based on experience in this field and the existence of CAD models and structure of technical documentation in their company. Although our findings are applicable for similar industrial contexts, future work can explore how the technologies are perceived on, and what benefits they bring, to other fields to determine common patterns. Utilizing both AR and VR in the industrial context is promising. However, identifying the requirements for such platforms that provide smooth collaboration and content creation within the VE requires further research.

The gaze data analysis requires adaptation and further development. Fixations can demonstrate only gaze landing at objects, and thus, may cause misinterpretation of results in terms of safety awareness. Considering the complexity of human vision, objects can be noticed without a direct focus. Thus, future work may concentrate on exploring in what circumstances (e.g., direction of the gaze path, design of the content itself, duration, and sizing) the augmented content is noticed and how the system can record this without a direct fixation. On a larger scale, in order to utilize gaze data efficiently in terms of time and resources, automated analysis methods should be developed. With the growth of machine learning, a viable direction for research, and practice, would be to automate the analysis process for both training and AR prototyping.

CONCLUSIONS
In conclusion, our industry-focused study demonstrates the potential of adopting virtual environments coupled with gaze tracking for AR prototyping. Assistive AR solutions are highly demanded in the industry, as they can support workers in their tasks and, hence, increase the safety and efficiency of work processes. Further, there is a need for flexible and resource-efficient ways to test AR solutions in a safe environment before deploying them in a hazardous, real-world industrial context. This study showed that VR and gaze tracking are a valuable combination to address safe and efficient AR development. Gaze tracking provides advanced metrics for detailed analysis of AR element usage, while VR is a safe and flexible testing environment, which enables fast iteration of AR solutions as well as the simulation of various aspects of see-through HMDs (e.g., FoV, tracking quality, image quality, and other related aspects). What is more, the deployment of such VR platforms is becoming easier due to the growth of digitalization and the availability of relevant materials (e.g., design models, documentation, and enterprise information system data) in digital format.

Finally, our paper indicates that the utilization of the MR continuum in industrial processes, especially blending various tasks under one comprehensive system, may be advantageous and should be further explored in terms of cooperation, training, and documentation and methods development.

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[34] Sanni Siltanen and Hanna Heinonen. 2020. Scalable and responsive information for industrial maintenance work – developing XR support on smart glasses for maintenance technicians. 10. https://doi.org/10.1145/3377290.3377296


[38] X. Wang, S. K. Ong, and A. Y. C. Nee. 2016. Multi-modal augmented-reality assembly guidance based on
bare-hand interface. *Advanced Engineering Informatics*
https://doi.org/10.1016/j.aei.2016.05.004


Paper II

ABSTRACT
Collaborative academia-industry development and evaluation of virtual reality (VR) systems is a mutually beneficial opportunity to investigate VR technology in a real context and conduct user studies with target users. However, such collaboration is rarely performed due to variations in project pace and work methods. In this article, we introduce the process of action research on joint design, development, and evaluation of a collaborative VR system to address industrial needs. The paper further presents employees’ subjective opinions and perceived value of industrial VR applications and reflects on their involvement throughout the process. The article concludes with a process-oriented framework for remote academia-industry collaboration, supported with practical suggestions on how to support this collaboration. Our experiences reveal the methods and advantages of remote collaboration in all phases of the process and signify the efficiency of the remote framework for academia-industry collaboration, especially relevant in the light of the COVID-19 pandemic.
Toward Efficient Academia-Industry Collaboration: A Case Study of Joint VR System Development

Alisa Burova¹, Hanna Heinonen², Paulina Becerril Palma², Tuuli Keskinen¹, Jaakko Hakulinen¹, Viveka Opas², John Måkelä³, Kimmo Ronkainen³, Sanni Siltanen², Roope Raisamo¹, Markku Turunen¹

¹ Tampere University, Tampere, Finland
{alissa.burova, tuuli.keskinen, jaakko.hakulinen, john.makela, kimmo.ronkainen, Roope.raisamo, markku.turunen}@tuni.fi
² KONE Corporation, Hyvinkää, Finland
{hanna.heinonen, paulina.becerrilpalma, viveka.opas, sanni.siltanen}@kone.com

ABSTRACT
Collaborative academia-industry development and evaluation of virtual reality (VR) systems is a mutually beneficial opportunity to investigate VR technology in a real context and conduct user studies with target users. However, such collaboration is rarely performed due to variations in project pace and work methods. In this article, we introduce the process of action research on joint design, development, and evaluation of a collaborative VR system to address industrial needs. The paper further presents employees’ subjective opinions and perceived value of industrial VR applications and reflects on their involvement throughout the process. The article concludes with a process-oriented framework for remote academia-industry collaboration, supported with practical suggestions on how to support this collaboration. Our experiences reveal the methods and advantages of remote collaboration in all phases of the process and signify the efficiency of the remote framework for academia-industry collaboration, especially relevant in the light of the COVID-19 pandemic.

CCS CONCEPTS
• Software and its engineering ~ Software creation and management ~ Collaboration in software development
• Human-centered computing ~ Human-computer interaction (HCI) ~ HCI design and evaluation methods ~ User studies

KEYWORDS

1 Introduction
With the growing capabilities and availability of virtual reality (VR) technologies, both academia and the manufacturing industry are investigating their potential and applications. The industries are striving to take a leading role in adopting the technologies into everyday use due to the potential of enhancing their working processes and overall efficiency while decreasing costs [23]. One of the major industrial use cases is using VR for remote collaboration and communication when performing design, development, and service-related activities in the field of manufacturing and construction [18, 23]. Industrial teams located across different countries require flexible tools for remote collaboration with rich ways of information representation and sharing.

In this case study, VR is approached from the perspective of the documentation creation process, based on iterative collaboration with multiple departments. Traditionally, for maintenance methods and documentation creation, the interpretation of the products’ 3D model has been conveyed via 2D screens, which may cause misunderstandings, such as scaling or spatial errors in the creation process (e.g., if certain parts in the product are not reachable). Such errors can cause product or documentation design flaws: For example, a situation where a maintenance technician’s hand or tool does not fit where it should when performing the task. VR, apart from introducing enhanced remote collaboration opportunities [5, 8], can be also applied to enrich visualization capabilities and simulate interactions with real objects to overcome the challenges mentioned above [1, 14, 30]. In addition, previous work has demonstrated a need and desire to utilize innovative technologies to increase employees’ motivation and overall company’s performance [7, 19]. The
topic of remote collaboration in VR became especially important in the light of the COVID-19 pandemic when in-person meetings have been restricted for safety reasons even for teams from one location, causing barriers for efficient communication.

To successfully and meaningfully implement VR technologies to support the industrial working processes in a cost-efficient manner, extensive research should be performed to identify users’ needs and contexts, system requirements and iteratively verify corresponding design solutions. Hence, industries can greatly benefit from collaboration with academia, whose knowledge expertise and research methods would ensure the validity and relevance of resulting designed solutions. Thus, the involvement of academia, despite possibly a slower work pace and more abstract goals [6], may decrease the overall duration and costs of a software development project [17].

The traditional model, where academia deploys prototypes and generates the knowledge as an outcome of user studies with these prototypes, and industry utilizes these afterwards, does not work efficiently in the vastly developing and changing world. Furthermore, traditional academic research, which is more focused on studying separate aspects, such as ergonomics and interactions, may not fulfill the industrial needs, and as a result, deliver irrelevant and ungeneralizable results due to a lack of access to target user groups and contexts. Academia, in turn, benefits from collaboration with industry by being exposed to real industrial needs and target users. [29] Hence, the collaboration between academia and industry is of undeniable value to both parties. Nevertheless, such collaboration often faces multiple challenges due to differences in working methods, goals, and time horizons [11, 24] and is, therefore, rarely performed [2]. To overcome these challenges and drive innovation development, there is a need for clear processes and methods to accommodate smooth and efficient collaboration between academia and industry.

This article presents the work done within the HUMOR project. The project provided an opportunity for academia and industry to work together to solve common issues, which resulted in open and efficient knowledge sharing and transfer. The two collaborating partners were a group of human-technology interaction researchers from academia and a group of research & development professionals from the manufacturing industry and industrial maintenance company. Based on the challenges of academia-industry collaboration mentioned above, our motivation for this article is to share our practices and demonstrate the benefits of such collaboration. Hence, we aim to answer the following research questions:

RQ1: What are suitable methods and processes to enhance remote academia-industry collaboration?

RQ2: What are the benefits of a joint academia-industry development process in the case of a VR system?

To address the research questions, we defined two research objectives. Firstly, we aimed to apply user-centered design and agile methods [10] to the design and development of the VR system and base the collaborative activities on involving relevant stakeholders to the decision-making process. Next, we planned to include expert employees from the industry to the development and evaluation process and measure their perception of the system design and its effectiveness for the company’s needs in an iterative manner.

In summary, this article demonstrates a collaboration between an academic and an industrial partner (KONE) to design, implement, and evaluate a collaborative virtual environment (CVE). The resulting system, called COVE-VR, was created to enable efficient department-to-department collaboration in the pipeline of service-related work – even between teams and people located in different places. Due to the COVID-19 pandemic, the development collaboration was shifted to happen remotely, which caused changes to the planned activities and the adoption of remote practices and methods. The performed work indicates the potential of executing remote collaboration processes: They can unite academics and industrial practitioners from around the globe to work jointly on a common task with mutual benefits for both sides.

The main contribution of this article is a framework of remote academia-industry collaboration, shown in Figure 1. It can be generalized to other use cases to build trust, shared understanding of research goals, and established time horizons, thus addressing the major barriers of academia-industry collaboration. The framework is further supported by a list of practical suggestions to ensure that the collaboration process is efficient and beneficial for both parties. Our evaluation results show that the company’s employees think very positively about integrating VR technologies into their working tasks and see value in it. These findings support the efficiency of the suggested framework: Through the joint efforts academia and industry accomplished their shared goal and delivered the software that caters to the needs of the target user group.

2 Related Work

This section presents two major topics of the article starting from the aspects of academia-industry collaboration and followed by a background to collaborative virtual environments (CVE), reflected from the industrial perspective.

2.1 Academia-Industry Collaboration

Academia-industry collaboration holds the potential to drive innovation and wealth creation [2, 4], especially in the fields of Human-Computer Interaction (HCI) and Software Engineering (SE). The knowledge and experience sharing between academia and industry addresses the lack of relevance in research by merging the actual industrial needs with research goals and scientific knowledge while utilizing
2.2 Industrial VR and CVEs

Due to increased adaptability and flexibility, VR offers an endless spectrum of possibilities when it comes to addressing industrial needs [7, 9, 23, 27, 30]. Industry aims for more efficient processes in product design and work method development, as well as overall shorter times to market including training the personnel about the product. One of the solutions to save time and resources, while optimizing the development and management processes, is to enable efficient remote collaboration in VR [18, 23]. Benefits are likely since remote development work via traditional conferencing tools can leave plenty of room for interpretation and cause misunderstandings. Virtual worlds, in turn, have proved to be a suitable collaborative environment for designers to support conceptual design activities due to enhanced communication, awareness, and the availability of virtual tools [15, 26].

Collaborative virtual environments (CVE), defined as virtual worlds shared over a network [16], provide solutions to several challenges in global collaboration in industrial settings [5, 8, 15]. CVEs may support synchronous and asynchronous remote collaboration while enabling flexibility in the visualization of shared data [8]. They may further enhance remote collaboration, experience and knowledge sharing [20] via increased immersion and realistic multisensory object manipulation with collision detection [1, 14]. Besides, due to a positive perception of VR technologies, collaboration within VE may advance employees’ motivation as well as the overall company performance [7, 19]. In concrete terms, CVEs can enhance the communication in the development process by providing access to 3D models, e.g., in virtual reality to all the relevant people and having them see what other parties are referring to. An example from the manufacturing field [30] presented a multimodal VR tool for design reviews and demonstrated that such a system can facilitate communication between assembly operators and engineers. In addition, such a VR system further enables validation of installation processes and simulation of testing and maintenance tasks.

Product development in CVEs can also enable the involvement of other departments in an earlier phase of the process, thus contributing positively to the time to market [23]. Creating a tool for enhancing the development process and including all relevant teams to collaborate has long been among the goals of the industry. Virtual reality caters partly for all these needs. Despite all the benefits, the implementation of VR technologies to the industry is still limited due to lack of time and specific knowledge or VR experts in addition to methodological flaws, such as discrepancies between industrial needs and the final solution and a rare utilization of target users (company employees) [27]. Hence, to reach the best possible outcomes in VR development, industry and academia should unite their forces and work in tight and open collaboration, whereas user-centered design and agile methods may be applied to coordinate the collaboration [10, 11, 22].

3 Academia-Industry Collaboration Process

The development process was structured by adopting a user-centered design model to the industrial context and involving various focus groups. One academic and three industrial groups, defined in Figure 1, participated in the whole processes.
The academia was represented by a team of multidisciplinary researchers, including VR developers, user experience and visual designers. The industrial partners (the manufacturing company with a strong focus on the maintenance of the equipment) participated in the process in three groups: 1) industrial research and development team (R&D), 2) managers and team leads, represented by industrial seniors, influencing the decision-making process, and 3) the future users, represented by the multinational company’s novice and expert employees. The collaboration process was performed between the academic research group and the industrial research group on equal terms, whereas the management team and target users were involved as focus groups. The industrial R&D team’s participation assures that industrial aims are tightened to the research process and grants access to the other groups. The management team’s presence guarantees that the performed research and development process corresponds to the business-oriented goals of the company, whereas the involvement of the company’s employees grants the access to specific, end-user knowledge and insights, which are important for the overall success. The process consisted of the following activities, presented in Figure 1 and detailed below.

1. **Kick-off Ideation meeting** was initiated with a goal to create a shared understanding of the industrial needs and core values of future collaboration. The kick-off meeting was held with the academic team, industrial researchers, management team, and representatives of the target user group. Started with presentations from industrial managers, the meeting evolved into an ideation workshop, where three major areas of interest related to VR were discussed (i.e., technical documentation aspects, department-to-department collaboration, and data collection and analysis). The ideation process happened in three dynamically arranged teams, which were, in turn, ideating and linking the aspects of three areas of interest into one topic. As a result, the attendees developed the concept of a virtual environment to enable department-to-department collaboration for employees involved in the technical documentation creation process.

2. **Maintenance Documentation Journey Workshop** was arranged to get a clear picture of the end-users and their work tasks. The creation of maintenance documentation involves two departments: subject matter experts (expertise on maintenance methods and equipment) and documentation experts (expertise on information design, technical writing and illustrating, and documentation tools), who co-create instructions and iterate them until a final version is approved, finalized, and published [13]. Academics, industrial R&D, and target users were involved in the workshop and discussion. A maintenance documentation journey (Figure 2) was presented to the participants to elicit their comments and important details about the process. The participants were then divided into three groups to discuss the challenges of the journey, the opportunities that the VR scenarios could offer, and the user requirements for the CVE system design.

The workshop took place in Finland at company premises. Two participants from India participated remotely; their participation was facilitated by a Teams video meeting on a laptop. A separate USB camera was used with the laptop, which enabled the remote participants to turn the camera to the current speaker or materials. A separate speaker microphone was used to ensure good audio quality.
The Indian participants felt they were well involved in the workshop and commented that the remote participation worked very well. The workshop resulted in the creation of the pipeline of working activities and corresponding users’ needs for the system to support those activities. Personas, drafted prior to the workshop, were finalized for each department representative as well as scenarios of how the work can be done within the virtual environment. Further, system functionality and required features were identified.

3. Survey on feature prioritization was designed to collect the perceived value of system features from the future end-users. The results from the workshops (i.e., all comments regarding Maintenance documentation journey, VR use cases, ways of working) were digitized, and all features of “an ideal collaborative VR environment” were listed. Features were divided into six categories: Tools, Notes, (VR) Environment, Integration, Timeline, and Other. People were invited to a guided Teams session to fill in the feature prioritization survey to ensure that everyone similarly understands the features and people have reserved time to answer the survey.

Firstly, the features were explained, and participants were able to ask questions if they had any doubts. Then, the participants opened the survey from their computers privately and filled it in. The Teams session was kept open until all participants had confirmed that they had finished the survey. In the survey, the features were evaluated on a Likert scale through the question: How important you consider the following features in VR? Since all features had already been identified as important earlier, the scale started from “somewhat important” instead of “not at all important” (1 = somewhat important, 5 = extremely important). Webropol tool was used to conduct the survey.

4. Iterative development process & Feedback via Demo Sessions was established as a process for academia to finalize the design and develop the system while getting constant input and reflection from industrial partners. The academic research team performed the process of designing the user experience and interactions with the system based on the previous phases of collaboration. The major goal was to find the balance between implementation feasibility and the level of complexity of interactions and user interface design. Once the system development progressed, video meetings with the industrial representatives were arranged to demonstrate how the system’s functionality was implemented. After video demonstrations, both parties discussed possible modifications and future development agenda and associated deadlines.

5. Survey on the system design was created to rapidly gather feedback on the system functionality from managers and target users in the company. When the first version of the system was deployed, the VR user studies were delayed due to the COVID-19 pandemic situation. Hence, we decided to collect both quantitative and qualitative data in a form of an online survey. It consisted of multiple parts, collecting subjective opinions on the perceived value of the system, virtual spaces, and virtual tools. The survey was designed by the academic research group and iterated based on the feedback from the industrial research group. The responses of the survey verified that the system design is sufficient and useful from the perspective of the company’s employees and management team and resulted in minor system modifications (e.g., the order of items in the menu). A more concrete description of the survey structure and respondents is presented in section 5.1.

6. User study with expert users was planned in meetings and asynchronous cooperative work between the academic team, industry researchers, and industrial experts. In the initial planning meeting, academics and industry representatives agreed on the features to test and divided test tasks according to the participants’ background and expertise. Afterwards, the academic team and the industry researchers drafted the user test plan asynchronously. Industry researchers and managers defined the scenarios and task list tests to mimic the company’s development process in the virtual environment; likewise, industry researchers managed the practicalities of the user test in the company: permits’ management, scheduling of participants, and equipment set-up. Academia completed the software updates, training video, and an online survey. The final planning meeting consisted of the academic team and industry researchers to confirm the roles and scheduling for the user test and means to share the collected data. More concrete descriptions of the user study methods, procedure, participants, and results are presented in sections 5.2 and 5.3.

7. Data Analysis was performed separately by both academia and industry research groups. Industry researchers collected and prepared for analysis the notes made by observers and the facilitator of the user tests; in total, 268 comments were gathered and listed in an Excel file. Further, the comments were tagged by the following categories: specific application features, such as tool-related comments, overall user experience (negative and positive), suggestions, and the impact of the application on the participant’s working methods. The data from the survey were analyzed by academic researchers using descriptive statistics. The resulting data were combined and utilized to form a discussion in a series of collaborative workshops between academia and industry research teams. The focus of collaborative work was to identify the weaknesses of the current design and plan the modifications of virtual spaces and virtual tools based on the user study findings. In addition, it was critical to establish a common understanding of the future system development and a plan for the next user study and related requirements.

4 COVE-VR: System Design

The COVE-VR is meant to facilitate department-to-department collaboration in a VE, with a focus on digital content creation and enhanced synchronous and asynchronous communication. This section presents the final design of the
system: the virtual environments and virtual tools available within. Two virtual environments were created to support the development of maintenance methods and related documentation tasks, shown in Figure 3. The Lab VE is a small working space for primarily individual work, and it replicates a real maintenance site. The Showroom VE is a big-sized working space for individual and collaborative work. It is designed as a meeting room and consists of two floors. This space can be used for in-depth analysis of 3D models on the pedestal via a dedicated panel located on the wall. Using this panel, the models can be scaled, rotated, and moved horizontally up to the second floor. The models can be also disassembled (Figure 3, bottom); the parts of the models can be highlighted and removed. The user can cancel the last action or restore the model to its original state.

Seven virtual tools were deployed to enable documentation content creation in the VEs; the tools are opened from a touchpad-activated radial menu. The (1) TextBox Tool is used to create text notes via speech-to-text or typing (Figure 3, top); the notes are left in the environment in the form of an open text window or message bubble. Text notes can be exported to the desktop as a document in the order of creation with a timestamp and author name. The (2) Camera Tool can record videos and capture photos in the VE, which are saved to the hard drive. To work with a 3D model, the user can open it with the (3) Model Placement Tool from the list of available models. With the (4) Measure Tool users may measure distances in the VE. The tools and models can be deleted with the (5) Delete Tool. The (6) Grid Snipping Tool can be used to lock the movement of the models to grid points or set angles, and it also has a precision mode which reduces the range of movement for more control over object manipulation. After completing the work, all VR objects can be saved for the next user with the (7) Save World State Tool.

5. System Evaluation: Methodology and Results

This section presents the methods and procedures of the COVE-VR system evaluation in two rounds, followed by the results on perceived value and performed collaboration process. Since this article is focused on the process of collaborative development and the evaluation of employees’ subjective perceptions, it does not include the description of methods or findings related to the system design.

5.1 Online Survey with Company Employees

The survey was open during September 2020. The link to the survey was shared by the industrial researchers via their internal mailing channels. As a result, we received 38 responses, 18 of which were complete, and thus, suitable for analysis; the rest were filled in only partly. Responding to the survey took on average 48 minutes. The respondents were aged from 26 to 62 (M = 36.5) and only 2 of them were female. Most of them (14) hold a bachelor or master’s degree, while the rest had a high school or vocational school degree.

5.2 User Study with Experts

The study investigated subjective perceptions of the system and its usefulness in accordance with the industrial tasks. The study was conducted at the company’s premises in Finland; facilitated and remotely observed by the industry researchers due to COVID-19 restrictions. In total, there were one pilot
test, six in-person user tests, and one remote user test facilitated for a participant located in the USA. An HTC Vive Pro headset with controllers was used for the testing procedure. The sessions were live-streamed and recorded using a USB camera to capture the participants’ actions in the virtual reality room together with the participants’ point-of-view from the VR. Lastly, a GoPro Hero 3 camera was set up to record the overall room set up as an offline backup.

**Methods.** Both qualitative and quantitative data were collected during the user study via observations, an online questionnaire, and interviews. The methods of data collection were created in collaboration between the academic and industry researchers. An observation form was created to ensure the systematic gathering of users’ general state of mind, workflow procedures, emotions, technical issues, suggestions, and improvement ideas. The online survey for the user study was based on the previous online survey to compare the results. Additionally, the SUXES questionnaire on users’ expectations and experiences [25] and statements on immersion and presence in VR, adopted from Presence Questionnaire (PQ) [28], were added. The semi-structured interview consisted of 10 questions: half of them were created by academics with the focus on user experience, user interaction with the application, and the exploration of system functionality; and half were created by the industry with the focus on department-to-department collaboration and the implication of VR use to the users’ ways of working.

**Procedure.** The procedure started with an introduction to the study and signing a written consent for participation. Next, the participants filled in background data and watched the demo video, describing the purpose and functionality of the system. After, they filled in the SUXES questionnaire on system expectations. Next, the participants had a training session with the application and proceeded to the actual user study tasks in VR. The tasks and content in VR were different for maintenance method technicians and documentation technicians. For maintenance, the focus was on developing the content with the help of tools. For the documentation department, the focus was on working with already created content. Throughout the user test sessions, the facilitator encouraged the “think-aloud” method to gain insights [3]. After the tasks in VR were performed, the SUXES part on experiences was filled in, followed by other survey parts and an interview. On average, the procedure took 2 hours and 17 minutes: the length of the procedure may be explained by the long preparation process and extensive interviews, which took at least 45 minutes. After the user tests were completed, the industry researchers conducted a debrief of the session and shared all the materials with the academic team using an encrypted online drive.

**Participants.** Since the user study procedure was time-consuming, a relatively small group of target users were approached for testing purposes. In total, seven target users, aged from 27 to 57 (M = 41), participated in the study. Four represented the Maintenance Development department (two novice and two expert users with an average of 9.3 years of experience) and three represented the Technical Documentation department (two experts and one novice users with 14.3 years of experience on average). Five participants were male. Six held a bachelor’s degree or similar. Six participants were residents of Finland and one residing in the USA. Finally, all the participants from the Maintenance Development department had responded to the previous survey on system design; and further, two of them had responded to the initial survey on feature prioritization.

5.3 Combined Results of the Evaluation

This section introduces the results of the collaborative iterative user study from two angles. Based on the comparison of the online survey and user study findings, supported with the interview responses, we demonstrate the value of the system to the end-users. Next, we reflect on the performed process of academia-industry collaboration.

5.3.1 User Perception of the system

The results of the online survey and the user study with experts were positive without a big variance in responses; the survey helped to verify that the design corresponds to the needs of the employees and business goals with two focus groups, whereas the user study allowed more in-depth evaluation of the system design with a focus on interactions and content creation. Based on the survey, the concept of the system was found to be a safe and convenient approach to ease up the remote communication and collaboration of departments. As one of the responders commented, this system “can make the cooperation in many points easier”, as it allows to “spontaneously work together on certain things, independent of location”. The major concerns about the system were (1) the price and still limited ergonomics of the VR headset and (2) the level of realism and preciseness of the virtual spaces and 3D models, which would be critical for efficient work process. However, none of the user study participants shared concern on the level of realism one of them even commented that “the graphics were realistic”.

As can be seen in Figure 4 the system was perceived extremely well overall. Still, there is a small decrease in the perception of the system between evaluating it based on videos (in an online survey) and based on interacting with the system (user study). Most of the target users believe that the potential of VR can benefit the company’s work processes and support the idea of transferring work processes into VE (Md1 = 7, Md2 = 6). Only one respondent of the survey was neutral, and one user study participant slightly disagreed that VR is flexible to be used for the company’s purposes (Md1 = 6, Md2 = 5). Most of the participants would like to use VR to perform their tasks (Md1 = Md2 = 6) and feel enthusiastic about it (Md1 = 6.5, Md2 = 6). Further, all the respondents agreed that the system design is useful for the company (Md1 = 5, Md2 = 4).
= 7, Mdn2 = 5); they think that VR would motivate them (Mdn1 = 6, Mdn2 = 5) and increase their performance (Mdn1 = 6, Mdn2 = 5). Participants also mostly agreed that the system would make their work faster (Mdn1 = 6, Mdn2 = 5), safer (Mdn1 = 6.5, Mdn2 = 6), and easier (Mdn1 = 6, Mdn2 = 6). Finally, all of them believe that VR technology can enhance department-to-department collaboration. Further, most of the survey respondents agreed that COVID-19 affected their working practices (Mdn = 6) and expressed the desire to use COVE-VR in addition to existing desktop applications, like Teams (Mdn = 6). All of them agreed that the system would make their work tasks easier and faster when working remotely (Mdn = 6).

As a result, the system evaluation demonstrates that the system design addressed the employees’ needs and is sufficient to support the work tasks of both maintenance methods developers and documentation experts. Apart from collaborating in the VE, some participants expressed the desire to export and share the notes and pictures from the VE to other means of communication, e.g., email. One of the participants from the documentation department commented: “You could take a picture of the component and the note that was written and share it via email for instance to have a different way of communication with designers and methods developers”. Also, many other benefits and use cases with the VR system were mentioned, for instance, training and learning based on 3D models, maintenance method reviews and tests, international meetings, and demonstrations. Moreover, for demonstration purposes, the presence of only one person in VR would be sufficient to benefit from enhanced visualization capabilities of VR when presenting products or 3D models; the others may be present via video conferencing.

5.3.2 Academia-Industry Collaboration: Roles and Processes

Four industrial researchers (R&D), three managers and around 15 company employees (with 1-20 years of domain experience) were included throughout the development process. The R&D team was the core group to collaborate with academia: They coordinated communications with academia and facilitated decision making inside the company. They also contributed to all the design and development process phases: the group outlined and shared company processes and related materials, facilitated most of the collaborations events, and contributed to the research methods and system design iteratively. In addition, the company involved an extended team of company employees to provide a wider viewpoint for decision making. The extended team was composed of people with different areas of expertise, who were involved when needed to provide an alternative or added vision from the company’s employees and verify decisions.

As for other industrial groups, three managers and four target users participated in the first collaboration event, which helped to identify users’ needs on a general level and the perspective of the management team and their vision for the company’s development.

![Figure 4. Results of system perceptions in the two phases.](image-url)
Toward Efficient Academia-Industry Collaboration

further system development. All data collection forms were collaboratively and iteratively designed by the academic and industrial researchers together. Thus, both parties were able to extract knowledge for their own purposes.

6 Discussion

This study introduced an academia-industry collaboration process with the goal to develop a VR system, which addresses industrial needs to enhance department-to-department communication. The article demonstrates the design process of the COVE-VR system and presents company employees' perception of the system, based on the data from the online survey and the user study. The article further reflects on this process and summarizes all performed activities under a process-oriented framework for remote academia-industry collaboration (Figure 1), generalizable to other cases of joint activities between industry and academia.

Our process-oriented framework details the methods and practicalities of maintaining experience/knowledge sharing and transfer between the academic and industrial partners throughout the user-centered design and development process in a remote and agile manner. In contrast to existing models, such as the Certus model [17] that addresses the collaboration from the practicalities of role sharing, commitment and knowledge sharing, our framework promotes clear steps and methods to maintain such practicalities. By adopting this framework, academics and industry representatives may pave the way toward smooth and efficient collaboration while minimizing the challenges [11]. The clarity of operations and enhanced communication, promoted by the framework, allows establishing common objectives and work methods, which in turn, minimizes organizational issues [6] and harmonizes the pace of the development process [11]. Continuous and constant communication, and follow up between the academic and industry activities aimed to produce rapid results to cope with the industry's frequent delivery requirements, at the same time accelerating the research process in the academia [22].

The results on the system perception demonstrate a high relevance of the designed solution to the target users; most of them found the system beneficial for collaboration and for the company's needs, despite a few interaction issues. The findings indicate the success of the performed collaboration process; joint activities resulted in the correct determination of industrial needs and system requirements. Furthermore, the system design, which combines virtual environments and virtual tools for collaborative content creation, can be utilized in any other fields, related to product development and corresponding service activities with a focus on extensive documentation (e.g., construction, heavy machinery, aircraft, and transportation). COVE-VR, or a similar system, can advance the communication between employees and departments while providing means of easy content creation. Furthermore, our results indicate that such systems would advance the work processes in the situation of forced remote work and minimize the issues of productivity and efficiency.

Our system concept could also bring benefits to multinational companies, who already utilize 3D CAD models for their operations. Such a system potentially reduces costs and the time span of industrial operations by providing an environment to efficiently use the existing company's materials and create new forms of it. Furthermore, our findings indicate that not every employee would require a VR headset for personal use to gain benefits from VR visualization capabilities. The presence of one person in VR would be sufficient to demonstrate 3D models and related issues, which can be further streamed or shared in a video format.

6.1 The Benefits of Collaboration

The collaboration between academia and industry provides clear benefits for both parties. In brief, for this case study, academia’s expertise in user experience and interaction design, as well as methodological knowledge of conducting user studies, proved invaluable to the company. Furthermore, prior experience with and knowledge of VR technologies and associated CVEs including the design and development of such systems from research and practical perspectives helped to develop the system without massive expenses. The company contributed by bringing in real-life use cases and associated challenges, in addition to existing real-life products and materials (3D models). Moreover, the company expertise in shared maintenance and maintenance development, documentation and localization, VR training and process management, as well as multicultural, global collaboration settings enabled a test environment to touch all these aspects.

From academia's perspective, such collaboration increases the relevance of research and opens new research directions, as has been discussed in previous works [11]. The knowledge sharing and transfer with industry provides an opportunity to gain a clear understanding of the gaps and challenges to be addressed as well as an industrial context and related user experience processes to investigate. The access to actual target users, which would have not been possible without the collaboration, resulted in the retrieval of realistic and relevant data for the analysis. These demonstrate a 50% response rate to the online survey, whereas it would be close to zero in case the academia would try to collect this information on their own from relevant respondents.

Furthermore, the user study with actual target users would not be possible at all without the involvement of the industrial R&D team. Shared timeframes and scheduled meetings to elicit feedback from the industrial researchers resulted in a more agile design and development process at the academia premises, while constant feedback ensured system pertinence. The collaboratively designed VR system (relevant to actual users) may be utilized for further experimental research to investigate multimodal interactions, presence, immersion, and collaboration aspects in VR in similar or other contexts.
**From industry's perspective**, such collaboration provides knowledge expertise and additional resources for the company's development. Furthermore, research projects provide an opportunity to test and validate in more detail, and to better understand companies' own user needs and requirements. Experimental studies are challenging in an industrial setting because of limited resources. The traditional way of working in the industry does not always allow that much time to be spent on research [11] due to tight project and production schedules. It is also impossible to recruit and employ the best experts from every area of expertise in industrial companies. Academia with its numerous universities has the best experts with the latest knowledge and peer-reviewed and validated research. Therefore, collaboration with academia increases the possibilities of doing research and experiments in companies. Acquiring state-of-the-art knowledge from academia together with experimental studies help companies to prepare for the future as one of the industry leaders. In-depth research results support the fast-paced development work done inside the company, driving the progress and innovation further, and strengthens the company's brand as an innovative company.

Furthermore, **industry-academia collaboration allows the industry to publish** and share their knowledge with others. Traditionally, research done in industrial companies is rarely published even if it does not contain any core business information about the company. Therefore, any development done remains in the companies and is shared through informal channels or benchmarking only. This is true even when the results concern non-IPR work or best practices. Collaboration with academia shares the results further, benefiting a wider audience. Additionally, research done in industrial companies is, in many cases, done with very specific company needs and use cases in focus. When working together with academia, it is more natural to think outside of the company box and generalize the ideas to a different level.

### 6.2 Practical Suggestions for Academia-Industry Collaboration

Based on our collaboration process, we framed a list of practical suggestions to support the proposed framework and enhance the communication and knowledge sharing between academia and industry:

1. **Define roles, procedures, and industrial focus groups.**

   Despite the collaboration mostly happening between academic and industrial researchers, our results demonstrated the value of including the management team and other employees throughout the process. Hence, we encourage identifying relevant (industrial) focus groups and keeping them involved via academic practices. Further, identifying the roles and responsibilities of each party and agreeing on the procedures would address not only the possible organizational problems and the lack of commitment [11] but also transaction-related barriers of collaboration [6].

2. **Establish trust and shared understanding.**

   To overcome orientation-related barriers of collaboration [6], it is critical to exchange and clarify each party’s own goals and expectations for the collaboration. Hence, we suggest initiating a collaboration process with an activity (in our case a kick-off meeting), that would include all relevant focus groups to ensure that everyone’s perspective is communicated. Further, as the result of such activities, we suggest establishing shared goals, objectives, and timelines, including long-term and short-term plans, to overcome misunderstandings while harmonizing the pace of joint work [11, 22]. Further to promote trust and openness while avoiding transaction-related issues [6], we suggest utilizing both official and unofficial channels of communication (e.g., email lists and Teams chats) as well as a shared storage option with equal access (e.g., OneDrive).

3. **Remote participation and iterative feedback.**

   Based on the success of our remote demonstrations and feedback sessions when developing COVE-VR, we highlight the importance of sharing unfinished work to elicit feedback and apply modifications iteratively from the earliest phases. Remote knowledge and experience sharing can be facilitated via traditional conferencing tools (e.g., Teams), where the progress of development can be presented via videos or streaming from VR. The lack of interaction may be addressed via an accurate spoken description of how the system is operating and open discussion.

### 7 Conclusion

In conclusion, our academia-industry collaboration process on the joint software development of the COVE-VR system demonstrated promising results. In a collaboration between academia and industry, we performed a user-centered design process and developed a VR system that enhances the remote collaboration of departments from different sides of the world and delivers virtual tools for content creation.

The system was evaluated through an online survey (18 respondents from the company) and a user study (7 target users). Our findings show a very positive perception of the VR system and the relevance of the design in accordance with the industrial needs. Virtual reality may not only enhance the communication between departments, but also facilitate the generation of digital content (e.g., text, pictures, and videos) as a result of this remote collaboration. Hence, VR has the potential to decrease development time and costs while increasing the company’s overall productivity. Nevertheless, being limited to a single company case, we acknowledge the need to investigate the use of CVE in similar contexts.

Finally, with this article, we promote the collaboration between academia and industry and provide a process-oriented framework and practical suggestions on how to maintain joint activities. This work presents the benefits of including various industry groups in the research activities and demonstrates a positive perception toward VR.
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REFERENCES
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Paper III


Asynchronous industrial collaboration: How virtual reality and virtual tools aid the process of maintenance method development and documentation creation

Alisa Burova a,⁎, John Mäkelä a, Hanna Heinonen b, Paulina Becerril Palma a,b, Jaakko Hakulinen a, Viveka Opas b, Sanni Siltanen b, Roope Raisamo a, Markku Turunen a

a Tampere University, Tampere, Finland
b KONE Corporation, Hyvinkää, Finland

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Maintenance method development

Abstract
In the light of Industry 4.0, the field of Industrial Maintenance faces a large digital transformation, adopting Extended Reality (XR) technologies to aid industrial operations. For the manufacturing corporations that provide maintenance services, the efficiency of industrial maintenance plays a crucial role in the competitiveness and is tightly related to the technical documentation supporting maintenance. However, the process of documentation creation faces several challenges due to lack of access to the physical equipment and difficulties in remote communication between globally distributed departments. To address these shortcomings, this research investigates the utilization of Virtual Reality (VR) to facilitate asynchronous collaboration of globally dispersed departments involved in the pipeline of maintenance method and documentation creation. The presented proof-of-concept (the COVE-VR platform) has been developed as an academia-industry collaboration and evaluated iteratively with subject matter experts. The proposed VR platform consists of two virtual environments and eight virtual tools, which allow interaction with virtual prototypes (3D CAD models) and means of digital content creation. Our findings show the high relevance of the developed solution for the needs of industrial departments and the ability to support asynchronous collaboration among them. This article delivers qualitative findings on the value of VR technology and presents guidelines on how to develop virtual tools for digital content creation within VR, adaptable to other industrial contexts. We suggest providing embedded guidance and design consistency to ensure smooth interactions with virtual tools and further discuss the importance of proper positioning, the transparency of operations and the information property of generated content.

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1. Introduction
For many industrial manufacturing companies, such as KONE, reliable and efficient maintenance is a key success factor and a significant part of the revenue. Following the Industry 4.0 interventions towards smart maintenance (Rødseth et al., 2017; Siltanen and Heinonen, 2020; Silvestri et al., 2020), a variety of research showed the potential of integrating Extended Reality (XR) technologies to address the current challenges in Industrial Maintenance (Fernández Del Amo et al., 2018; Frank et al., 2019; Guo et al., 2020). Due to the possibility to safely simulate real contexts and experiences, Virtual Reality (VR) may advance the effectiveness, safety and accessibility of training (Guo et al., 2020; Leyer et al., 2021; Wen and Gheisari, 2020), hence directly contributing to maintenance services processes. Further, VR may advance maintenance management internally by facilitating the collaboration process of multinational industrial departments (Wolfartsberger, 2019; Wolfartsberger et al., 2020). By providing interactive access to 3D CAD models in realistic surroundings, collaborative VR enhances communication and knowledge sharing in a variety of industrial scenarios throughout the product development lifecycle (Berg and Vance, 2017; Choi et al., 2015; Guo et al., 2020; Wolfartsberger et al., 2020). By enforcing the multidisciplinary collaboration between product development and
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b KONE Corporation, Hyvinkää, Finland

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maintenance departments, VR can contribute achieving sustain-
ability and optimization of industrial working processes (Rad Seth et al., 2017; Silvestri et al., 2020). Augmented Reality (AR), in turn, may increase the performance and occupational safety of main-
tenance technicians by overlaying on-site assistive documentation (Fernández Del Amo et al., 2018; Gattullo et al., 2022; Keil et al., 2015; Tatić and Tešić, 2017).

**Maintenance documentation**, a subcategory of Technical Documentation (TD), is the primary component of industrial main-
tenance and the critical element of AR/VR integration. It delivers maintenance method information to support the training, learning and execution of maintenance tasks, which is further used in a variety of industrial scenarios and end devices. For the majority of industrial multinational corporations, the process of maintenance method development and corresponding documentation creation, validation, and renewal is complex and involves multiple depart-
ments that are globally distributed (Stock et al., 2005).

Due to the diversity of devices under maintenance, unavailability of physical prototypes or limited access to them, maintenance methods are often created based on interaction with 3D CAD models or 2D images over desktop user interfaces. The documentation is created based on remote communication over email, Microsoft Team's chat or shared PDF files. Therefore, the process of main-
tenance method development and documentation creation is errone-
ous due to the possibility of unwanted scaling, spatial mis-
interpretations, and communication misunderstandings, which may result in extra work or even massive expenses to fix mistakes. The final documentation is stored in multiple outputs such as HTML/ XHTML or PDF, which requires further work to be used in VR or AR glasses (Burova et al., 2020; Siltanen and Heinonen, 2020).

With the growing demand for adopting technical documentation for a variety of end devices (from tablets to AR glasses) (Siltanen and Heinonen, 2020) and the vulnerability of the current design process, there is a need for novel methods of technical documentation creation (Stock et al., 2005). Despite VR being a potential design tool (Wolfartsberger, 2019) to address the challenges of technical docu-
tentation, there is no generalizable knowledge on how it can be applied to support these activities. To address these shortcomings and further explore the role of VR as a collaborative space for global teams, this article presents a case study on how the COVE-VR plat-
form (Burova et al., 2021) can be used to facilitate remote asyn-
chronous collaboration of multinational departments and deliver novel ways of generating digital content for documentation pur-
poses. The article contributes to the field of Industrial Maintenance by answering the following research questions:

**RQ1:** What is the value of transferring collaboratively performed industrial maintenance method and technical documentation creation into VR?

**RQ2:** How to design virtual tools to facilitate the creation of digital content for technical documentation within VR?

The case study was conducted in collaboration between aca-
demia and industrial researchers from KONE, involving subject matter experts throughout the design and development process. The collaborative practices of the COVE-VR development are presented in the preceding study (Burova et al., 2021), whereas this qualitative study is focused on an exploration of how VR may transform current working practices to fulfill Industry 4.0 needs.

### 2. Background on industrial collaboration

VR, being one of the most important technologies for Industry 4.0 (Frank et al., 2019), holds a variety of possibilities for industrial growth and may shift the traditional ways of working (Guo et al., 2020; Narasimha et al., 2019). In this chapter, we discuss the benefits and use cases of integrating VR in industrial contexts and provide reasoning for a collaborative VR solution for technical documenta-

tion creation.

#### 2.1. Virtual reality in industrial maintenance

Industrial Maintenance and Assembly (IMA) is the second-largest application field for VR technologies (Guo et al., 2020). VR training has been proven to positively affect knowledge transfer and increase the performance and accuracy of maintenance technicians (Gavish et al., 2015; Guo et al., 2020; Leyer et al., 2021; Schwarz et al., 2020). The same VR environments can be re-utilized to enable AR prototyping in VR (Burova et al., 2020), which in turn contributes to the IMA field by delivering in-field guidance and ways of visualizing technical documentation in a real context (Gattullo et al., 2022).

VR has shown the potential to support the design stage of the product development cycle (Berg and Vance, 2017; Fillatreau et al., 2013; Guo et al., 2020; Murray et al., 2003) including the scenarios of product management, immersive product testing, manufacturing process review and collaborative design review (Schina et al., 2016). The application of VR may potentially reduce the lifecycle timespan and design flaws due to increased visualization capabilities (Frank et al., 2019) and the possibility to interact with virtual objects in a real-life 1:1 scale in a natural manner. Collaborative design reviews in the early product development phase improve design for main-
tainability, which in turn positively affects design optimization and reduces overall costs (Stapelberg, 2016).

Collaborative virtual environments (CVE) support synchronous and asynchronous collaboration and may increase the quality of communication, knowledge sharing and interactions among different stakeholders and multidisciplinary teams (Berg and Vance, 2017; Narasimha et al., 2019; Pedersen and Koumaditis, 2020; Schina et al., 2016; Wolfartsberger et al., 2020). Multiple studies (Burova et al., 2020; Schwarz et al., 2020) noted positive perceptions of VR technologies and, consequently, increased motivation towards using them among industrial employees. A recent study (Berg and Vance, 2017) showed the success of using immersive VR applications to support decision-making at the earliest design phases and an increased sense of team engagement. Similarly, another study (Wolfartsberger et al., 2018) showed how a VR system supports communication between engineers and assembly operators and enables validation of installation processes and maintenance oper-
ations. Nevertheless, there is still no fully automatic method of converting large 3D CAD models into VR, which causes challenges for seamless VR application in the field of industrial maintenance (Guo et al., 2020).

#### 2.2. Maintenance method and documentation development process

Despite the need for novel means of Technical Documentation creation (Stock et al., 2005) and the evidence of VR being able to address it (Di Girónimo et al., 2013), the industry has not adopted these practices yet.

**Maintenance documentation** is usually created and updated within projects or releases with tight schedules and deadlines, using tradi-
tional conferencing tools and PDF files. In our case study, two depart-
ments are iteratively involved in the creation process (Fig. 1): Maintenance Development Department (MDD) and Technical Docu-
mentation Department (TDD). Their collaboration can be synchronous and asynchronous; their tasks can be done individually or in teams.

Initially, MDD experts design the maintenance methods - outline instructions on how to perform certain maintenance tasks. In many cases, due to the physical equipment unavailability, the method de-
velopment process is based on 2D images or 3D models on a computer screen without proper context, resulting in the experts not always being aware of the dimensions of a component. The lack of spatial and contextual understanding may lead to situations where the designed
the subject matter experts traditionally use paper notes, images, and 
markups in existing instructions to create the outline, which is then 
delivered to technical writers and illustrators from TDD, who create 
the maintenance instructions for technical documentation. The 
starting point for any instruction is analyzing the product and the 
outline; a draft instruction is created as an outcome of the analysis. 
Due to lack of access to actual equipment, there are misunderstand-
ings in interpreting the outline and complications in the illustrations' 
creation. Once available, the draft is reviewed by the MDD. The draft is 
usually sent back and forth, with comments and changes during each 
round. The number of iterations is increased by general remote com-
munication problems, such as misunderstandings, lack of detailed 
information or difficulties interpreting hand-drawn sketches. Finally, 
after the instructions are approved and officially released, they are 
used in field operations.

VR offers many possibilities to enhance the collaboration of the 
two departments [global teams located in different time zones] in-
volved in the pipeline of maintenance documentation creation. 
Instead of trying to figure out the dimensions and scale of the 
equipment, they can experience it in an immersive VR environment 
(Fillatreau et al., 2013; Tea et al., 2021; Wolfartsberger et al., 2018).
Furthermore, images, videos and notes made within VR are easier to 
interpret, store and access than handwritten or hand-drawn sket-
ches. A single multifunctional collaborative VR platform can be used 
to support individual work activities, whereas facilitating asyn-
chronous collaboration would be the first step to optimize the pro-
cess of documentation creation.

3. Methods and materials

This chapter details the COVE-VR requirements and functionality, 
linked to industrial scenarios and describes the expert user study 
procedure and methodology.

3.1. Case study scenarios: Asynchronous collaboration

The case study scenarios were identified during a workshop, 
which involved subject matter experts from Finland and India. The process of maintenance method and documentation creation was 
analyzed, and the use of VR was discussed, resulting in several ap-
plication scenarios (Fig. 2). This article is focused on asynchronous 
collaboration scenarios.

3.2. COVE-VR: Design and architecture

To address the above-mentioned challenges, the platform design 
should aid the asynchronous collaboration of two global teams lo-
cated in different time zones analogously to collaborative group 
work in the cloud: when working alone, they can leave notes and 
comments for others to see, save and continue their work later. 
Additionally, they should be able to create digital content, e.g., visual 
assets such as photos, videos, and text, which can be re-utilized for 
instructions or further communication.

To facilitate the identified industrial scenarios, the COVE-VR 
platform consisted of two virtual environments (VEs) and eight virtual 
tools. The components of the platform are shown in Fig. 3.

The virtual Lab is a small working space for individual and pair 
work. It replicates the real working environment - the elevator shaft 
based on the existing 3D CAD model - to allow safe access to the 
virtual space, which is a time consuming and hazardous process in 
real life. The Showroom is a larger space to facilitate collaboration 
activities and accommodate client presentations. The Showroom is 
equipped with the Disassembler, which allows in-depth investigation 
of 3D models, including disassembling into parts and changing the 
size, rotation, and vertical position (via the wall menu).

The virtual tools were designed based on the input of subject 
matter experts to (1) facilitate interaction with virtual prototypes and 
(2) generate digital content (media and text). Virtual tools are defined 
as virtually tangible elements, which may be used for digital content 
creation or manipulation of the environment to facilitate the es-
ecution of industrial tasks. The tools are generic enough to support 
many other industrial use cases.

In both spaces, seven virtual tools may be opened via the wrist-
menu. The Model Placement tool is used to import 3D CAD models 
anywhere in the virtual space. The TextBox tool is used to create 
textual notes via speech recognition or typing on a virtual keyboard. 
The Camera tool is used to take photos and videos; it has an in-
tegrated timer and is opened in selfie-mode. The Measure tool 
measures the distances between two points, while the Grid Snipping 
tool allows moving objects over grid points to add accuracy. With the 
Delete tool, users can delete virtual objects or other tools and with 
the Save World State tool they can save the environment with all 
created materials or upload existing “saved environment”. All con-
tent generated in VR is saved to the hard drive's folder and can be 
accessed later, so the content (images, videos, notes) is easily uti-
lizable in common office tools and other applications.

The COVE-VR system follows a client-server model, with two 
servers handling synchronous and asynchronous collaboration se-
parately (Fig. 4). The system consists of VR Client, a RESTful web 
service, the self-developed Model converter, and a commercial off-
the-shelf component PUN (Photon Unity Networking) Server.

VR Client was developed using the Unity game engine and VRTK 
(Virtual Reality Toolkit) 3.3.0, because they contain most of the 
components needed for a VR application, including a renderer, a 
physics engine, a scripting runtime, a visual editor, an input system, 
3D model importers, a build system with multiplatform support and 
components for VR user interfaces. We further utilized PUN for 
synchronizing activity in the environment between multiple users
tests would likely not have revealed these kinds of bugs, except for especially when multiple users affect the world state. Automated unit collision physics, and the effects of unanticipated user input, especially at the integration and system level. The most common bugs than the benefits of extensive verification for research software of experiences from early implementations. We consider the time savings from proceeding quickly to implementation more significant than the benefits of extensive verification for research software of this kind.

Both internal and external validation testing were performed, mostly at the integration and system level. The most common bugs discovered were related to desynchronization, serialization failure, collision physics, and the effects of unanticipated user input, especially when multiple users affect the world state. Automated unit tests would likely not have revealed these kinds of bugs, except for serialization failure. It is a matter for future work to explore how user input should be simulated for automated tests; we are not aware of an existing test framework that supports VR user input simulation in Unity at this time (Andrade et al., 2019).

3.3. Remote user study

The COVE-VR platform was evaluated in two rounds: firstly, the concept of the VR platform and virtual tools was evaluated with a video-based online survey, and then, its usability and usefulness were measured in a user study with experts. This approach allowed to rapidly verify the design solutions with a wider circle of users, including the management team, and further concentrate on usability evaluations with a smaller expert group.

3.3.1. Online survey on the platform concept

The survey was created to elicit expert feedback and improvement ideas on the concept of documentation creation within VR and the design of virtual tools. To provide a comprehensive description of the system and virtual tools, the survey incorporated two 360-videos of VEs, user's viewpoint videos with voice-over and pictures/graphics whenever applicable.

The survey was opened for a month (September 2020) and received 38 responses; 18 were fully completed and suitable for the analysis. The respondents were aged between 26 and 68 years (M = 40) and represented seven countries and three departments: MDD (9), TDD (5), and Learning and Development (4). All respondents were familiar to an extent with XR technologies: five of them had used VR or AR applications a couple of times, three had used them before but had heard about them, nine had received 38 responses; 18 were fully completed and suitable for the analysis. The respondents were aged between 26 and 68 years (M = 40) and represented seven countries and three departments: MDD (9), TDD (5), and Learning and Development (4). All respondents were familiar to an extent with XR technologies: five of them had used VR or AR applications a couple of times, three had used them before but had heard about them, nine had used VR or AR applications a couple of times, three had used them many times and one is a frequent user of VR.

3.3.2. Expert study

The qualitative expert study was conducted to explore how the COVE-VR platform facilitates the process of asynchronous collaboration of departments and to evaluate the effectiveness of the virtual tools. The goal was to investigate how experts would...
approach their working tasks within VEs (based on a pre-defined scenario) and what kind of content they can generate using virtual tools.

Seven experts (from Finland, India, China and the USA) aged 27–57 (M = 40) participated in the study; four of them represented the MDD and three represented the TD department (with on average 10 and 14 years of experience). The evaluation tasks for these two groups were different to mimic their real work activities: the first group created the digital content from zero, whereas the second group could see some “pre-created materials”. However, the general workflow was the same: both groups visited two virtual environments and used six virtual tools. In the Showroom, they used the Disassembler to investigate a 3D CAD model and tested the functionality of the wall menu. In the Lab VE, they imported an
interactive 3D CAD model, measured its components, and created digital content (textual notes, videos, and pictures of the disassembly instructions for that model).

The user study was conducted using an HTC Vive Pro headset at the premises of KONE. Due to COVID-19 restrictions, only one facilitator was present in the room; the session, therefore, was recorded and streamed via Microsoft Teams for observation. On average, the entire procedure took 2 h and 17 min per evaluation.

3.3.3. Data collection and analysis

The study utilized mixed research methods, collecting both qualitative and quantitative data. The qualitative data was collected via open-ended questions (survey) and semi-structured interviews (expert study). The interviews were transcribed, and the quotes were further sorted by the categories in an excel file and analyzed.

During the user study, the system’s usability was evaluated with a validated SUXES questionnaire (Turunen et al., 2009), which allows accessing the expectations of and experiences with a multimodal system. To further evaluate the design and usefulness of virtual tools, a self-designed set of statements was used in both iterations. The statements were designed together with industrial researchers to cover the company’s requirements since no validated survey on the design of virtual tools was identified. Due to the small sample size, descriptive statistics were used to analyze the quantitative data.

4. Results

In this section, we present the combined results of the survey and expert user study focusing on qualitative findings. The concept of the COVE-VR to support the asynchronous collaboration of global departments in the pipeline of maintenance method and documentation creation was evaluated positively. The value of VR technology was seen in simplifying work processes and advancing internal communication and knowledge transfer; however, concerns about the complexity and costs of developing such a VR system were raised (Fig. 5).

The expert study results verified that the COVE-VR is a desired and useful software that addresses many existing process-related problems. Both test groups successfully finished their tasks and were able to generate relevant digital content and explanatory notes to support asynchronous collaboration. The experts highlighted that system is beneficial to support their communication. For instance, instead of textual explanation over email, a method developer could record a video in VR, demonstrating the 3D object and explaining the method with words. Further, they can take a photo of the component from a needed angle, and that can be used by a technical illustrator as a reference to produce a vector image.

They further expressed the usefulness of both synchronous and asynchronous collaboration in VR. Industrial experts see the VR system as a central point of information to store all project-related materials and would like to utilize it during the whole product development cycle. They especially marked the importance of multi-department meetings in the beginning and end phases of the project, commenting: “Kick-off in VR at the first meeting so that the designers can explain what they design, and everyone can ask questions”.

The results of the SUXES survey (Fig. 6), showed that the system is required to be developed further to achieve smooth performance; the system was evaluated as less pleasant, natural and error-free than expected. Nevertheless, despite the moderate number of errors spotted, subject matter experts still found it to be useful, fast and would like to use it in the future.

4.1. Virtual tools evaluation

In this section, we present the evaluation of four virtual tools (Fig. 7)—since they were reviewed as the base for technical documentation tasks. Overall, despite several interaction difficulties, the tools were evaluated positively. Experts found the virtual tools to be useful and valuable for their working activities, which may become easier and safer. However, all tools require further development in terms of interactions and functionality, and experts expressed many ideas on how to make them better. Experts’ comments, development items and the UI/interaction changes are presented in Appendix A. The Disassembler in the Showroom got extremely positive feedback from method developers, while technical writers and illustrators were less enthusiastic and pointed out the need for more functionality. For instance, they mentioned enhancing the wall menu position and controls in addition to adding more functionality over disassembled 3D CAD models, such as labeling, components grouping, highlighting, and removing.

The TextBox Tool was also perceived positively, especially its speech recognition feature. All experts agreed that it was easy to use and expressed the need to attach textual notes or recorded audio messages to the 3D CAD model components. They also highlighted the importance of visualizing the author and the order of created textboxes to support asynchronous collaboration.

The Camera tool and The Measure tool were evaluated with less enthusiasm since most of the participants faced difficulties in using them. For the Camera tool, the UI elements were found to be non-intuitive – for instance, the switch between photo and video modes were not obvious. In addition, primary camera orientation (in self-
What are the benefits of using VR to facilitate ***’s working processes?

- **R1**: “VR would enhance the accuracy of technical documentation as it helps the [technical] writer to get closer to a product than ever.”
- **R2**: “Benefits in easier understanding of complex process”
- **R3**: “Large equipment is often hard to see in real, especially with a group of people. VR will enable this, safely.”
- **R4**: “Safety. This is the most important. Also using VR can make work processes more convenient.”
- **R5**: “You don’t need to visit site or lab a many times like now you need to.”
- **R6**: “Easier to collaborate especially remotely. Can give people a better understanding in a safe and controlled environment.”

What are the benefits of using VR to facilitate department-to-department collaboration?

- **R1**: “VR provides transparency and clarity of information to be discussed across departments.”
- **R2**: “Good for meetings and handling models. Installation and maintenance procedures can be discussed in a room with all the members and handling models directly.”
- **R3**: “Communication becomes faster because you can just show things.”
- **R4**: “Users from different departments do not need to cooperate face to face. They can work together by using VR online.”
- **R5**: “Better communication and understanding between departments.”

What are the limitations and drawbacks of using VR to facilitate ***’s working processes?

- **R1**: “Building VR environment matching to actual site conditions would be challenging. VR infrastructure with fast and smooth computing/navigation is required.”
- **R2**: “Procedures captured in camera in VR should be correct, real sites may have other surrounding features also.”
- **R3**: “The real work environment is more various.”
- **R4**: “Price and needed devices”
- **R5**: “It is only a simulation of the real world and can give false impressions to people with no experience of the real environment and components etc”

In summary, the results demonstrated that the COVE-VR platform, although requiring further development, is seen as valuable software to facilitate industrial work tasks related to technical documentation creation. The results also suggest the need for (better) familiarization with the system, which would solve most of the usability issues.

5. Discussion

In this case study, we explored how the COVE-VR platform supports the asynchronous collaboration process of maintenance
method and documentation creation and how it may transform traditional industrial processes in line with Industry 4.0. The study contributes to the field by providing qualitative findings, verified by industrial experts. Together with the platform design, we present the method for converting large 3D CAD models into VR, which previously was found to be one of the stopping factors towards seamless VR integration (Guo et al., 2020).

Previous studies (Berg and Vance, 2017; Narasimha et al., 2019; Schina et al., 2016; Wolfartsberger et al., 2018) demonstrated clear benefits of VR to facilitate product design lifecycle activities, resulting in reducing costs, optimizing the design process, and improving product quality (Guo et al., 2020). Similarly, our findings demonstrate the value of utilizing VR to enable the collaboration between method developers and documentation designers, which in turn, would increase the quality of services related to the product. Despite the focus on maintenance documentation, our findings are generalizable to other technical documentation processes that include multidepartment activities, such as installation instructions, safety-related documentation, and others. Further, the virtual tools’ design can be applied to other digital content creation practices within VR, for instance to customer presentations or product reviews. With this article, we do not provide a ready-to-market VR solution but present the proof-of-concept technology to support service-related activities, which can be further explored in other industrial contexts.

Answering the RQ1, our study validates that the COVE-VR is flexible enough to support asynchronous collaboration and “provide transparency and clarity of the information to be discussed across departments” (R3). By immersing method developers and documentation designers into collaborative virtual spaces, we allow...
them to interact with virtual prototypes and also enable digital content creation, (e.g., text, pictures and videos) that can be further used for documentation and communication via common office tools. Successful asynchronous collaboration is especially relevant for multinational corporations with globally scattered departments from different time zones (in our case China, India, Finland, and the USA), who are remotely working on same projects. Further, expert feedback showed the need for synchronous collaboration sessions since it would be a more efficient way of information exchange in several tasks. They also highlighted the appropriateness of an asymmetric approach, when a single user streams the session from VR, while the rest watch it over traditional conferencing tools, thus, minimizing the expenses of VR devices.

In accordance with previous studies (Berg and Vance, 2017; Burova et al., 2020; Narasimha et al., 2019; Schwarz et al., 2020; Wolfartsberger et al., 2018, 2020), our findings showed the desire and strong interest of employees towards using VR to accomplish their work activities, despite some complications when using it. One of the survey respondents noticed that "VR enhances innovation minds of employees" (R3), which corresponds to the goals of Industry 4.0.
However, to make a shift towards using VR daily, special attention should be placed on the smooth adoption of these technologies.

5.1. Guidelines for virtual tools implementation

Answering the RQ2, we formulated the list of guidelines for virtual tools implementation that can be generalized to other industrial needs:

1. Embedded guidance and help. VR platforms may be viewed as completely new graphical shells, diverging radically from the desktop environment. Our findings showed that some of the VR interactions, such as teleporting or manipulating virtual tools, are not intuitive (for novice users) and require training. Hence, in addition to advancing general user experience, proper training procedures should be implemented within the VR platform, including introductory step-by-step guidance about the functionality of the system and tools, and easy-to-access reminders or hints in case there are some issues during the work process. The guidance and instructions should be linked to the industrial work tasks and therefore, be slightly different for different departments.

2. Design consistency and real-world resemblance. To enable a smooth learning curve, all virtual tools should follow a similar logic of manipulation and control. In our case, tools, virtual objects and created content can be removed from VEIs with the Delete tool. However, the Delete tool itself was closed via a wrist menu, which caused some level of confusion. More specifically for VR applications, users may expect a stronger consistency between real-world physical movements and events in the virtual world; with the Delete tool, some participants wanted to smash objects to destroy them instead of pressing a button.

3. Positioning and orientation of virtual tools. Many issues with the COVE-VR were related to wrong positioning since collaborative VEIs provide an immersive sense of space (Lou, 2011). Hence, the location of virtual tools should be decided based on the user’s head and controller position and opened in the user’s field of view at a comfortable grabbing distance. Otherwise, the user might be confused and mistakenly open multiple tools, which would negatively affect overall user experience and performance of the system.

4. Constant feedback and transparency of operations. The system’s background processes should be explained to users to avoid confusion or disorientation, caused by being in a fully simulated environment. When the system requires time for uploading or processing, which is especially relevant when converting large 3D CAD models, multimodal feedback should be implemented to inform the users about the progress of operations and avoid disorientation. Multimodal feedback, specifically visual feedback supported by audio or haptic, should be consistently implemented for all users’ actions to increase the situational awareness (Guo et al., 2020) and the feeling of control, immersion and presence that are required for successful operations in VR.

5. Authorship and information property. When it comes to collaboration in VE, it is important to establish authorship and information hierarchy. Hence, for any created digital content, we propose to log at least the author, date of creation and order, if the content was created in a sequence. This data should be available both from VR and from a desktop version when reviewing content. The next step would be to establish user groups and their rights for content manipulation (e.g. a right to delete or edit virtual materials).

To summarize, VR platforms have much to offer for industrial operations, especially considering that VEIs can be re-utilized to facilitate most of the needs of the industry. However, such platforms should be developed in coordination with industry representatives (Burova et al., 2021), evaluated and expanded further based on expert involvement.

The major limitation of the study was the involvement of only one corporation with the general documentation process. Further analysis could explore how other manufacturing companies, for instance with a proprietary process, would integrate VR into their documentation creation activities and whether there are specific-to-sector differences. Future work should also include the review of synchronous collaboration within VR for documentation creation, including the scenarios when all the employees attend VR sessions or the scenario when a single user operates in VR and shares the video over a traditional conferencing tool. Additionally, the interactions with virtual tools and objects can be explored, especially from the perspective of direct or indirect manipulation. Finally, the approach of converting large 3D CAD models should be optimized and developed further.

6. Conclusions

In the light of Industry 4.0, large manufacturing corporations strive to integrate VR solutions to advance their operations. However, currently, the technology is not mature enough to allow smooth integration. The full benefits of VR would be fully discovered once other important technologies of Industry 4.0 (Digital Twin, IoT, AI) would be utilized over the whole product lifecycle. However, the evidence shows that the use of VR for industrial tasks is beneficial and may transform existing working processes. This indicates the need to explore the application of VR in a variety of industrial scenarios and to identify the potential advantages already now.

In this article, we presented how industrial experts perceive the utilization of the VR platform for department-to-department collaboration in the pipeline of maintenance method development and documentation creation and based on their insight, we provided a list of guidelines for virtual tools design for similar solutions.

CRediT authorship contribution statement

Alisa Burova: Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources, Data Curation, Writing – original draft, Writing – review & editing, Visualization. John Mäkelä: Conceptualization, Software, Validation, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing. Hanna Heinonen: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing. Paulina Becerril Palma: Investigation, Writing – review & editing. Jaakko Hakulinen: Resources, Writing – original draft, Writing – review & editing, Viveka Opas: Writing – review & editing. Sanni Siltanen: Conceptualization, Methodology, Formal analysis, Resources, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition. Roope Raisamo: Writing – review & editing, Project administration, Funding acquisition, Project administration, Funding acquisition. Markku Turunen: Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

**Interaction problems / requests:**

4 Note is floating, cannot be attached to a specific object.
2 Switching languages requires a button press
2 User didn’t know how to start the recording

**Comments:**

“As a maintenance developer is good to have the 3D model and make a note.”
“The voice thing is nice; you can make quick notes with that.”
“When you have so many notes in the environment, it would make sense to have several pages in a note instead of separate notes”

**Interaction problems / requests:**

7 Back view of the camera is needed
5 Icons are not intuitive enough
3 Zoom feature
2 Camera position is too close to the user

**Comments:**

“The camera is showing a different angle of what I am looking at “slightly illogical” (about selfie-mode)
“Camera flip feature like mobile phone (flip button)”
“Actually is very close to me”

**Interaction problems / requests:**

4 Measurement tool appears in VE behind the user
4 Hard to grab the ending points in the measurement tool

**Comments:**

“Maybe adding a snap command to make the measurement more precise and being able to place inside the components and measure”
“It is difficult to place the starting point because now it is giving an approximate measurement”

**Interaction problems / requests:**

7 To be able to see the name/identifier of the components
6 Consider the location of the menu, closer to platform/In relation to platform
4 To group components, and explode those groups instead of every single item
3 To be able to make some components transparent/semi-transparent, or highlight components

**Comments:**

“I see all the parts in the platform, that is good. [...] It is easy, I get all the information and I don’t need to go anywhere.”
“I enjoyed looking at things from different angles, to explore things.”
“Part removal in the platform would be useful, having more control on what to explode”
“X-ray feature would be good – pointing at a lid, for example and seeing through – transparency/semi-transparency. You sometimes want to show something inside of something else without losing the context”

References


Paper IV


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1. Introduction
In light of the recent shift towards remote working and social distancing, due to the COVID-19 pandemic, collaboration in VR (Virtual Reality) has become a viral topic of discussion in the fields of HCI (Human-Computer Interaction) and CSCW (Computer Supported Cooperative Work). In over three decades of academic and industrial research [1–4], VR has shown its potential to diminish the barrier between the real and the virtual. It can safely simulate diverse industrial contexts [3] and provide support in a variety of industrial use cases: from training [5–7] to virtual prototyping [8,9] and collaborative design reviews [8–10]. VR has been evaluated as one of the most important emerging technologies for Industry 4.0 interventions [11,12] due to flexibility of operations within virtual environments (VEs), and the richness of communication and multimodal interactions with virtual objects [13] coupled with enthusiasm toward utilizing novel technologies among industrial employees [14].
Distributed Asymmetric Virtual Reality in Industrial Context: Enhancing the Collaboration of Geographically Dispersed Teams in the Pipeline of Maintenance Method Development and Technical Documentation Creation

Alisa Burova 1,*; Paulina Becerril Palma 2; Phong Truong 2; John Mäkelä 1; Hanna Heinonen 2; Jaakko Hakulinen 1; Kimmo Ronkainen 1; Roope Raisamo 1; Markku Turunen 1; Sanni Siltanen 2,*

1 Faculty of Information Technology and Communication Sciences, Tampere University, 33014 Tampere, Finland; john.makela@tuni.fi (J.M.); jaakko.hakulinen@tuni.fi (J.H.); kimmo.ronkainen@tuni.fi (K.R.); roope.raisamo@tuni.fi (R.R.); markku.turunen@tuni.fi (M.T.)
2 KONE Corporation, Myllykatu 3, 05830 Hyvinkää, Finland; pbbecerr@gmail.com (P.B.P.); truongphong101097@gmail.com (P.T.); hanna.heinonen@kone.com (H.H.)
* Correspondence: alissa.burova@tuni.fi (A.B.); sanni.siltanen@kone.com (S.S.)

Featured Application: Based on data from multinational domain experts in the field of Industrial Maintenance, this study demonstrated the application cases and advantages of asymmetric VR set-up to address needs present in the industry.

Abstract: Virtual Reality (VR) is a critical emerging technology in industrial contexts, as it facilitates collaboration and supports the product development lifecycle. However, its broad adoption is constrained by complex and high-cost integration. The use of VR among devices with various immersion and control levels may solve this obstacle, and increase the scalability of VR technologies. This article presents a case study on applying asymmetry between the COVE-VR platform and Microsoft Teams to enable distributed collaboration of multinational departments and enhance the maintenance method and documentation creation processes. Overall, five remote collaborative sessions were held with 20 experts from four countries. Our findings suggest that asymmetry between head-mounted display and Teams users enhances the quality of communication among geographically dispersed teams and their spatial understanding, which positively influences knowledge transfer and efficiency of industrial processes. Based on qualitative evaluation of the asymmetric VR setup, we further suggest a list of guidelines on how to enhance the collaboration efficiency for low-cost distributed asymmetric VR from three perspectives: organization, collaboration and technology.

Keywords: collaborative VR; asymmetric VR; industrial maintenance; distributed collaboration; maintenance method development; technical documentation

1. Introduction

In light of the recent shift towards remote working and social distancing, due to the COVID-19 pandemic, collaboration in VR (Virtual Reality) has become a viral topic of discussion in the fields of HCI (Human-Computer Interaction) and CSCW (Computer Supported Cooperative Work). In over three decades of academic and industrial research [1–4], VR has shown its potential to diminish the barrier between the real and the virtual. It can safely simulate diverse industrial contexts [3] and provide support in a variety of industrial use cases: from training [5–7] to virtual prototyping [8,9] and collaborative design reviews [8–10]. VR has been evaluated as one of the most important emerging technologies for Industry 4.0 interventions [11,12] due to flexibility of operations within virtual environments (VEs), and the richness of communication and multimodal interactions with virtual objects [13] coupled with enthusiasm toward utilizing novel technologies among industrial employees [14].
When it comes to the manufacturing and maintenance of heavy machinery, such as in the operations of KONE, VR technology provides solutions to overcome the limitations of the real world and, hence, addresses the challenges present in the industry [3,8]. Integrating VR technology into the whole product development lifecycle [15,16] demonstrates positive effects on overall optimization even at the early stages, by supporting design efforts and decision making [17]. Multi-user VR further advances quality and efficiency of collaboration among geographically dispersed teams in multinational companies [16,18] and integrates industrial practices in depth, such as Lean and Agile [15,19]. Moreover, the same industrial Collaborative VEs (CVEs) can be re-utilized to support other industrial activities, such as maintenance method development and associated technical documentation creation for heavy machinery. Industrial Maintenance and Assembly is the second largest application case for VR [20], as efficient maintenance plays a critical role in companies’ competitiveness, in addition to being an important source of revenue. VR allows experts from different multinational departments to collaboratively access simulated environments in cases where it would be difficult, unsafe, or impossible with real equipment. Further, they can interact on a 1:1 scale with virtual tools and virtual prototypes, thus advancing their spatial understanding and enriching communication. That potentially contributes to overall optimization and maintainability [2,21] via decreasing the number of design errors and associated high costs. In addition, industrial VR systems can be utilized for other critical tasks, such as prototyping of AR-based (Augmented Reality) in-field guidance for maintenance technicians [14], which in turn is another desired technology of Industry 4.0 to enhance maintenance services [22–24].

Despite all the benefits, industrial use of VR technology is still associated with a high cost-to-benefit ratio. Implementation is slowed down due to significant implementation costs [25], since every employee should have Head-Mounted Displays (HMDs) and/or powerful personal computers to utilize VR in their work. Additionally, the pandemic caused significant disruptions for supply chains for HMDs and PCs, further hindering the adoption rate of VR technologies in industries. This obstacle might be partly addressed with asymmetric VR usage, a relatively fresh research direction, studying the use of VR among devices with different levels of immersion and control, focusing on non-HMD user groups. The current body of research on asymmetry is mostly focused on co-located settings [26–29], where the physical presence of collaborators is an important design factor.

With forced social isolation, due to the worldwide pandemic, remote collaboration and, particularly, distributed asymmetric VR, becomes a more prominent research direction, the nature of which is still not fully explored [13,30]. By distributed asymmetric VR we refer to the technically supported remote collaboration of global teams, who use VR as an enhancement technology and have different access to it. In our case, we investigated the asymmetry when merging the collaboration over two digital worlds: the COVE-VR platform (see Figure 1) and Microsoft Teams (the company’s existing communication and teamwork tool). One distributed user group (referred to as VR-users) is present in the immersive multi-user collaborative environment, wearing HMDs and can interact with 3D CAD models and virtual tools. The second user group (referred to as Teams-users or non-interactive desktop users) can see the virtual environment through the eyes of VR-users and communicate with them via voice connection. Despite Teams users having no interaction with the virtual environment itself, they still have an active participatory role in the collaboration process by taking notes and snapshots with their laptop tools, thus contributing to the shared tasks.

This practical approach originated as a response to a preceding study [31,32], which suggested that the increased visualization capabilities of VR may be achieved even with a single user being present in VR and their interactions recorded or streamed to other industrial groups. Furthermore, the COVID-19 pandemic severely limited the availability of VR equipment on the global market and set some limitations to the study setup. The goal of the study was to explore how distributed asymmetric VR usage between VR and Teams users may shift traditional industrial practices in the pipeline of maintenance method.
development and technical documentation creation. The study addressed the following research questions:

**RQ1**: What are the relevant and beneficial use cases of applying asymmetric VR to aid industrial collaboration activities of geographically distributed teams?

**RQ2**: How to efficiently adopt distributed asymmetry between VR platforms and traditional conferencing tools in the industrial context?

To address the research questions and explore the asymmetry between a traditional conferencing tool and a VR platform in the industrial context, we conducted a remote user study with 20 experts from 4 countries: Finland, China, India and the USA. The study procedure was built to replicate the actual industrial tasks between geographically isolated teams.

![Figure 1. Multi-user interaction in COVE-VR platform.](image)

**2. Related Work**

Virtual Reality (VR) is a promising technology to address the challenges of industries and shift traditional ways of working into virtual spaces [20,33]. Considering the rapid digitalization and increasing quality of digital content in line with industry 4.0 [11], VR can safely simulate a variety of industrial contexts and enable natural interactions with virtual objects, for instance, with 3D CAD models [4,9,34]. This is especially beneficial for many industries, such as elevator manufacturing and maintenance, since access to real objects may be time consuming, difficult, not possible, or even dangerous in real-life scenarios. In this section, we firstly describe the application of VR for industrial needs and further provide background on collaborative VR solutions and VR asymmetry.

**2.1. Industrial VR**

Following the Industry 4.0 intervention, industries strive to innovate and increase the productivity and efficiency of their operations by transforming traditional practices with the use of emerging and convergent technologies [11]. The major goal of Industry 4.0 [12] is to intertwine and centralize tasks in product development through automation and digitalization. The possibilities of VR technology, blended with other immersive technologies and supported via integrated data chains [3,35], offer ways not only to advance the Industry 4.0 production model, but also to affect management philosophies positively, such as Lean and Agile [19,36,37]. Virtual reality and other immersive technologies have the potential
to enhance the Lean principles of waste reduction to optimize value creation [19,38]. For instance, an example from the construction field [37] demonstrated how a combination of innovative technologies, such as AR, VR and BIM (Building Information Modelling) positively influence key performance metrics and sustainability, thus enhancing Lean Construction. Similarly, as technology evolves, Agile practices procure and enhance team collaboration, and performance can benefit from adopting virtual reality, especially for distributed teams [36,39].

The usefulness of VR technology to support the design process in complex product development and related services is definite. For over three decades, multiple sectors have adopted VR solutions to explore its potential in different stages of the product development process [17,20,35,40–42]. These studies demonstrated that VR is a powerful production tool [20], which delivers benefits throughout the following activities of the whole production cycle [8]: early design phases, 3D modelling and virtual prototyping, co-design and design review sessions, product evaluations, virtual assembly, and education and training. In early design phases, VR enables the sense of scale which allows design and testing of virtual prototypes and identification of critical design flaws that are often overlooked with traditional computer tools [17,20]. This, in turn, supports design for maintainability [2,21] and helps to guide existing and future design directions [17], thus positively affecting overall product optimization [43]. Further, VR enables the creation of full-scale and immersive virtual environments that simulate the industrial context, where users can naturally, and safely, interact with virtual prototypes in different scenarios [20,25]. Evidence has shown that users experience a strong physical presence and provide both real-life physical and psychological responses in a VR environment [44–46]. Moreover, the same VE can be utilized to facilitate design reviews and enable employees to examine digital prototypes [15,47–49] to support maintenance method development and documentation creation [21,31], to perform product evaluations and testing with end-users [48,50] and training activities [6,7,51] in a safe and controlled environment.

2.2. Collaborative VR

As remote work has become more common, collaborative multi-user VR applications have gained popularity, offering a wide range of commercial-based and research software for use [42,52]. Collaborative VE (CVE), or “distributed virtual environments” [1], is known as a better alternative to traditional video-conferencing tools for many tasks related to product development. CVEs are capable of immersing employees from various teams and distributed geographical locations into a shared virtual workspace, where they can interact with each other and have access to virtual objects (e.g., 3D CAD models). Furthermore, multi-user VR ensures discussion quality [44,53] by providing a shared context, awareness of others, clarity, richness and openness of distributed communication, which are the critical elements of effective remote collaboration [46]. Due to the potential of blurring geographical barriers and delivering realistic experiences within completely virtual environments, collaborative VR systems may not only enhance the quality of communication, knowledge transfer, and interactions among multidisciplinary teams [17,33,52] but also potentially support business goals, while decreasing project duration, resource span, and overall costs [52].

The industry is the driver in adopting and developing collaborative VR, which is used mostly for the “Meetings” and “Design” use cases [52]. Collaborative VR has proven its potential to facilitate the collaboration of multidisciplinary industrial experts throughout the product development process [16,25,40]. In the early design phases, the use of VR leads to significant benefits for the team’s design efforts when applied to support design reviews in the field of manufacturing [17]. Further, in the design chain, VR is proven to be useful to facilitate communication between engineers and assembly operators, which enables the validation of installation processes, testing of services and maintenance tasks [49]. Another case study on VR-integrated collaboration workflow in the design chain, despite demonstrating the usefulness of VR simulations to address industrial challenges, highlighted...
that software and hardware expenses are the major obstacles to the wide adoption of VR technologies [25]. One of the ways to overcome the scarcity of equipment and reduce hardware expenses is to facilitate a hybrid collaboration between users who are present in fully immersive virtual environments (VR-users) and users who access VR via other devices (non-HMD-users), thus enabling the asymmetric use of VR.

2.3. Asymmetric VR

Asymmetric VR is a relatively new definition that originated from studies on virtual telepresence [54]. It describes a variety of interactions of co-located users in multi-user VE [55–57]. Lately, the traditional focus on single-user experiences with VR has shifted towards exploring multi-user VR interaction [58], which may occur on different levels of immersion and control among user groups. Despite asymmetry in cooperation being initially reviewed as a challenge to overcome, it delivers benefits in terms of flexibility and freedom in degree of participation [29]. Presence and experience in asymmetric VR were found to be significantly influenced by roles and tasks that were assigned to user groups [58]; therefore, when designing asymmetric VR collaboration, the asymmetry should be leveraged by defining roles in a way to embrace the differences of user groups [27] and extract their advantages [26].

A variety of research studies demonstrated how to increase immersion and presence of non-HMD users and facilitate the co-located asymmetric collaboration between a variety of devices. Gugenheimer et al. [26] presented the ShareVR proof-of-concept (co-located multi-user VR system), which increases the non-HMD users’ enjoyment, presence, and social interaction by immersing them into VE via floor projection and mobile displays in combination with positional tracking. Another article [28] identified the challenges and goals of asymmetric VR based on expert interviews and conducted a co-located user study on collaboration between VR-users and external users who observed VR-users via external tablet and interacted with the virtual environment by directly drawing over it. The presented TransceiVR system was proved to increase the quality of communication and positively affected task completion time, error rate, and task load index. A recent study [59] demonstrated an asymmetric collaboration setup between technicians in VR and experts in a meeting room based on a video stream from VR. Their findings showed the potential of the approach for other use cases and suggested a base virtual collaboration on several spaces, rather than focusing on a single space with rich interactions. Despite the presented positive effects on collaboration, the proposed systems still rely on costly additional technologies and were explored in a co-located setup, where the attributes of the physical world play a significant role [59]. According to the Composite framework for Asymmetric VR (CAVR) [56] in co-located settings, the simultaneous engagement of physical and virtual worlds is the base for facilitating collaboration over a mixed-reality space. The framework further introduced the dimensions of asymmetry: spatial copresence, transportation, informational richness, team interdependence, and balance of power.

Nevertheless, there is no clear understanding of how asymmetry might occur in distributed settings, when all users are located in different physical spaces and have different levels of interactivity with the virtual space and each other. Furthermore, there is a lack of generalizable knowledge on how VR and other novel technologies affect remote collaboration [30]. To address this gap and further explore the effects of asymmetry in distributed settings, our article explores how VR can be used as an enhancement technology to facilitate collaboration among geographically dispersed departments in an industrial context. Since in some countries access to technology was limited, due to the pandemic situation, we investigated how communication and shared tasks would be performed by VR-users and remote users who observe video feeds from VR streamed over Teams. By merging two virtual spaces, an immersive virtual world and a digital space in Teams, we generated a mixed-reality space for asymmetric VR collaboration.
3. Materials and Methods

This study is action-based research, conducted in collaboration with industry and academia. In this section, we firstly describe the industrial corporation, its processes and associated challenges. Further, we detail the requirements for VR system design, linking these to the industrial scenario and required tasks. Finally, we briefly describe the components of the COVE-VR platform that are relevant for the user study conducted.

3.1. Industrial Context: Maintenance Method and Technical Documentation Creation

KONE is a large manufacturing company, producing elevators, escalators, and automatic building doors. In addition, KONE provides maintenance services, which is an essential part of the revenue. Design for maintainability is an important area of product innovation, and maintenance methods are developed, and corresponding documentation created, as a part of the product development process. The maintenance instructions on how to perform maintenance tasks are used both in field work and in training [60].

Maintenance methods and the related technical documentation are developed iteratively in close cooperation with the maintenance development department (MDD) and the technical documentation department (TDD). The departments consist of multinational multidisciplinary teams, located in different locations and time zones. The major challenges of such collaboration include the lack of access to real equipment and the limitations of traditional channels (e.g., Teams, emails) to communicate complex product information, such as geometry and assembly/disassembly procedures.

Figure 2 shows the current pipeline of maintenance method development and technical documentation creation. Method developers create and design maintenance methods, which are further written and illustrated by technical writers and illustrators from TDD. Due to the frequent unavailability of physical equipment or prototypes, the method developers might never interact with real equipment and perform their tasks based on 2D images or 3D models on a computer screen. Such an approach is error-prone due to the limited spatial and contextual understanding and might lead to a situation where the method cannot be performed in reality, or requires unexpected additional work. Maintenance method developers use markups in existing pdf files or paper copies to create an outline: a draft version of the maintenance method. Once the outline is ready, technical writers and illustrators develop it further into technical instructions. If the writers and illustrators have no access to the equipment, they rely solely on the outline and notes given by the maintenance method developer. In many cases, this results in misinterpretations and mistakes. When a draft is available, it is reviewed and commented on by the method developer, and the comments are then implemented into the draft by the technical writer and illustrator. The commenting might take several rounds until both parties are happy with the draft. The number of rounds is increased by any misunderstandings or communication problems, especially if the parties involved are not physically in the same location.

![Figure 2. The process of maintenance method development and documentation creation at KONE.](image-url)
VR technology can optimize these processes by facilitating both asynchronous and synchronous collaboration activities within a simulated virtual environment and provide access to virtual prototypes throughout the method development process. Whereas the preceding study [31,32] investigated and demonstrated the usefulness of VR for asynchronous collaboration scenarios (where the departments were accessing VR in a sequence), this study is focused on synchronous collaboration practices. In particular, it explores the role of the synchronous collaboration scenario 1 at the phase “outline preparations” (see Figure 3), which may potentially minimize the misinterpretations and communication problems in the later phases of the maintenance method and technical documentation creation. In this scenario, both departments can jointly access virtual prototypes for the first time, exchange knowledge and generate digital content together, e.g., text and pictures, that can be re-utilized for technical documentation creation.

**Figure 3.** Maintenance Method Development and Technical Documentation creation.

### 3.2. COVE-VR: VR System for Industrial Collaboration

The platform was designed as a co-creation project between academic and industrial researchers from KONE, imitating the industrial process of product development [31]. The major purposes of this VR system are the following: (a) facilitate easy access to, and natural interactions with, virtual prototypes (3D CAD models), (b) aid the synchronous and asynchronous collaboration of multinational remote teams and (c) enable digital content creation directly in VE. By digital content we refer to materials, such as textual notes, photos, and videos that may be further used for communication and documentation purposes. The COVE-VR platform consists of two virtual environments and seven virtual tools.

#### 3.2.1. Virtual Environments

Two virtual environments were created to cover multiple scenarios of synchronous and asynchronous collaboration (shown in Figure 4). The Lab VE (1) is a small-sized working space for individual or pair-work that replicates a real elevator shaft based on existing 3D CAD models. This space allows quick and safe access to the virtual "space", which is a time consuming and hazardous process in real life. The Showroom VE (2), on the contrary, was designed to allow assembly/disassembly of virtual prototypes and facilitate collaborative work between larger groups of people, including client presentations.
Figure 4. Working virtual environments: (a) the Lab VE, which replicates a real elevator shaft and (b) the Showroom VE with a disassembled 3D CAD model.

3.2.2. Virtual Tools

We define virtual tools as virtually tangible elements of VE, which have a function to perform over VE (whether it be the creation of new digital content or manipulation of VEs to facilitate the execution of industrial tasks). Eight virtual tools were created to aid the process of maintenance method development and technical documentation creation.

The Showroom is equipped with a 3D model pedestal, the so-called (1) Disassembler, which allows in-depth investigation of 3D models (assembly/disassembly), including changing their size, rotation, and vertical position via the wall menu. The models can be disassembled into parts, which in turn can also be highlighted or removed.

All other tools are accessible in both virtual spaces; they are opened via the wrist menu on the left controller. The Model Placement tool (2) allows importing any 3D CAD model in the STEP format to the virtual environment. The models are converted asynchronously in the background by a separate application, which we developed to continuously check for new models placed in the application’s directory. The import process in the VR application itself was also made to be as asynchronous as possible, although it still resulted in slowdown and a loading screen was therefore added. Several levels of detail are created, of which the highest is only used for visuals and the lower levels can be used for collision. However, in our case, a simple box collider was enough and significantly faster for interactions in the VE. Colors are preserved, but metadata is not converted, which is a shortcoming of our approach.

The TextBox tool (3) was designed to create textual notes in VR, which can be used to support asynchronous communication or directly as textual elements for technical documentation. Text can be inputted via speech recognition or virtual keyboard in two languages (in our case study): English and Finnish. Support for other languages could be added as needed. The note can be left as a text box or as a smaller message bubble icon in virtual space. All text notes created in VR are further able to be exported to a file with the author’s name, the message number and a timestamp.

The Camera tool (4) is a multipurpose tool made to allow taking pictures and videos from a virtual environment. All created media files can be accessed from the desktop. In addition to regular photo and video modes in front- or back-facing mode, with or without a timer, the tool also supports outline rendering, which captures only the line art in black and white.

The Measure tool (5) was added to allow taking measurements of the dimensions and distances required for maintenance method creation. To lock the movements of 3D models and measures over grid points, the Grid Snipping tool (6) was created. The grid size can be adjusted. With the Delete tool (7), 3D objects and other tools can be removed from a virtual
environment. Finally, the Save World State tool (8) is used to save all created content in the VE, or to load an existing state, for example, one left by the previous worker.

In summary, our virtual tools were designed to fulfill industrial needs: to advance department-to-department communication and to enable digital content creation for maintenance documentation. At the same time, the tools are generic enough to support many other industrial use cases that were not considered here.

3.3. Hybrid User Study with Domain Experts

This article presents the action-research case study with domain experts on how the COVE-VR platform, designed to advance industrial practices in the pipeline of maintenance method development and technical documentation creation, can be integrated into the company’s working processes to support collaboration among geographically distributed departments. The goal of the study was to investigate the role of asymmetry between the VR platform and the currently used teamwork tool, the Teams, and how to expand the VR system design to advance collaboration practices. The study aimed to measure the experts’ perception of VR technology and remote collaboration, as well as find the differences in workload, and other elements of user experience, between two distributed participant groups. To address the study goal, a remote user study that replicates the actual industrial collaboration tasks was conducted with expert participants.

3.3.1. Participants

In total, 20 experts (16 male and 4 female) aged from 27 to 60 (with an average of 40), participated in an asymmetric VR collaboration process between the COVE-VR and Teams. All the participants belong to KONE company with, on average, 5.5 years of experience in their areas (Min = 1, Max = 22); ten of them represented the technical documentation department (TDD), eight represented the maintenance development department (MDD) and two were from mechanical design. Regarding education level, 17 participants hold a bachelor’s degree or similar, two hold a master’s degree or similar and one graduated from a vocational school. In terms of country of residence, 11 participants were from Finland, six from India, two from China and one from the USA. Five experts had previous single-user experience with the COVE-VR system.

3.3.2. Participant Groups and Roles

The participants were divided into two groups: (1) VR-participants, who were present in the virtual environment and were able to interact with it, and (2) Teams-participants who watched a streamed video from the perspective of one of the VR-participants via Teams desktop application. Teams-participants were able to communicate verbally with VR-participants and performed tasks outside of the VE using their laptop tools. In total, 5 remote sessions with 20 participants were organized: ten VR-participants, wearing HMD, and ten Teams-participants (referred to as VR and T). Each session was planned to have four participants: two VR and two Teams participants. However, due to a scheduling conflict, one Teams participant skipped their session and joined a later one, causing one session to have 3 participants, and another session 5 participants.

The battery replacement procedure was performed collaboratively during the test; every participant had their own role and related set of tasks, represented in Table 1, thus mimicking their real work tasks and role. The battery replacement task was chosen because it is a fairly complex procedure consisting of identifying the components and parts, opening and closing lids, releasing fixings, and disconnecting and reconnecting cables. As the task is performed in a high-risk environment, the replacement also involves several safety measures both before and after the replacement. The tasks were further split into two scenarios: (1) 3D CAD model exploration in the Showroom space and (2) Assembly/Disassembly of a 3D CAD model in a simulated context (Lab VE). The VR-participant 1 acted as the eyes for the Teams participants while performing assigned tasks and followed the instructions from Teams participants to find the best view. VR-participant 2 was mostly responsible for inter-
acting with 3D models and virtual tools. Teams-participant 1 took notes during the whole process as well as asked for more details, e.g., additional measures of the 3D components. Teams-participant 2 instructed VR-participant 2 to find the best possible position and took screenshots from their view. Overall, the tasks were designed to perform the collaboration between VR-participants as well as collaboration between VR and Teams participants.

Table 1. Tasks for the user study.

<table>
<thead>
<tr>
<th>Task Number</th>
<th>Task Description</th>
<th>Task Type</th>
<th>Participants</th>
<th>Tool Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Open a 3D model, explode it and adjust the scale, distance and levitation</td>
<td>Individual</td>
<td>VR2</td>
<td>Disassembler</td>
</tr>
<tr>
<td>2</td>
<td>Locate a component (batteries), find a good angle and take a screenshot</td>
<td>Shared</td>
<td>VR1, T1, T2</td>
<td>Disassembler, desktop tools</td>
</tr>
<tr>
<td>3</td>
<td>Take a photo to support the illustrators for the battery replacement task in outline rendering mode</td>
<td>Shared</td>
<td>VR2, T2</td>
<td>Camera tool–outline mode</td>
</tr>
<tr>
<td>4</td>
<td>Get additional photos in outline rendering mode</td>
<td>Shared</td>
<td>VR2, T2</td>
<td>Camera tool–outline mode</td>
</tr>
<tr>
<td>5</td>
<td>Take a photo to support the illustrators for the battery replacement task using a regular camera mode</td>
<td>Individual</td>
<td>VR1</td>
<td>Camera tool–regular mode</td>
</tr>
<tr>
<td>6</td>
<td>Teleport to Lab VE</td>
<td>Individual</td>
<td>VR1, VR2</td>
<td>Wrist-menu</td>
</tr>
<tr>
<td>7</td>
<td>Take general measurements of the component</td>
<td>Individual</td>
<td>VR2</td>
<td>Measure tool</td>
</tr>
<tr>
<td>8</td>
<td>Take additional measurements (from the component to the wall) and record them via a screenshot</td>
<td>Shared</td>
<td>VR1, VR2, T1, T2</td>
<td>Measure tool, desktop tools</td>
</tr>
<tr>
<td>9</td>
<td>Document the battery replacement workflow via speech input</td>
<td>Individual</td>
<td>VR1</td>
<td>Textbox tool–speech-to-text</td>
</tr>
<tr>
<td>10</td>
<td>Add a text note with the name of the component via virtual keyboard</td>
<td>Individual</td>
<td>VR2</td>
<td>Textbox tool–virtual keyboard</td>
</tr>
<tr>
<td>11</td>
<td>Delete the last text note on request</td>
<td>Shared</td>
<td>VR2, T2</td>
<td>Delete tool</td>
</tr>
</tbody>
</table>

3.3.3. Remote User Study Set-Up

The user study was held remotely, meaning that all the participants were present from different locations. In each session, VR-participants performed testing at KONE facilities from two different rooms, whereas Teams-participants connected from other countries.

All communication was conducted via Teams, as shown in Figure 5. The main facilitator moderated the user test from the same room with VR-participant 1, whose point-of-view was streamed over Teams. The support facilitator was present in another room with VR-participant 2 to provide guidance and technical assistance. The chat facilitator was present in Teams meetings to manage Teams-participants and track the completion of their tasks. All sessions were observed by at least one industrial researcher.
VR-participants and facilitators could listen and talk to others on the call using external speakers with built-in microphones, while the meeting audio was transferred to the VR headsets utilizing their built-in microphones for communication by adjusting Teams audio settings. In other words, the headsets acted as the aforementioned external speakers. Additionally, the rooms with VR-participants were equipped with standalone cameras to stream the physical view of the rooms via Teams. A more detailed description of the setup and procedure is presented in [61].

The user study procedure started with signing the consent forms, followed by a brief introduction to Teams and a training video about the COVE-VR. After which participants filled in a pre-survey on expectations. VR-participants proceeded with a hands-on training session in VE (both used Vive Pro Headset), while Team-participants observed the training and could ask questions in the Teams chat. To avoid the risk of motion sickness in VR, VR-participants were instructed to immediately take off their headset and inform the moderator in the event of feeling any sickness.

Next, the collaboration process between the COVE-VR participants and Teams-participants was performed, based on a set of tasks designed to replicate a real industrial context (Table 1). All the participants were encouraged to follow the think-aloud protocol for the duration of the procedure and freely express any emotions and opinions aloud. After all the tasks were completed, the participants discussed their experience in a group interview and filled in a post-survey.

### 3.3.4. Collected Data and Analysis

Both qualitative and quantitative data was collected during the study. The qualitative data was collected through a semi-structured interview and observations, while the quantitative data was collected via online pre- and post-questionnaires, created with the LimeSurvey tool.

In the pre-questionnaire, participants shared their expectations on the COVE-VR system based on the video they watched. This was the first part of the SUXES questionnaire, which was used to access the differences in expectations and experiences with VR technology [62]. The post-questionnaire consisted of six parts: (1) experiences with the system (as the 2nd part of the SUXES), (2) self-designed statements on collaboration, (3) workload via raw SIM-TLX [63], (4) self-designed statements on the perception of VR technology, (5) statements on immersion for VR-participants, adopted from Presence Questionnaire [64],
and (6) background information. In this paper, we present the data from the 1st, 2nd, 4th and 6th sections.

The semi-structured group interview was conducted at the end of the study by the main facilitator to raise discussion on the usability of the system, the asymmetry between VR and Teams and related collaboration practices; the participants were asked to turn on their cameras during the interview (Figure 6). The interview script consisted of five sections, covering (1) general UX, (2) VR system’s usefulness and efficiency for industrial tasks, (3) experiences of asymmetric use between VR and Teams, (4) roles and tasks in asymmetric collaboration, and (5) improvements for the COVE-VR platform and asymmetric collaboration practices. Additionally, observation forms with pre-defined questions were used to collect observation-based data systematically.

The collected data was analyzed in collaboration with academic and industrial researchers. A descriptive statistical analysis was performed over quantitative data because of the relatively small sample size. The observations and interviews were analyzed using thematic qualitative data analysis [65]; the gathered data was categorized by themes with affinity diagrams. The most popular themes were multi-user and teamwork interaction, roles in asymmetric interaction, remote participant UX, VR tools, and complimenting teamwork with voice commands.

4. Results

This section presents the combined results of qualitative and quantitative results, starting from overall reaction to the industrial VR platform, its usefulness for the company’s processes, and usability of the asymmetric use, followed by evaluation of the digitally-hybrid collaboration process and reflection on how to advance it. The results of the questionnaires, as well as experts’ quotations, are presented by the participant groups, since VR-participants’ (VR#) and Teams-participants’ (T#) experiences with the system were different in terms of interactivity with VE and immersion.

In summary, both participant groups actively participated in the collaboration process, seriously accepted their roles and were able to finish their tasks successfully, helping each other, sharing knowledge, and generating useful digital materials. Based on the observations, the shared tasks and communication between VR- and Teams-participants not only positively influenced the efficiency of the industrial work process, but also increased the spatial understanding of both participant groups. Teams-participants supported this observation during the interview:
T2: “With the current tools [it] is really hard to see the views from the product, with this kind of view it would be easier and easily understandable to begin the illustrations at the beginning [of the documentation process]”

T3: “Measurements were excellent, for example, you get the scale of things”.

4.1. Overall Reaction and Usability of the COVE-VR Platform

The concept of a VR system to facilitate the collaboration of multinational departments in various phases of product, and related services, development was found to be extremely advantageous by industrial experts. They further reviewed it as “a low-cost option” (VR1) to address existing industrial challenges, to “save a lot of time”, and “reduce the number of iterations” (T4). One of the VR-participants further suggested:

T6: “I think VR has to be done in every milestone so we can really integrate VR to the KONE process. The milestones in the process should be aligned with the product workflow so then it aligns with the schedule of the product”.

The digitally hybrid collaboration approach with the COVE-VR was found to be beneficial by both participant groups, whereas virtual working spaces and interaction with virtual prototypes were seen as a way “to improve the communication and have high-efficient meetings” (T1). The results of the survey on the subjective perception of VR technology are shown in Figure 7, that visualizes the minimum, maximum and median of survey answers in two groups: orange for VR-participants and violet for Teams-participants. The figure demonstrates the main trends of perception and minor differences between the two groups, by showing the division of answers over a 7-point scale, together with the middle value of answers. The results revealed that all industrial experts agreed or strongly agreed that the potential of collaborative VR can benefit the company’s working processes and supported the idea of transferring their working processes into VR. In general, the figure shows that VR was evaluated as a technology to advance industrial working processes by a majority: only one VR-participant and two Teams-participants left negative responses to several statements. On the opposite side, all experts believed that VR can enhance department-to-department collaboration. Further, 95% of the experts found VR to be flexible for the company’s work processes, felt enthusiastic to use VR to perform their work tasks and believed that the use of VR would increase their motivation. 90% would like to use VR at work and agreed that VR would increase their performance. Finally, when counting the percentage of agreements for the statements, the use of VR was found to make their work easier by 85%, safer by 75%, and faster by 70%.

The usability of the COVE-VR was measured by the SUXES questionnaire, which compares expectations towards the system and the actual experiences with it (Figure 8). Overall, expectations and experiences for both participant groups were mostly positive and neutral; none of the participants selected negative extremes. Furthermore, VR-participants and Teams-participants found the COVE-VR system to be useful and would like to use it in the future. In addition, the general trend observed was that the expectations were lower than the actual experiences with the COVE-VR system; only two VR-participants and two Teams-participants somewhat disagreed with several statements after using the system.

Additionally, the figure shows the increase in the VR-participants’ perception after using the application: the VR-participants perceived the system to be faster, clearer, and easier to learn after completing the user study tasks. Decrease was only observed for the statement that the application functions error-freely; several interactions and UX errors were identified during the user study.
The iteration would benefit from having it in the future. In addition, the general trend observed was that the expectation participants and Teams and Overall, expectations and experiences for both participant groups were mostly positive compares expectations towards the system and the actual experiences with it (Figure 8).

Figure 7. Employees’ perceptions of VR technology for the industrial context.

Figure 8. Expectations and experiences with the VR platform.
4.2. Digitally-Hybrid Collaboration

The asymmetric COVE-VR use between VR-participants and Teams-participants was reviewed as a more promising alternative to traditional communication channels (such as emails and video calls, or chatting over Teams) for industrial collaboration needs. The results of the survey showed (Figure 9) that although the asymmetric collaboration was perceived less positively than the COVE-VR system itself, the medians are still on the positive or neutral side. Only one Teams-participant, who is highly experienced with VR technologies, left negative or extremely negative responses to all the statements on collaboration.

![Figure 9. The results of the collaboration-related questionnaire.](image)

Otherwise, 95% of experts agreed that the system could help the team to establish agreements on future action points and 80% agreed that the system made it possible to create a cooperative atmosphere among the team members. The experts, who participated through Teams, highlighted the usefulness of a multi-user VR environment, where “one can do things in the same location even if not in the same place” (T5). Moreover, such hybrid collaboration was found to save time during the collaborative task by 60% of the experts and may further save time by advancing the Lean and Agile philosophy, since “the iterations can be reduced because some clarifications can be done there with other team members.” (T7). Another expert commented that with collaborative VR, “we can avoid ping-pong email-you can directly ask and discuss” (VR2).

Further, some VR- and Teams-participants alike reported positive effects of the VR system on co-presence, commenting: “Even though *name* was there virtually, it felt like he was really there” (VR3) and “it looked like that we were in the same environment. I thought people...” (T2).
were standing besides me” (VR4) and “I was asking the VR participants to change views or do things and I was seeing directly their view, so I felt we were in the same place” (T2).

However, the quality of communication between experts and the efficiency of asymmetric collaboration could be significantly increased; even though 75% of experts agreed that the COVE-VR system design positively affected the collaboration process, only 55% found that the virtual tools were useful for collaboration and would like “to have better tools for interaction” (VR6). In general, hybrid collaboration would benefit from having more visual elements to support the communication, which were lacking in the current system design. Additionally, it was not easy to see and understand participants in VR, and also 40% of the VR-participants found it somewhat difficult to understand the participants who joined via Teams. Experts commented that they wish to have “more transparency on what the other participants are doing” (VR5) and “would like to have pointers from the other participants” (VR1 and VR7, or the “possibility to highlight objects” (VR8), which would support the collaboration process visually.

During the interview, experts further discussed the issues of asymmetric settings and provided suggestions to enhance it. One of them commented that “the communication with all the participants was quite natural, the only issue was that I didn’t know who was talking” (VR1). Another participant commented: “I don’t think there was many differences between the communication among participants. Ultimately, we all were in different places” (VR9). Interestingly, the experts’ communication greatly benefited from the “think-aloud” approach, used for research purposes. Although the lack of visual elements hindered the overall experience, some experts commented that “the voice helped us communicate with others” (VR9). The verbal communication happened mostly between Team- and VR-participants; by the end of the sessions, Team-participants gained more confidence to guide the VR-participants to overcome the lack of visual cues. However, for some participants, the non-interactive role within VR was not sufficient, one of them said “[I was] lacking the immersion, lack of being able to control things was difficult.” (T8); they suggested adding access to the COVE-VR via the desktop user interface; “even partial control for remote [desktop] users for the viewpoint [would be good], I was trying to scroll to get my own view—would be good to have a possibility to get your own view as remote user” (T9).

5. Discussion

This article presented the results of the expert case study on integrating COVE-VR platform using asymmetric setup with Teams to facilitate the collaboration of geographically distributed departments involved in the pipeline of maintenance method development and technical documentation creation. The study addressed the actual challenge present in the industry, whereas the study design on asymmetric VR was dictated by real-life limitations, such as travel restrictions during the COVID-19 pandemic and the unavailability of HMDs for purchase in global markets.

Previous studies on asymmetric VR have mostly focused on co-located settings and explored how to increase the immersion and feeling of control for non-HMD users relying on additional costly technologies [26,28,55]. However, there is still no clear knowledge on how asymmetry might occur in distributed settings. To address this shortcoming, this study explored a scalable approach to distributed asymmetric VR, based on adding desktop users via Microsoft Teams, who get a visual representation of VE over streamed video and can interact with the VR-users over voice to complete shared tasks. This setup can still be referred to as collaboration over a mixed-reality continuum, since the collaboration happened via merging two virtual worlds with different immersion levels. The strongest contribution of this industry-focused study lies in eliciting the data involving multinational domain experts based on actual industrial scenarios, roles, and tasks.

Overall, our study indicates the potential of a practical asymmetric VR setup to fulfill industrial needs. By merging the use of VR with traditional conferencing tools, it is possible to extract the value of VR technology without the need to provide expensive equipment to every employee. In contrast, distributed asymmetric use of VR is sufficient to improve
the communication of departments in several industrial scenarios, which, in turn, leads to increased scalability, accessibility, and cost reduction. Therefore, with this article, we suggest that the adoption of VR technology for industrial needs can reach a wider range of interactive and non-interactive users when it can be performed without extensive hardware costs, which was noted as one of the main obstacles towards wide VR adoption [25].

5.1. Industrial Use Cases for Asymmetric VR

Supporting the previous studies [2,8,16,17], we argue that VR technology is a game-changer for industrial processes and one of the most important production tools to supplement and optimize product and related services design and development processes in line with Industry 4.0.

 Particularly answering RQ1, our case study demonstrated the value of asymmetric VR settings to support the collaboration of multinational departments in two key ways: (1) to design maintenance methods and (2) to draft technical documentation. Design for maintainability requires an understanding of how maintenance can be done efficiently (e.g., Can the technician reach something? or Is there enough space for performing maintenance tasks?). Hence, it is critical to correctly perceive the scale of the space. One shortcoming of exploring 3D CAD models on a 2D computer screen is lack of understanding of the real spatial dimensions. Therefore, one of the major tasks for these use cases is to accommodate 3D model exploration tasks in VE on a 1:1 scale among geographically distributed experts. In addition to improving the spatial understanding of the VR-users [57,66], our expert study showed that the spatial understanding of the Teams-users was also improved with the asymmetric settings. The possibility to communicate verbally while observing and guiding VR-users (and their avatars) to interact with the 3D model in virtual space improved their understanding of the scale. Furthermore, the use of virtual tools for content creation (e.g., Textbox or Camera tools) enables easy capture of digital materials that can be utilized for compiling draft versions of documents and further supporting the communication process.

Interaction with 3D CAD models is an important task in many industrial contexts [4,34,49] which may be performed throughout the product development lifecycle in other use cases. The asymmetry for this task can be applied to boost scalability and include users with no access to HMDs in the collaboration process, thus addressing existing challenges of industrial maintenance, such as the lack of understanding of the real scale when developing maintenance methods. The asymmetry in both use cases can be dynamically arranged to enable appropriate knowledge transfer, depending on team composition, and requires only one VR-user to manipulate a 3D model and demonstrate it to remote users.

Expert insight also showed the value of the asymmetry between VR-users and non-interactive desktop users for other industrial use cases, such as (3) global training and (4) virtual maintenance assessment. Asymmetry in the training process is based on knowledge transfer from experts to novice learners in a simulated safe environment [7]. In this scenario, an expert (knowledge owner) would participate as the VR-user, whose point-of-view would be streamed to learners via traditional conferencing tools. This way, learners may follow the educational materials from any physical location and any platform. Similarly, as described by Clergeaud et al., [59], another use case for asymmetric VR settings in industry is in virtual maintenance assessments. In this case, the asymmetry is reversed. The maintenance expert (knowledge owner) would be a desktop user, who would follow a technician’s actions in VR and evaluate the efficiency of the maintenance method. Performing both use cases mentioned in a real industrial context might be dangerous or even impossible. Hence, applying asymmetric VR to enable global training and virtual maintenance assessment could improve the company’s overall accessibility and sustainability by granting access to flexible simulated environments and, consequentially, reducing travel costs. Therefore, distributed asymmetric VR in the industry can prompt agility in the processes by reducing travelling times to training or testing sites [67] while increasing access for users that do not have HMD hardware available [35].
5.2. Advantages of Asymmetry

Our study highlights that the distributed asymmetric VR between VR-users and non-interactive desktop users is a valid low-cost solution to advance the communication and knowledge transfer between multinational and geographically dispersed departments in a variety of industrial use cases. The majority of experts were intrinsically motivated toward utilizing VR in any available form despite several usability issues. The experts’ desire to adopt VR for their work tasks and synchronize it with product development milestones highlights the value of the designed COVE-VR system for industrial contexts.

Expanding on the previous findings [17], our article suggests that asymmetric VR positively affects decision making and increases the number of employees who may participate and contribute to the collaboration process, because it enables accessibility for employees that do not have access to HMDs or other advanced technologies. Such asymmetry may further advance flexibility in terms of engagement levels and degree of participation in work activities [3], which potentially increases workplace satisfaction levels. Further, due to the ability to support industrial collaboration [4,42,48,49] by providing rapid access to virtual prototypes and tools for content creation, asymmetric VR is a promising approach to advancing and integrating Lean and Agile industrial practices [19,39]. Our study showed that distributed asymmetric collaboration in VR may reduce the number of iterations in product development and, thus, minimize lean waste and support cost reduction. It also allows faster and less expensive execution of industrial tasks, resulting in faster time-to-market and overall optimization.

Our findings further indicate that such an asymmetric approach, apart from enhancing teamwork and communication between industrial departments from different countries, may also raise awareness and knowledge of VR among industrial employees with no previous experience and access to VR devices, which potentially delivers several benefits. One of the remote participants (a first-time user of VR, located in India) commented: “It was an amazing, very thrilling experience. Once when we get the real VR experience it would be great” (T2). First, this allows extending the pool of test users, who might be included for further VR software development, which is critical for adopting and localizing the software for different cultural user groups in multinational companies. Additionally, such an approach would enable a smooth introduction to VR technologies and steadily prepare employees for Industry 4.0 interventions. Therefore, our study suggests that asymmetric collaboration between VR platforms and traditional conferencing software, such as Teams, is a worthy strategy to facilitate knowledge transfer between industrial experts, and is generalizable to other industrial contexts and collaboration scenarios.

5.3. Asymmetric VR: Guidelines

In this section, we answer RQ2 by summarizing our findings in a form of six guidelines on how to support remote industrial collaboration and efficiently adopt distributed asymmetry between VR platforms and traditional conferencing tools for this purpose.

The guidelines are supported by Figure 10, which visualizes the nature of asymmetry between VR platform and traditional conferencing tools and further determines the perspective from which the guidelines should be approached: organization, collaboration and technology perspectives.

**Guideline 1: Identify the Use Case and Assign Roles and Tasks.** Our case study, supporting previous work [27,55], demonstrated that a clear division of roles and tasks may ease up the collaboration process in asymmetric distributed settings. Hence, based on the scenario of asymmetric VR and the pattern of knowledge transfer, all collaborators should be assigned roles to ensure that every participant has a shared understanding of their and others’ tasks and how mixed-reality space accommodates these. In particular, this would support the dimensions of asymmetry (e.g., transportation, team interdependence and power balance [56]) as well as potentially ensure team dynamics and collaborative tasks accomplishment despite the limitations of asymmetry.
would support the dimensions of asymmetry (e.g., transportation, team interdependence, VR software development, which is critical for adopting and localizing the software for a variety of industrial use cases. The majority of experts were intrinsically motivated toward tasks accomplishment despite the limitations of asymmetry and power balance [56]) as well as potentially ensure team dynamics and collaborative their and others' tasks and how mixed-reality space accommodates these. In particular, this should be assigned roles to ensure that every participant has a shared understanding of the scenario of asymmetric VR and the pattern of knowledge transfer, all collaborators on the three perspectives.

5.3. Asymmetric VR: Guidelines

The guidelines are supported by Figure 10, which visualizes the nature of asymmetry as a user or as a facilitator. This lowers the bar for using a new technology and speeds up stress associated with the use of novel technology. For remote users, training would raise awareness of the possibilities of VR, prepare them for the limitations of non-interactive users and educate them on how to overcome these.

Guideline 2: Present the Value and Limitations via Training. To accomplish efficient digitally hybrid collaboration, all the users should be aware of why VR is used to supplement their work activities and what the value and functionality of the VR software is. The users should receive specific training on remote or HMD use since the capabilities and UX is different depending on the user group. For VR-users, training would increase the usability of the system, which positively affects feelings of control and reduces the stress associated with the use of novel technology. For remote users, training would raise awareness of the possibilities of VR, prepare them for the limitations of non-interactive users and educate them on how to overcome these.

Guideline 3: Nominate and Train the Key VR User. In addition to regular training, our findings suggest that at least one person, who is familiar with the VR environment and defined as the key VR user, should be present in every session or be available online, either as a user or as a facilitator. This lowers the bar for using a new technology and speeds up technology acceptance [68].

Guideline 4: Embrace Voice Interaction. Since the main link between the two digital worlds is direct communication via voice, the use of it should be emphasized to the greatest extent possible. Special techniques, similar to the “think-aloud” approach, may be integrated into the collaboration process to raise employees’ confidence and support trust and open discussions, as well as more concrete instructions from non-HMD users. This would positively affect the team interdependence dimension [56], the quality of communication in general, and the accomplishment of shared goals [69].

Guideline 5: Increase Visual Fidelity. The major goal of asymmetric VR setup is to share the spatial understanding of virtual simulated space and the virtual objects inside

Figure 10. Guidelines on how to support asymmetry between VR and traditional conferencing tools.
it, related to the information richness dimension [56]. Hence, visual clarity is a critical factor affecting the quality of asymmetric industrial collaboration, and it can be enhanced in several directions. One of them, suggested previously [28], would be to provide a static and stable video picture that would be streamed to non-HMD users. By implementing a virtual camera that can be manipulated by VR-users, it is possible to increase the quality of pictures from VE and support more detailed observations for non-HMD users. Furthermore, enhancing VR-users’ visibility would positively affect the collaboration of both user groups. That would include using graphics and animations to visualize VR-users’ movements in VE and their interactions with virtual objects.

Guideline 6: Support the Collaboration directly in VR. Previous work demonstrated that the role of VE’s features on the overall user perception is more significant than the platform used [54,58]. Hence, when creating VR systems to support industrial working activities, both VR-users and non-HMD users should be considered. In case of the VR software being initially developed to support single-user interactions, additional functionality should be considered to add transparency to VR-users’ actions and enhance the collaboration practices. This can be achieved by integrating supportive collaborative tools to visualize the users and the objects with which they interact. Highlights, pointers and teleportation trajectory were suggested by experts among other solutions, which would further contribute to information richness.

5.4. Limitations and Future Work

A limitation of this study is its narrow focus on a single company’s work processes. Despite the value of presented asymmetry to industrial scenarios, the influence of asymmetry in distributed settings should be further explored in the work processes of other large manufacturers, as well as in other fields and contexts. Additionally, further work on using asymmetric VR, and especially a comparison of collaborative activities in multi-user distributed VR and in similar asymmetric VR, would shed more light on the topic, since both setups have advantages, limitations and application scenarios [60]. Future research may also look into advancing the scalability of the approach and expanding the asymmetry towards portable devices.

To further advance the communication and teamwork quality, it is critical to address the lack of immersion and interaction of the non-HMD user. Additionally, it is critical to identify resource-efficient ways to increase the sense of co-presence when merging the use of VR and traditional conferencing tools. Our results demonstrated the desire to obtain at least some level of control, which suggests the use of VR user interfaces designed for 2D screens. In this case, it is not obvious to what extent freedom of interaction and control for non-HMD users would affect the collaboration practices. The symmetry between 2D and 3D VR asymmetry when applied remotely in an industrial context is another topic to investigate, since it holds the potential to advance the feel of co-presence without massive costs.

6. Conclusions

With a recent shift towards remote work practices, and the rapid development of emerging technologies, collaboration over the mixed-reality continuum is becoming a more prominent research topic in HCI and CSCW fields. VR in combination with other maturing technologies of Industry 4.0 offers a way to shift and optimize traditional industrial operations. Evidence has shown that VR is an efficient production tool [6,11,46,49] to support product development and related processes, especially for geographically dispersed teams. Immersive VE, with realistic simulations and multi-user support, may significantly reduce costs and project span by offering a digital space for many industrial operations that are difficult, dangerous, or time consuming. However, due to many external factors, the wide adoption of VR technology is still not possible.

This study explored the asymmetry between VR-platform and the traditional conferencing tool (Microsoft Teams) to facilitate the collaboration of multinational departments...
in the pipeline of maintenance method development and documentation creation. The study stands out from the existing work by involving domain experts as participants in realistic industrial scenarios. The study demonstrated that distributed asymmetric VR is a low-cost and scalable solution that can easily integrate with current industrial remote working practices. Furthermore, not only does it positively influence the adoption of VR in the industrial context, but also enhances Lean and Agile practices. Based on expert insight, we identified four use cases in the field of Industrial Maintenance, which would greatly benefit from distributed asymmetric VR: maintenance method development, technical documentation creation, global training, and virtual maintenance assessment. To further boost the adoption of VR technologies in the industrial context, we provided a list of guidelines on how to support the asymmetry between VR and traditional conferencing tools. The guidelines address the asymmetry from three perspectives: organization (assign roles and tasks based on the use case), explain the value of VR to the employees and nominate the key VR user), collaboration (embrace voice interaction), and technology (advance visual fidelity and support collaboration directly in VR).


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**References**


Paper V


Evaluating the Benefits of Collaborative VR Review for Maintenance Documentation and Risk Assessment

Hanna Heinonen 1,*
Alisa Burova 2,*
Sanni Siltanen 1,
Jussi Lähteenmäki 1,
Jaakko Hakulinen 2,†
and Markku Turunen 2

1 KONE Corporation, Myllykatu 3, 05830 Hyvinkää, Finland; sanni.siltanen@kone.com (S.S.); jussi.lahteenmäki@kone.com (J.L.)
2 Faculty of Information Technology and Communication Sciences, Tampere University, 33014 Tampere, Finland; jaakko.hakulinen@tuni.fi (J.H.); markku.turunen@tuni.fi (M.T.)
*Correspondence: hanna.heinonen@kone.com (H.H.); alissa.burova@tuni.fi (A.B.)
†This author has passed away.

Abstract:
Technical documentation creation is a collaborative process involving several departments in R&D. Even though virtual reality (VR) has been demonstrated to facilitate industrial collaboration and advance the product development lifecycle in earlier studies, it has not been utilized for technical documentation review and risk assessment processes in industrial companies. This article presents a case study where the benefits of VR to maintenance documentation reviews and risk assessments were studied. The virtual reality environment was tested by nine domain experts from an industrial company in a user study that replicated their actual real-life industrial collaboration tasks. Both qualitative and quantitative data were collected during the study. Our findings show that collaborative VR has the potential to enhance the documentation review and risk assessment processes. Overall, the concept of using virtual reality for documentation review and risk assessment processes was rated positively by participants, and even though further development is needed for the review tools, VR was viewed as a concept that facilitates collaboration, enhances the current review practices, and increases spatial understanding. The benefits of VR are evident, especially for geographically scattered teams that rarely meet face-to-face or do not have access to the actual physical equipment. In cases where traditional means of communication are not enough, process improvements are needed for documentation review and risk assessment processes, and our proposed solution is VR.

Keywords:
virtual reality; technical documentation; maintenance method development; risk assessment; collaborative VR; industrial maintenance

1. Introduction
For many industrial companies, the maintenance business is growing in importance, and more focus is paid to providing support and technical instructions to the maintenance technicians on the field. Industrial maintenance tasks are often complicated, and technicians need instructions to perform the tasks in a safe and efficient manner.

KONE Corporation is a global leader in the elevator and escalator industry [1]. KONE operates in more than 60 countries with approximately 30,000 field employees. KONE publishes hundreds of new or revised maintenance instructions each year to support its service business. As the safety and accuracy of technical instructions are essential to the company, there is no room for ambiguity or misunderstandings in the instructions delivered to the field. To achieve this, KONE has been developing both the practices and processes for maintenance instruction creation and the digital channels for technical information delivery to field employees.
Evaluating the Benefits of Collaborative VR Review for Maintenance Documentation and Risk Assessment

Hanna Heinonen 1,*, Alisa Burova 2,*, Sanni Siltanen 1, Jussi Lähteenmäki 1, Jaakko Hakulinen 2,† and Markku Turunen 2

1 KONE Corporation, Myllykatu 3, 05830 Hyvinkää, Finland; sanni.siltanen@kone.com (S.S.); jussi.lahteenmaki@kone.com (J.L.)
2 Faculty of Information Technology and Communication Sciences, Tampere University, 33014 Tampere, Finland; jaakko.hakulinen@tuni.fi (J.H.); markku.turunen@tuni.fi (M.T.)
* Correspondence: hanna.heinonen@kone.com (H.H.); alissa.burova@tuni.fi (A.B.)
† This author has passed away.

Featured Application: Based on data from a globally operating industrial company, this study demonstrated the benefits of VR to maintenance documentation review and risk assessment processes.

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Technical documentation creation is a collaborative process involving several departments, including technical documentation, subject matter, and risk assessment experts. While the technical documentation experts prepare the drafts, the subject matter and risk assessment experts validate the content in reviews. Both the preparation of the draft and its review are equally important in the development of a technical instruction. The review of maintenance instructions calls for the collaboration of technical documentation, maintenance method development and risk assessment. Preferably, this review is performed so that all the parties are in the same location and have access to both the equipment and instructions. However, due to the lack of access to the physical equipment and difficulties in remote communication between globally distributed teams and departments, these reviews are in many cases carried out by technical documentation experts sending out PDF files or links to review portals and subject matter experts commenting on them remotely. This trend was further accelerated by the COVID-19 pandemic and related restrictions when people from the same location were also forced to work remotely from home. Therefore, instead of an interactive collaborative process, the review becomes a process where the parties work in isolation. Because the work is carried out individually, the reviewers might send conflicting review comments, or some questions might be left unanswered altogether.

In most of the existing technical communication literature and guidelines used in companies, documentation reviews are discussed at a fairly abstract level and the focus is on different types of checklists, tips, and best practices. For example, Hackos and Jayaprakash discuss the importance of reviews, both technical reviews and peer reviews, their effect on the quality of documentation, and the parties that should be involved in the review process [2,3]. However, the technical communication literature does not go into detail on how reviews should be physically arranged, especially in globally operating companies. Similarly, risk assessment is generally guided by regulations that do not discuss the actual best practices of risk assessments or the physical setup.

Some research has been conducted for evaluating the use of novel technologies, such as virtual reality (VR) for the technical documentation creation process [4], but their use has not been implemented in practice in industrial companies. Furthermore, even though the use of VR has proven efficient for engineering design review [5], VR has not, until now, been studied or utilized for technical documentation reviews and risk assessments, processes that have much in common with engineering design reviews. As VR has been proven to be an effective tool to aid collaboration and cooperation [6], it would also be a good fit for technical documentation reviews and risk assessments as both processes are inherently very collaborative.

The work described in this paper contributes to the research in the fields of virtual reality applications in industrial systems and technical communication. The study investigates the potential of VR as a collaborative review and risk assessment platform and specifically addresses the following research question:

**RQ: What are the benefits of collaborative virtual reality to maintenance documentation reviews and risk assessments in industrial companies?**

To address the research question, we conducted user tests with domain experts that are representative of the intended users of the VR system. A total of nine users from KONE Corporation tested the VR environment and gave their feedback on the usefulness and benefits of the system for technical documentation reviews and risk assessments. The tasks performed during the user testing were designed to replicate an actual review and risk assessment of a maintenance method and instructions related to a product from KONE. Even though this study is focused on a single industrial company’s documentation and risk assessment processes, the documentation review and risk assessment are universal collaborative processes that are very similar in other industrial companies. Therefore, this case study is representative of the generic maintenance documentation review and risk assessment processes used in many industrial companies.
2. Background

In this section, we firstly introduce VR as a technology to facilitate collaboration and demonstrate its application cases and resulting advantages in the industrial context. Then, we provide a more detailed background for areas that are relevant to this case study, including industrial maintenance, the maintenance documentation process, and risk assessment. In industrial maintenance, it is essential that maintenance tasks are performed in an optimal and safe way, and maintenance methods are, therefore, carefully designed, authored, tested, documented, and risk assessed. Even though these processes in industrial companies’ R&D are inherently collaborative in nature, collaborative VR has not, until now, been utilized to enhance these processes in industrial companies.

2.1. Collaborative VR

The application of VR to industrial needs has been investigated for several decades, showing the potential to aid, enhance and transform many of industrial tasks and processes [7,8]. With a given flexibility to simulate dangerous contexts and enable natural interactions with virtual objects in immersive virtual environments [7,9–11], VR has been successfully applied in industry to facilitate training [12,13], AR-prototyping [14,15] as well as different phases of product development cycle [7,16–19].

“Distributed virtual environments” [20], also widely referred as collaborative VR (CVR), have become especially in demand during the COVID-19 pandemic, when people all over the globe were forced to work remotely. The major advantage of collaborative VR is the possibility to blur geographical barriers and immerse people from diverse locations into shared working spaces [21], addressing the needs of multidisciplinary global collaboration. Due to the increased feel of presence and immersion together with the ability to communicate verbally and non-verbally, collaboration in VR is understood as more efficient and flexible than the collaboration via traditional conferencing tools. Evidence has shown that VR is capable of positively affecting the elements of remote communication, such as the clarity and richness of communicated information, and enhance the quality of discussion and knowledge transfer due to shared context and awareness of others [22–24].

A case study by Berg et al. [16], for instance, demonstrated the application of VR to support early design decision making, which resulted in escalation of identified design issues and provided solutions, in addition to increased sense of team engagement and participation in the collaboration process. Furthermore, a recent study demonstrated that real-time collaboration over multi-user VR leads to increased performance in comparison to the traditional approach [25]. The studies by Wolfartsberger et al. [17,26], which explored the use of VR to aid the collaborative design review process, concluded that VR technology is a “useful addition”, and not a replacement”, which potentially accelerates the process and ensures inclusion of all professional groups. Other studies reported that collaboration in VR may strengthen lean and agile practices [27–30], optimizing value creation and team performance, while reducing resource waste and time span. Furthermore, collaboration in VR supports the innovation mindset of employees and overall sustainability [31], whereas VR itself is recognized as motivating and engaging technology by industrial employees [12,14].

2.2. Industrial Maintenance and Maintenance Documentation

Industrial maintenance aims at keeping machinery running and in good condition. Companies have different maintenance strategies; in the era of data analytics, the trend is towards preventive and condition-based maintenance. Complete optimization of material and workforce costs both per visit and over the equipment lifecycle, increasing equipment uptime, and avoiding risk of breakdown have transformed the nature of maintenance visits. Where earlier it was typical to have predetermined maintenance visits with predefined task lists, modern service companies use real-time sensor data to monitor the condition of the machinery and artificial intelligence to define the optimal time for each maintenance task to be performed. This means that the content of each maintenance visit is different,
and the composition of tasks varies across the visits. Thus, maintenance technicians need instructions on what to do as they cannot rely on their experience or tacit knowledge as before. Because of the quest for financial optimization, it is equally important to instruct what not to do on the visit.

Regardless of the maintenance strategy and how the composition of tasks for each maintenance visit is determined, it is important that maintenance tasks are performed in an optimal and safe way. Therefore, maintenance methods are carefully designed, authored, tested, documented, and risk assessed.

Technical communication is a field that conveys technical or specialized information, uses technology to communicate, or provides instructions on how to do something [32]. The maintenance documentation process is a subcategory of the more generic technical documentation process [33,34], and the outcome of the maintenance documentation process is a set of maintenance instructions that help the end users, maintenance technicians, complete their tasks in an efficient and safe manner. The content creation process is inherently collaborative, where people from different departments are working together to achieve a common goal. The process starts from maintenance method and outline creation by maintenance method developers. The outline is then passed on to the technical documentation experts, who start working on a draft. The draft instructions are developed iteratively with the maintenance method developers, by reviewing and revising. When both parties are satisfied with the draft, the maintenance method and the safety of the instructions are evaluated with the help of risk assessment experts. If the risk assessment finds deficiencies in the instruction or the method behind the instruction, they are revised and reviewed again until the requirements for safety are satisfied. Finally, the instructions are officially checked and approved by the organization, and then published into relevant delivery channels. See Figure 1 for an overview of the maintenance documentation process.

![Diagram of Maintenance Method development and Technical Documentation (TD) creation](image)

Figure 1. Maintenance documentation process.

From the technical point of view, the process of documentation review has remained the same for the past years. Even though the use of VR for the technical documentation process has been studied [4], the use of novel technologies, such as VR, has not been implemented for the review and assessment of technical instructions in industrial companies. Typically, technical instruction reviews and risk assessments are carried out by sending out links to PDF files or online review portals. If all participants are located on the same site, a face-to-face meeting can be arranged, but global teams rarely have the option of doing this. In practice, meetings are held in conferencing tools, such as Microsoft Teams, or, more often, reviewers comment on the PDF file and send it back to documentation experts via email or file sharing systems. In many cases, the teams have to work without any access to the actual product. As the development cycle in industrial companies is short, the technical instructions have to be completed in an increasingly short time frame, often before any actual prototypes exist [4]. Furthermore, even if a prototype exists, it is usually located on one site only and not accessible to everybody, especially in the case of globally scattered teams. In a conference call, even when a 3D model is shown via screen...
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3.3. Risk Assessment and Codes and Standards

The lifetime use of machinery, including the phases of transport, assembly, operation, adjustment, maintenance, dismantling, disabling and scrapping, must be safe. This is a legal requirement in, for example, European regulations [35,36].

While the regulations and, for example, the European harmonized standard EN 13015 [37] for maintenance instructions of lifts and escalators do not give explicit require-

When creating solutions or services, risk assessments can be performed in VR in different phases of the solution creation process, from assessing the initial concept to assessing final designs with prototype and piloting feedback. There are studies on risk assessing designs from user safety point of view [40,41], some concentrating on ergonomics [42].

The use of VR has also been studied for training [43]. The psychological risk-taking decision process is discussed in de-Juan-Ripoll et al.’s work [44], recommending that VR enhanced with physiological measurements is further studied for assessing attitudes to risk, risk perception, and conditioning factors. Using VR for delivering safety training has been studied in Leder et al.’s work [45], considering the impacts of VR on risk perception, learning, and decision making.

To build on these, technical documentation needs to provide accurate information for a solution or service, including important safety related information. Thus, technical documentation itself can be considered a subject for risk assessment. When assessing technical instructions, risk assessment experts check the tasks described in the instructions for any unsafe methods. They sometimes also request that warnings are added to the instructions to mitigate risks. They might recommend a different way of performing a task or safety measures that need to be carried out before or after the task to prevent injury to people or damage to equipment. After the risk assessment, the instructions are deemed to be safe to be published and used by field employees.

Even though the use of VR has been studied for several areas of risk assessment, until now, there are no studies that evaluate the benefits of VR to risk assess the contents of technical instructions.

3. Materials and Methods

In this section, we detail an exploratory user study, which is the third iteration round of a project that investigates the application of VR for technical documentation creation purposes. The previous iterations were focused on the early phases of documentation creation [46–48], while in this work, we demonstrate how VR can be used for collaborative technical documentation reviews and risk assessments. The focus of this study is not on the development of a VR platform but evaluating the usefulness and benefits of VR for the case study.

3.1. Methodological Proposal—Workflow

The aim of our study was to investigate the application of collaborative VR in an area where it has not studied earlier, maintenance documentation review and risk assessment. Both of these processes are very collaborative but in reality, especially in globally operating companies, people involved often do not get to meet face-to-face or have access to the equipment, which complicates the processes.
We propose that collaborative VR is a good fit to tackle these challenges in technical documentation reviews and risk assessments. Instead of meeting in conference calls or working individually by studying 3D models from computer screens and commenting on PDF files, we propose that the experts involved in the process use collaborative VR to meet each other, study the virtual equipment, demonstrate the maintenance method, review the related maintenance instructions, and assess if there are any risks involved in the tasks described in the instructions.

3.2. Implementation: VR Platform for Industrial Collaboration

The VR platform used in the user study, COVE-VR, was designed based on the input of subject matter experts and evaluated in collaboration between industrial and academic researchers [46] in several iterations and scenarios [46–48]. The following two virtual environments (Lab and Showroom) were deployed to facilitate a wide scope of industrial tasks: (1) a small-sized Lab replicates the realistic context of an elevator shaft based on a 3D CAD model and (2) a Showroom is a larger space to facilitate collaboration of multiple multidisciplinary teams and in-depth investigation of 3D CAD models that would not be possible to perform in a smaller space. To accomplish industrial tasks in VR, the users can utilize virtual tools that are opened from a wrist menu, which is the main menu of the platform. It is visualized as a circle menu around the user’s wrist and opened when the user is hovering their finger over the controller’s touchpad. When a user is opening their wrist menu, the menu is not visible to other users, but any virtual tool opened from the menu is visible to all users working in the VR. Additionally, all the components in the VR environment are visible to all users.

The users are visualized as simplistic avatars with a name label as shown in Figure 2; the voice icon appears over the avatar when the user is talking. Users can view each other as avatars, working in the VR and interacting with the components in VR. The users are able to locomote in the VR by moving in the physical space or by teleporting in the VR environment.

Figure 2. Screenshot of collaborative review of technical documentation in VR. A user is immersed in VR and looking at the avatars of two other users, complete with name labels for identification.

In this article, we provide a description of the virtual tools that are available in the VR environment used in the study and relevant for the “review of technical documentation” scenario. First of all, technical documentation can be opened in VR with the DocPanel tool; it reads XML files and visualizes maintenance methods and technical instructions in the form of text and graphics over a floating window that users can view and control in the VR (see Figure 2). The XML files have been created in the company content management system (CMS), exported from the CMS, and stored in the VR computer. The instructions can then be loaded to the DocPanel from a menu. Once the instruction is loaded to the DocPanel, it shows the task step by step, and the user may jump between pages, move the panel freely in the virtual environment, and place it in a comfortable spot for the users immersed in the VR. The concept of the DocPanel as a floating window was adopted from a preceding study [14], where it was used to visualize maintenance instructions for in-field
AR guidance and to test it in VR. The DocPanel tool is available to all users in the VR. Once a user has opened the instruction in the DocPanel, all the users in VR can view it and control the DocPanel and its functionalities.

In addition, previously tested [46–48] TextBox, Camera and Measure tools can be used as supportive tools during the review. With the TextBox tool, a user can input text via speech recognition (English or Finnish) or a virtual keyboard. The camera tool can be used to take pictures and videos in the VR environment, and the measure tool to take measurements of the dimensions and distances of the components in the VR environment. All generated digital content (e.g., text sequence, pictures, and videos) are saved to a storage folder, which can be further accessed via the desktop.

3.3. Case Study

This article describes a case study that was designed to test the usefulness and benefits of virtual reality for the maintenance documentation review and risk assessment process. The goal of the study was to explore if collaborative VR can enhance the company processes and collaboration of globally scattered teams. To address the research question, the VR scenario was tested by domain experts of KONE Corporation, a globally operating leader in the elevator and escalator industry, in a user study that replicates the actual real-life industrial collaboration tasks related to maintenance documentation reviews and risk assessments, both at KONE and other industrial companies.

3.3.1. User Study Procedure and Task Description

The virtual reality environment was tested by participants from three different departments that collaborate in the maintenance documentation process, including documentation, maintenance method development, and risk assessment. In the user test, each of the participants had their own dedicated role related to the actual department they work in at the company. The test participants were requested to work with a maintenance instruction displayed in the DocPanel tool (see Figure 3) and interact with the components in the VR environment. The instruction described a battery replacement task for a component, involving the removal of the battery and its cabling, installation of a new battery and reconnection of its cables and all the safety information related to the tasks. The documentation expert was responsible for leading the review, controlling the DocPanel tool and taking notes with the TextBox tool. Both virtual keyboard and speech-to-text functionalities were available to the users, and they could use both features according to their preferences. The maintenance method expert acted as the subject matter expert, reviewing the technical details of the instructions, and clarifying any open issues with the component or the maintenance method. The maintenance method expert demonstrated the maintenance method by, for example, opening the cover of the component and removing the battery. The documentation and maintenance method expert then reviewed the draft instructions and noted down any missing information or need for additional illustrations to be generated. When the parties agreed that an additional illustration should be added, the documentation expert used the camera tool to take a picture to help with the creation of the illustration that would take place after the review. While the other parties reviewed the technical correctness of the instructions, the risk assessment expert reviewed the safety of the working environment and the maintenance method. If the risk assessment expert noticed any deficiencies in the safety information in the reviewed instructions, they commented on it to the other users, and the users then proceeded to discuss what type of warnings, for example, would need to be included in the instructions. The documentation expert then noted down the final decision of what needs to be added with the TextBox tool.
During the test, the participants were encouraged to interact with each other and utilize the tools available in the VR environment (TextBox, Camera and Measure). The participants were also encouraged to comment on the functionalities of the tools and their suitability for the tasks they were responsible for. Thinking aloud and participant observation were used as the methods for collecting the data. The participants were asked to think aloud while performing the tasks, thus enabling the observers to understand what they liked and disliked. Thinking aloud also made it clear to the observers if the participants had trouble using the system or understanding some functionalities. The sessions were video recorded so that observers could go back and check details after the user tests if needed.

### 3.3.2. User Study Setup

In each session, three user study participants were located in different rooms, each wearing a VR head-mounted display. Two HTC Vive and one HP Reverb VR sets were used. One on-site facilitator was present in each of the three rooms to provide assistance and ensure the safety of the participants. The user study procedure was moderated by one of the on-site facilitators via Microsoft Teams on a laptop, connecting with the participants, asking them to accomplish the tasks, and encouraging their full participation in the tests. Teams established an audio connection between the rooms; the audio from the VR sets was muted so there was no interference with the audios. Teams also streamed the video of the physical space of the main facilitator and the participants from two rooms. The VR view from one user test participant was also streamed to Teams; the VR computer was used for sharing this stream.

The user study was observed by three observers; two were present on site observing the participants, and one was observing the procedure remotely with the Teams video stream. Observers were watching for certain behaviors and taking notes on the things that they observed the participants doing. The user study setup and the view of the Teams streams can be observed in Figure 4.

![Figure 3. Task step visualized in the DocPanel Tool (left), the same step in the original PDF instruction (right).](image-url)
The user study participants were immersed in VR, and the Teams stream was not visible to them; it was only used for audio and observation purposes. The Teams sessions were recorded for future reference. Figures 5 and 6 show user tests in progress.

**Figure 4.** User study setup, showing both the video streams in Teams and the setups of the rooms and locations.
The test setup, researchers’ roles as well as the instructions and tasks for the participants were tested in a separate pretest session. Based on the learnings from the pretest, some modifications were made. For example, in the VR environment, the participant names and department were added above each avatar to make it easier to recognize participants in VR. Some details of the tasks for the participants were also modified to bring clarity to the test sessions. After the pretest, no modifications were made between actual user tests; thus, they were all equal.
3.3.3. User Study Participants

Three user test sessions of the collaborative review process were held in the COVE-VR platform. In each of the sessions, we had three participants, i.e., one subject matter expert from each of the departments involved, including maintenance method development, technical documentation, and risk assessment. This makes a total of nine experts (aged from 34 to 64 (M = 49); seven males and two females). All participants had a university degree, six bachelors and three master’s degrees. On average, their experience at their role was 9.5 years, with a minimum at 2 and maximum at 21 years. Four experts had already been included in the process of testing COVE-VR in earlier studies; two of them had participated in all of the iterations and two were partly involved. Our test participants were carefully selected as they have high domain-specific expertise from the three fields; therefore, their opinions carry considerable weight for evaluating the benefits of collaborative VR for documentation review and risk assessment.

3.3.4. Collected Data and Analysis

Both qualitative and quantitative data were collected during the study. The quantitative data were collected via pre and post online surveys, created with the LimeSurvey tool. The validated evaluation method SUXES was used to collect user experience and analyze differences in expectations and actual experiences with the VR environment [49]. As SUXES captures both the expectations and the actual experiences of the user, one can measure the gap between the metrics and compare them, therefore providing a method to understand the user experience [49].

In the pre-survey (the first part of SUXES), participants evaluated their expectations based on an introductory video of the VR system shown to them. The post-survey had five sections with the statements answered on a 7-point Likert scale, where 1 = strongly disagree and 7 = strongly agree. The survey evaluated the participants’ actual experiences with the system (the second part of SUXES), views of the DocPanel tool, the perception of collaborative review sessions in VR, and perception of VR technology in general. In this paper, we use data from four sections of the surveys (both parts of the SUXES, the DocPanel tool, and collaborative review); data from the fifth section (perception of VR technology in general) has been published in another study.

After each user test session was completed, the main facilitator conducted a semi-structured group interview. Discussion revolved around topics such as general feelings and attitudes towards the tested system, participants’ evaluation of the system as a review and collaboration tool, and assessment of the current features and tools implemented in the environment. Participants were also asked what type of additional features or tools they would have liked to have been in the VR environment.

Qualitative data were collected during and after the test. During the test, observers noted down statements by the participants as they were thinking aloud and discussing with each other. After the session, further data were collected during the interview and noted down by the facilitator and observers. The data were analyzed with thematic analysis. Due to the small size of the test group, the statistical results are indicative only, but as domain experts are the real experts with their own tasks, the expert evaluation carries much weight in evaluating the usefulness and benefits of the environment for industrial maintenance tasks.

4. Results

Overall, experts left positive evaluations of collaborative reviews of technical documentation in COVE-VR. Figure 7 shows how experts perceive the value of collaborative reviews in VR by visualizing the division of answers via minimum, maximum and median of the answers for each statement. All experts agreed that review sessions in VR would positively affect the company’s overall performance, would accelerate the project span, and advance the knowledge transfer between the departments. Furthermore, eight experts agreed that collaborative review sessions in VR would help to identify more design errors
and that a VR review session is more efficient than reviews via traditional conferencing tools. Finally, all experts agreed that review sessions in VR should be integrated to the company’s working practices.

Figure 7. The results of collaboration-related statements, answered on a seven-point Likert scale.

The results of the SUXES survey, which compares the expectations and experiences with the VR system, are shown in Figure 8.

Figure 8. Expectations and experiences with VR platform. A seven-point Likert scale was used.
The survey results show that for most of the statements, the expectations of subject matter experts were met. They also demonstrate the overall positive evaluation of the system’s usability. Most of the experts found the system to be fast, pleasant, clear, easy to learn and natural to use, with a median at 5. In addition, all the participants found it to be useful. However, for about half of the experts, using the application was not effortless. The decrease between expectations and experiences happens in two statements—the experts expected the application to function less error-free than experienced. In addition, less enthusiasm was demonstrated towards using the application in the future after experiencing it; however, no expert showed a negative attitude to this statement.

Figure 9 demonstrates how experts evaluated the DocPanel tool. The tool was found to be useful for the review processes and easy to use. In addition, experts believed that the tool would positively affect the collaborative review process and make it easier, faster, and more efficient. The results also show that the tools should be further advanced in terms of design and interactions.

The usefulness and benefits of VR technology to facilitate the collaborative review of technical documentation and the virtual tools were discussed in a semi-structured group interview. Despite the main focus of the interview being the DocPanel tool and the feasibility of the review process in VR, the participants were very engaged and gave many comments and improvement ideas on the other tools and the multiuser collaboration in general.

The concept of the DocPanel tool was evaluated as very useful by experts participating in the user testing. When reviewing technical instructions, one must have access to the actual document files; therefore, the instructions must be available in the VR. Participants were able to use the DocPanel tool and review the instructions in it while checking the components in VR. However, participants suggested several functionalities and improvements to the DocPanel tool that would enhance the review process in VR. Firstly, better navigation features would be needed. The DocPanel tool had basic next and back functionalities, but all participants agreed that a navigation pane or table of contents would be needed to obtain a comprehensive view of the instructions and to easily navigate to different parts of the instructions. With the next and back buttons, you can move inside one task, but navigating
to a completely different part of the instruction is very cumbersome and laborious with them. The DocPanel had page numbers, but some participants commented that a progress bar would be a more suitable indicator of the progress made while reviewing a task. Secondly, all documentation experts commented on the need for markup or annotation tools for the DocPanel. The TextBox tool was used to take the notes, but as one could not attach a note to a specific page or a task in the DocPanel, it was thought of as quite clumsy. Users commented that attaching notes in the same way as with the commenting features in Adobe Acrobat would be a good addition to the DocPanel tool. Thirdly, users liked the idea of a floating window that you can move freely in the virtual environment. However, some users commented that the window was too small, and they would like it to be resizable so that you can freely decide what size suits you the best.

The participants discussed multiuser VR collaboration in length and agreed that it enhances both the documentation review process and the risk assessment process when compared to the current practices. The participants noticed an increased level of social presence and concentration on the task. Despite being physically located in different parts of the country or the world, the participants noted that VR would give a sense of being in the same room. One participant commented the following: "This is much more visual than the current process. You are forced to participate; you can’t read emails and so forth at the same time, but you have to concentrate on the task at hand.” The participants also suggested that desktop-based access to VR would be beneficial, calling people participating this way silent members or observers. The desktop participants would be then able to follow the review process in VR and also possibly take notes. One documentation expert suggested that an observer could be the one taking notes in the instructions outside of the VR in, for example, the PDF file. The VR participants would be then able to concentrate on reading and reviewing the instructions in the DocPanel tool, and already existing tools would be used to annotate and mark up the file by an observer. This type of hybrid setup would offer an easy adoption of VR, as good commenting tools already exist. However, it would require that an extra person is always available as an observer taking notes, which might prove problematic resource-wise. One documentation expert noted that if the session was recorded, they could watch it afterwards and make the needed changes in the instructions while watching the recording.

All the test participants agreed that even though COVE-VR would be useful for documentation review, you cannot review very long instructions in it but need to take breaks in between. Reviewing the whole instructions (e.g., the overview of the whole maintenance of a certain component) in VR would take quite some time with frequent breaks. Furthermore, many participants commented that documentation review in VR would mostly benefit the early draft reviews and entirely new tasks where you concentrate more on a specific task.

The participants agreed that risk assessments in VR would enhance the current process where the equipment to be risk assessed is not always available or accessible. They noted that it would be especially good for early risk assessments when the actual physical prototypes rarely exist. However, from a risk assessment point of view, the whole equipment needs to be modelled in VR in a way that it can be interacted with. In our tests, only certain components were modelled in such a way, and the risk assessment experts commented that you have to be able to interact with the full model or then have a blank virtual room with just the component you are reviewing in it. The risk assessment process takes the surroundings and environment into account, and the risk assessment for the method for replacing a component, for example, is seldom carried out on its own but rather reviewed in the context. Risk assessment experts also commented that haptic gloves and motion feedback would enhance the user experience, as you could also feel the objects you are touching. They also discussed the importance of importing standard maintenance tools, such as screwdrivers and wrenches, into the VR environment because the use of the tools is also considered in the risk assessment. The risk assessment experts also commented on the
use of personal protective equipment and how it would be important to be able to model that in VR.

All the test participants commented on the need of a pointer tool to point out objects to others. In addition to the DocPanel navigation improvements, the pointer was the most requested enhancement proposal from the participants regardless of their role in the tests. One participant started using the measure tool as a pointer, placing it on objects he was talking about and stated the following: “Are you others able to see where I am pointing with this?” This further indicates that there is a great need for a pointer tool, and it would considerably enhance the collaboration in a multiuser VR environment. One test participant suggested that color-coded pointers would make it easy for everybody to recognize who is showing something. In addition, maintenance method developers asked for arrow and freeform drawing tools, as they would make it easier to explain details to others. Some participants also noted that a magnifying glass would be good so that details could be enlarged.

The participants enjoyed the multiuser collaboration in VR. They said that the avatars made it evident that they were not alone at the virtual equipment even though not everybody talked at the same time. However, several participants noted that realistic avatars with real faces would be good and would further enhance the collaboration and feeling of being in the same space, stating the following: “Avatars with real faces would be great, you would recognize people.” Some suggested that the Office365 picture of the persons could be used as the avatar as that is something they are used to viewing and would recognize immediately. Avatar heads used in COVE-VR were also viewed as too large and smaller ones would be good as the current heads get in the way of seeing things, especially in a cramped space with many concurrent users. Finally, the participants noted that “the VR is not a replacement for real equipment but a good addition”.

5. Discussion

This article presented the results of an expert case study on enhancing maintenance documentation review and risk assessment processes with the use of collaborative virtual reality. The study addressed the actual challenges in the industry, where access to physical equipment is limited or non-existent and experts work in different locations and are, many times, unable to meet face-to-face. Since the beginning of the 1990’s, many academic and industrial studies have demonstrated the value of VR for industrial operations in various fields [7,16,25,50]. However, even though the use of VR has been promoted in industrial companies, its main application areas in companies are still training and design reviews. Our study demonstrates that the use of VR can also enhance other research and development related processes in industrial companies. Previously, the cost of the hardware was noted as the greatest obstacle for VR adoption in companies [9], but as prices have come down considerably during the past few years, this is not a major issue any more and companies are investing more in VR and related equipment. Furthermore, for companies where VR technology has been already adopted, e.g., for training purposes, the integration of other processes and use cases for VR would be fairly easy to achieve. Exploring all the possible potential VR scenarios based on existing hardware would also boost the adoption of industry 4.0 interventions.

5.1. Benefits of VR to Collaboration and Inclusiveness

Previous studies reported that VR enhances communication and collaboration activities [23,26,51]. Accordingly, our study demonstrates that the greatest advantage of virtual reality for the maintenance documentation review and risk assessment processes is its positive effect on the collaboration of the team working together towards a common goal. Instead of people working independently and alone at their desktops or joining conference calls, VR offers them a collaboration platform where they have, despite of their physical location, a sense of being together in the same room [21,22,47,52]. Not only does VR enhance the current collaboration process by offering virtual access to equipment that
is not available [4], it also promotes inclusiveness, as additional team members from other countries can easily join documentation review and risk assessment sessions from their own locations. The benefits of multiuser VR are evident when comparing it to the current practice of reviewing and commenting technical instructions (in PDF files or by attending conference calls in tools such as MS Teams), which are not thought of as very collaborative. Furthermore, when comparing to physically being present in the same meeting room, remote participation through multiuser VR enables diverse experts from other countries to engage without a need to travel and physically attend meetings. This is both a clear benefit for globally operating companies and their employees from both a cost and sustainability point of view. VR also provides more equal opportunities globally and facilitates viewpoints from globally scattered team members, benefiting both the multi-national company and its employees. Lifelike, realistic avatars would further improve the sense of togetherness and working as a team, as people would be easily recognized in VR [53].

5.2. Benefits of Collaborative VR to Documentation Review and Risk Assessment

The results of our user testing demonstrate that the concept of documentation review and risk assessment in VR was rated positively by the participants. Our concept was tested with the COVE-VR platform, but any collaborative VR environment with similar tools would offer an efficient platform for maintenance documentation review and risk assessment processes. The DocPanel tool offers the ability to test maintenance methods and concurrently review the technical instructions, even when there is no physical equipment available. In comparison to working independently with files on a laptop, collaborative VR offers the ability to show how a task is performed, to point out components, and to demonstrate their functionalities. It also introduces an enhanced sense of being together and working as a team. The user test participants noted that the combination of people and departments in our tests was good, but clear roles are needed so that everybody knows what to do. For example, before a review session starts, it must be defined who is responsible for operating the DocPanel and leading the documentation review and who takes notes of any needed changes.

Spatial understanding is essential for many industrial processes [54]. For example, in maintenance method development, it is important to understand whether there is enough space to carry out the maintenance task. The sense of scale is easily lost when looking at the 3D model from computer screen, which can lead to maintenance methods that are impossible to perform. The related maintenance instructions are then impossible to follow, which can then both frustrate the users and cause safety issues when the users invent their own way of performing the task. These kinds of mistakes are avoided with the 1:1 scale in VR, as VR creates a sense of spatial understanding.

5.3. Limitations of Collaborative VR in Documentation Review and Risk Assessment

Some limitations still exist in fully using VR for maintenance documentation review and risk assessment processes. Most of the user test participants noted that reviews in VR would be good for early drafts and early risk assessments. However, the 3D model might not be always ready and available in very early phases of product development. Further focus needs to be given, therefore, to integrating the early creation of 3D models to the product development process. Additionally, as the 3D model is often updated during the product development cycles, it would also be essential to easily update the VR model when there are changes in the 3D model. Additionally, it would be beneficial if the VR environment would be able to indicate the changes made in the 3D model so that recent changes can be easily noticed.

The quality of immersion and sense of presence improve the ability to identify risks. The modelling of tools and animating the movement of objects proposed in the results of this study agree well with other studies [40]. One problem for risk assessment in VR is that the environment is typically ‘clean’, with no odors, no noise, no temperatures, or equivalent. Hazard identification is based only on the visual observation of environment [41]. Therefore,
people performing risk assessment need to be aware of and competent enough to identify hidden hazards.

To improve the situation, we propose the following to enhance VR hazard identification: objects must have hazard-related metadata attached to them. This data can be made visible as an additional visualization layer that can be switched on and off. For example, objects connected to voltage sources could have a blue aura or shimmering, objects with chemical hazards a yellow aura, and hot objects a red aura. Different visualization, or audio feedback, if available, could be given similarly to any hazard, be it of mechanical origin, irradiation, pressure and so on.

Even though the concept of the DocPanel was rated positively, its implementation had its limitations. For the DocPanel to be an efficient tool, enhancements and additions would be needed especially in navigation and annotation tools. As people are used to the current navigation and commenting functionalities of common office tools, such as Adobe Acrobat and MS Word, replicating those in DocPanel would lower the learning curve for the users of COVE-VR. From a multiuser collaboration point of view, a pointer tool would be essential. Maintenance method developers, documentation experts and risk assessment experts discuss details when reviewing instructions and assessing risks, and many times need to point out a small detail. In real life, with access to real equipment, this would be carried out with a finger, and all the participants looked for a way of pointing a detail or component to others in VR. In addition, drawing tools would further enhance the collaboration features of COVE-VR. The development of the DocPanel and the related tools and their usefulness to the processes described in this paper would offer an interesting further research area.

5.4. Limitations of This Study and Areas of Further Research

This study’s limitation is the focus on a single industrial company’s documentation and risk assessment processes. However, documentation review and risk assessment are universal processes in industrial companies on a general level, and even if the details of the process may vary from one company to another, the processes are still collaborative by nature. Studying other companies’ processes and the usefulness of VR to those processes would offer further insight into how generalizable the results of this study are to the fields of documentation review and risk assessment. Additionally, the potential enhancements to the VR environment and tools suggested by the experts in our user study would offer an interesting development and further research area for collaborative VR.

6. Conclusions

Even though virtual reality environments are already in active use in many industrial companies, their use has been mainly focused on training or design reviews. However, VR has much to offer to other functions and product development departments, especially in the case of globally operating companies and globally scattered teams.

This study explored the benefits of VR to maintenance documentation review and risk assessment processes. The concept of reviews in VR and the DocPanel tool were evaluated by an industrial company’s domain experts in user tests. Overall, our study indicates the potential of VR as a tool to enhance maintenance documentation review and risk assessment processes. Even though the focus of this study was on a single industrial company’s documentation and risk assessment processes, the processes are universal processes used in other industrial companies as well. Therefore, the results are largely generalizable to other industrial companies and their processes. We used the COVE-VR platform in our study, but our any collaborative VR environment with similar tools would offer an efficient platform for maintenance documentation review and risk assessment.

The study demonstrates that VR had a positive effect on the collaboration of the cross-organizational team working towards a common goal. In globally operating multinational companies where experts work in different locations and are, many times, unable to meet face-to-face, VR offers a collaboration platform, strengthens the sense of being
part of a team, and promotes inclusiveness. It also gives virtual access to equipment in cases where the physical prototype does not exist or is inaccessible to the members of the team. VR also strengthens spatial understanding, and, therefore, results in more accurate maintenance methods and related maintenance instructions. Even though reviews in VR were not viewed as a replacement for documentation review and risk assessment processes regarding real equipment, VR was rated a very useful alternative in cases where access to the physical equipment is limited or non-existent.


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References


Details of the dissertations are available at https://research.tuni.fi/tauchi/dissertations/

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2. **Mika Käkä**: Enhancing Web Search Result Access with Automatic Categorization
3. **Anne Aula**: Studying User Strategies and Characteristics for Developing Web Search Interfaces
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30. Tomi Nukarinen: Assisting Navigation and Object Selection with Vibrotactile Cues
31. Akkil, Deepak: Gaze Awareness in Computer-Mediated Collaborative Physical Tasks
32. Toni Pakkanen: Supporting Eyes-Free User Interaction with Vibrotactile Haptification of User Interfaces
33. Antti Sand: Adding Haptic Feedback to Interaction with Unconventional Display Devices
34. Jukka Selin: Tietomallin pelillistäminen ja toiminnallisen suunnittelun suunnittelun apuna
35. Zhenxing Li: Efficient and Accurate Hand-based Kinesthetic Interaction for Virtual Reality
36. Csaba Kertész: Collaborative development on artificial intelligence can solve challenges for social robotics
In the field of industrial maintenance, xReality (XR) technology has a potential to advance or even shift many traditional operations and practices. The application of Augmented reality may aid workers operations in hazardous industrial contexts and thus, increase efficiency and occupational safety. Virtual reality may be further used to enhance operations related to product development and service design, which result in advanced collaboration and integration of lean and agile methodologies. Nevertheless, the adoption of xReality has slowed down due to many factors, including, yet limited technological capabilities, human resistance to novel technologies, and the lack of unified design, development, and adoption practices.

This dissertation aims to uncover hidden stones on the way to a smooth and responsible adoption of industrial XR with a goal to deliver maximum value to users and organisations. Based on action-based research in a tight academia-industry collaboration with KONE Corporation, a global elevator manufacturer and maintenance provider, this work provides generalisable knowledge on how to design and develop XR solutions, extracting insights from two case studies with domain experts. As an outcome, this work demonstrates the potential application scenarios of XR technology and suggests the design and adoption strategy, focusing on scalability and inclusion.