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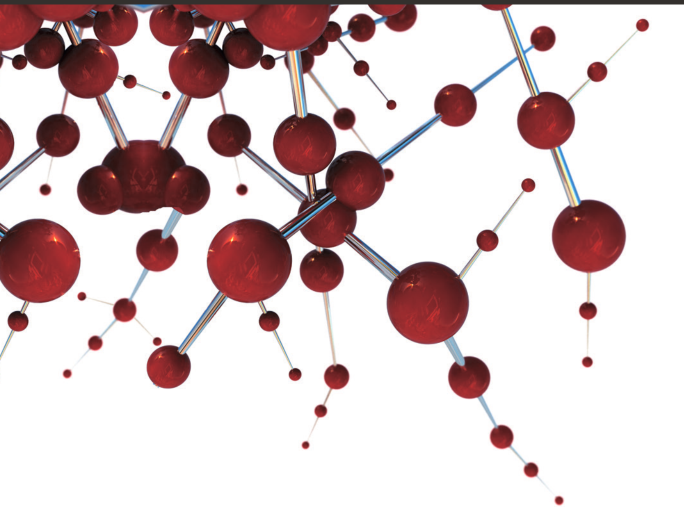

Hanna Heinonen

The Benefits of Extended Reality for Technical Communication: Utilizing XR for Maintenance Documentation Creation and Delivery

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ACADEMIC DISSERTATION
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ACADEMIC DISSERTATION IN INTERACTIVE TECHNOLOGY

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Abstract

The main goal of this dissertation is to explore the benefits of extended reality for technical communication. Both of these fields offer opportunities and also pose challenges to each other, and this dissertation provides insight into this relationship. The research was initiated by the author's personal interest in both fields and also human-technology interaction and user needs in general. Even though this is an academic dissertation, it is first and foremost a practitioner's view of these evolving technologies and their potential uses in industry and, specifically, in industrial maintenance and technical communication.

Under the umbrella of extended reality and technical communication, this dissertation focuses on two main themes. The first part studies virtual reality as a technology to facilitate collaboration and digital content creation for technical documentation in industrial companies, and the second part explores the possibilities of augmented reality and smart glasses as a delivery channel for maintenance instructions. The developed concepts were tested by domain experts in user tests. The overall results of testing were positive, and domain experts expressed enthusiasm toward the concepts and technologies in general.

The technical documentation process is an inherently collaborative process involving stakeholders from different teams and organizations, and virtual reality was evaluated to have a positive effect on that process, especially in the case of globally scattered teams. The developed tools were also rated positively for digital content creation. Therefore, virtual reality offers many benefits for technical documentation creation, an area where it has not been utilized until now.

On the augmented reality side, domain experts were generally enthusiastic about the use of smart glasses even though the technologies are not yet mature enough for field use in industrial maintenance. Furthermore, the results show that content created in the technical communications industry standard, DITA XML, works well when delivered to smart glasses, and the same content can be single sourced to other delivery channels. The use of DITA XML, therefore, eliminates the need to tailor content for each delivery channel separately, and offers an effective way to create and update content for AR applications in industrial companies. This, in turn, can advance the use of AR technologies and related devices in field operations in industrial companies.

In conclusion, the findings of this dissertation show that the fields of technical communication and extended reality have a significant amount of synergy. In this dissertation I establish use cases and guidelines for these areas.

Acknowledgements

When I graduated with my Master's in 2004, I shortly toyed with the idea of continuing as a researcher and combining my love of the humanities and technology. Instead, I stepped into the working life as a technical communicator in industrial companies. It took me 15 years to cultivate my research idea, but I like to think that the period also taught me a great deal both professionally and as an individual. These past four years as a PhD student have been an exciting journey and I am very happy that I had to courage to try my wings in academia.

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I believe that this is not the end of something, but rather a new beginning. I feel that I have only touched the surface of things, and there is so much for me to do in research and life. *Non progredi est regredi.*

Hyvinkää, June 12, 2023

Hanna Heinonen

Contents

1 INTRODUCTION 1
1.1 Motivation 1
1.2 Key Concepts 3

2 OBJECTIVES AND SCOPE 7
2.1 Organization of the study 8

3 METHODS AND DATA COLLECTION 11
3.1 Mixed methods approach 11
3.2 Expert evaluation 15
3.3 Data collection 15

4 CONTEXT OF RESEARCH AND RELATED PROCESSES AND TECHNOLOGIES 21
4.1 Industrial maintenance 21
4.2 Technical Communication 23
4.3 Extended reality 27

5 COLLABORATION IN VIRTUAL REALITY 31
5.1 Summary of original articles I-IV 32
5.2 Results 38

6 AUGMENTED REALITY AND SINGLE SOURCING OF TECHNICAL INFORMATION FOR DIFFERENT MEDIA 41
6.1 Summary of original articles V-VII 41
6.2 Results 46

7 DISCUSSION 49
7.1 Implications of research 50
7.2 Limitations and future work 59

8 CONCLUSIONS 61

REFERENCES 63

Abbreviations

3D	Three dimensional
AR	Augmented reality
CAD	Computer-aided design
CBM	Condition-based maintenance
CCMS	Component content management system
CVE	Collaborative virtual environment
DITA	Darwin Information Typing Architecture
DTD	Document Type Definition
HMD	Head-mounted display
HTI	Human-Technology interaction
IoT	Internet of Things
IR	Informed reality
MR	Mixed reality
PM	Planned maintenance
R&D	Research and development
SME	Subject matter expert
UCD	User-centered design
UI	User interface
VE	Virtual environment
VR	Virtual reality
XML	Extensible markup language
XR	Extended reality

List of Publications

This dissertation is composed of a summary and the following original publications, reproduced here by permission.

I. Alisa Burova, Hanna Heinonen, Paulina Becerril Palma, Tuuli Keskinen, Jaakko Hakulinen, Viveka Opas, John Mäkelä, Kimmo Ronkainen, Sanni Siltanen, Roope Raisamo, and Markku Turunen. 2021. Toward Efficient Academia-Industry Collaboration: A Case Study of Joint VR System Development. In *Proceedings of the 24th International Academic Mindtrek Conference (Academic Mindtrek '21).* Association for Computing Machinery, New York, NY, USA, 176–185. https://doi.org/10.1145/3464327.3464367 77

II. Alisa Burova, John Mäkelä, Hanna Heinonen, Paulina Becerril Palma, Jaakko Hakulinen, Viveka Opas, Sanni Siltanen, Roope Raisamo, Markku Turunen. 2022. Asynchronous industrial collaboration: How virtual reality and virtual tools aid the process of maintenance method development and documentation creation. In *Computers in Industry*, Volume 140, 2022, 103663, ISSN 0166-3615. doi:10.1016/j.compind.2022.103663 91

III. Alisa Burova, Paulina Becerril Palma, Phong Truong, John Mäkelä, Hanna Heinonen, Jaakko Hakulinen, Kimmo Ronkainen, Roope Raisamo, Markku Turunen, and Sanni Siltanen. 2022. 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. In *Applied Sciences* 12, 8: 3728. doi:10.3390/app12083728 105

IV. Hanna Heinonen, Alisa Burova, Sanni Siltanen, Jussi Lähteenmäki, Jaakko Hakulinen, and Markku Turunen. 2022. Evaluating the Benefits of Collaborative VR Review for Maintenance Documentation and Risk Assessment. In *Applied Sciences* 12, 14: 7155. doi:10.3390/app12147155 131

V. Sanni Siltanen and Hanna Heinonen. 2020. Scalable and responsive information for industrial maintenance work: developing XR support on smart glasses for maintenance technicians. In *Proceedings of the 23rd International Conference on Academic Mindtrek (AcademicMindtrek '20).* Association for Computing Machinery, New York, NY, USA, 100–109. doi:10.1145/3377290.3377296 153

VI. Hanna Heinonen, Sanni Siltanen, and Petri Ahola. 2021. Information Design for Small Screens: Toward Smart Glass Use in Guidance for Industrial Maintenance. In *IEEE Transactions on Professional Communication*, vol. 64, no. 4, pp. 407-426, Dec. 2021. doi:10.1109/TPC.2021.3110616 165

VII. Hanna Heinonen, Jenni Virtaluoto, Tiia Suomivuori, Kristian Forsman, Tuomas Kangas, and Sanni Siltanen. Minimalism for the win - User-centered design for maintenance guidance. In *IEEE Transactions on Professional Communication*, vol. 65, no. 4, pp. 485-501, Dec. 2022. doi:10.1109/TPC.2022.3205468 187

The Author's Contribution to the Publications

In Article I, the author was responsible for the parts related to technical communication and the perspective of the industrial company. The author worked in the industrial research group and was responsible for requirements gathering from the industrial company. The author participated in the design and practical arrangements of the user tests and in the analysis of the collected data. The author participated in the writing of the article from the industrial point of view.

In Article II, the author was responsible for the parts related to technical communication and the perspective of the industrial company. The author was responsible for defining the technical documentation journey, participated in the arrangements of the workshop for the case study scenarios, and analyzed the results of the workshop. The author participated in the design and practical arrangements of the user tests, observed the user tests, and participated in the collection and analysis of the qualitative data. The author participated in the writing of the article collaboratively with the other authors.

In Article III, the author was responsible for the parts related to technical communication and the perspective of the industrial company. The author participated in the design and practical arrangement of the user tests, observed them, and participated in the collection and analysis of the qualitative data. The author participated in the article by writing, reviewing, and commenting on the manuscript.

In Article IV, the author was responsible for the parts related to technical communication and the perspective of the industrial company. The author was the main responsible for the concepting, planning, and realization of the user tests. The author was the main responsible for collecting and analyzing the data from user tests and writing the article.

In Article V, the author was responsible for the selection and conversion of technical instruction content for user tests and for the collection and analysis of the data related to technical information. The author participated in the writing and reviewing of the article.

In Article VI, the author was responsible for concepting the delivery mechanism for the information content. The author participated in the concepting, planning, and realization of the user tests. The author was the main responsible for collecting data from user tests, analyzing the data, and writing the article.

In Article VII, the author concepted and designed the concept of layered information delivery and created the content for user tests. The author was responsible for the concepting, planning, and realization of the user tests and the pilot project. The author was the main responsible for collecting data from user tests, analyzing the data, and writing the article.

1 Introduction

Both communication and technologies are continuously developing and evolving, and our times are characterized by the evolving concept of the information society. Technology touches practically every aspect of our daily lives, and people are surrounded by digital systems, data, and all types of information. Therefore, research into human-technology interaction (HTI) is now more important than ever as it provides the human perspective to technology and its advances. With technology we can accelerate, enhance, and even automate many processes in society, but the human aspects are deeply rooted in these processes. Consequently, the human focus is of utmost importance and requires constant consideration when implementing the technologies in our daily lives. The aim of this dissertation is to focus on the human and their needs in midst of the technology and to investigate the relationship of technical communication and extended reality.

1.1 Motivation

The foundation for this dissertation has been laid in my professional career. I have always worked with the more technological side of technical communication, trying to bridge the gap between the product, the instructions, and the user. My first love in computer-human interaction was software online helps, and I was intrigued to find new ways of embedding instructions directly into the user interface (UI) of the software. Soon I turned my focus into a less studied area of technical communication, hardware, and realized that field employees were working, in many cases, completely without instructions or with outdated paper manuals even with hazardous tasks. At the same time, augmented reality (AR) technologies became more mainstream, but most of the devices required that content displayed in the device is developed and tailored directly for that device. It also seemed that many of the implementations were solely based on 3D augmentations where steps to be performed are animated on top of a machine. In my role as a practitioner working for an industrial company, I have always tried to find solutions that can be used in productions settings. 3D augmentations are expensive to create and also expensive to update, and, therefore, would require considerable investments from companies.

Furthermore, 3D augmentations are often not genuinely needed when guiding, for example, how to screw a bolt in place. In my role as a researcher, I also wanted to keep the realities of industrial companies in focus and started experimenting with the use of DITA XML as a way to overcome this challenge.

To complement the AR side of the study, I also wanted to dive into the use of virtual reality (VR) for the technical documentation process. I had barely started this part of the research when the COVID-19 pandemic hit. My intention had been to study collaborative VR, and at first the pandemic seemed like a massive challenge to this goal as people started working remotely. Nevertheless, I accepted the challenge and turned it into an opportunity to study remote collaboration, an area that had suddenly become more important than ever before. Many of the findings are also applicable to the post-pandemic era as people continue to work remotely, at least partly. Furthermore, in globally operating countries, day-to-day work often consists of collaboration with teams that are scattered in different countries, and the results of this study are directly applicable to these types of settings.

Even though this is an academic dissertation, it is first and foremost a practitioner's view of the evolving technologies and their potential uses in the industry. As a technical communicator, my professional experience is strongly rooted in industrial maintenance, and, therefore, my goal has been to study and develop concepts that can be implemented in industrial companies with the resources that are available and with a level of practicality that enables the implementation beyond proofs of concept and also brings business value when deployed to production settings. When writing this dissertation, I have intentionally followed technical communication principles where clarity and explicitness of language is favored instead of complex sentence structures and complicated, higher-register phrases. As it has generally been recognized that there is a divide between technical communication practitioners and academics (Andersen, 2014; Blakeslee & Spilka, 2004; Bosley, 2002; Cleary, 2012; Virtaluoto, 2015), and the accessibility of academic research and the clearness of communication have been noted as major factors determining the relevance of research to the industry and its daily practices (Andersen &

Hackos, 2018), I see this as a method to advance the accessibility of my research globally and among the practitioners of the field.

1.2 KEY CONCEPTS

1.2.1 Technical Communication

Technical communication is a field that conveys technical or specialized information, uses technology to communicate, and provides instructions on how to do something (Defining Technical Communication, 2022). The range of products that technical communicators work with is diverse, ranging from small household items such as toasters or coffee makers to large industrial machines such as paper machines and elevators. Subsequently, the instructions can be targeted for consumers or professionals, but the goal is always to create information to meet the needs of the user.

Under the umbrella of technical communication, there is a multitude of different jobs and roles, for example, information designers and architects, technical writers and illustrators, localization professionals, and usability experts. All the people working in these roles work toward a common goal: They take complex technical information related to a product or system and turn it into clear, safe, and usable instructions, deliver that information through the right delivery channels, at the right time, to help the users of the products to achieve their goals.

Traditionally, technical information has been delivered on paper either in the product packaging or in delivery binders. As a way of cutting costs at the production phase and also to offer basic online access for the users to the files, electronic prints in the form of PDF files became more common, and are still, in many cases, the main delivery format for technical instructions for many companies (Adobe Technical Communication Industry Survey 2022, 2022). Software products are commonly supported by embedded online helps whose scope is sometimes broadened to also support self-paced learning (Dutke & Reimer, 2000). More recently, technical instructions have been delivered via online portals, and some companies are using dynamic delivery through web services (Andersen & Evia, 2019; Hackos, 2002; Manning, 2002; Ziegler, 2020).

1.2.2 DITA Content Model

Darwin Information Typing Architecture (DITA) is an XML-based content model that has become the technical communication standard for structured, modular writing (Bellamy et al., 2011). The first DITA specification was published in 2005, and has been updated twice, with the latest full version being 1.3 from 2015 (DITA Version 1.3 Specification, 2015). Current focus of the OASIS DITA Technical Committee is the development of Lightweight DITA as on option to ease DITA adoption in companies (Lightweight DITA SC | OASIS, 2022). Apart from the evolution of the DITA standard and related development of authoring software, very little development has taken place in the field of technical communication and many of the practices both in the creation of technical information and on content delivery side have remained the same over the last decade.

1.2.3 Extended Reality

In recent years, there has been rapid development in XR technologies. In this dissertation, the term XR is used to refer to all technologies combining real and virtual environments such as augmented reality (AR), virtual reality (VR), and mixed reality (MR). For a visual representation of the XR umbrella, see Figure 1.

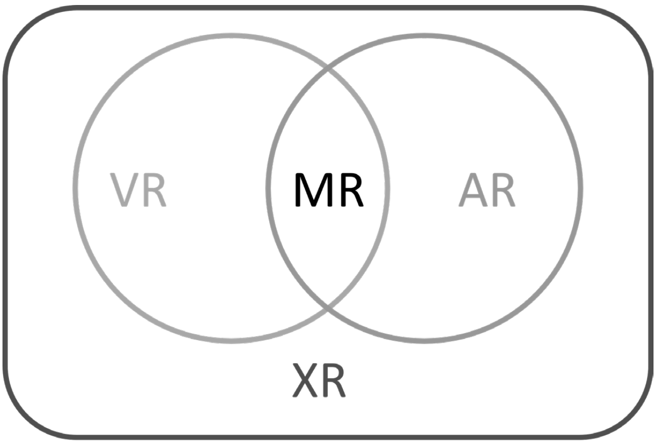

Figure 1. Simplified positioning of virtual reality (VR), augmented reality (AR), and mixed reality (MR) under the extended reality (XR) umbrella.

The technical advances with XR technologies have made it possible that powerful and reasonably priced virtual and augmented reality devices have entered the consumer market (Eschen et al., 2018). The high cost of the devices has slowed down the adoption of XR in industries, but the more affordable prices encourage the use of them in industrial maintenance. Therefore, we are nearing the era when these devices could be utilized on a wider scale in industrial maintenance and also be used as a delivery channel for technical instructions in industrial companies. This offers new possibilities for both fields: XR can both aid in the creation of technical information and act as a new delivery channel, and technical communicators can help the industries adopt the novel technologies by creating content for XR devices and applications. However, very little has been done to create any guidelines for the use of the new media and technologies in technical communication (Tham et al., 2018).

1.2.4 KONE Corporation

KONE Corporation is a global leader in the elevator and escalator industry (KONE in Brief - KONE Corporation, 2023). The company develops and manufactures elevators, escalators, and automatic building doors and provides solutions for the maintenance and modernization of the equipment. KONE was founded in Finland in 1910 and operates in more than 60 countries with more than 60,000 employees around the world. KONE serves approximately 550,000 customers, including building contractors and owners, facility managers and owners, architects, and authorities. KONE has over 1.5 million units in its equipment maintenance base and moves over one billion people daily. In 2022, KONE had annual net sales of EUR 10.9 billion and is listed on the Nasdaq Helsinki Ltd. in Finland.

KONE R&D leads the product development in the company's Technology and Innovation unit. The operational environment of KONE product development follows agile principles.

1.2.5 Industrial Maintenance

Industry 4.0, Internet of Things (IoT), growing connectivity, and remote monitoring are changing the face of industrial maintenance. Earlier many maintenance tasks were standardized, and maintenance technicians learned to perform the tasks by working with the equipment for years. Therefore, experienced technicians rarely needed instructions. However, with the rise of remote and condition-based maintenance (CBM), tasks vary from one day to another and one piece of equipment to another, and the technician does not know the contents of a specific preventive maintenance visit, for example. Therefore, even the more experienced technicians need guidance to be able to work efficiently. At the same, there is an increasing need to get that information created faster and more precisely, and get it delivered to the field in an efficient way. For an example of a maintenance technician working at equipment, see Figure 2.

Figure 2. Maintenance technician accessing instructions with smart glasses and QR codes (published in Article I).

We are living now in the era of 4.0, but rapidly moving towards Industry 5.0. The Fifth industrial revolution, Industry 5.0, aims at creating prosperity beyond jobs and growth, ensuring sustainable development, and focusing on the well-being and needs of the worker (Industry 5.0, 2021). In short, whereas Industry 4.0 is all about digitalization and connectivity, Industry 5.0 aspires to put humans and their needs back into the loop. Even though I often refer to Industry 4.0 in this research, this work is a prerequisite for Industry 5.0. as I am looking at the technologies from a human and user-driven perspective.

1.2.6 Human Optimized XR

The research related to collaboration in VR was conducted within the Business Finland funded Human Optimized XR (HUMOR)[1] project where the aim was to develop a platform for the production and use of VR for technical documentation. The focus of the research project was on KONE Corporation use cases for elevator maintenance, but the developed solutions are also applicable to other industrial sectors.

[1] https://humanoptimizedxr.org/wp/

2 Objectives and Scope

The objective of this work is to advance the use of XR in the field of technical communication, and, at the same time, offer a content creation platform for XR. Until now, only limited research has been conducted to evaluate the use of XR for technical documentation processes (Stock et al., 2005), and very little has been done in technical communication to establish guidelines for the use of the novel media and technologies in technical communication (Tham et al., 2018). Furthermore, the current solutions for producing and presenting documentation in XR are quite naïve and usually hand tailored to specific devices, which makes the adoption of XR solutions costly and resource-wise difficult for field operations in industrial companies.

The research problem for this work is **How can extended reality be applied in technical communication?** This research problem is further divided into the following research questions:

RQ1: How can virtual reality support digital content creation for industrial maintenance?

RQ2: How should technical information be designed for augmented reality applications?

This research is multidisciplinary, and it deals with the areas of technical communication and extended reality. I approach the research areas and research questions from the industrial maintenance point of view and focus on the work of domain experts in both industrial company's product development and field work.

Figure 3 demonstrates the positioning of the articles I–VII in the main research areas.

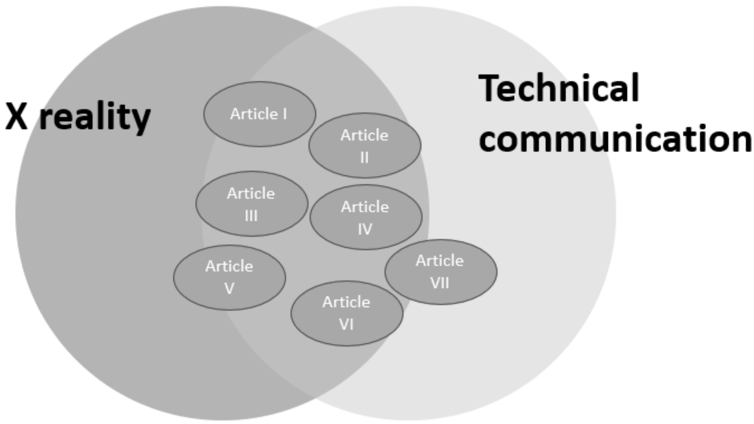

Figure 3. Positioning of articles in main research areas.

Even though this research is conducted from the industrial maintenance point of view, the results are in most parts generalizable to other areas utilizing technical information in XR, for example installation. The focus of the research is on the relationship of extended reality and technical communication: how the processes and outputs of technical communication can be utilized in the content creation for extended reality applications, and how extended reality can be utilized in the content creation of technical instructions and as a delivery channel for technical instructions.

The development of XR software, hardware, and devices are a necessary part of the processes mentioned above. However, this dissertation focuses on the content, and these are, therefore, out of scope for this research. As the use of 360° videos has been already studied quite extensively and it has been also noted in technical communication research that 360° videos can easily be created for virtual reality (Tham et al., 2018), they are left out of scope of this dissertation. Furthermore, the use of VR in field operations is problematic due to the immersive nature of the technology, and, therefore, I see VR as an enabler for technical information content creation and not a delivery channel for technical instructions for industrial maintenance.

2.1 ORGANIZATION OF THE STUDY

This dissertation is based on a collection of seven peer-reviewed articles, which fall under two main topics. The first part (articles I, II, III, and IV) examines how technical information is created in collaboration within the product development in an industrial company. The second part (articles V, VI, and VII) explores how technical information is designed and delivered to technicians on the field. Both parts fall under the umbrella of extended reality (XR); the first part concentrating on virtual reality (VR) and the second part on augmented reality (AR) and the single sourcing of information to different media.

The methods and data used in this study are discussed in detail in the next section, followed by a summary of the articles and presentation of the findings. Finally, I will discuss the implications of this research to the research fields and the industry in general and present concluding remarks.

3 Methods and Data Collection

This section presents the methods and data collection used in the research. I have used a mixed methods approach that integrates both qualitative and quantitative data as it addresses the research questions from a variety of different perspectives, provides opportunities for collecting and analyzing information, and helps to develop a deeper understanding of the issues (Green et al., 2015).

3.1 MIXED METHODS APPROACH

Qualitative and quantitative studies collect different type of data, and their data collection methods differ considerably. To put it simply, quantitative studies are designed to collect numbers, and qualitative research is intended to collect words (Jennifer C. Greene et al., 1989). For this dissertation, I chose mixed methods as neither quantitative nor qualitative method alone would have been sufficient. I wanted to use a method that would explain the results, involve the participants in the research, and generalize the exploratory findings of the research (Creswell & Clark, 2017). Even though the focus of my research is on the qualitative and participatory methods that are known to reveal the users' behavior and attitudes (Kawulich, 2005), the balanced combination of qualitative and quantitative data collection and analysis gives more depth for the results. Specific statistical formulae such as ANOVA have not been used in this study as the sample sizes are small, but the quantitative results have been interpreted through experts' observations and comments. From the quantitative data the distribution of data is also visible, giving insight into whether the user study participants considered issues positive or negative.

In the following sections I will go through each of the methods used in the research.

3.1.1 Qualitative Methods

Participant observation is an ethnographic research method where people are studied in real life situations. Participant observation is a systematic description of events and the behaviors of the participants in the chosen setting (Marshall et al., 2015), and it gives the researchers a way to learn through involvement in the activities of the test participants (Schensul et al., 1999). Researchers can observe nonverbal expressions, study participants' interaction and communication with each other, and check on time spent on different activities (Schmuck, 2006). On the other hand, participant observation also has its limits: the presence of observers might affect the behavior of the observed participants, and researchers might have a problem in choosing what to focus on, what to note down, and what to ignore (Berger, 2018). Furthermore, often researchers have to go beyond studying what the participants do and find out why they are performing certain activities (Berger, 2018). As a way of overcoming the problem of mind reading, I have utilized the thinking aloud method.

Thinking aloud is a method where test participants are asked and encouraged to make spoken comments as they are working with a task. By thinking aloud, the participants enable researchers to understand how they view the tasks at hand, and it also gives insight into any misconceptions that the participants might have, providing a clear understanding of what the participants think of the system and the tasks that they are testing (Nielsen, 1994). Thinking aloud has its limitations: for example, some participants might not engage in talking consistently and remain quiet, background noise might make it difficult to hear and understand what the participants are saying, and not everything a participant thinks can be presented verbally (Güss, 2018). Especially in the case of experts, the execution of tasks is so quick and sometimes unconscious and automated that they might not have anything to say (Nielsen, 1994). To combat these problems, the facilitators of our user tests frequently reminded the participants of thinking aloud, and the tests were also video recorded in case something needed to be checked after the tests.

Interviews are, to put it simply, conversations between the researcher and the test participant, and they are the basic method of data gathering in research (Williamson, 2013). Three types of interviews are used in scholarly research: unstructured interviews, semi-structured interviews, and structured interviews (Brinkmann, 2020). The amount of control the researcher has over the flow of the interview depends on the type of the interview. In this research, I have utilized the *semi-structured interview* that is the most frequently used interview technique in qualitative research (DiCicco-Bloom & Crabtree, 2006). It is an interview where the researcher has prepared a set of questions but maintains a more flexible quality reminiscent of the unstructured interview. With the semi-structured interview, the purpose is to collect the perceptions and attitudes of the participants in a flexible way but to ensure that the participants focus on the issues that are relevant to the study in question (Williamson, 2013). The advantages of the semi-structured interview are its flexibility, versatility, and the interaction possibilities between the researcher and the participant where the researcher can improvise follow-up questions based on the responses of the participant (Kallio et al., 2016), leading to a more thorough discussion of selected items of interest and knowledge-producing potential (Brinkmann, 2020). However, the qualitative interview is not as simple a process as it sounds: it is always an artificial situation where the researcher asks the participant to answer questions, many times under time pressure (Myers & Newman, 2007), and often the researcher will receive multiple and even contradictory views from the participants (Williamson, 2013) that then need to be analyzed further. Certain amount of domain expertise and knowledge is also required from the researcher so that they can lead the discussion in the interview.

Focus group discussions are unstructured discussions by a group of people under the guidance of a facilitator where selected topics are discussed (Berger, 2018; Mansell et al., 2004). As the discussion takes place in a group, the participants should be reasonably homogenous and the discussion should revolve around a fairly limited number of items and questions, giving each group member opportunities to contribute to the discussion. The facilitator focuses the discussion on specific themes and uses the dynamics of the group to include different perspectives on the selected themes (Brinkmann, 2020). The focus group interaction encourages interesting ideas and points of discussion (Williamson, 2013), and the goal of the discussion is not to reach consensus about the theme but discuss different viewpoints and perspectives (Brinkmann, 2020). However, even when the focus group is meticulously moderated, depending on the group dynamics, some views may predominate and the full range of views from the participants may not be presented (Williamson, 2013).

Questionnaires are a set of questions given to participants that are completed in written format (Marshall, 2005). Qualitative data can be collected with open-ended questions, and they allow the participants to express their attitudes and perceptions freely, without having to choose between predefined options or categories that might not completely fit their needs (Williamson, 2013). The disadvantage of the open-ended questions is that they require post coding and analysis (Lavrakas, 2008) as the answers given by the participants can have great variation.

Thematic analysis is a method where patterns of themes and meaning are identified and interpreted within qualitative data (Clarke & Braun, 2017). Thematic analysis is a flexible research method, which allows for rich, detailed, and complex analysis and interpretation of data (Braun & Clarke, 2006). The goal of thematic analysis is not to summarize the contents of the data, but to identify and interpret the main features of the data with focus on the research questions (Clarke & Braun, 2017).

Affinity diagrams organize unstructured and seemingly diverse qualitative data in the form of ideas, opinions, or issues into themes, groups, and relationships (Lucero, 2015). The process of creating an affinity diagram involves the statement of the problem to be solved, generation of ideas, display of ideas, sorting of the ideas into related groups, creating header cards, and drawing the diagrams (Sahay, 2017).

3.1.2 Quantitative Methods

Questionnaires with closed-ended questions are used to collect quantitative data. The closed questions can be classified as factual or opinion (Williamson, 2013). The advantages of questionnaires include, for example, inexpensiveness and nonexistence of interview bias (Berger, 2018; Marshall, 2005). Questionnaires also enable data collection in a standardized way from each respondent to provide comparable results across the sample (Addington-Hall, 2007). On the other hand, questionnaires also have disadvantages: people may not interpret questions correctly, and the response rate might be low (Berger, 2018). The participants might also have trouble choosing between predefined options if none apply directly.

When collecting quantitative data with questionnaires, I have utilized two methods that are discussed below.

Likert scale is a set of statements where the respondents are asked to show their level of agreement with each of the given items (strongly disagree to strongly agree) (Joshi et al., 2015). Likert scale can be either symmetric, where neutrality lies in between the two end statements, or asymmetric, where more choices are given on either side of the neutrality (Joshi et al., 2015). The number of points of the Likert scale can vary and there can be, for example, 5-point, 7-point, or 10-point Likert scales. The more points a Likert scale has, the less the respondents tend to resort to choosing the neutral option on the scale (Matell & Jacoby, 1972). Therefore, in our studies, we used the 7-point symmetric Likert scale.

SUXES is a validated evaluation method for collecting subjective metrics from user experiments both before and after the use of the application. It captures the pre-test expectations and post-test perception, or actual experiences, of users, and provides, therefore, a method to understand the overall experience of the users (Turunen et al., 2009).

3.2 EXPERT EVALUATION

Expert evaluation or interview emerged as a method in the early 1990s (Döringer, 2021). Even though there has been some debate about the definition of "expert" and "expert knowledge" (Gläser & Laudel, 2009), experts are commonly recognized as having specific knowledge of a particular subject and holding a specific position in the organization or community. Expert evaluation aims at collecting data about a field in which the expert has specific knowledge (Meuser & Nagel, 2009), and it is a powerful method of validating concepts with the target group. This approach is commonly used in user-centered design (UCD) in industrial companies, where experts validate concepts generated by others (Sanders & Stappers, 2008), and the development of products is guided by the expert evaluation.

The participants for our user tests were carefully selected to represent people who work in similar roles in the industry, and are, therefore, experts at their own work. Therefore, their opinions carry considerable weight when evaluating new tools and processes related to their own work roles. To collect the opinions and feelings of the experts, we used qualitative and participatory methods that gave us insight into the thinking of the experts who represent the intended future users of the tested systems (Kawulich, 2005).

3.3 DATA COLLECTION

The research conducted for this dissertation was iterative in nature and the lean start-up method (Ries, 2011) was used to develop the concepts. The build-measure-learn feedback loops allowed for ideas and concepts to be tested flexibly. Each of the articles focus on one main iteration of research, its testing, and analysis.

A separate data set was used for each of the seven articles included in this dissertation except for the pre-test questionnaire that was used both in Articles I and II. The articles are discussed in more detail in sections 5.1 and 6.1.

For this dissertation, the qualitative data collection methods include observation with thinking aloud, interviews, questionnaires, and focus group discussions. Quantitative data was collected with questionnaires. These are also research methods that are commonly used in the mixed methods approach (Bryman, 2006). The collected qualitative data was analyzed with thematic analysis. In case of user observation interviews and focus group discussions, researchers transcribed user comments, searched for patterns and themes in the data, and interpreted the data. In the case of open-ended replies in questionnaires, there was no need to transcribe comments as they were already in written form. At least two researchers were involved in the thematic analysis of each data set.

For a summary of the research methods and sample size used for each article, see Table 1. As data was collected with multiple methods from some test participants, the table lists a breakdown of sample sizes per method as well as the total sample size for each article.

Article #	**Observation**	**Interview**	**Questionnaire (open-ended)**	**Focus group discussion**	**Questionnaire (closed-ended)**	**Total number of participants**
1	N = 7	N = 7	-	N = 7	N = 18	N = 25
2	-	N = 7	N = 7	-	N = 25	N = 32
3	N = 20	N = 20	-	-	N = 20	N = 20
4	N = 9	N = 9	-	-	N = 9	N = 9
5	N = 27	N = 12	N = 12	N = 17	N = 12	N = 38
6	N = 21	-	-	-	N = 21	N = 21
7	N = 9	N = 13	N = 13	-	N = 22	N =22

Table 1. Summary of methods and sample size used for each method.

I Toward Efficient Academia-Industry Collaboration: A Case Study of Joint VR System Development.

This article describes a case study for the requirements gathering, software development, and user testing of a VR platform to address industrial needs for maintenance documentation creation. Both qualitative and quantitative data were collected during the study.

Qualitative data was collected before user tests in a workshop in a focus group interview. Five domain experts participated in the workshop onsite in Finland, and two participants from India participated remotely.

Quantitative data was collected before user tests with an online questionnaire. The questionnaire was shared in an industrial company. 38 responses were received, of which 18 were complete and included in the analysis. The rest of the questionnaires were not fully completed by the respondents and were, therefore, not included in the analysis. The respondents were selected in the industrial company based on their roles, and the response rate was heavily affected by their other work duties and the rather lengthy questionnaire (responding to the survey took on average 48 minutes).

The respondents were from 26 to 62 years in age, two were female and the rest male. Most of the respondents held a bachelor or master's degree, while the rest had a high school or vocational school degree. Six of the respondents were from Finland, four from China, four from India, and the rest were from Australia, Netherlands, Germany, and Malaysia. Nine of the respondents represented maintenance development, five represented technical documentation, and two were from learning and development. The data used in this article consisted of background information, overall VR system perception, and COVID-19 related statements.

Seven users participated in the user study. Four participants represented maintenance method development, and three represented technical documentation. Five participants were male, the rest female. Six held a bachelor's degree or similar. Six participants were residents of Finland and one a resident of the USA. During the user study, quantitative data were collected for comparison with the pre-test data via an online questionnaire. Users' expectations and experiences were collected with the validated evaluation method SUXES, and statements on immersion and presence in VR were also included. Qualitative data were collected via observation and interviews.

II Asynchronous Industrial Collaboration: How Virtual Reality and Virtual Tools Aid the Process of Maintenance Method Development and Documentation Creation

This article presents a case study where VR is used to facilitate asynchronous collaboration between maintenance method development and technical documentation in an industrial company. During the study, both qualitative and quantitative data were collected. Data from pre-test questionnaire described above in connection with Article I was also used for this study.

Seven participants from Finland, India, China, and the USA participated in the user study. Four of the participants represented maintenance method development (on average 10 years of work experience), and three represented technical documentation (on average 14 years of experience). The participants were aged 27–57.

Quantitative data were collected with online questionnaires. The SUXES method was used to collect users' expectations and actual experiences before and after the user tests.

Qualitative data was collected via online questionnaires and a semi-structured interviews with the user test participants.

III 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

This article explores the asymmetry between VR and Microsoft Teams to enhance the collaboration of globally scattered teams in maintenance method and documentation creation. Both qualitative and quantitative data were collected during the study.

A total of 20 participants from Finland, India, China, and the USA participated in user tests. Sixteen of the participants were male and the rest female. The participants were aged between 27 to 60 years. Ten of the participants represented technical documentation, eight represented maintenance method development, and two were from mechanical design. Seventeen of the participants held a bachelor's degree or similar, two hold a master's degree or similar, and one had graduated from a vocational school.

Quantitative data were collected with online questionnaires before and after the user tests. The SUXES method was used to collect users' expectations and actual experiences before and after the user tests.

Qualitative data were collected via participant observation and a semi-structured interview with the participants.

IV Evaluating the Benefits of Collaborative VR Review for Maintenance Documentation and Risk Assessment

This article examines the benefits of synchronous collaborative VR to maintenance documentation reviews and risk assessments. Both qualitative and quantitative data were collected during the study.

A total of nine experts participated in the user tests. Three represented maintenance method development, three technical documentation, and three risk assessment. Seven of the participants were male and two females. The participants were from 34 to 64 in age. All participants had a university degree: six had a bachelor's and three master's degrees. On average, the participants' experience at their role was 9,5 years, with a minimum at 2 and maximum at 21 years.

Quantitative data were collected before and after user tests with online questionnaires. The evaluation method SUXES was used to collect user experience and analyze differences in users' expectations and actual experiences.

Qualitative data were collected during and after the test. During the test, user observation was used as participants were thinking aloud and discussing with each other. The participants verbalized their thoughts as they explored the environment and tools, and then addressed each other when they wanted to discuss something with another user. After the user test session, further data was collected in a semi-structured group interview.

V Scalable and Responsive Information for Industrial Maintenance Work: Developing XR Support on Smart Glasses for Maintenance Technicians

This article studies the delivery of technical instructions authored in DITA XML to smart glasses to support industrial maintenance and the work of maintenance technicians. Qualitative data were collected during this study via participant observation, questionnaires, interviews, and a focus group discussion.

The testing was conducted in four consecutive experiments, and a total of 38 people participated in user testing. In the first experiment, twelve users participated in the tests, eight of them male and the rest female. The participants had diverse expertise in industrial maintenance, technical documentation, XR, documentation, IT, and maintenance analytics and applications. In the second experiment, nine people participated in user tests, six of them male and the rest female. They participants had expertise in industrial maintenance, technical documentation, IT, and XR. In experiment 3, ten people were involved in testing, with nine being male and one female. Seven of the participants had maintenance-related roles, two roles related to maintenance training, and one related to competence development. In experiment 4, seven participants were involved in testing. All the participants had maintenance related roles.

VI Information Design for Small Screens: Toward Smart Glass Use in Guidance for Industrial Maintenance

This article describes a study where technical information authoring solutions and information design methods were developed to scale content automatically to different devices and applications. Both qualitative and quantitative data were collected in this study.

A total of 21 people participated in the user tests. 18 of them were male and the rest female. Most participants were from the 30–39 (N = 8) or 50–59 (N = 7) age groups, the rest being from 40–49 (N = 4), 20–29 (N = 1), or > 59 (N = 1). Six of the participants were very experienced with the maintenance environment, two were familiar with it, and six were somewhat familiar with it. The rest of the participants had very limited experience of the field environment (N = 2) or no experience (N = 6). Most of the participants had their background in industrial maintenance (N = 10) or technical documentation (N = 5). Participants also had their background in engineering, installation, or IT. One participant was a student studying to become an elevator technician.

Quantitative data were collected with questionnaires, and qualitative data were collected via participant observation.

VII Minimalism for the Win - User-centered Design for Maintenance Guidance

This article presents a study where the delivery of technical instructions built on the principles of minimalism was evaluated. Both qualitative and quantitative data were collected during the study.

The testing was conducted in two iterations. In the first iteration, a total of nine people participated in the testing. Four of them had two or more years of maintenance experience, and three less than two years of experience. In the second iteration, a total of 13 people participated in a pilot project. All the participants had more than two years of maintenance experience.

Quantitative data were collected with questionnaires. Qualitative data were collected with questionnaires, participant observation, and semi-structured interviews.

4 Context of Research and Related Processes and Technologies

This research is multidisciplinary by nature, and it deals with the areas of technical communication and extended reality. I approach these two research areas and the research questions from the industrial maintenance point of view and focus on the work of domain experts in both industrial company's product development and field work. In the following sections I will go through the processes and technologies that form the context for this dissertation.

4.1 INDUSTRIAL MAINTENANCE

Industrial maintenance is the work performed by maintenance technicians to maintain and manage equipment and machinery to keep it operational and safe to use. Maintenance activities can be divided into two general categories: corrective maintenance and preventive maintenance. Corrective maintenance is executed when the equipment or system fails or is not working properly, whereas predictive maintenance is performed to prevent this type of failure or malfunction (Tsang, 1995). The main purpose of industrial maintenance is to improve the company's performance by preventing breakage before it would happen or reducing the impact resulting from malfunction in the most control-efficient way. Typical tasks of the maintenance technicians in industrial maintenance include planned preventive maintenance, inspections and troubleshooting, adjustments, repairs, replacements, calibration, and testing (Reason, 2016).

Traditionally, industrial maintenance has been characterized by tacit or tribal knowledge that is difficult to manage or capture, and that is also strongly linked to the quality of field work (Cárcel-Carrasco & Cárcel-

Carrasco, 2021). Whereas explicit knowledge can be transferred in formal and systematic languages from one person to another, tacit knowledge is more difficult to communicate (Aromaa et al., 2015). Therefore, when globally operating companies are expanding to new areas, it is often difficult to find skilled workforce for company-specific and equipment-specific maintenance tasks.

However, Industry 4.0 is changing the face of industrial maintenance. Internet of Things (IoT), digitalization, increasing connectivity, and smart technologies have a fundamental effect on maintenance business and industrial work (Johnson, 1998). With the introduction of remote monitoring and connected equipment, the focus is moving from planned annual planned maintenance (PM) plans to condition-based maintenance (CBM). With planned maintenance plans, maintenance is executed at fixed intervals with a predefined list of checks or tasks, whereas in condition-based maintenance computers help humas detect failures and hidden problems (Zou et al., 2019). Therefore, issues with equipment and systems are identified and repaired before breakage and callouts.

With traditional planned maintenance plans, maintenance technicians have been able to build up on their expertise and knowledge of specific equipment and memorize tasks, therefore erasing the need to have the instructions always available when completing tasks. However, with condition-based maintenance, the tasks vary from one piece of equipment to another, and each maintenance visit is unique. Therefore, even experienced maintenance technicians find themselves in needing guidance on the contents of each maintenance visit. At the same time, technicians at the more novice end of the expertise continuum still need much more detailed instructions.

For globally operating companies, the maintenance landscape is also changing in other ways. As the maintained equipment base grows larger and is located around the world, efficient global maintenance business becomes even more important, and companies have turned their focus to finding new ways to support their maintenance technicians (del Amo et al., 2018). Industrial maintenance tasks are often highly complicated, and they need to be executed in an efficient and safe way. Industrial companies create technical instructions to combat this problem and guide the work of the technicians. Traditionally, these instructions have been delivered on paper, as PDF files, or through online portals. However, industrial maintenance is often hands-busy type of work where it is impossible to hold papers or any handheld devices while performing the tasks, and, therefore, the accessibility and usability of documentation has been a major issue.

4.2 TECHNICAL COMMUNICATION

Technical communication is a specialized field dedicated to communicating technical or otherwise specialized information, using technology to convey that information, and providing instructions on how to complete a task or do something (Defining Technical Communication, 2022). Scholz (1994) defines five phases in the technical documentation process:

1. Assessing the need for technical documentation.
2. Analyzing the intended audience and its requirements.
3. Planning the budget, resources, schedules, and the outcome of the documentation project.
4. Developing the information product by iteratively writing and illustrating the draft, reviewing it, and revising and editing it until it is considered ready.
5. Validating the information product by inhouse or customer testing.

Similarly, Pringle and O'Keefe (2000) identify several phases in the documentation process:

1. Identifying the needed information products.
2. Developing an information plan.
3. Creating a project plan with tasks and schedules.
4. Deciding on the template to be used.
5. Creating the content.
6. Creating the illustrations, videos, and animations.
7. Reviewing the draft with subject matter experts.
8. Editing and revising the draft.
9. Indexing the content.
10. Publishing to the delivery channels.

More recently, Virtaluoto et al (2018) have studied the documentation process from minimalism point of view, where the focus is on the user and their information needs. The steps of the process are:

1. Collecting user and product information.
2. Planning the documentation, reviews, tests, and updates.
3. Writing and illustrating the instruction draft.
4. Reviewing and testing.
5. Updating based on review and test comments.
6. Arranging the final review.
7. Publishing to the delivery channels.
8. Collecting internal and external feedback.

The documentation process is the driver and enabler for documentation creation, and it guides the practical actions in companies. Even though the specific details of the process descriptions may vary from one author to another and one company to another, they all have one thing in common: The technical documentation process is a collaborative process, where technical communicators and subject matter experts (SME) work together to develop technical instructions iteratively and to publish them to relevant delivery channels.

4.2.1 Maintenance Documentation Process

Even though it has not been defined as a separate process in technical communication literature, a more detailed maintenance technical documentation process is commonly used in industrial companies such as KONE Corporation to create maintenance instructions. The maintenance documentation process is a subcategory of the technical documentation process, where the outcome is maintenance instructions that help maintenance technicians perform their tasks in a safe and efficient way. After identifying the documentation needs, the maintenance documentation process commonly continues with the maintenance method developer creating the maintenance method and a related outline for maintenance instructions. Documentation experts use the outline to create a draft that is then reviewed and revised in collaboration with the method developers and other subject matter experts. When the draft is ready, the safety of the maintenance method and instructions is typically evaluated by risk assessment experts. If risks are identified in the assessment, the instructions are again revised and reviewed until all parties are satisfied with them. Finally, the instructions are checked and approved by nominated people in the company and released into relevant delivery channels where maintenance technicians can then access them. See Figure 4 for an overview of the maintenance documentation process.

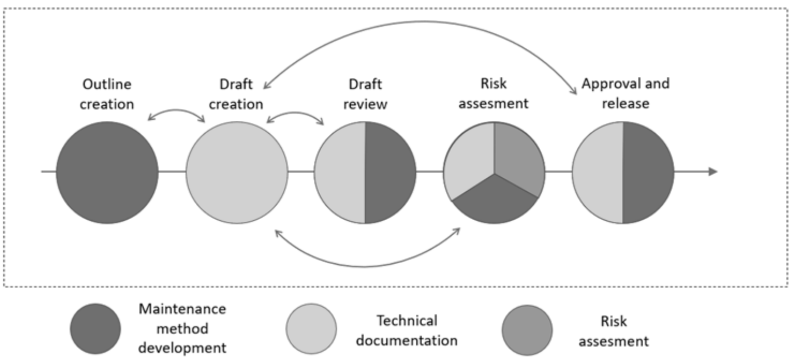

Figure 4. Overview of the maintenance documentation process.

Maintenance documentation creation usually takes places in product development projects or releases with very tight deadlines. The collaboration between the involved parties—technical documentation, maintenance method development, and risk assessment—can be synchronous or asynchronous: the tasks can be performed individually or in meetings. Often there is no access to the physical equipment: the equipment or prototype does not exist yet or, especially in the case of globally operating companies, it might be located on a different site or even in a different country. Therefore, maintenance method development is often based on 2D images or 3D models that are viewed on a computer screen without the context. This might result in misunderstandings both contextually and spatially. The outcome might be that the maintenance method is problematic or even impossible for the maintenance technicians to perform. The documentation experts also face challenges if they have no access to the equipment: the outline might be interpreted incorrectly, or the illustrator's work is unnecessarily complicated. Risk assessing a maintenance method or related maintenance instructions is similarly challenging if there is no access to the equipment.

When working with a draft, it is sent back and forth, with the involved parties commenting and editing it. Especially in geographically scattered teams, communication usually happens via conferencing tools such Microsoft Teams or by sending files via email. The remote communication typically cause misunderstanding, and this, consequently, adds to the number of iteration rounds.

Even though there is some research into utilizing novel technologies such as VR to overcome these challenges in the technical documentation creation process (Stock et al., 2005) and also some evidence of VR being able to address them (Di Gironimo et al., 2013), the technical communication industry has not adopted these practices yet.

4.2.2 DITA Content Model, Reuse, and Single Sourcing

DITA is an acronym for Darwin Information Typing Architecture, an XML-based content model that is the industry standard for structured, modular writing (Bellamy et al., 2011). Content models determine the structure of organization's content in protocols, guidelines, templates, and structure (Rockley et al., 2003).

One of the main principles of DITA is information typing, and DITA defines structures for concept, task, reference, and troubleshooting topics (OASIS Darwin Information Typing Architecture (DITA) TC | OASIS, 2022) in the technical communication domain. Concepts provide a context or tell what something is like, tasks describe procedures, references are used for presenting reference material (Bellamy et al., 2011), and the recently added troubleshooting topic type offers corrective action information (DITA Version 1.3 Specification, 2015). DITA is an evolving standard, and if needed, it is possible to develop new specialized topic types that are consistent and compatible with the standard topic types (Rockley et al., 2009). Document Type Definitions (DTDs) guide the writing, and authors are only allowed to create content that follows a specific structure (Rockley et al., 2003). DTDs, therefore, harmonize and unify the content. DITA topics have a defined and recognizable structure that is always repeated for the same topic type (Rockley et al., 2009).

DITA is topic-oriented by design (Rockley et al., 2009). In practice, authors create small, granular pieces of information (Rockley et al., 2003) that are designed to be independent but can be mixed and matched together to compile a full publication (Rockley et al., 2009). Structured authoring makes it easy to create consistent and usable modular information that can easily be combined into publications. The content is typically managed in a component content management system (CCMS), which enables the organization of content at granular, component level, and tracks links, object versions, and metadata for each component.

The modular nature of content authored in DITA is an enabler for reuse. DITA was explicitly designed to support the reuse of content, and the content model makes it simple to include a topic, or even a smaller fragment, in several publications. Reuse denotes writing the content once and using it many times by either referencing the information in the publication or drawing it from a database, and the process does not involve managing multiple sources (Rockley, 2001).

As content and format is separated in DITA (Rockley et al., 2009), it also supports single sourcing. Single sourcing is a method of reusing information for different formats or purposes. Instead of authoring content for a specific media, such as for online portal, technical writers develop modular content that can be then published to different media or for different audiences (Ament, 2002). For a simple example of single sourcing, see Figure 5.

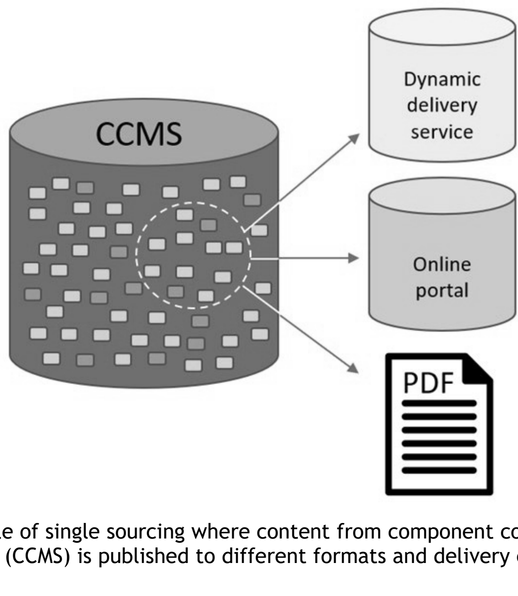

Figure 5. Example of single sourcing where content from component content management system (CCMS) is published to different formats and delivery channels.

Naturally, the primary driver for single sourcing is efficiency: instead of tailoring outputs individually for various media, the source content is designed in such a way so that it works in all the different outputs, and then the actual publishing happens with a click of a button. The relevant styles are applied automatically by the publishing engine, and the result is the different outputs. A further distinction in single sourcing can be made between repurposing (delivering exactly the same content to multiple output formats or media) and re-assembling (re-organizing content for different purposes and audiences using, for example, DITA mechanisms) (Ament, 2002; Rockley, 2001).

4.3 EXTENDED REALITY

Extended reality (XR) refers to all combinations of the real and virtual environments and human-machine interactions that originate from computer and wearable technologies (Alizadehsalehi et al., 2020; Fast-Berglund et al., 2018). In this dissertation, I use the term extended reality (XR) to refer to all technologies that combine real and virtual environments such as augmented reality (AR), virtual reality (VR), and mixed reality (MR).

This dissertation concentrates on two of these technologies, virtual reality and augmented reality, and their relationship with technical communication. In the following sections, I will shortly introduce these technologies.

4.3.1 Virtual Reality

The idea of interactive virtual reality was first described by Ivan Sutherland in 1965:

“Make that (virtual) world in the window look real, sound real, feel real, and respond realistically to the viewer’s actions” (Sutherland, 1965). In the 1990’s, the development in the field of virtual reality accelerated and the term started to be popular knowledge in society (Mazuryk & Gervautz, 1996). VR can be defined as an immersive, multisensory experience; an interactive, participatory environment; and a virtual space that can be shared by many users (Gigante, 1993).

VR offers many possibilities for industrial companies to enhance their processes, and industrial maintenance and assembly is the second-largest application field for VR (Guo et al., 2020). VR has been proven to both enhance remote collaboration (Murray et al., 2003) and be effective for engineering design reviews (Murray et al., 2003; Schina et al., 2016; Wolfartsberger, 2019). Furthermore, one of its main application areas in industrial companies is learning and development where it offers a flexible and realistic way to simulate hazardous working environments (Burova et al., 2020; Büttner et al., 2017; Gavish et al., 2015).

Virtual environments (VE) are computer-generated simulations of real environments that are experienced by users via a human-machine interface (Holden & Dyar, 2002; Loomis et al., 1999). Collaborative virtual environments (CVE) are multi-person virtual realities that support collaboration and communication in an active manner (Maher, 2011). CVEs have been proven as a way to overcome challenges in industrial companies, especially in global settings (Bleakley et al., 2020; Churchill & Snowdon, 1998; Koutsabasis et al., 2012). Both synchronous and asynchronous collaboration is supported in CVEs (Churchill & Snowdon, 1998), offering flexibility and opportunities for several use cases. In synchronous collaboration, collaborators are working together in real time, whereas in asynchronous collaboration they are not present at the same time but can work whenever it is convenient to them (Pidel & Ackermann, 2020). Several studies show that CVEs have the potential to increase the quality of communication and knowledge sharing within organizations and stakeholders (Berg & Vance, 2017; Narasimha et al., 2019; Pedersen & Koumaditis, 2020; Schina et al., 2016). CVEs contribute to ecological and economical sustainability as they lessen the need to travel especially for organizations working in a global setup. Furthermore, as the remote working practices became increasingly common during the COVID-19 pandemic, it is even more important that people have a sense of being together and being part of a team even if they are not physically together, and CVEs have the potential to offer that.

Although the maintenance documentation process is very collaborative by nature, VR has not been widely used or its use researched in the field of technical communication. However, Tham et al (2018) have noted the need to create guidelines for the use of VR technologies in technical and professional communication as technical communicators will find themselves working with novel technologies such as VR in the near future.

4.3.2 Augmented Reality

While users in VR are completely immersed in the virtual environment, augmented reality (AR) allows users to see and experience the real world with virtual objects overlaid or superimposed upon it (Azuma, 1997). AR combines the real-time physical environment with virtual computer-generated objects, and it enhances the user’s perception of reality and interaction with the real world (Furht, 2011). AR can potentially apply to different senses, and, therefore, augment vision, smell, hearing, smell, and touch.

The concept of AR dates back to the 1940s when radar information was displayed on the windshield of a fighter jet (Berryman, 2012). The term AR itself is generally attributed to Tom Caudell and David Mizell, who designed a head-mounted display (HMD) in 1990 to display the technical drawings of an airplane on the factory floor to help workers wire aircrafts correctly (Berryman, 2012). In the recent years, AR has become mainstream in society by being incorporated in many areas of life: for example, gaming, visual arts, movies, photography, digital media, industries, and healthcare (Lavingia & Tanwar, 2020). Several potential use cases have been identified for AR, including maintenance and repair, visualization for medical field or interior design, retail, construction, education, entertainment, and military operations (Azuma, 1997; Bellalouna, 2020; Siltanen, 2012).

The benefits of augmented reality have been studied widely for different types of maintenance operations. For example, Bordegoni et al (2014) evaluate that augmented reality-based applications improve maintenance services and lower operational costs, and Fiorentino et al (2014) describe how augmented reality technologies simplify the understanding of problems, completion of tasks, and localization of specific components. Furthermore, Wilson et al (2013) note that AR clearly enhances the performance of combat medics in medical procedures due to needed information being readily available. However, even though many studies conclude that AR would enhance operations and that AR can serve as a context-sensitive help, the use of AR applications has been studied mainly from the technology and equipment point view, and very little focus has been paid to the process of defining how to design usable technical information content for AR applications, especially in industrial companies where project schedules are often hectic, and resources limited.

Some researchers make a distinction between augmented reality and informed reality (IR) (see, for example, Hamesse et al., 2020). I consider IR to be a subcategory of AR, where the information displayed on smart glasses is not only 3D augmentations positioned on the real-world objects (Bellalouna, 2020), but any relevant information needed for task completion, for example procedural information in the form of text, illustrations, videos, and animations. Naturally, the instructions can also contain embedded augmented parts whenever it provides added value.

5 Collaboration in Virtual Reality

This part of the dissertation (articles I, II, III, and IV) examines how VR can be utilized in the creation of technical information within the research and development (R&D) of an industrial company. It provides an answer to this research question:

RQ1: How can virtual reality support digital content creation for industrial maintenance?

The research related to this part was conducted within the Human Optimized XR (HUMOR) research project. In the HUMOR research project, a platform for the production and use of VR for technical documentation was created.

The VR platform, COVE-VR, was developed in collaboration with industrial and academic researchers. It was based on the input of domain experts and evaluated in several user tests. COVE-VR has two virtual environments, Lab and Showroom (see Figure 6), and they were designed to facilitate the workflows in industrial tasks and collaboration.

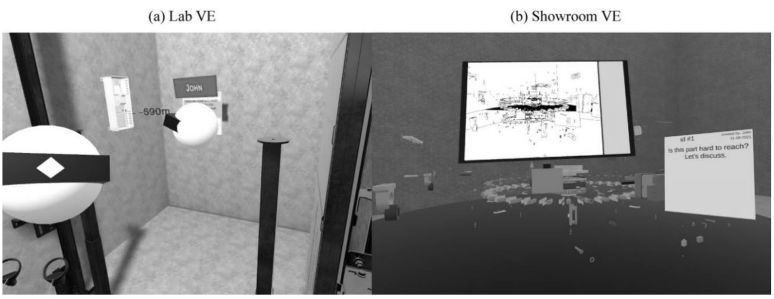

Figure 6. Lab (a) and Showroom (b) in COVE-VR (published in Article III)

Virtual tools were also developed for COVE-VR. The Model Placement tool allows the import of 3D CAD models into the VRE, and the Disassembler allows the in-depth investigation of the models. With the TextBox tool users can create textual notes either by inputting via speech recognition or virtual keyboard, and with the Camera tool they can take pictures and videos from the virtual environment. The Measure tool allows the users to take measurements of the dimensions and distances in the virtual environment. With the Grid Snipping tool, the users can lock the movements of 3D models and measures over grid points. With the Delete tool, 3D objects and other tools can be removed from the virtual environment. The DocPanel tool reads XML files and visualizes technical instructions in the form of text and graphics over a floating window that users can see and control in VR. Finally, the Save World State tool can be used to save all created content in the virtual environment, or to load a previously saved state. The users are visualized as avatars in the virtual environment, and they are able to locomote by moving in the physical space or by teleporting in the virtual environment. COVE-VR supports both asynchronous and synchronous collaboration.

5.1 SUMMARY OF ORIGINAL ARTICLES I-IV

This section summarizes the contents of articles I-IV.

5.1.1 Toward Efficient Academia-Industry Collaboration: A Case Study of Joint VR System Development (Article I)

This article describes a case study for the development of a VR platform to address industrial needs for maintenance documentation creation. To achieve that goal, industrial and academic researchers adopted a user-centered design model to the industrial context and involved various focus groups in the design, development and testing of the VR platform.

Although academia-industry collaboration has been proven to foster innovations (Ankrah & AL-Tabbaa, 2015; Barnes et al., 2002) and give relevance to research by matching industrial needs with scientific knowledge and verified academic knowledge with data collection (Bruneel et al., 2010; Garousi et al., 2020; Sandberg et al., 2011), it is a not a straightforward collaboration process due to differences in practices, frames of reference, targets and aims, and time schedules (Garousi et al., 2016; Sandberg et al., 2011; Siegel et al., 2003). For instance, industry often has tight deadlines and schedules and, in many cases, needs to set short-term priorities, whereas academia mostly works on more theoretical and abstract levels to achieve long-term research goals (Garousi et al., 2016). This article presents a generalizable process-oriented framework for remote academia–industry collaboration, and also gives practical suggestions for supporting this type of collaboration.

Even though the main contribution of this article is a framework of remote academia-industry collaboration, it also describes the requirements gathering, software development, and user testing of the COVE-VR platform. COVE-VR is designed to facilitate department-to-department collaboration in a virtual environment, with focus on digital content creation for maintenance documentation. Maintenance documentation creation involves two departments in companies: subject matter experts (with expertise on maintenance methods and equipment) and documentation experts (with expertise on documentation tools, information design, technical writing, and illustration). The maintenance documentation process is an iterative process where the involved parties co-create the instructions until a final version is published (Hackos, 2002).

The industrial researchers gathered requirements directly from domain experts in the industrial company resulting in an actual workflow of maintenance documentation tasks, personas of the experts involved in the process, and scenarios of how the work could be done within the virtual environment (see Figure 7). The requirements gathering phase resulted in a wish list of features for the virtual environment, and a survey was conducted with domain experts to prioritize the features. The prioritized list of features was then delivered to the academic researchers, who finalized the system design and developed the virtual environment. During system design and development, industrial researchers gave constant input and reflection to academia, making sure that the developed system would be according to the gathered and prioritized features.

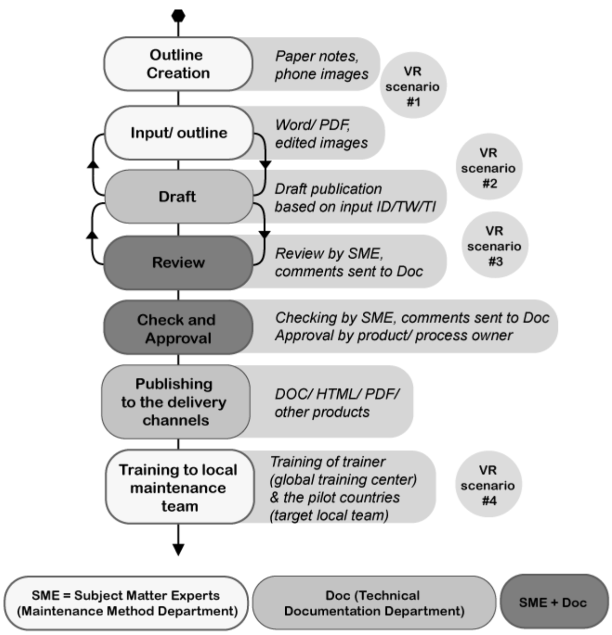

Figure 7. Maintenance documentation journey with identified VR scenarios (published in Article I).

The developed VR platform, COVE-VR, was designed to facilitate department-to-department collaboration in VR. Two virtual spaces were available to support tasks related to the development of maintenance methods and documentation tasks: one space designed for primarily individual work small, replicating a real maintenance site, and another for individual and collaborative work, replicating a meeting room. COVE-VR had seven virtual tools for documentation content creation: TextBox Tool for creating text notes via speech-to-text or typing, Camera Tool for recording videos and capturing images, Model Placement Tool for opening different 3D models, Measure Tool for measuring distances, Delete Tool for deleting tools and models, Grid Snipping Tool for locking the movement of models to grid points, and Save World State Tool for saving all VR object for the next user or session.

COVE-VR was tested by seven domain experts at KONE in a user study that focused on asynchronous VR collaboration. In total, eight sessions were held: one pre-test in Finland, six in-person user tests in Finland, and one remote user test with a participant located in the USA. Qualitative and quantitative data were collected during the user study via observations, an online questionnaire, and interviews.

5.1.2 Asynchronous Industrial Collaboration: How Virtual Reality and Virtual Tools Aid the Process of Maintenance Method Development and Documentation Creation (Article II)

This article discusses the benefits derived from using VR for collaboratively performed industrial maintenance method and technical documentation creation tasks. It presents a case study on using VR to facilitate asynchronous collaboration between different departments in an industrial company and generating digital content for maintenance documentation.

Collaborative virtual environments (CVE) have been proven to support both synchronous and asynchronous collaboration and to increase interactions, knowledge sharing and also the quality of communication among people working in teams and projects (Berg & Vance, 2017; Narasimha et al., 2019). Research has also shown that employees in industrial companies show positive perceptions of VR technologies and, thereupon, increased motivation towards using them (Burova et al., 2020; Schwarz et al., 2020). Even though the creation of maintenance documentation is inherently collaborative in nature, and there is some evidence of novel technologies such as collaborative VR being able to enhance the processes involved (Di Gironimo et al., 2013; Stock et al., 2005), industry have not adopted these practices yet for documentation processes.

Our case study concentrated on asynchronous collaboration scenarios related to maintenance documentation creation. The scenarios were identified during a workshop with documentation and maintenance method experts, and the expectation was that VR would enhance the asynchronous collaboration of two teams located in different time zones. Each expert worked by themselves, leaving notes and comments for others to see later (see Figure 8), and they were also able to create digital content such as photos and videos. The visual assets could then be used in maintenance instructions or as a means of communicating issues to others.

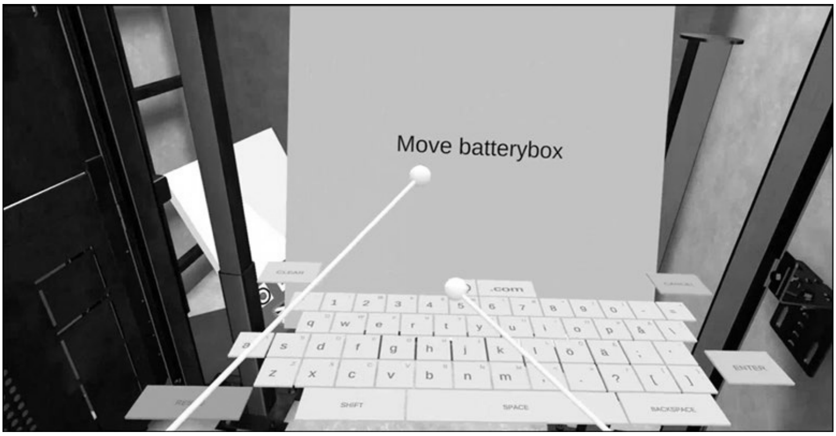

Figure 8. Test participant using the TextBox Tool in user tests.

The COVE-VR platform was used for testing the asynchronous collaboration scenarios. The usefulness of the concept and the tools were evaluated first with a video-based online questionnaire, and the usability of the VR platform was tested in a user study with domain experts. The questionnaire received 38 responses, of which 18 were fully completed and included in the analysis. Seven experts from Finland, India, China, and the USA participated in the user study: four from maintenance method development and three from technical documentation. The tasks of the user test participants were representative of the experts' actual work tasks in the company. Both qualitative and quantitative data were collected during the user tests via open-ended questions (questionnaire) and semi-structured interviews (expert study).

5.1.3 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 (Article III)

In this article, the aim was to investigate asymmetry between VR and Microsoft Teams to enhance the distributed collaboration of globally scattered team members for maintenance method and documentation creation processes. Specifically, we studied which use cases are beneficial for asymmetric VR in the industrial context and how distributed asymmetry can efficiently be adopted between VR platforms and traditional conferencing tools.

Even though the benefits of collaborative VR are evident in the industrial context (Guo et al., 2020; Narasimha et al., 2019), and VR has been proven to simulate a variety of industrial contexts in a safe manner and enable interactions with virtual objects (Ben Hadj et al., 2015; Murray et al., 2003; Wolfartsberger, 2019), the industrial use of VR is still associated with rather high implementation costs (Zaker & Coloma, 2018). This was further accelerated by the COVID-19 pandemic as remote work became the norm: more employees would need to have head-mounted displays (HMD) of their own as there was no access to shared ones. The pandemic also caused significant disruptions in supply chains, further delaying the adoption of VR technologies in industries. The slow adoption rate of VR can be partly overcome with the use of asymmetric VR, where non-HMD user groups are included, and users have different levels of immersion and control in VR.

In our case study, we investigated asymmetry over two digital tools: the COVE-VR platform and Microsoft Teams. VR-users were present in the immersive multi-user collaborative VR environment and could interact with 3D CAD models and virtual tools. The second user group, Teams-users, were able to see the virtual environment through the eyes of VR-users and communicate with them via voice connection over Microsoft Teams (see Figure 9).

Figure 9. Teams view of the user test: (1) streamed VR view, (2) streamed video of VR-participants, (3) Teams chat (published in Article III)

Twenty domain experts from Finland, India, China, and USA participated in user tests to evaluate the concept of asymmetric VR collaboration between the COVE-VR and Teams. Ten of the participants represented technical documentation, eight maintenance development department, and two mechanical design. Both qualitative and quantitative data was collected during the study via semi-structured interview, observations, and questionnaires.

5.1.4 Evaluating the Benefits of Collaborative VR Review for Maintenance Documentation and Risk Assessment (Article IV)

This article presents a case study where the benefits of collaborative VR to maintenance documentation reviews and risk assessments were studied. Even though the use of VR for industrial needs has been researched for decades, and its potential to aid and enhance many industrial tasks and processes has been proven (Guo et al., 2020), it has mainly been applied to training (Schwarz et al., 2020), AR-prototyping (Burova et al., 2020; Pfeiffer-Leßmann & Pfeiffer, 2018), and different parts of the product development process (Berg & Vance, 2017; Berni & Borgianni, 2020; De Silva et al., 2019; Guo et al., 2020; Wolfartsberger et al., 2017). Moreover, although some research has been conducted for evaluating the use VR for the technical documentation creation process (Stock et al., 2005), its use has not been implemented in practice in industrial companies. Instead, the process for documentation review has remained the same for years, and maintenance instruction reviews and risk assessments are typically performed by sending out links to instructions that are in PDF or HTML format. Face-to-face meetings can be arranged if all participants are located on the same site, but especially in globally operating companies, teams might be scattered on different sites and countries and there is no option to meet face-to-face. Therefore, in practice, meetings are held in conferencing tools such as Microsoft Teams, or reviewers work independently with the draft instructions and send review and risk assessment comments back via email or a file sharing system. Even in cases when there is a possibility to meet face-to-face, the teams often have to work without access to the actual product as the prototype might not exist yet or might be located on a different site.

We conducted an exploratory user study in the COVE-VR platform to evaluate if collaborative multiuser VR can be used for technical documentation reviews and risk assessment. The DocPanel Tool was used in the VR environment as the tool to display maintenance instructions. The tool reads XML files and visualizes the instructions in the form of text and graphics, and the users are able to view and control the instructions in VR in it. The users are also able to move the DocPanel and place it in a comfortable spot in the VR environment. In addition, previously tested TextBox, Camera and Measure tools were available for the users as supportive tools during the review. The virtual reality environment was tested in user tests by nine domain experts from three different departments: documentation, maintenance method development, and risk assessment. The test participants worked with a maintenance instruction displayed in the DocPanel tool and interacted with the components in the VR environment (see Figure 10).

Figure 10. User test participant working with a DocPanel Tool and VR view displayed in a monitor

The test participants were immersed in VR, able to see each other as avatars, and encouraged to interact with each other during the user tests. Both qualitative and quantitative data were collected during the study via observations, online questionnaires, and semi-structured group interviews.

5.2 RESULTS

Three collaborative VR setups with different levels of immersion were tested for this research:

- Asynchronous collaborative VR (Article I and II)
- Synchronous collaborative VR, hybrid setup with VR and Microsoft Teams (Article III)
- Synchronous collaborative VR, all-in-VR setup (Article IV)

Our results show that overall, the company's employees had a strongly positive attitude toward using VR technologies in their working tasks, and the design of the tested VR environment was in accordance with their needs for collaborative work in maintenance documentation creation even though there were some interaction issues. The interaction issues were mainly features not fully developed (for example, recognizable avatars) or missing (for example, pointers that would be visible to all users). The concept of using VR with different levels of immersion for collaboration related to maintenance documentation creation—asynchronous, synchronous with a hybrid setup, and synchronous all-in-VR setup—was evaluated positively in user tests. Additionally, the findings also demonstrate the success of the academia-industry collaboration process; the co-creation activities resulted in the correct determination of industrial needs and system requirements that were correctly transferred to the system design.

5.2.1 Asynchronous Collaborative VR Setup (Articles I and II)

Our study shows that VR enhanced the communication between experts, and also facilitated the generation of digital content. According to the results, VR offers many possibilities to enhance the collaboration of the departments—global teams located in different time zones—involved in the process of maintenance documentation creation. Experts saw VR as a tool for simplifying processes and eliminating communication hurdles even though they raised some concern for the costs of developing and implementing such a system. In user tests, test participants were successful with their assigned tasks, and evaluated VR to be beneficial to support their communication and collaboration. Overall, the results demonstrated that although further development needs were identified for the tested VR environment, it was seen as a useful tool to facilitate tasks related to maintenance method development and documentation creation.

5.2.2 Synchronous Collaborative VR, Hybrid Setup with VR and Microsoft Teams (Article III)

Our findings suggest that asymmetry improves the quality of communication among geographically scattered team members and heightens their spatial understanding. The digitally hybrid collaboration approach was found to be beneficial by both the VR-users and Teams-users. All the domain experts who participated in the user testing agreed that collaborative VR can improve the company's working processes, and they were in favor of transferring their working processes into VR. Furthermore, even though many improvements were suggested to the current design of the tested VR environment, the asymmetric use of VR and Teams was evaluated a better alternative to traditional communication channels such as emails and conference calls for industrial collaboration tasks. The study demonstrated that distributed asymmetric VR is an efficient low-cost solution to enhance maintenance method and documentation creation processes in globally operating companies where team members are globally dispersed.

5.2.3 Synchronous Collaborative VR, All-in-VR Setup (Article IV)

The experts evaluated collaborative reviews in VR positively. All the experts evaluated that maintenance documentation review and risk assessment sessions in VR would positively affect the overall performance of the company, expedite projects, and advance knowledge transfer between involved departments. Moreover, experts agreed that both documentation review and risk assessment processes in VR would be more efficient than the current practice of reviewing via traditional conferencing tools. Our study also showed that VR had a positive effect on the collaboration of the team. Especially in globally operating companies where experts rarely meet face-to-face, VR strengthens the sense of being part of a team and promotes inclusiveness. VR also provides virtual access to equipment in cases where the physical prototype is not accessible to the team, strengthens spatial understanding, and, therefore, results in more accurate maintenance methods and maintenance instructions. Even though VR was not seen as a replacement for working at the real equipment, it was rated a useful alternative in cases where there is limited or non-existent access to the physical equipment.

To conclude, collaborative VR was rated positively by the participants in our user studies, and the participants were willing to integrate it to their daily practices related to the maintenance documentation process.

6 Augmented Reality and Single Sourcing of Technical Information for Different Media

This part of the dissertation (articles V, VI, and VII) explores how to design and deliver technical information to technicians on the field. It provides an answer to this research question:

RQ2: How should technical information be designed for augmented reality applications?

The research related to this part was conducted within elevator product development. The focus of the project was on elevator maintenance use cases, but the developed solutions are also applicable to other industrial sectors.

6.1 Summary of original articles V-VII

The second part of this dissertation consists of three peer-reviewed articles (articles V, VI, and VII). This section summarizes the contents of each of these articles.

6.1.1 Scalable and Responsive Information for Industrial Maintenance Work: Developing XR Support on Smart Glasses for Maintenance Technicians (Article V)

In this article, the aim was to explore if technical information authored in DITA XML is usable when viewed and used with smart glasses. We wanted to see if it is possible to deliver technical instruction content to smart glasses to support industrial maintenance, and if the content can be used in a scalable and responsive way in smart glasses to support the work of maintenance technicians.

The on-going industrial revolution, Industry 4.0, has been transforming industrial work. Traditionally, maintenance technicians working in the industrial field have possessed tacit knowledge, and there has been a challenge to find proficient technicians, especially in the developing markets (Gattullo et al., 2017). Digitalization, Internet-of-Things (IoT), connectivity, smart technologies and related devices are changing many industrial work roles (Johnson, 1998; Kaasinen et al., 2018). The importance of maintenance business and its efficiency is growing, and companies are thinking of different ways of getting support to their maintenance technicians.

Until now, technical information has been delivered on paper or as electronic prints, online helps or through online portals or web services. Yet, industrial maintenance is, many times, work that requires the use of the technicians' hands as they might have to hold equipment parts or tools. Therefore, it might be difficult or even impossible for the technician to check the instructions simultaneously as they are performing the task. Technicians are also often required to wear personal protective equipment such as gloves, making the use of touchscreen devices challenging. Therefore, we investigated the use of AR as a delivery channel for technical instructions as smart glasses enable the simultaneous use of the instructions while working with the equipment or tools, leaving the hands free to perform the tasks.

Many of the current AR solutions are designed so that the content has to be manually authored for each application or device (Palmarini et al., 2018). In this study, we investigated the use of company's existing technical information, in the format of DITA XML, and focused our study on the usability of that information in different devices (for an example, see Figure 11).

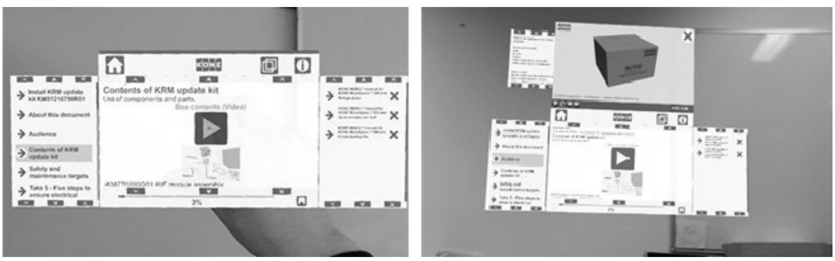

Figure 11. Technical instructions displayed in an application developed for HoloLens (published in Article V).

Our study consisted of four consecutive development cycles, referred to as experiments. Each of these experiments consisted of one or more build-measure-learn loops. Three different AR glasses were used in testing, and a diverse team of experts were engaged in the testing from the fields of maintenance, industrial XR, technical documentation, and IT. Qualitative data were collected during the study via participant observation, interviews, questionnaires and focus group discussions.

6.1.2 Information Design for Small Screens: Toward Smart Glass Use in Guidance for Industrial Maintenance (Article VI)

This article describes a study that focuses on developing technical information authoring solutions and information design methods to scale content automatically to different devices and applications, with the focus on delivery to small screen devices such as smart glasses.

Many use cases have been presented for utilizing smart glasses in maintenance, with one of the most prominent ones being work instructions for maintenance technicians (Klinker et al., 2018). Previous studies (Aitken & Ross, 2019) have shown that users perform faster and with less errors when using such smart glass systems. Users also have a feeling of more competence and satisfaction with these systems (Henderson & Feiner, 2010; Xue et al., 2019). Therefore, instructions delivered to smart glasses immediately enhance the users' skills.

Maintenance technicians have varying skill levels. Experts possess tacit or tribal knowledge, they know how to perform even the more complicated tasks (Webel et al., 2013), and prefer to have detailed instructions only rarely (Aromaa et al., 2016). At the other end of the continuum, trainees and novices need more detailed instructions to be able to complete their tasks. Technical communication has recognized the need to categorize users into different groups based on their skills levels (Hackos, 2002), and different types of instructions can be created for each user group. However, in reality the expertise of the user and the need for guidance depends on the equipment and task at hand and the concept of expertise needs to be flexible. Furthermore, with the condition-based maintenance programs, the tasks vary from one equipment to another, and it is not feasible for even the more experienced maintenance technicians to know all the tasks related to a specific preventive maintenance visit, for example. Consequently, there is an increased need for guidance even for expert users.

Standardized guidelines in technical communication enforce rules for information design. Technical communication literature recommends that there are a maximum of nine steps in a task (Laan & Hackos, 2012) or that information is chunked into meaningful pieces to help reduce the user's cognitive load (Coe, 1996; Kahn et al., 1990; Redish, 1993; Schriver et al., 2013). These guidelines have had a considerable effect on the design of technical information.

We conducted a user study to evaluate how information should be designed and created to support use in small-screen devices. We also wanted to find out how the same content could be utilized to deliver relevant instructions for users based on their skill levels. Authentic elevator instructions were used in the user tests. Three different information design methods were utilized in the creation of the content: conventional, visual manual, and minimalist. The conventional was based on the original instructions of the tasks and used as the reference version in this study. Visual manual was based on the approach by Gattullo et al (2019) where text is replaced by graphics, symbols, and icons. The minimalist version was based on the minimalism heuristics by van de Meij and Carroll (1995) where a user-centered approach is used, often producing tasks where a mixture of text and graphics support each other. The test content was authored in DITA XML, and smart glasses were used in user tests to evaluate the usability of the information (see Figure 12). A total of 21 test participants participated in the user tests. Both qualitative and quantitative data were collected via thinking aloud, participant observation, and questionnaires.

Figure 12. User tests in progress with the test participant using HMT-1.

6.1.3 Minimalism for the Win - User-centered Design for Maintenance Guidance (Article VII)

This article discusses the application of minimalism and user needs in technical communication. It describes an exploratory study in which technical instructions built on the principles of minimalism were evaluated. Traditionally, minimalism has been applied to the content creation phase, but in our study we expanded the principles of minimalism to the delivery of technical instructions.

Minimalism is a user-centered, use-centered, and action-oriented approach. Its original application was software and target audience novice users (Draper & Oatley, 1992), and even though it has also been thought of in the context of hardware (Suomivuori et al., 2020), its main application areas to date are in software guidance. The focus of minimalism is the optimizing of information (van der Meij, 2003): presenting only the information that the user needs at any given moment.

User profiling based on expertise is an established concept in technical communication (Hackos, 2002; Jayaprakash, 2008; Laan & Hackos, 2012; van der Meij et al., 2009). DITA XML also supports profiling through filtering content for different audiences (DITA Version 1.3 Specification, 2015). The outcome of the filtering is usually a different set of instructions for pre-defined user groups, for example, a quick guide for experts and full instructions for novice users.

In the recent years, Industry 4.0 and growing connectivity has changed industrial maintenance. Traditionally, preventive maintenance visits were time-based, and maintenance technicians performed the same set of tasks at certain intervals. Today, sensor data and artificial intelligence are used to get insight into the condition of the equipment (Zonta et al., 2020). Companies are moving to the condition-based maintenance programs due to their higher reliability and lower costs (Zou et al., 2019). For a maintenance technician, this means that the contents of each maintenance visit are different, and they can no longer memorize the tasks related to the visits. Therefore, there is an increased need for guidance for experts, but at the same time the needs of the novices need to be catered for as before. In addition, the concept of expertise has to be flexible and context sensitive as a maintenance technician can be an expert with some equipment or tasks and novice for others, depending on what they have been working in the past.

In this article we explore how the semantic structure of DITA XML can be used in the delivery of technical information to support users with different skill levels, and how a layered system of information can support the principles of minimalism.

We tested the concept of layered information in two iterations. In the first iteration we had two layers of information: the first layer was for experts, and the second layer provided further details for novices. Nine participants tested the prototype created with Adobe XD with their mobile phones in user tests. For the second iteration, the concept was further developed based on the feedback from the first iteration, and information was delivered in a three-layer approach (see Figure 13.). For the second iteration, an application was built for mobile phones, and it utilized the DITA XML semantic structure to target information for three groups: experts, standard users, and novices. The concept was tested in a pilot project that included 13 maintenance technicians, involved the use of 610 pieces of equipment, and lasted for six months.

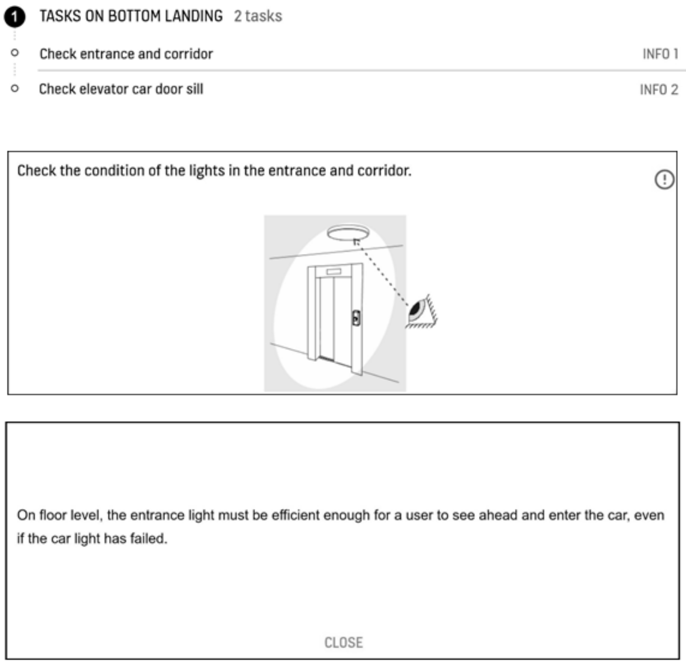

Figure 13. Three layers of information: Task list with titles for experts (top), standard instructions (middle), and additional information for novice users (bottom) (published in Article VII).

Both qualitative and quantitative methods were used for data collection in this study: participant observation (Iteration 1), interviews (Iteration 2), and questionnaires (Iteration 1 and 2).

6.2 RESULTS

6.2.1 Using Technical Information in Smart Glasses (Articles V and VI)

Among our participants, the general attitude toward using technical information in smart glasses was positive, and the instructions displayed on smart glasses helped the users perform the tasks. Many participants stated that they would prefer guidance delivered via smart glasses to traditional paper manuals, but the information has to be usable in the smart glasses and the devices and applications intuitive to use. The devices were still seen as too immature, and the technology and the usability of the devices needs to be improved before this type of industrial use is feasible.

In Article V, the use of converted legacy information was tested. As the technical information used in our testing was not designed to be displayed on a small screen, the topics were too long, making it difficult to follow the sequencies in step lists. The content did not fully fit on the screen, and scrolling was fairly complicated with the smart glasses. Participants also stressed the importance of good navigation and bookmarking systems and noted that they sometimes had problems understanding where they were within the instructions. Even though there were some usability issues with the content, generally the delivery and use of DITA XML in the smart glasses was proven to be successful. Therefore, even though it is important that existing technical information can be utilized, and content does not need to be tailored for AR applications, the information needs to be designed and authored in a way that supports delivery to small screens in addition to the more traditional delivery channels.

Article VI explored different information design methods to facilitate the delivery of technical information to smart glasses and other small screens. The chosen information design methods successfully compressed technical information, and the user-centered approach of minimalism was the preferred method among our test users. Having the instructions proceed step-by-step was a well-received concept as users could simultaneously work with the equipment and proceed when they felt comfortable. This also made the number of steps or chunks irrelevant in task as the users no longer have to memorize the steps.

6.2.2 Targeting Information for Different Skill Levels (Articles VI and VII)

Filtering information based on DITA XML elements proved to be an efficient and flexible way to target information to different skill levels. In Article VI, the expert-level information was shown to users and other content was hidden by the application. In Article VII, the concept was developed further, and technical instructions were delivered in layers. The users were, therefore, empowered to choose the depth of instructions they needed for each task. Our user studies show that the users rated the filtering and the layered system positively. The users were very satisfied with the readability and clarity of the instructions. As the information is delivered in layers, it fits onto the smaller screen and, therefore, the layered system facilitates the delivery of information to smart glasses and other small screens. Our results also show that the concept of context-sensitive level of expertise fulfills the requirements of minimalism as it empowers the user to decide on the depth of the technical instructions they need, and that minimalism can also be applied to hardware instructions.

6.2.3 Single Sourcing of Content for Different Devices (Articles V-VII)

The filtering system based on DITA XML elements supports the reuse of information as the same DITA XML files can be used to resolve the full contents or to filter for some other use cases. By design, DITA XML supports single sourcing and omnichannel delivery. Articles V and VI explore the delivery of DITA XML to smart glasses. Article VII, in contrast, studies the delivery of DITA XML to mobile phones. In both of these delivery channels, the technical instructions and their translations worked well, and, therefore, our study further validates the possibilities that DITA XML offers with regards to single sourcing.

7 Discussion

This doctoral thesis aimed at exploring the challenges and opportunities that extended reality poses for technical communication. I have approached this research problem from both technical communication and extended reality point of view. The dissertation is divided into two different parts. The first part (articles I-IV) investigated how VR can be utilized in the creation of technical information within the product development of an industrial company, and the second part (articles V-VII) explored how to design and deliver technical information to technicians on the field with focus on AR and single sourcing of information. Therefore, this dissertation covers both the content creation and content consumption of technical information and their relationship with XR.

Over twenty years ago, Ann Rockley stated that until then, technology had been the driving force in deciding what technical communicators can offer to users, but technical communicators must start driving the configuration of the technology:

"The technology supports us in our task but does not predetermine how information should be presented. Only information developers can effectively configure the technology to support user needs. Without a clear understanding of information, media, and user needs, our use of the new technologies will fail. We now have a wonderful opportunity to make technology work for us and our users." (Rockley, 2001)

However, not much has happened technology-wise in the area of technical communication since then with the exception of the adoption of online portals and dynamic delivery services in some companies. Furthermore, as Tham (2018) put it, very little has been done to create any guidelines for the use of XR in technical communication. This statement applies to both research in the areas of technical communication and XR and also to guidelines in companies creating technical instructions. I have accepted this challenge and established guidelines for the area in this dissertation. The use cases and guidelines are discussed in the following sections.

7.1 Implications of Research

In this section I will explore the implications of this research from both virtual and augmented reality point of view. I will also discuss the research questions and the solutions to the research questions presented by the results of my research.

7.1.1 Virtual Reality

VR has significant potential to transform the current working practices and processes in industrial companies (Guo et al., 2020). Even though the use of collaborative virtual environments has been researched widely and its benefits proven, its main application area in industrial companies is still training (Andaluz et al., 2018; Schwarz et al., 2020), and in other areas the implementation of VR is still limited (Wannerberg et al., 2019). In this research, I have investigated the use of VR for the technical documentation process, and the results show that VR has potential to enhance both the process itself and the creation of digital content.

As VR offers many possibilities to enhance collaboration between departments, it is a well-suited technology to enhance the technical communication process. Technical documentation creation is a collaborative process that involves stakeholders from different departments: technical documentation and subject matter experts, and, in many cases, risk assessment is also involved. Traditionally, the collaboration has taken place in meeting rooms or, in the case of globally operating companies, in conference calls or emails, and the inherently collaborative work often turns into individual work at the computer, resulting in misunderstandings and unneeded iterations of the draft instructions. With VR, that lone work can be transformed back to a collaborative process, leading to a more efficient process.

Furthermore, as the equipment being documented is not always available or accessible to the team, experts often have to work with 3D models only, without ever seeing the equipment or being able to explore it. This, in turn, might result in spatial misconceptions and tasks that are difficult or even impossible to perform. VR has been proven to be effective in removing these types of problems (Fillatreau et al., 2013; Tea et al., 2022; Wolfartsberger et al., 2017), leading to a correct understanding of the scale and more accurate work methods and instructions. Moreover, the tools built for COVE-VR further aid in both the understanding of the scale and dimensions of equipment and offer possibilities for digital content creation.

In this research I tested three different VR setups for technical documentation creation: asynchronous collaborative VR (Articles I and II), synchronous collaborative VR with a hybrid setup (Article III), and synchronous collaborative VR, all-in-VR setup (Article IV). The requirements for the VR environment were collected from domain experts in an industrial company, prioritized, and developed accordingly. The results of this research show that the company's employees had a promising attitude towards using VR in their daily work tasks, and the setups and the tools developed for the CVE were rated positively. The asynchronous collaborative setup works especially well in cases where the experts are not present at the same time due to, for example, working in different time zones, and it can, therefore, especially enhance the work of teams that are globally scattered. The tested hybrid setup was achieved by adding desktop users via Microsoft Teams, offering, therefore, a scalable and low-cost solution where all the employees do not need expensive VR equipment to attend a session but can still receive benefits and value from the VR technology. The all-in-VR multiuser setup mimics the real-life meeting at the equipment, offering a way to interact in real time even if not located physically in the same place. As the tested VR platform, COVE-VR, supports all of these setups and works as a single multifunctional collaborative VR platform, it has potential to enhance collaboration in many ways. In the synchronous modes, collaborators can work together in real time, ask questions, and discuss details as if in the same physical space, whereas in the asynchronous collaboration mode they can work whenever it is convenient to them (Pidel & Ackermann, 2020), leaving notes and remarks for others to read later on.

Overall, the results of this research demonstrate that although further development needs were identified for the tested VR environment, COVE-VR, it was rated positively by domain experts and seen as a useful tool to facilitate tasks related to technical documentation creation. Especially in companies where the VR technology is already adopted for some functions, for example training, the integration of VR to the technical documentation creation process would be fairly easy to achieve. As evidenced by Article III, especially the hybrid setup offers a reasonably low-cost way to implement VR in industrial companies, and the use can be then scaled up to other VR setups that require more devices.

7.1.2 Augmented Reality

Efficient and reliable maintenance operations are a key success factor and a significant part of revenue for many industrial companies. However, the maintenance industry is facing new challenges with the more complicated, globally scattered equipment base that has a longer lifecycle, and more focus is paid to the ways of delivering support to company maintenance technicians (del Amo et al., 2018). Traditional means of delivering technical information—paper copies or electronic prints, online portals, and help systems—are problematic in the context of industrial maintenance where tasks often require the use of the technician's hands. It is challenging to check these types of information sources simultaneously when holding equipment parts and tools, and the use of personal protective equipment such as safety gloves makes the handling of instructions difficult when they are delivered on paper and via handheld devices.

Assistive documentation delivered with AR applications has been evaluated to increase the performance and safety of maintenance technicians (del Amo et al., 2018; Engelke et al., 2015; Funk et al., 2015; Gattullo et al., 2020; Tatić & Tešić, 2017; Uva et al., 2018), and industrial companies have presented use cases where maintenance instructions are displayed on smart glasses (Kaasinen et al., 2018; Palmarini et al., 2018). Even user satisfaction and feeling of competence have been evaluated to increase with the use of AR (Henderson & Feiner, 2010; Xue et al., 2019). However, the adoption of AR technologies in industrial maintenance has been hindered by both the fact that smart glass hardware is not yet mature enough and authoring solutions and content management tools have not been available for AR (Palmarini et al., 2018).

Research papers usually discuss augmented reality instructions in the form of 3D augmentations on top of a machine. However, in most cases the necessary instructions can be presented in the form of text and graphics, and 3D augmentations can be considered overengineering. For example, with a simple task such as tightening a screw, it is enough to indicate it with text or an icon instead of the more elaborate 3D augmentation. Not only it is faster and more cost-efficient to create the original textual or graphical information, but it is also faster and more cost-efficient to update those type of instructions when the need arises. Therefore, for industrial maintenance, informed reality (IR) is the key to adopting the augmented reality technologies for production use.

In this dissertation, my focus has been to develop a solution that is device independent. When working in production settings in industrial companies, resources are often limited, and instructions cannot be tailored to different devices. Instead, the information must be in a scalable format that works in different devices with various screen sizes: personal computers, mobile phones, smart glasses, and even smart watches and other wearable displays. When the information is designed in a smart way, it can be single sourced to all possible output channels, eliminating the need to tailor it for specific channels.

Single sourcing is one of the fundamental themes in technical documentation and supported by the DITA content model, and DITA XML offers a flexible way to author content for omnichannel delivery as the same content can be rendered in AR devices without any manual steps or actions required from content creators. In Article V, we tested the delivery of XML-based technical information to smart glasses. The concept of using smart glasses to deliver maintenance instructions to technicians was a well-received concept, but it was evident that information design and compression of topics is needed when the information is viewed with smart glasses. In Article VI we explored how information should be designed for small screens such as smart glasses and concluded that the user-centered approach of minimalism works best, and the message is most reliably communicated with a mixture of text and graphics that support each other. This is especially important in industrial maintenance where the working environment is often hazardous and work instructions must be unambiguous. As minimalist instructions only include information that is needed and omit unnecessary details, the result is unambiguous instructions that guide the user to task completion. In Article VII, we explored the delivery of the same type of information—DITA XML designed with minimalist principles—to mobile phones, further verifying the concept of successful single sourcing of technical information. When the content is separated from style, the same information can easily and flexibly be published to any channel.

Xue et al. have noted that to improve usability, information delivered to AR-assisted maintenance systems should be contextualized, for example, to the skill and expertise level of the users (Xue et al., 2019). This was explored in Articles VI and VII where the structure of DITA XML files was used to filter information for different skill levels. This concept was well-received and proved to be an efficient way to scale technical information for different user needs. The concept of context-sensitive level of expertise developed in Article VII empowers users to decide on the depth of instructions that they require to complete the task at hand according to the principles of minimalism, but it also facilitates the delivery of instructions to small screens as the information is provided in layers and does not overflow from immediate view on the smaller screens.

As industrial companies are not yet ready to adopt smart glasses for production use for maintenance technicians due to the immaturity of the hardware, I see the delivery of instructions to mobile phones a low hanging fruit. Even though the delivery of technical instructions to handheld devices is not ideal for hands-busy type of work, they enable the delivery of technical information to the field in more efficient ways than the traditional electronic prints or paper copies. In comparison to personal computers or tablets, a mobile phone has a small screen, and the information design principles explored in Articles VI and VII facilitate the delivery of information to mobile phones in a way that improves the user experience and satisfaction, and, consequently, task completion.

The concept of context-sensitive level of expertise and the layered approach tested in Article VII has proven so successful that it is currently in production use in the industrial company, has received positive feedback from maintenance technicians, and is facilitating the rollout of condition-based maintenance programs in the company. As our testing has verified that technical information authored in DITA XML works in a similar way when delivered to mobile phones and smart glasses, the company could switch to the use of smart glasses and continue to use the same concept and content in AR. Therefore, this dissertation offers a solution for authoring solutions and content management tools for AR: when smart glasses are ready hardware-wise for use in industrial maintenance, technical information currently delivered to mobile phones can also be used in smart glasses.

7.1.3 RQ1: How Can Virtual Reality Support Digital Content Creation for Industrial Maintenance?

For this dissertation, four possible VR scenarios were identified along the maintenance documentation journey (see Figure 14), and three of them were evaluated in user tests. The fourth one, training to local maintenance team, was excluded from this study as it did not involve actual content creation but was considered a post-publishing activity.

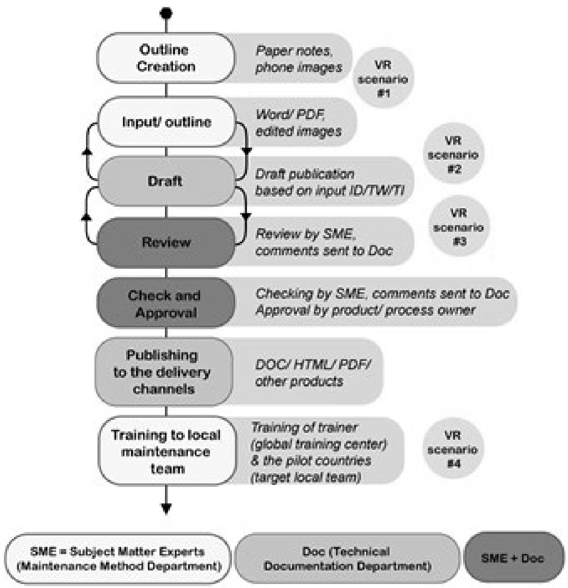

Figure 14. Identified VR scenarios along the maintenance documentation journey (published in Article I).

This research shows that VR can enhance the maintenance documentation process in different ways and support digital content creation in industrial companies. First and foremost, VR has a positive effect on the collaboration of the team. Globally operating teams traditionally rely on email and conferencing tools such as Microsoft Teams. With VR, they have a sense of being together and working as a team. VR also enhances the communication between virtual team members as people are able to point out objects in, for example, 3D models instead of trying to describe it in calls or emails. If there are misunderstandings or confusion, people can directly clarify them when collaborating in VR instead of sending a question in email or chat and waiting for a reply. Therefore, collaboration becomes more efficient and the output of the process, the maintenance instructions, are created faster and are technically more accurate. This supports the rapid speed of product development in industrial companies. The tools that were developed for COVE-VR support both asynchronous and synchronous collaboration in VR, and users can either use multi-user VR or access the virtual environment by themselves depending on the tasks at hand and also the time zones they are working in.

When documenting a new piece of equipment, there might not be any prototype available. Traditionally people rely on 2D or 3D images that are viewed on a computer screen. This traditional process results, in many cases, in misunderstandings both contextually and spatially, and the result is a maintenance procedure that might be difficult or even impossible to perform in the real environment. VR offers an easy access to virtual equipment that can also be updated as the design changes during product development. VR also offers an excellent platform for technical communications specialists—information designers, technical writers, and illustrators—to safely explore the working space and get acquainted with the equipment. The Camera Tool in COVE-VR offers possibilities to easily take images and videos that can be then discussed and reviewed with subject matter experts. The current practice of drawing a new image manually might take hours and might, after a discussion with a subject matter expert, result in a need to redraw the whole image. Therefore, with the images exported from VR, the illustrator can easily validate the idea, and once the subject matter confirms, they can continue with the illustration task. Depending on the needed output quality, the images exported from VR can also be used as such in instructions. Compared to the traditional process of illustrating maintenance instructions, this saves a substantial amount of time in the process. The same is true for animations exported from VR.

7.1.4 RQ2: How Should Technical Information Be Designed for Augmented Reality Applications?

The results of this dissertation show that using smart glasses as a delivery channel for maintenance instructions is a well-received and a validated concept, and DITA XML is a suitable format for AR content creation. Furthermore, as discussed earlier, with DITA XML the same content can be single sourced and used as is in several delivery channels. However, in order for the omnichannel delivery to be successful, the source DITA XML content has to be well-designed and well-formed. Even though my tests proved that technically anything authored in DITA XML can be displayed in smart glasses, it is of utmost importance that the content is designed by professional content creators. Smart information design and well-designed delivery of that information is an enabler for context-sensitivity that supports maintenance technicians in performing their tasks in an efficient and safe manner.

AR devices have a small screen compared to many of the more traditional devices used in the delivery of technical information. Therefore, careful design is needed for the content so that it works on smaller screens. If content does not fully fit on the screen and overflows from immediate view, scrolling is needed and, especially with voice commands typical of many AR devices, that is often clumsy and challenging as the devices scroll too fast past the desired point. Therefore, content has to be designed so that it proceeds step by step, and each step completely fits on the screen. However, the sense of location is very important if the instruction flows this way so that the users know how long the full procedure is.

Figure 15. Different information design methods being tested with smart glasses.

Some researchers have suggested that textual elements are reduced in AR applications or removed altogether and only images and icons are used instead (Gattullo et al., 2017; Scurati et al., 2018). However, my research shows that the images-only approach is often difficult to understand and leaves room for ambiguity. Therefore, it is not suited for high-risk tasks where the clear understanding of the task and steps involved is essential. This applies to a majority of tasks in industrial maintenance. The most unambiguous and efficient design combines both text and graphics (see this type of step being tested in Figure 15) but even then, the goal, tasks, and preferences of the users need to be taken into account when designing the information and its delivery. Therefore, the user-centered approach of minimalism is a good starting point for information design for single-sourced content that also works when delivered to small screens such AR devices.

7.1.5 Research Problem: How Can Extended Reality Be Applied in Technical Communication?

As discussed earlier, the technical documentation process is an inherently collaborative process, and VR offers an efficient platform for that collaboration, especially in the case of globally scattered teams. Instead of the current practice of meeting in conference calls or working individually and commenting on files that are sent back and forth, the experts can use collaborative VR to meet each other live. In many cases, there is no prototype of the equipment available, or it is not accessible to all team members, and VR offers a way see and study the equipment in ways that are not possible when working at the computer with 3D models. When working with technical information, it is essential that you have the possibility to explore the features of the equipment, see the scale of the components, and have an understanding of the working space and conditions. In many cases, and especially in the case of industrial maintenance, technical communication experts have to rely on what others can tell you of the product or use pictures that someone else has taken. VR offers an easy and also safe access to the product and the working environment. On the other hand, new use cases for collaborative VR in areas where VR has not been used yet—such as the maintenance documentation process— increases the adoption rate of VR in industry, giving a boost to both the technology development and sales. The benefits of the relationship are, therefore, evident.

Furthermore, the possibilities of capturing images and videos in VR brings much needed agility and flexibility to the technical illustration process. However, digital content works both ways as my research shows that it is also possible to import XML files into VR and use them to render maintenance instructions that can be then reviewed by relevant parties (see Figure 16).

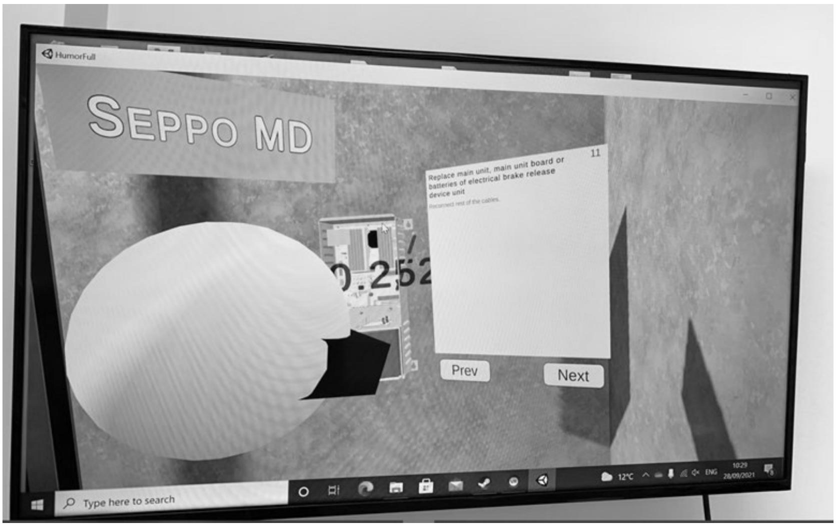

Figure 16. Maintenance method developer working with equipment and related instructions in VR.

By importing the source XML files into VR, technical instructions can be reviewed in any part of the maintenance documentation process, as an early draft or as a more mature set of instructions. The concept of the DocPanel tool was rated positively by domain experts, and it enables the easy testing of maintenance methods and related instructions before they are released to maintenance technicians. It is also possible to test technical instructions in simulated AR inside of VR (Burova et al, 2020), a setup that offers a safe way to test AR-based guidance, further proving that there are many benefits in the relationship between technical communications and extended reality.

On the augmented reality side of this research, smart glasses offer a new delivery channel for technical instructions, especially for maintenance instructions delivered to the technicians working in industrial companies. Industrial maintenance is typically hands-busy type of work, and many of the maintenance tasks require that technicians hold equipment parts or tools in their hands. Consequently, it is often unfeasible to check instructions with their phone or even on paper without interrupting the task and placing the objects they are holding on the floor or table, and with some tasks that is not possible at all. For many industrial maintenance tasks, technicians are also required to wear personal protective equipment such as gloves, and the technician's gloves or hands often get dirty while performing the tasks. This makes the use of touchscreen-based mobile devices challenging. With instructions available on smart glasses, technicians can simultaneously perform the task, hold the needed parts and tools, and get the guidance and safety information they need (see Figure 17).

Figure 17. Maintenance technician reading instructions with smart glasses while performing elevator maintenance (published in Article I).

Currently most solutions for producing and presenting documentation in AR applications are hand-tailored for a specific device and application. Even though 3D augmented instructions are elaborate and intriguing, in many cases there is a certain degree of overengineering involved. For example, an elevator maintenance technician goes to the elevator car roof tens of times each day while performing basic elevator maintenance. That can be instructed with an augmented animation that is positioned on the real-word elevator car roof but seeing the same animation over and over again will cause frustration with experienced maintenance technicians. Instead, a simple phrase or icon instructing to go to the car roof is more usable in the context of industrial maintenance and professional maintenance technicians.

7.2 LIMITATIONS AND FUTURE WORK

Even though the concepts developed in this dissertation are in most parts generalizable to other industrial companies, the testing was conducted within one company's context and processes. This can be considered a limitation of this study. In further research, the same studies could be conducted with larger sample sizes from several industrial companies to validate the results in a more extensive frame of reference. Technology acceptance and users' willingness to use new technologies with technical instructions should also be considered in future research.

As this dissertation is exploratory research and combines different themes from both technical communication and XR, there are also several options to extend the knowledge.

The development of collaborative VR offers many interesting opportunities to collaboration in general and especially for remote setups. As VR devices become more mainstream in industrial companies, it offers fascinating opportunities for the implementation of these technologies to the daily activities in different parts of the product development. Special attention should be paid to the early creation and flexible update of 3D models that can be then utilized for different activities in product development, including collaborative virtual environments and their utilization for technical documentation creation. Naturally this also supports other activities related to the industrial metaverse, for example, the development and utilization of digital twins in industries.

Further development of the VR tools we built and evaluated in the scope of this research also offers another interesting research area. Notably the Camera tool with the options to export raster images, line drawings, and videos has potential to offer substantial benefits to technical documentation creation where illustration tasks are mostly manual and time-consuming. The quality of the outputs from the Camera tool and the use cases for this type of digital content could be investigated and tested further, especially in the context of rapid product development where frequent updates are needed to digital content.

Interesting further research areas also exist on the augmented reality side. Even though my research focuses on informed reality and the use of instructions based on text and graphics, in some use cases, animations and augmentations would bring extra value. Therefore, I propose that my research is continued by investigating how to embed augmented reality content in the XML files and building an application that can switch to AR mode whenever augmented content is available. Such a scenario would help with complicated tasks where overlaid augmentations would support with task completion and accuracy, but the rest of the content would be derived from DITA XML. Information design methods, their suitability for content creation for different media, and practical testing in industrial companies would also offer many opportunities for further studies as this dissertation has only touched the surface of this area.

Generally, practical research in the area of technical communication is very scarce, and I would like to encourage this type of research as it would help in bridging the recognized divide between technical communication practitioners and academics and offer valuable contributions to both the practitioners and academics in the field.

8 Conclusions

This dissertation explored the relationship of technical communication and extended reality and examined the ways of applying extended reality to technical communication. Under the umbrella of extended reality and technical communication, the research was divided into two parts: virtual reality and augmented reality, and the following research questions were explored:

RQ1: How can virtual reality support digital content creation for industrial maintenance?

RQ2: How should technical information be designed for augmented reality applications?

The first part explored the benefits of collaborative virtual reality to the technical documentation creation process in industrial companies, and the second part studied the possibilities of augmented reality a delivery channel for maintenance instructions. All the developed concepts were tested by domain experts in user tests. The overall results of user testing were positive, and domain experts expressed interest toward the developed concepts and adopting XR technologies to their daily work.

Technology-wise, the technical documentation creation process, content creation guidelines, and delivery channels have remained the same for years or even decades. On the XR side, VR has been adopted in industrial companies but mainly for training purposes, whereas the adoption of AR is still mostly work in progress. This dissertation proves that extended reality has benefits to offer to technical communication.

The results of this dissertation show that VR has potential to enhance the technical documentation process, especially in globally operating companies where experts might be located in different countries or sites and rarely get to meet each other live. Furthermore, in many cases the equipment being documented does not yet exist or is otherwise inaccessible, and experts have been forced to work with 3D models only. Working in VR increases spatial understanding and removes miscommunication and misunderstanding, leading to more accurate and safe technical instructions that can be created with fewer iterations and review rounds. VR also offers a platform for digital content creation, which has potential to accelerate the process of releasing technical instructions.

As Armfield et al (2018) put it, "professional and technical communicators, with knowledge of visual design, minimalism, structured authoring, and user experience, are crucial for the development of content required for AR". As extended reality technologies develop further and the devices become more suitable for industrial use, more focus needs to be put on the design of content that is displayed in smart glasses. The more flexible and agile the content creation process is, the more likely the industries are to adopt these technologies for production use. Furthermore, the goals and preferences of the users need to be taken into consideration when designing the content. The dissertation demonstrates that DITA XML, the technical communication content creation standard, is a good format for AR content creation as it erases the need for tailoring instructions specifically for smart glasses. Instead, the same source content can be single sourced from a company's information repository to different delivery channels, for example, online portals, mobile phones, electronic prints, smart glasses, and other wearable devices. This device-independent approach will increase the likelihood of industrial companies adopting AR technologies for field guidance as existing documentation processes and authoring tools can be used to create the content. This dissertation, therefore, establishes guidelines on the creation of content that works efficiently in omnichannel delivery, with special focus on small screens.

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Paper I

Alisa Burova, Hanna Heinonen, Paulina Becerril Palma, Tuuli Keskinen, Jaakko Hakulinen, Viveka Opas, John Mäkelä, Kimmo Ronkainen, Sanni Siltanen, Roope Raisamo, and Markku Turunen. 2021. Toward Efficient Academia-Industry Collaboration: A Case Study of Joint VR System Development. In *Proceedings of the 24th International Academic Mindtrek Conference (Academic Mindtrek '21)*. Association for Computing Machinery, New York, NY, USA, 176–185. https://doi.org/10.1145/3464327.3464367

Toward Efficient Academia-Industry Collaboration: A Case Study of Joint VR System Development

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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

Academia-Industry Collaboration, Industry-Academia Collaboration, Virtual Reality, Collaborative Virtual Environment, Industrial Maintenance

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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 fulfil 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 and 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 verified academic methods to extract data from industry experts and target users [6, 12, 22]. Additional benefits of such collaboration are increased funding efficiency, the stability of processes, privilege growth, access to varied expertise, state-of-art equipment and facilities [2].

Nevertheless, academia-industry collaboration is not a simple process due to differences in objectives, perspectives, working methods, operating modes, and time horizons [11, 22, 24]. For instance, academics may fully concentrate on projects and work on more theoretical and abstract levels to achieve long-term research goals, whereas industry has its rapid deadlines, short-term priorities and practicalities overriding academic interests [11]. This may result in a lack of understanding, unrealistic expectations, and even mistrust between parties. Other challenges include a lack of relevancy, experience, and skills to support a collaboration process, minimal commitment and interest, inflexibility, and managemental and organizational issues [11]. The barriers may be further categorized as orientation-related (differences in orientation and stimulus) and transaction-related barriers (conflicts over administrative procedures and knowledge property), of which the latter are harder to mitigate [6].

To address these barriers and connect academics and industries worldwide closer together, there is a *need for a generalizable process-oriented framework of remote collaboration*. Various models and guidelines, summarized in the literature review by Garousi et al. [11], have been proposed to enhance collaboration and support information and experience sharing, for instance, based on agile [22] and action research [21] practices. The latest proposed model, called Certus, based on eight years of longitudinal qualitative research, highlights the importance of seven elements of the collaboration to support knowledge co-creation: problem scoping, knowledge conception, knowledge and technology development, transfer, exploitation, organizational adoption and market research [15]. However, to the author's knowledge, none of the existing models provides a clear understanding of processes to establish *remote collaboration and knowledge sharing* between academia and industry. To fill this gap, based on the best practices of user-centered design and agile methods [9, 20], this work presents the process-oriented framework to support the academia-industry collaboration on VR system development.

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.

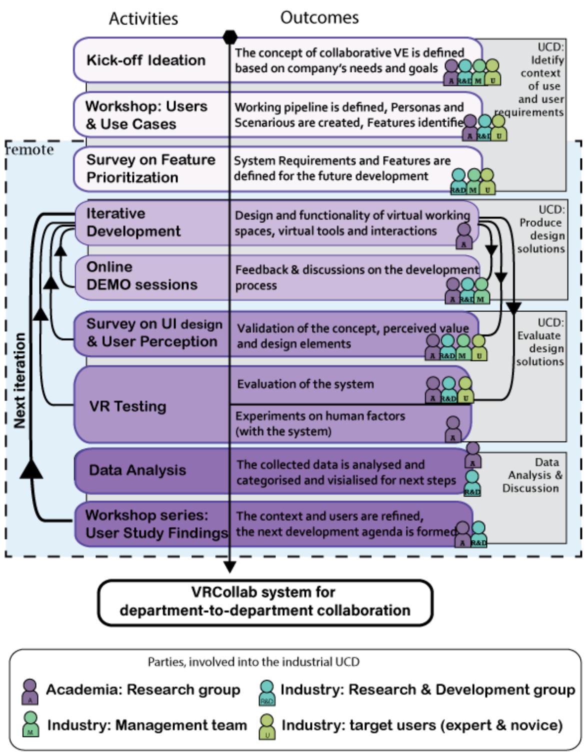

Figure 1. The framework of remote academia-industry collaboration.

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.

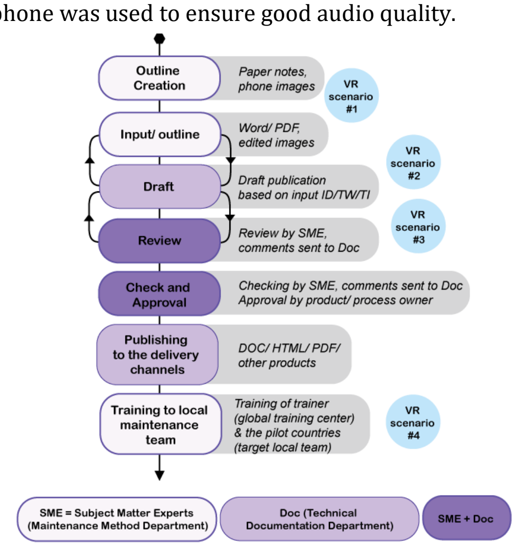

Figure 2. Maintenance documentation journey

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.

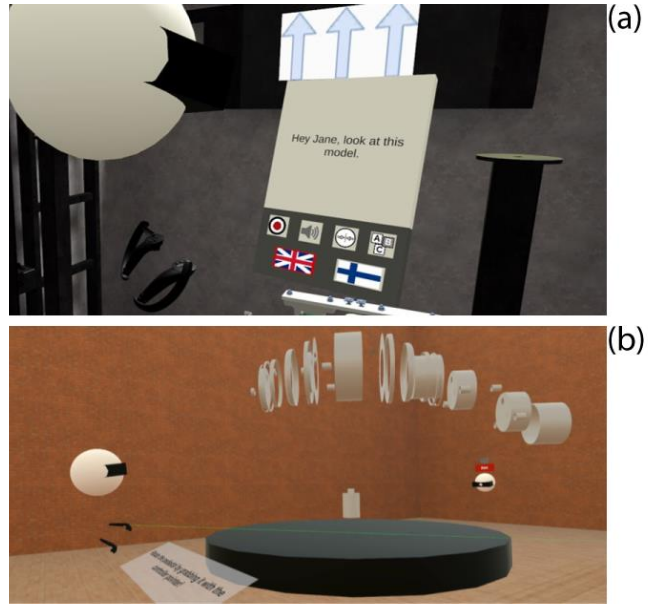

Figure 3. The Lab VE with TextBox Tool opened (a) and the Showroom VE with a disassembled 3D model (b).

By country of residence, six were from Finland, four from China, four from India, and the rest were from Australia, Netherlands, Germany, and Malaysia. Nine of the respondents represented the Maintenance Development department, five represented the Technical Documentation department, and two were from the Learning and Development department.

The survey was created via the *LimeSurvey* tool and it incorporated two 360-videos of virtual environments, videos with voice-over to demonstrate the usage of virtual tools, pictures of icons, and a variety of questions. The survey consisted of six sections, however, in this article we disclosure the materials only from three of them: 1) *background information*, 2) *overall system perception*, and 3) *COVID-19-related statements*. The background data section collected the respondents' age, gender, role at work, previous experiences of using VR/AR applications, and participation in the previous survey on feature prioritization. The overall system perception was collected in a form of 12 statements answered on a 7-point Likert scale and 5 open-ended questions on drawbacks, benefits, and ideas related to working and collaborating in VR. The COVID-19 section (5 statements) collected subjective perceptions on how the pandemic situation had changed working activities and how the designed VR system could address it.

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 ($Mdn_1 = 7$, $Mdn_2 = 6$). 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 ($Mdn_1 = 6$, $Mdn_2 = 5$). Most of the participants would like to use VR to perform their tasks ($Mdn_1 = Mdn_2 = 6$) and feel enthusiastic about it ($Mdn_1 = 6.5$, $Mdn_2 = 6$). Further, all the respondents agreed that the system design is useful for the company (Mdn_1

= 7, Mdn_2 = 5); they think that VR would motivate them (Mdn_1 = 6, Mdn_2 = 5) and increase their performance (Mdn_1 = 6, Mdn_2 = 5). Participants also mostly agreed that the system would make their work faster (Mdn_1 = 6, Mdn_2 = 5), safer (Mdn_1 = 6.5, Mdn_2 = 6), and easier (Mdn_1 = 6, Mdn_2 = 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.

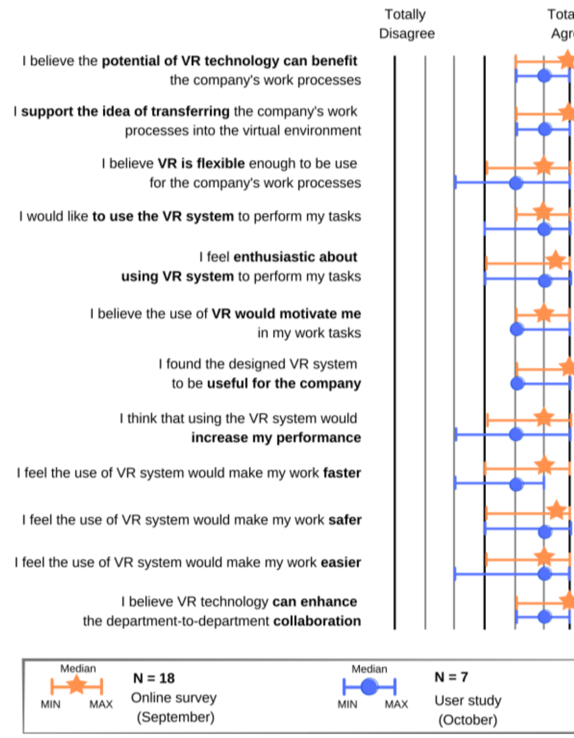

Figure 4. Results of system perceptions in the two phases.

Further, six target users from two countries participated in the follow-up workshop to investigate user-related aspects and system requirements while exploring working context and tasks. The identified system requirements were further prioritized by two managers and four target users. That helped to establish the design direction and include opinions of both actual users and people with decision-making power. All the above-mentioned activities, which relate to the first phase of the user-centered design process, resulted in the creation of personas, user workflow and scenarios and system functionality together with the list of features to be implemented to accomplish these scenarios. The system was further developed by the academic research group; the industry researchers' involvement via a series of remote meetings and demonstrations were held to assure that the design complements the requirements.

Then, the designed system was evaluated via online surveys (due to the COVID-19 pandemic). Since the online survey was anonymous, the concrete number of managers and employees who contributed is not known; the survey was shared with seven managers and 27 target users, which resulted in 18 complete fill-ins. However, this process helped us to verify the chosen design solutions (e.g., virtual environments and tools) and to measure the employees' perception of the system's benefits for the company prior to the actual user study. Finally, seven company employees participated in the user study, which leads to an in-depth analysis of the system efficiency and usability, resulting in 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 generation, our framework provides 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 have 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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Paper II

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

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A B S T R A C T

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.

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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maintenance departments, VR can contribute achieving sustainability and optimization of industrial working processes (Rødseth et al., 2017; Silvestri et al., 2020). Augmented Reality (AR), in turn, may increase the performance and occupational safety of maintenance 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 maintenance 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 departments 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 maintenance method development and documentation creation is error-prone due to the possibility of unwanted scaling, spatial misinterpretations, 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 documentation, 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 platform (Burova et al., 2021) can be used to facilitate remote asynchronous collaboration of multinational departments and deliver novel ways of generating digital content for documentation purposes. 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 academia 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 documentation 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 maintainability, 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 operations. 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 Gironimo 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 traditional conferencing tools and PDF files. In our case study, two departments are iteratively involved in the creation process (Fig. 1): *Maintenance Development Department (MDD)* and *Technical Documentation 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 development 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

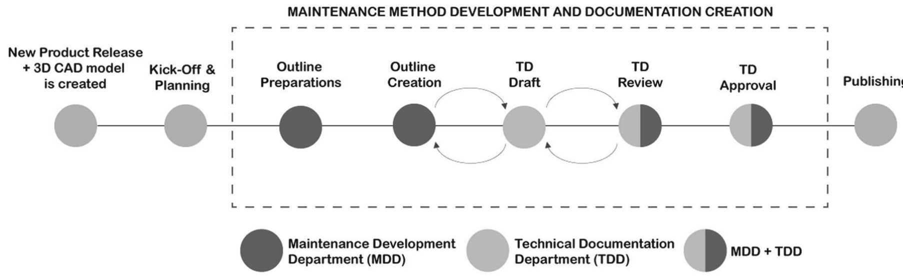

Fig. 1. The process of technical documentation creation at KONE.

maintenance method is difficult or impossible to perform in reality: the technician might be unable to reach a component or operate tools. 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 misunderstandings 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 communication 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) involved 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 sketches. A single multifunctional collaborative VR platform can be used to support individual work activities, whereas facilitating asynchronous collaboration would be the first step to optimize the process 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 application 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 located 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 execution 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 integrated 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 content generated in VR is saved to the hard drive's folder and can be accessed later, so the content (images, videos, notes) is easily utilizable in common office tools and other applications.

The COVE-VR system follows a client-server model, with two servers handling synchronous and asynchronous collaboration separately (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

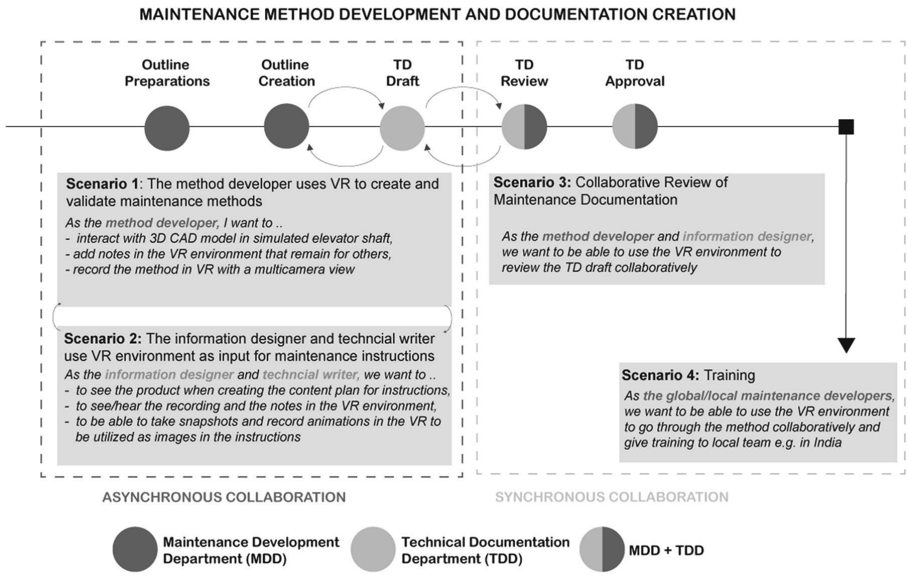

Fig. 2. Scenarios of VR application to the process of technical documentation creation.

(within a session) and developed our RESTful web service to save the state of the VE between the sessions for asynchronous collaboration, since PUN Server does not support long-term data persistence.

We found the most consequential software architectural decisions concerned serialization, the process of translating objects and data structures for transmission over the network or saving to a file. Odin Serializer was selected because it allows to directly serialize most standard Unity objects and our custom classes, reducing the need for separate data classes, which are needed with many other serialization libraries. Therefore, the burden to implement synchronization and snapshot saving was significantly reduced in cases where the default serialization behavior was enough. Even in more difficult cases, Odin Serializer enabled us to define our serialization override methods, which still reuse the default behavior for most member variables.

Our 3D model converter supports the generation of several levels of detail (decimation) and renders preview icons, which are important features for real-time use cases that are not always included in commercial STEP model converters. Replacing FreeCAD with a low-level library for reading STEP files would decrease the number of dependencies and allow parsing the metadata in the STEP file in addition to basic mesh and material data.

Software requirements with priority levels were gathered from KONE technical documentation personnel, but due to small team size and time constraints, requirements specification was not performed to a level where extensive verification could take place at an early stage. Rather, many requirements were later modified based on experience 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 = 36,5) and represented seven countries and three departments: MMD (9), TDD (5), and Learning and Development (4). All respondents were familiar to an extent with XR technologies: five of them had not 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

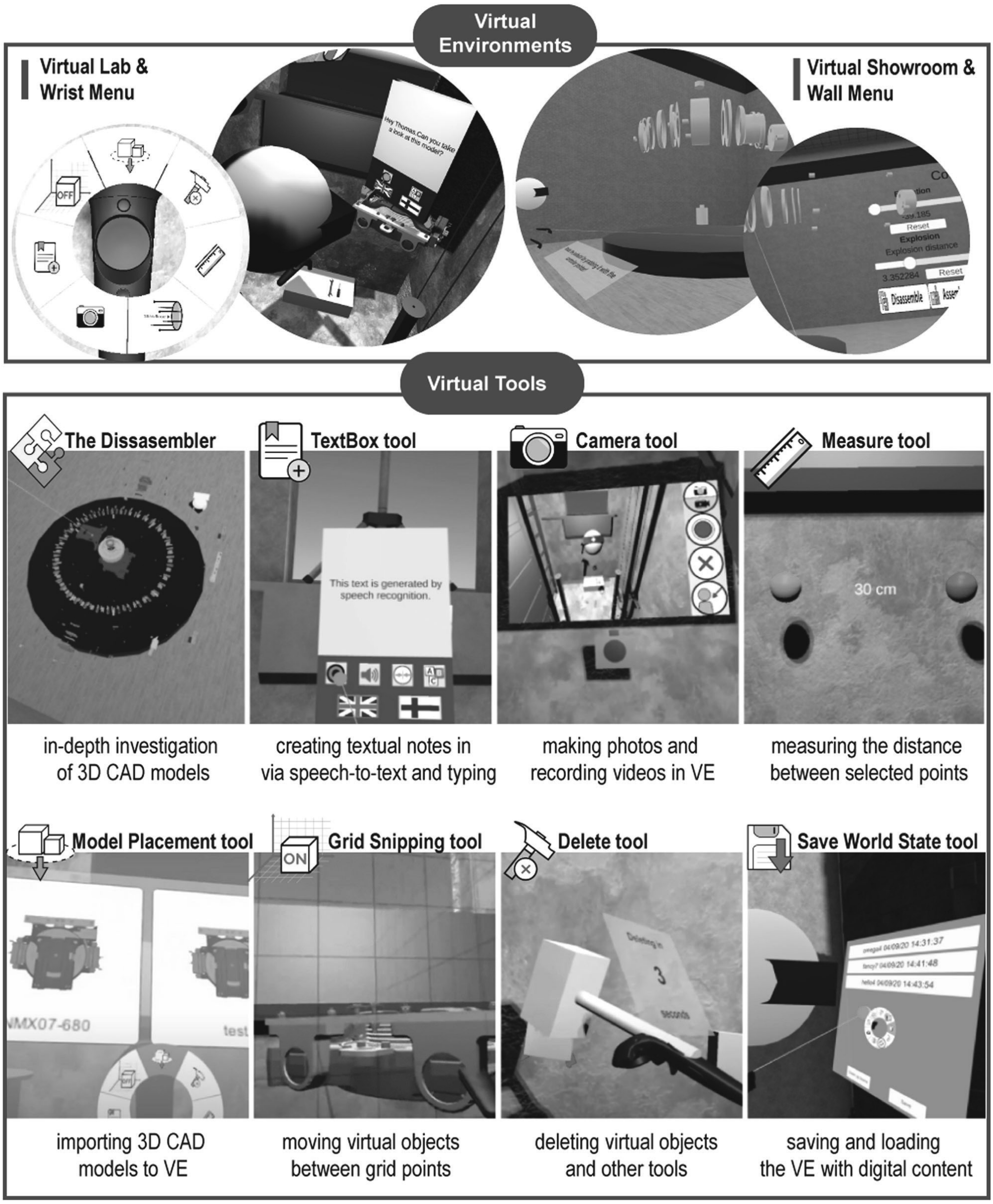

Fig. 3. COVE-VR virtual environments and tools.

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

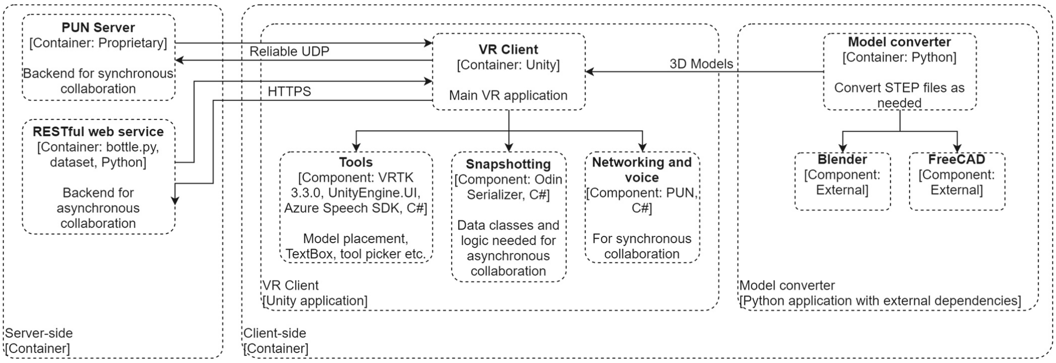

Fig. 4. COVE-VR platform architecture.

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 erorr-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 selfie-

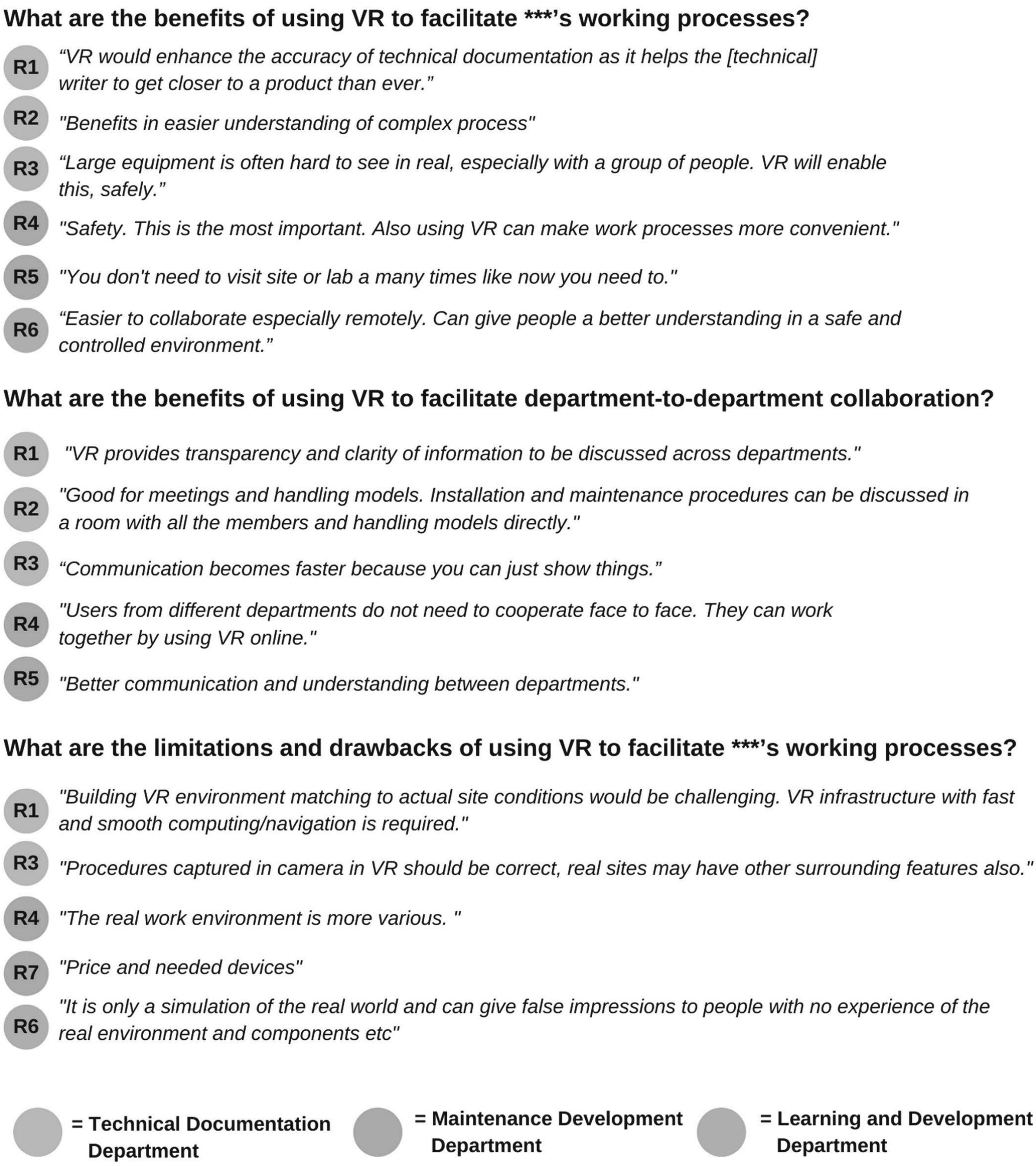

Fig. 5. Quotes from the open-ended questions from the online survey, color-coded based on the respondent's department.

mode) was perceived negatively by experts from TDD as well as the need to physically rotate the camera to capture the other side. For the Measure tool, experts required more accuracy in measures, so it can be directly used for technical documentation specifications. Furthermore, five experts had difficulties with grabbing the ending points and for four experts the tool was opened behind, causing confusion.

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

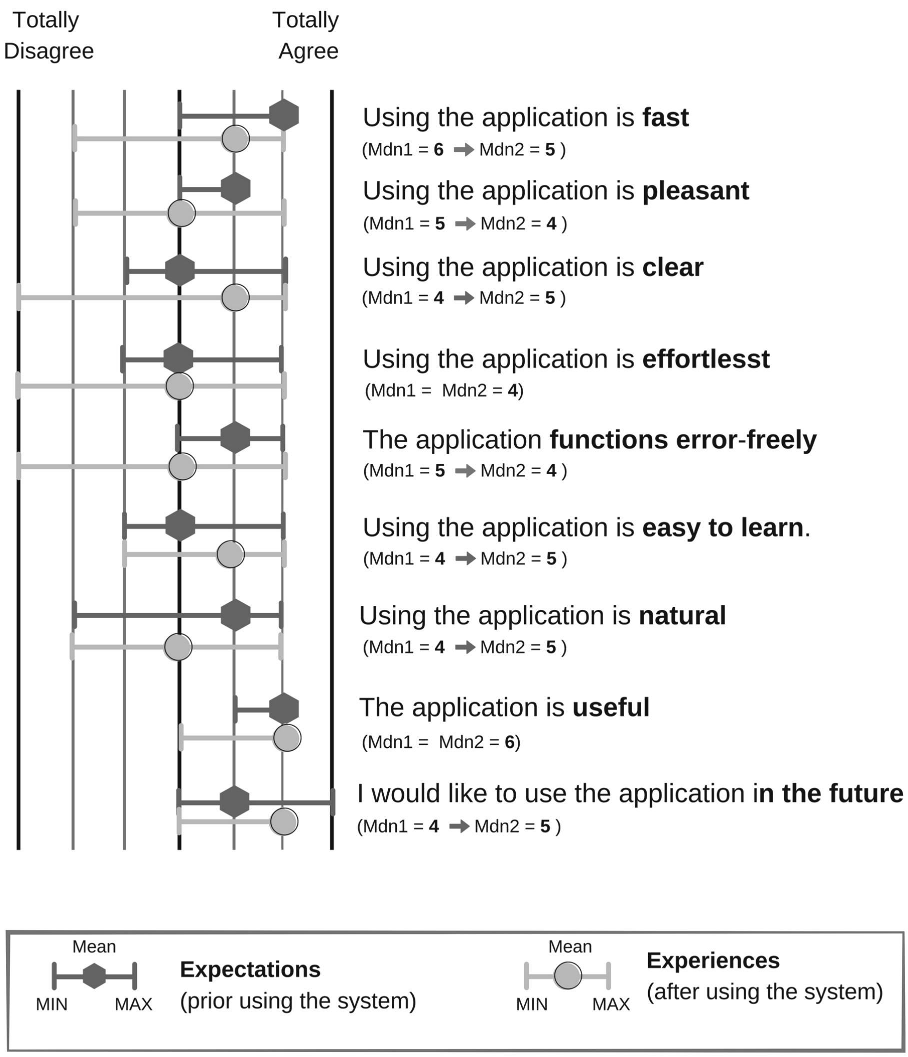

Fig. 6. The comparison of expectations vs. experiences with COVE-VR plarform.

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

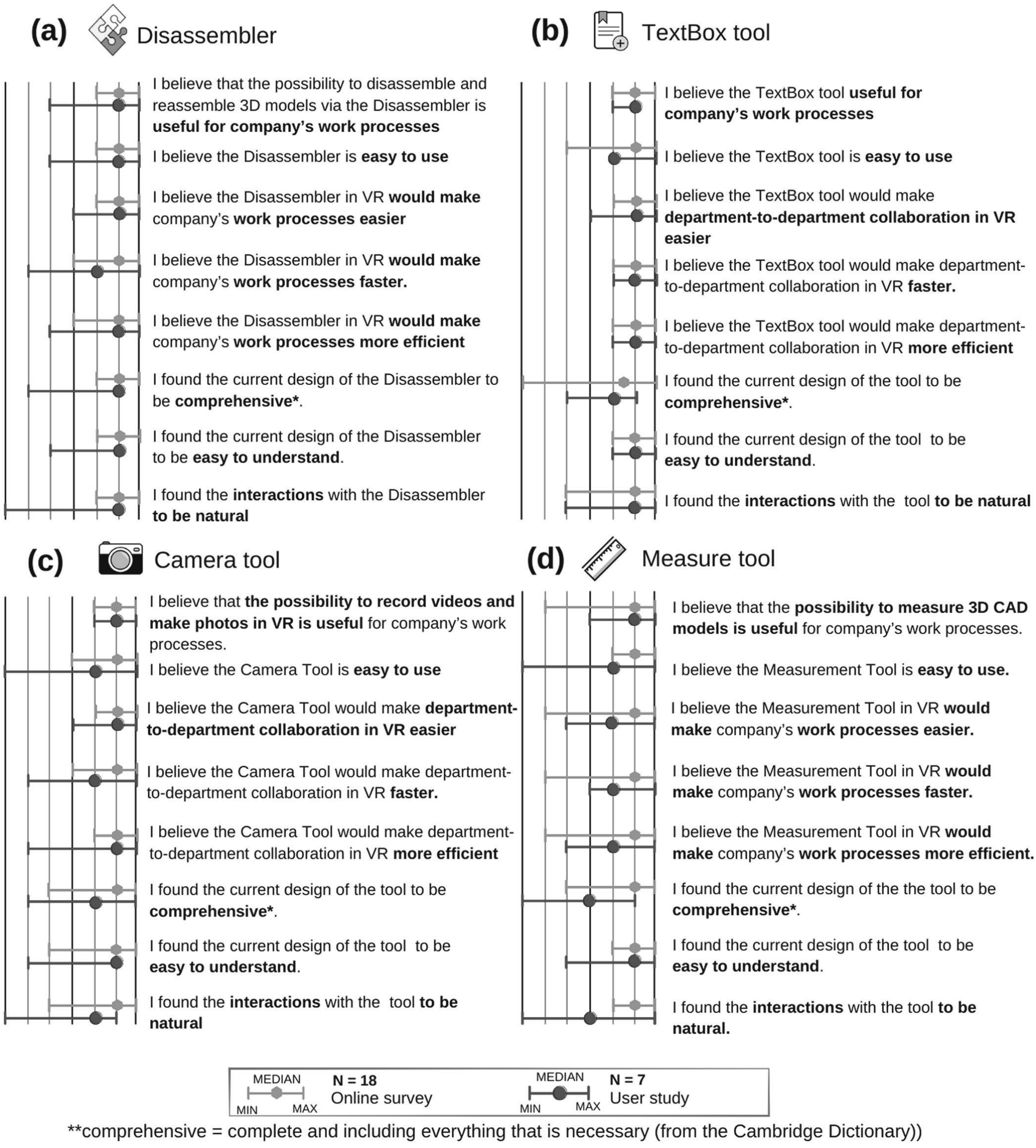

Fig. 7. The results of virtual tools evaluation.

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 formulized 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 VEs 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 VEs 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 VEs 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. **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

TEXTBOX TOOL

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"*

CAMERA TOOL

Interaction problems/ requests:

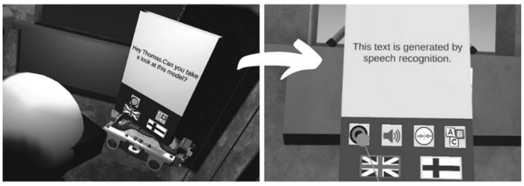
7 Back view of the camera is needed
5 Icons are not intuitive enough
3 Zoom feature
2 Camera position is too close to the user

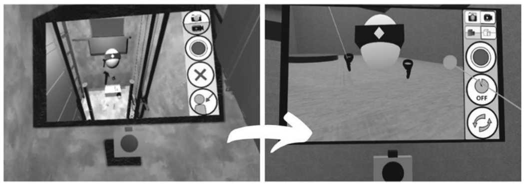
Comments:

*"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"





MEASURE TOOL

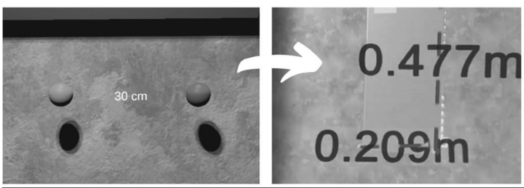
Interaction problems/ requests:

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**"*



DISSASEMBLER

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/semitransparent, 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**"*

*"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"*

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Paper III

Alisa Burova, Paulina Becerril Palma, Phong Truong, John Mäkelä, Hanna Heinonen, Jaakko Hakulinen, Kimmo Ronkainen, Roope Raisamo, Markku Turunen, and Sanni Siltanen. 2022. 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. In *Applied Sciences* 12, 8: 3728. doi:10.3390/app12083728

applied sciences

MDPI

Article

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] and Sanni Siltanen [2,*]

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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

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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].

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.

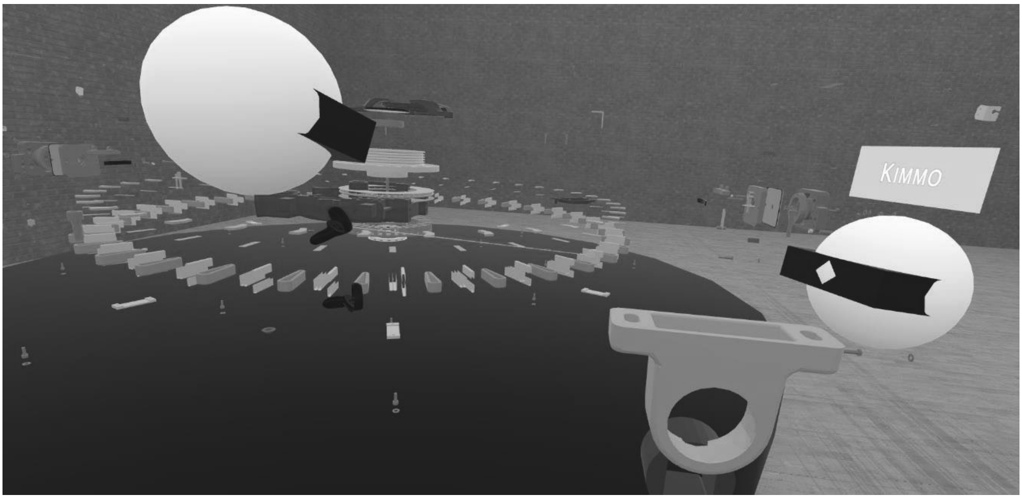

Figure 1. Multi-user interaction in COVE-VR platform.

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 feed 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.

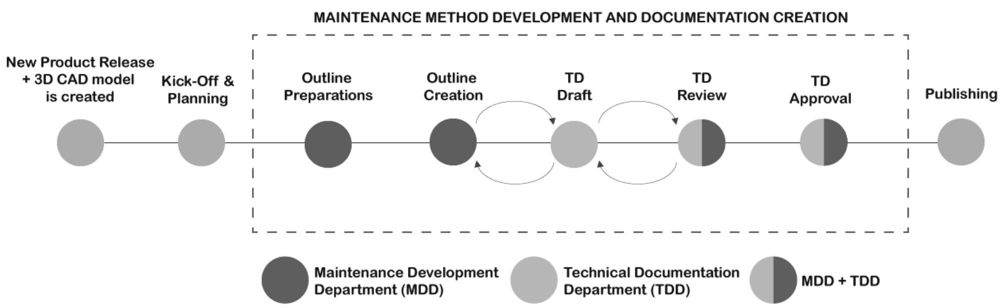

Figure 2. The process of maintenance method development and documentation creation at KONE.

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.

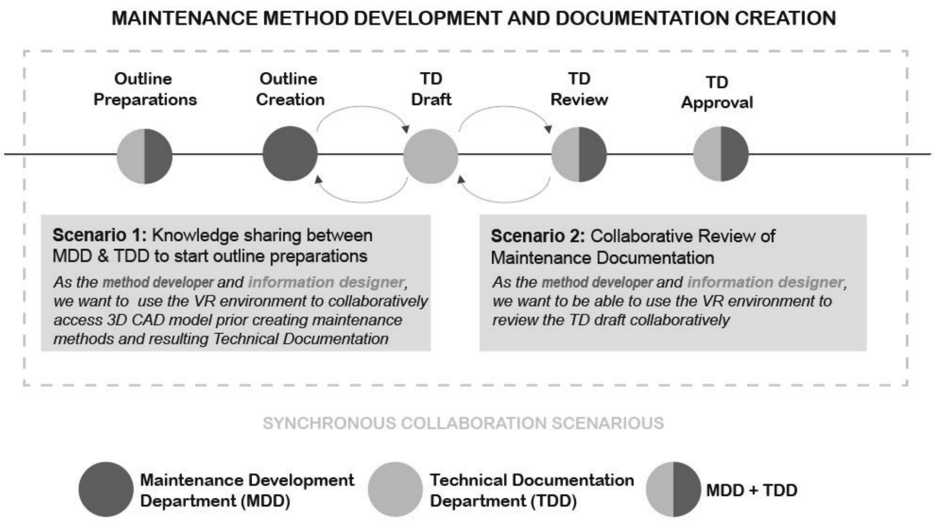

Figure 3. Maintenance Method Development and Technical Documentation creation.

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.

(a) Lab VE (b) Showroom VE

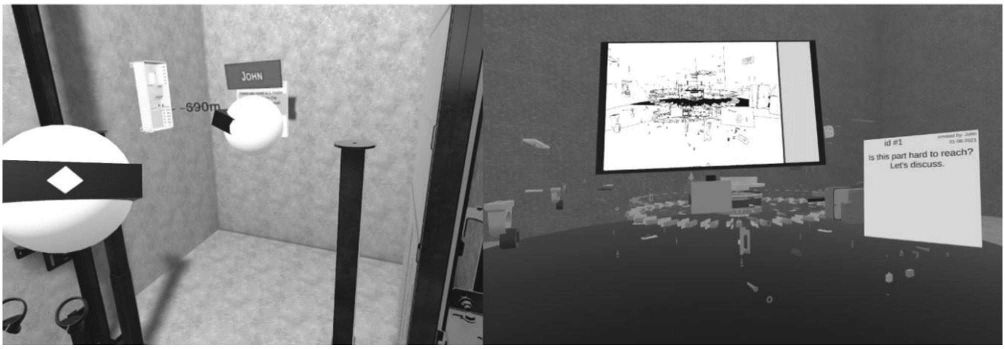

Figure 4. Working virtual environments: (**a**) the Lab VE, which replicates a real elevator shaft and (**b**) the Showroom VE with a disassembled 3D CAD model.

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 fulfil 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. Bin 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 interacting 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.

Task Number	Task Description	Task Type	Participants	Tool Used
Scenario 1–a 3D CAD model exploration in collaborative space (Showroom VE)				
1	Open a 3D model, explode it and adjust the scale, distance and levitation	Individual	VR2	Disassembler
2	Locate a component (batteries), find a good angle and take a screenshot	Shared	VR1, T1, T2	Disassembler, desktop tools
3	Take a photo to support the illustrators for the battery replacement task in outline rendering mode	Shared	VR2, T2	Camera tool–outline mode
4	Get additional photos in outline rendering mode	Shared	VR2, T2	Camera tool–outline mode
5	Take a photo to support the illustrators for the battery replacement task using a regular camera mode	Individual	VR1	Camera tool–regular mode
6	Teleport to Lab VE	Individual	VR1, VR2	Wrist-menu
Scenario 2-Assembly/disassembly of a 3D CAD model in a simulated context (Lab VE)				
7	Take general measurements of the component	Individual	VR2	Measure tool
8	Take additional measurements (from the component to the wall) and record them via a screenshot	Shared	VR1, VR2, T1, T2	Measure tool, desktop tools
9	Document the battery replacement workflow via speech input	Individual	VR1	Textbox tool–speech-to-text
10	Add a text note with the name of the component via virtual keyboard	Individual	VR2	Textbox tool–virtual keyboard
11	Delete the last text note on request	Shared	VR2, T2	Delete tool

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.

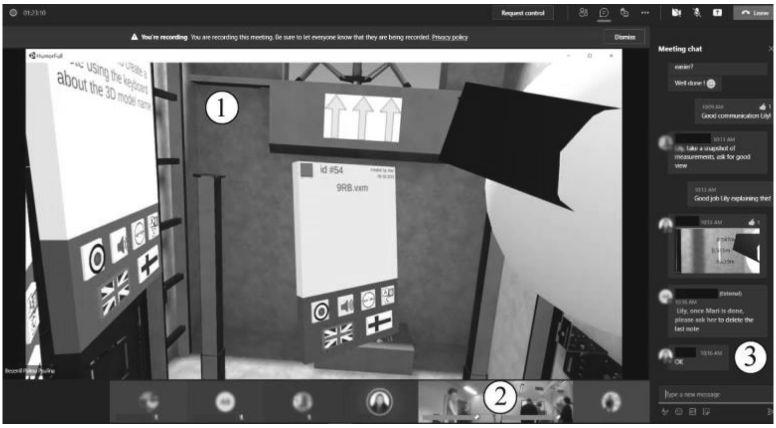

Figure 5. Screenshots from the test procedure: (**1**) streamed VR image from the VR-participant's point-of-view, (**2**) streamed video of the VR-participants, (**3**) Teams chat activity.

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.

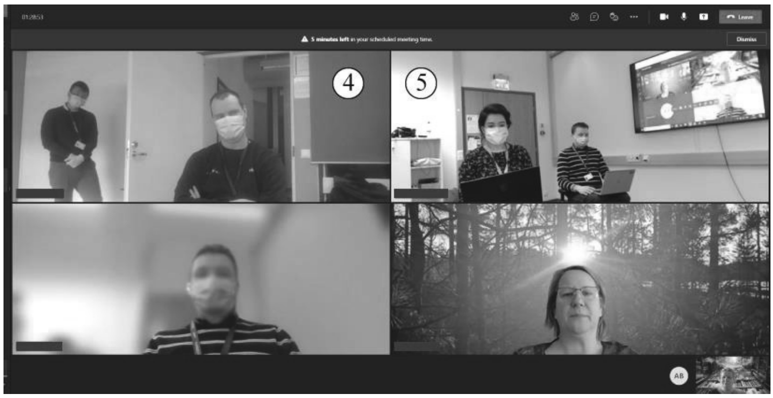

Figure 6. Group interview via Teams: (**4**) VR-participant 2 and support facilitator, (**5**) VR-participant 1 and main facilitator.

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.

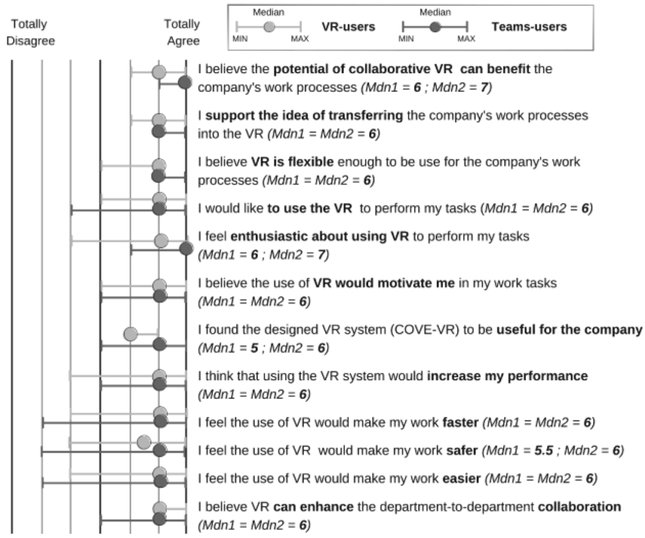

Figure 7. Employees' perceptions of VR technology for the industrial context.

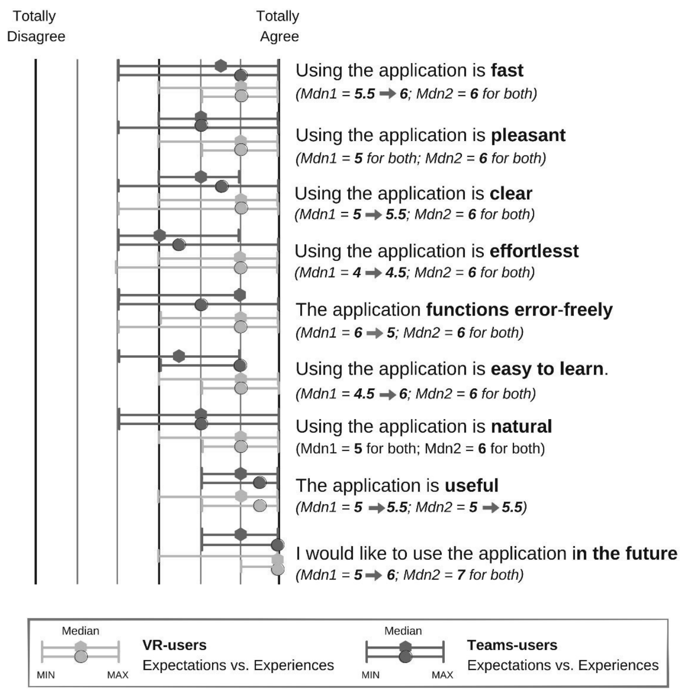

Figure 8. Expectations and experiences with the VR platform.

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.

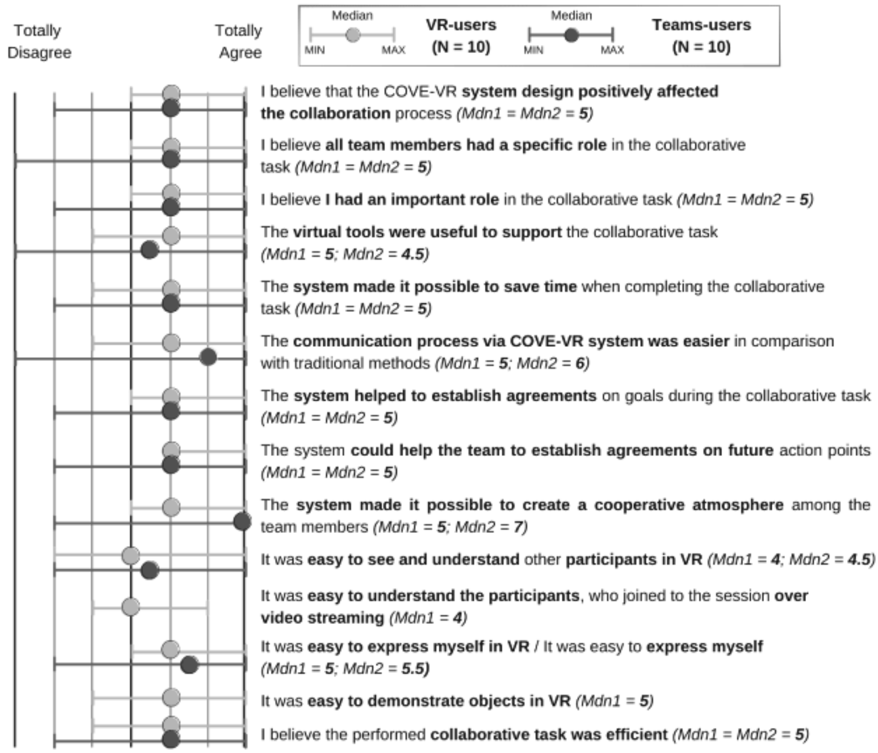

Figure 9. The results of the collaboration-related questionnaire.

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* *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 fulfil 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.

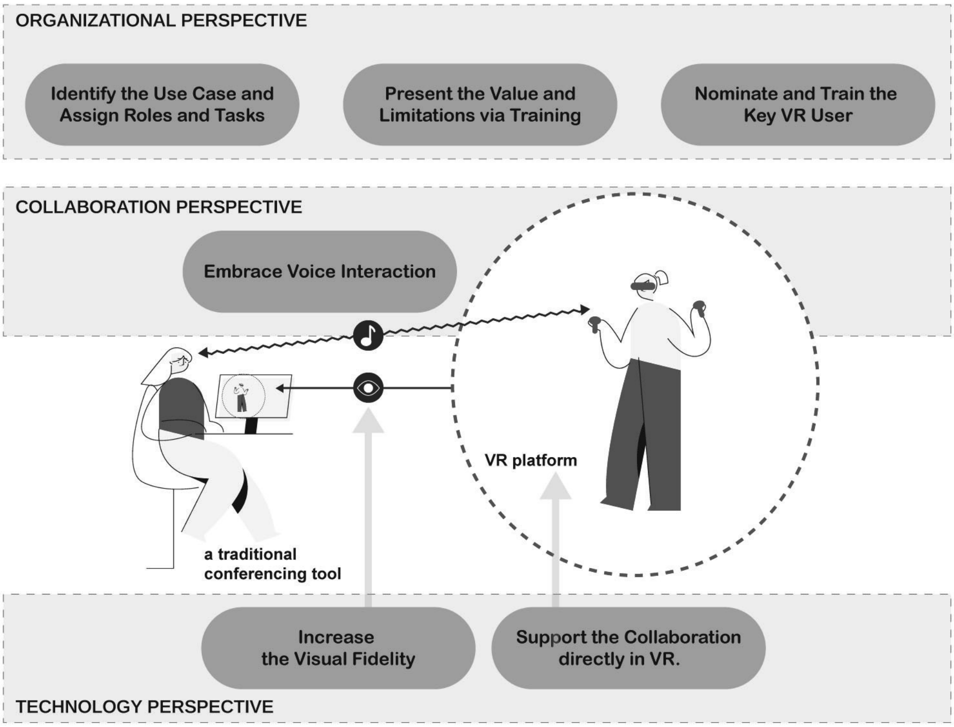

Figure 10. Guidelines on how to support asymmetry between VR and traditional conferencing tools.

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 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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Paper IV

Hanna Heinonen, Alisa Burova, Sanni Siltanen, Jussi Lähteenmäki, Jaakko Hakulinen, and Markku Turunen. 2022. Evaluating the Benefits of Collaborative VR Review for Maintenance Documentation and Risk Assessment. In *Applied Sciences* 12, 14: 7155. doi:10.3390/app12147155

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Article

Evaluating the Benefits of Collaborative VR Review for Maintenance Documentation and Risk Assessment

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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.

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

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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.

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.

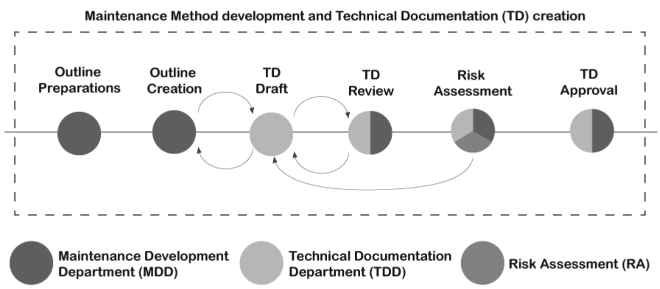

Figure 1. Maintenance documentation process.

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 risk 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 share, spatial understanding is missing and explaining product proportions and features is difficult, if not impossible. To combat these problems, process improvements are needed for documentation review and risk assessment, and our proposed solution to these challenges is VR.

2.3. 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 requirements when and how the safety risk assessment should be carried out, there are certain standards to follow. ISO 12100 [38] gives generic guidance on how a risk assessment should be carried out. For lifts under lifts directive and for escalators under machinery directive, there is an international standard ISO 14798 [39] that provides a well-defined risk assessment methodology to follow.

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 risk 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.

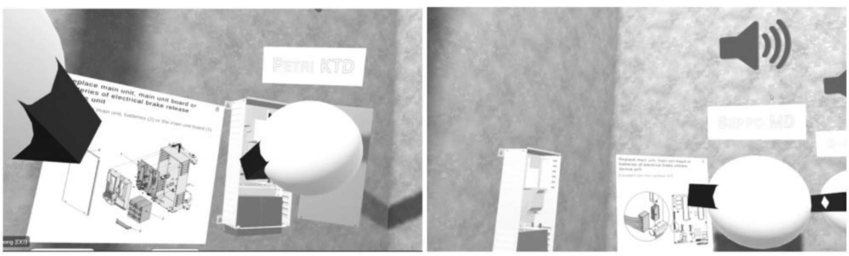

Figure 2. Screenshot of collaborative review of technical documentation in VR. A user is immersed in VR and looking at the avatars of two other users, complete with name labels for identification.

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 export 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.

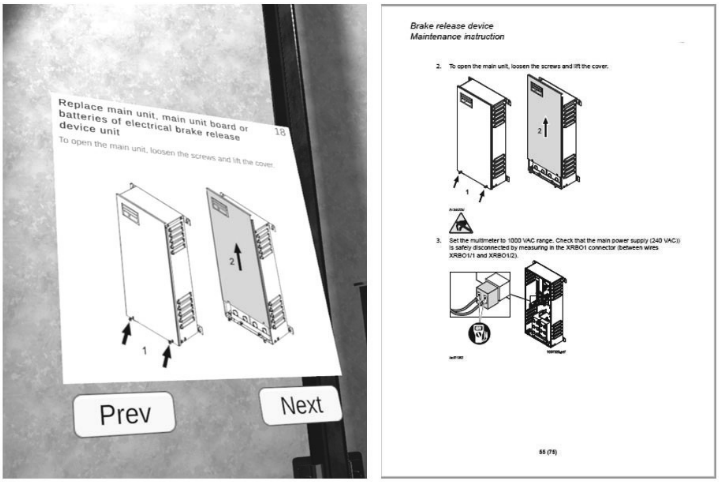

Figure 3. Task step visualized in the DocPanel Tool (**left**), the same step in the original PDF instruction (**right**).

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.

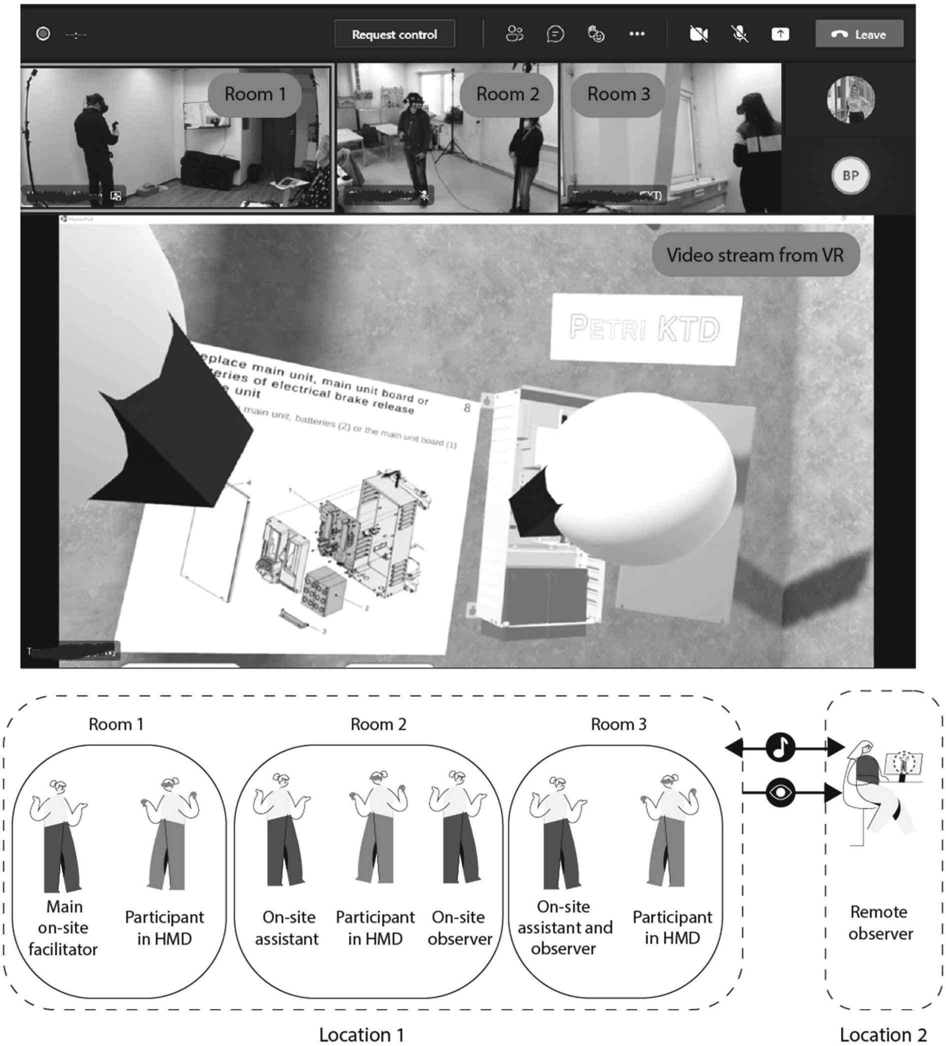

Figure 4. User study setup, showing both the video streams in Teams and the setups of the rooms and locations.

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 5. User tests in progress. Laptop streaming the participant's VR view can be observed in the background. An USB camera is connected to the laptop in the background, streaming the physical space of the room to Teams.

Figure 6. User test participant and VR view displayed in a monitor.

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.

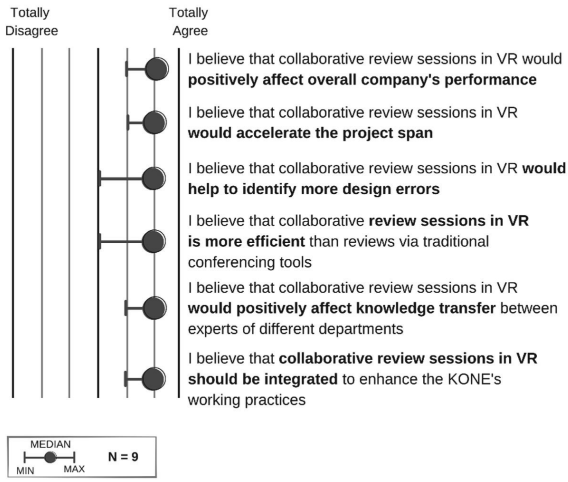

Figure 7. The results of collaboration-related statements, answered on a seven-point Likert scale.

The results of the SUXES survey, which compares the expectations and experiences with the VR system, are shown in Figure 8.

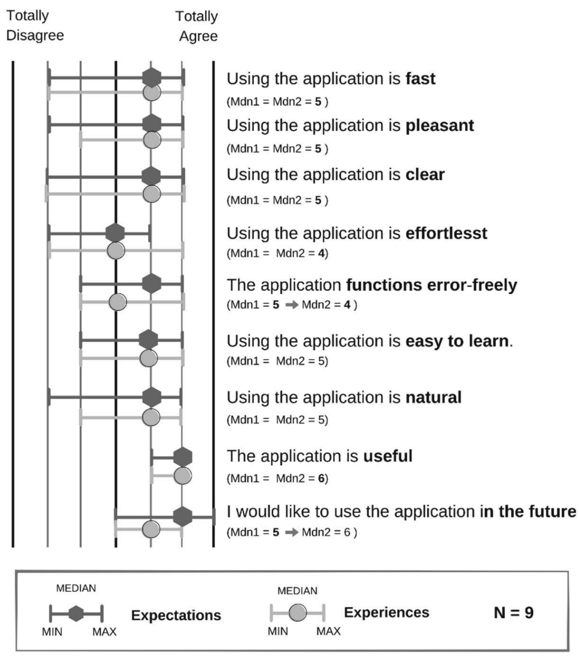

Figure 8. Expectations and experiences with VR platform. A seven-point Likert scale was used.

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-freely 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.

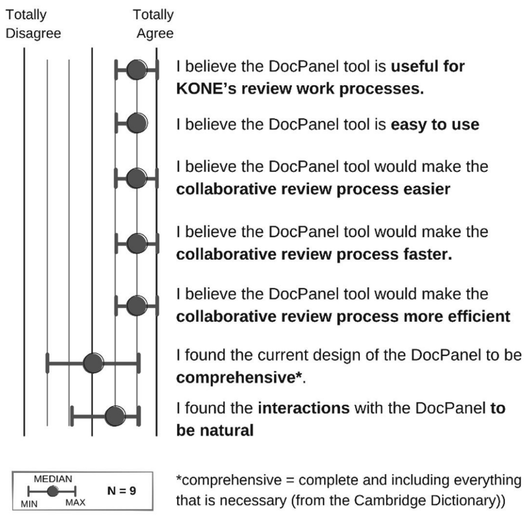

Figure 9. Evaluation of the DocPanel tool for collaborative review in VR. A seven-point Likert scale was used.

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 resourcing-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 Assesment

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 Documetation Review and Risk Assesment

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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Paper V

Sanni Siltanen and Hanna Heinonen. 2020. Scalable and responsive information for industrial maintenance work: developing XR support on smart glasses for maintenance technicians. In *Proceedings of the 23rd International Conference on Academic Mindtrek (AcademicMindtrek '20)*. Association for Computing Machinery, New York, NY, USA, 100–109. doi:10.1145/3377290.3377296

Scalable and responsive information for industrial maintenance work – developing XR support on smart glasses for maintenance technicians

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ABSTRACT

This paper describes the process and results of bringing responsive and scalable technical documentation to smart glasses to support industrial maintenance. Development and testing was done in four development cycles to discover how maintenance information can be delivered to smart glasses to support maintenance technicians. Test case was elevator maintenance, and several user tests were performed in a real or realistic environment by real maintenance experts. The concept of using smart glasses to view technical information during a maintenance task was received very well by the test users. This study confirms that DITA XML is a good candidate for the creation of technical information content for smart glasses, but information design is needed to ensure the scalability and usability of the information.

CCS CONCEPTS

• **Information systems~Document topic models** • Information systems~Information systems applications • **Human-centered computing~Mixed / augmented reality**

KEYWORDS

XR, AR, smart glasses, technical documentation, XML, DITA, html5, Information 4.0, industrial maintenance, field work, informed reality, assisted reality

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1 Introduction

The on-going fourth industrial revolution, Industry 4.0, is changing the concept of industrial work. Traditional industrial work has been characterized by tacit knowledge and a challenge to find skillful workforce especially in developing markets [9]. Digitalization, Internet-of-Things (IoT), smart devices and technologies, and growing connectivity radically change many industrial work roles [11, 12].

Fernández del Amo et al explain how the maintenance industry is facing new challenges as the maintained equipment base grows more complicated, is more scattered globally and has a longer lifecycle. As a result of this, maintenance business is growing in importance, and more focus is paid to the ways of getting support to the maintenance technicians [4]. Many times the maintenance tasks tend to be complicated and varied, and technicians need hundreds of instructions to perform the tasks in a safe and efficient manner. **Traditionally, technical information has been delivered on paper or as electronic prints, as embedded online helps or, more recently, through online portals or web services.** Online documentation has established benefits over paper-based documents: newest revisions are always available and can be accessed with smart phones and other handheld devices.

However, **industrial maintenance is often hands-busy type of work**. Users may be holding equipment parts and/or tools in their hands and, at the same time, need to check some information or get guidance on the task they are performing. Furthermore, the technician must wear personal protective equipment such as cut-resistive gloves. The maintenance assignment often contains tasks where users' hands get dirty and greasy. This setup makes user interaction with touchscreen-based smart phones difficult. Hence, we turn to XR, DITA and Information 4.0 to solve this challenge.

1.1 Key concepts

The following concepts are closely related to this study. As this study is interdisciplinary by nature, the key concepts are also related to different fields.

X Reality (XR) stands for extended reality, which covers all forms combining real and virtual elements, e.g. Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR). The

XR field is expanding rapidly and XR technologies and XR devices are developing fast, and, therefore, the naming conventions are not fixed. Both augmented and mixed reality terms are used for systems representing information on smart glasses, even when the information is not spatially aligned with the real environment. When presenting information on screen without aligning it with the environment, the term informed or assisted reality is also used.

DITA (Darwin Information Typing Architecture) is an XML model and the industry standard for structured, modular writing. To facilitate the creation and delivery of information, DITA specifies three main topic types: concept, task, and reference. A concept explains what something is like or how it works, a task describes a procedure, and a reference is for presenting reference material [4]. Topics are stored in a repository and can be reused across different publications.

Information 4.0 is technical communication's answer to Industry 4.0, and makes it possible to implement, maintain, leverage and understand Industry 4.0 systems. In Information 4.0 the content is smart, and it can be assembled, transformed and rendered dynamically and contextually according to users' needs. [8]

1.2 Related work

Kaasinen et al presented the Mobile Service Technician 4.0 concept, where new practices and tools are introduced to support maintenance technicians for preparing for a maintenance visit, identifying equipment faults, performing maintenance tasks, receiving remote support from colleagues and reporting on completed tasks. These solutions utilize the industrial internet and new technologies to enhance maintenance technicians' work performance and satisfaction. [9] In recent years, technical advances have made it possible that the devices outlined in the Mobile Service Technician 4.0. concept, (e.g. smart glasses) have entered the consumer market [3]. As these devices are now more powerful and reasonably priced, they have great potential to be used on a wider scale in industrial maintenance to deliver technical information to support technician's tasks.

Industrial companies have presented several use cases where **maintenance instructions are displayed on smart glasses** [12, 15]. The concept has been validated: users are able to perform faster with a lower error rate [2, 7, 21], and even user satisfaction and feeling competent is increased [10, 23]. However, the smart glass market is full of different types of smart glasses: monocular, binocular, see-through, video-see-through, holographic, virtual retinal displays, and so forth. According to an extensive review on AR in industrial maintenance, development is still needed on smart glass technology even though the advantages for industrial maintenance have been proven. The high fragmentation among hardware, software and solutions also makes it difficult for industrial companies to select and develop AR systems. The same review also notes that authoring solutions and content management tools need to be developed for AR. [15]

1.3 Aim of this research

Due to the fragmentation and constant evolution of AR hardware markets, our focus was to **study how technical information best accommodates different devices**. Rather than testing certain devices and their features as such, we selected three different types of smart glasses that are commonly used in industrial AR applications. Additionally, as the needs and circumstances of the users vary, the information delivered to technicians must be in a format that works in different devices with different screen sizes, from personal computers to tablets, mobile phones and also smart glasses. This way, the same information can be utilized in all the devices. DITA XML is the industry standard for technical writing, and, therefore, we see it as a good candidate as the information authoring format for XR use. However, two challenges can be identified: 1. How to design and deliver that information so that it also supports hands-busy type of work in addition to more traditional reading modes? 2. How to create the content so that it can easily be updated and revised in a production setting?

To maintain a competitive edge in the highly competitive maintenance business, maintenance technicians need to perform their tasks efficiently. Therefore, in an industrial maintenance setting, **applications need to be intuitive and easy to adopt**. Companies do not want to invest too much time and money for the learning curve, and employees may not be willing to invest their time in learning if the application seems complicated. Therefore, the usability of the smart glass applications and the information delivered to these devices are in the focus of our research.

Many of the existing AR applications have been designed in such a way that the content has to be specifically tailored or manually authored for each use case and task [15]. However, we are aiming one step further and are researching ways to **bring instructions from the company's information system automatically available for the user according to Information 4.0 principles**.

2 Experiments

The aim of this research is to develop a working concept for smart maintenance aid for elevator maintenance, i.e. bring technical instructions to smart glasses. As no off-the-self solutions exist, we utilized the lean start-up method to test the usability of the concept iteratively and to develop it further. In the lean start-up method the core component is the build-measure-learn feedback loop. The phases of the loop are: idea (hypothesis), build (proof of concept), measure (evaluations), and learn (adjust). These quick learning cycles are repeated as many times as necessary. [17]

Our study consisted of four consecutive development cycles, which we call experiments. Each experiment consisted of one or more build-measure-learn loops. In the first experiment the proof-of-concept applications were implemented and tested on Vuzix 100 and Microsoft HoloLens. In the rest of the experiments the proof-of-concept applications were implemented and tested on ODG R-7 and HoloLens. An overview of experiments is presented in Table 1. Our main interest was the presenting and reading of content, and little effort was put on user interface design. All application user interfaces were implemented in English.

Table 1. Overview of the experiments

	Exp. 1	Exp. 2	Exp. 3	Exp. 4
Devices	Vuzix M100 HoloLens	HoloLens ODG R7	HoloLens ODG R-7	ODG R-7
User test task	install alarm phone	replace drive component	install alarm phone	replace drive component
Instruction location in evaluations	locally saved	web portal	web portal	web portal
Application	default web browser	separate viewer application	separate viewer application	separate viewer application
Number of test users	12	9	10	7

To develop and evaluate the concept, we selected conventional qualitative and participatory methods, which are known to reveal the behavior and perception of users. The selected methods were focus groups, focus interviews, think aloud, user observation and questionnaires.

2.1 Smart glasses used in experiments

Three different types of smart glasses were used in field experiments.

Figure 1. The devices used in field experiments from left to right: Vuzix M100, ODG R-7, and HoloLens.

Vuzix M100 are monocular video-see-through smart glasses with a small display on the side of the user’s view (Figure 1). They are equipped with a speaker and a camera. There are control buttons for user interface, and the device supports voice control.

ODG R-7 are binocular video-see-through glasses (Figure 1). With ODG R-7, the content is tied to the display, i.e. the content is always visible regardless of head movements. This means that the content moves with the display when user turns their head.

Microsoft HoloLens are binocular-holographic glasses (Figure 1). With HoloLens the user had two possibilities for interaction with the application UI: speech and gestures. The available gestures were HoloLens standard features (pinch and bloom). Speech commands consisted of a predefined vocabulary such as “next”, “previous”, and “scroll down”. Spatially aware devices, such as Microsoft HoloLens, allow the system to present information on spatially arranged windows, which can be moved around in the desired physical position. This means that the windows do not move with the head movements when user turns their head.

2.2 Experiment 1

Use case: maintenance field worker performing hands-busy type of task, getting instructions on head mounted display with no internet connection
User test task: maintenance task for installing alarm phone components
Devices: Vuzix M100 and HoloLens

A simple QR code reader application was developed for both devices. With the applications the user was able to scan a QR code (Figure 2) and the correct instruction was opened automatically in the browser.

Figure 2. User scanning the QR-code to start the instruction (HoloLens on the left, and Vuzix on the right).

After Experiment 1 was completed, Vuzix M100 was updated to Vuzix M300, and we no longer have the M100 available. Figure 3 shows an instruction retrieved from the web portal using the default browser on Vuzix M300 glasses. It might appear slightly different from the browser view of M100 that was used in Experiment 1.

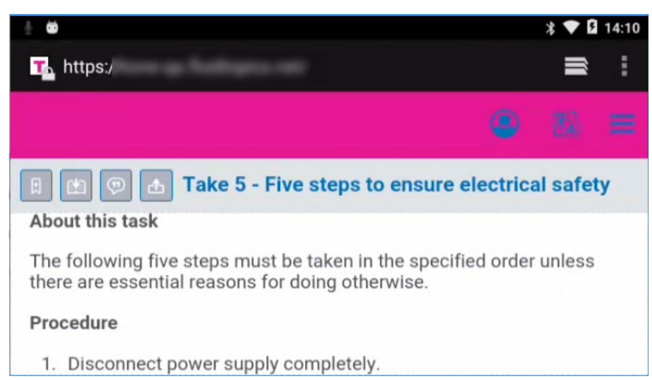

Figure 3. Instructions retrieved from web portal with default browser on Vuzix glasses.

The user tests were conducted at a real equipment in Hyvinkää, Finland. Twelve users evaluated the proof-of-concept applications without performing actual maintenance tasks. Four of them were female and eight male. They had expertise in industrial maintenance, technical documentation, X reality, documentation IT architecture, maintenance analytics and maintenance applications. They had little or no experience of augmented reality and smart glasses, except for one user. All of them were native Finnish speakers. After testing, the users answered a questionnaire, where they were also able to give free-form comments. All users were also verbally asked for free comments after the test, and the comments were written down.

During these evaluations the users had the equipment under maintenance visible and could compare the maintenance instructions against the real components, but they did not physically perform the maintenance task. These evaluations lasted for approximately 15-30 minutes. Figure 4 shows one of these short evaluations in action with Vuzix 100 glasses.

Figure 4. Short evaluation with Vuzix M100 ongoing.

One test user (maintenance expert) performed the complete maintenance task using the instructions on smart glasses. The completion of the first part of the task was done with Vuzix and took approximately 1.5 hours. Second part was done with HoloLens and took approximately 2 hours. With this user, we used user observation and the think aloud method. The user was instructed to comment on everything while working, and all the feedback and comments were written down during the test. The user test was also video recorded. Three persons observed the user test. Figure 5 shows the test setup. After the tests, the user answered the same questionnaire as other users, and he was also asked to give free-form comments.

Vuzix glasses were attached to a hardhat or safety glasses. HoloLens was integrated in a hardhat.

The original instructions for the task existed in FrameMaker format and had previously been published as PDF files. The instructions were in English. They were modularized and rewritten into DITA 1.2 XML format and stored in the repository. The modularized instructions contained 29 topics (18 tasks, 5 concepts, 5 references). The topics contained procedural and descriptive information and no tabular data. A total of 16 animations (.mp4) were linked to topics (2 in concepts, 1 one reference and 13 in tasks). Due to XML repository system limitations, animations were not stored in the repository. The XML content was exported from the repository, and references to animations were added to the XML files in a local hard drive. The files were then uploaded to the devices. In the process, references to animations were updated to follow the correct path in the device.

Figure 5. User tests in progress (Experiment 1)

In addition to the locally stored test material, the users were able to log into the web portal and search and open any instructions. These instructions were not formally recorded or analyzed.

2.3 Experiment 2

Use case: maintenance field worker performing hands-busy type of task, getting instructions on head mounted display from a web portal
User test task: maintenance task for replacing drive component
Devices: HoloLens and ODG R7

The learnings from Experiment 1 were taken into account when developing the viewer applications for Experiment 2. Most importantly, the amount of text visible in the application was optimized by changing the UI elements. Vuzix was replaced with ODG R7 as Experiment 1 showed that displaying this much information on the small screen of Vuzix was inconvenient for the users.

Figure 6 shows the HoloLens UI of demo application used in Experiment 2. In the middle we have *document window*, on the left *table of contents window*, and on the right *bookmark window*. When the user clicks the video in the document window, *video window* opens above the document window. *The information symbol* on top right corner of document window opens an *information window* above the table of contents window. The font size can be changed from the application settings before opening the document. There is no standard font size in augmented reality, as the relative size of the text also depends on how far from the user the text is placed.

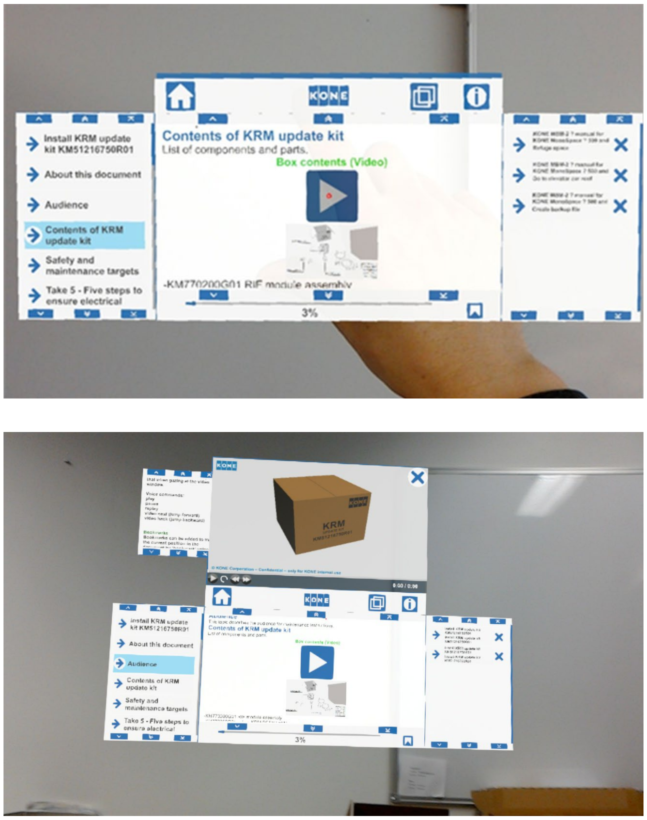

Figure 6. HoloLens UI, Experiment 2. Above application start view, below all windows visible

In Experiment 2, users typically placed the application windows in HoloLens in 1-3 meter distance from themselves. Font size was selected so that the users were able to read the text well and as much content as possible was visible. The user placed the UI on the side, e.g. on the elevator shaft wall, so that it did not cover the working area, yet was readily available when needed.

Figure 7 shows the application user interface used in Experiment 2. In ODG the application was divided into tabs. One tab had no content and the display was dark, i.e. the user was able to see the real world well through the display with the glasses on. When the content was displayed on ODG, the instructions for replacing drive component occupied a total of 33 pages.

The applications were developed in cycles of 1-2 weeks during a two-month period. Nine people were involved in testing the applications during the development phase. Three of these users were female and six males. All of them were native Finnish speakers. They had expertise in industrial maintenance, technical documentation, IT solution architecture and X reality. Not all users were involved in testing each cycle. Most of them were also involved in Experiment 1, so they were already familiar with the concept.

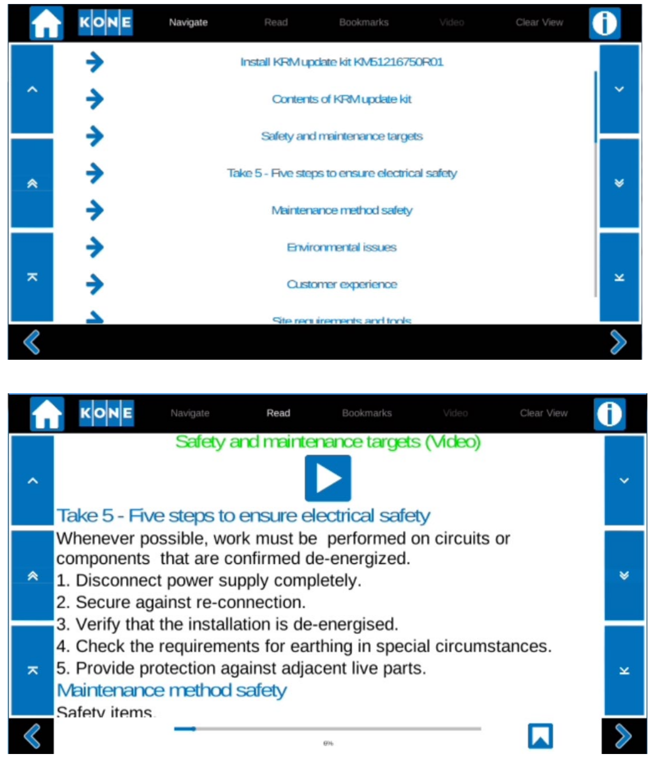

Figure 7. Screenshots of application user interfaces at ODG R-7. Above Navigate tab (Table of Contents), below Read tab (content).

The users tested the application for approximately 15-60 minutes in an office environment without performing the actual maintenance task. During the tests, users were observed and the think aloud method was used. Their feedback was verbally collected after the test, and notes were taken. The users tested the application mostly with the same content as in Experiment 1, but the users were able to select any of existing instructions from the web portal and occasionally other content was also used to get as much user feedback as possible.

A synthesis of comments was always used for the next software development cycle. The feedback focused on technical issues, UI, and the features of the application. In addition, users also commented use scenarios and possible use cases and safety issues.

After the proof-of-concept applications were ready, thorough user tests were conducted at an elevator simulator in Hyvinkää, Finland. One maintenance expert performed the whole maintenance task using both devices for half of the task. With this user we used user observation and the think aloud method to evaluate the user test. During the user tests, HoloLens was integrated in hardhats and ODG R7 was used with a hardhat.

The original component replacement instructions had been modularized into DITA 1.2 XML format and stored in the repository. The instructions were in English. The structured XML content was processed into HTML through DITA Open Toolkit and published in a web portal. A network connection was needed for this experiment. The instructions were accessed in the portal by navigating to the front page of the portal. Exact document name was needed to be able to fetch the correct instructions for the task. The modularized instructions contained 52 topics (24 tasks, 5 concepts, 23 references). No animations were included in the instructions. Tabular data was included in 12 topics (11 references, 1 task). The application was also able to scan a QR-code and automatically retrieve the desired instructions.

2.4 Experiment 3

Use case: maintenance field worker performing hands-busy type of task, getting instructions on head mounted display in multiple languages
User test task: maintenance task for installing alarm phone components
Devices: HoloLens and ODG R-7

The viewer applications of Experiment 2 were further developed in Experiment 3. The user interface and the functionalities of the application were improved based on learnings from Experiment 2. In addition, some minor bug fixes were made to the software. For example, horizontally split text lines were fixed and totally visible. Navigation inside the application was improved.

Ten different people were involved in testing in this experiment. Seven of them had maintenance-related roles (maintenance technicians, maintenance troubleshooters and maintenance managers), two maintenance training-related roles and one competence development related role. Nine of the testers were male and one female. All participants were native German speaking. User tests were carried out in class room environment in Hannover, Germany, and user feedback was collected in group discussion after testing. User observation was also used during the testing. English instructions from Experiment 1 were saved locally in the devices. Additionally, test users were able to retrieve German content from the web portal. Each user was able to select the instructions they wanted to test, and the used instructions were not formally recorded or analyzed.

2.5 Experiment 4

Use case: maintenance field worker performing hands-busy type of task, getting localized instructions on head mounted display
User test task: Real maintenance task for replacing drive component using guidance
Device: ODG R-7

For this experiment, no changes were made to the application, but the content was adapted to better suit smart glasses use based on the learnings from previous experiments. One of the major learnings was that wide tables do not work well when viewed with smart glasses. The original instructions for the maintenance task were in PDF format. The original instructions were heavily based on tabular data and, during the modularization process into DITA 1.2 XML format, the information was rewritten to remove some of the wider tables. The topics were stored in the repository. The modularized instructions contained 58 topics (27 tasks, 22 concepts, 9 references). No animations were included in the instructions. Even after the modularization process, 18 topics (8 concepts, 8 tasks, 2 references) contained tabular data.

User evaluations were carried out in training facilities with an elevator simulator. The environment was identical to a real situation; the task was performed in an identical way as it would be done in a real situation.

The users were all German speaking and all content used in this field experiment was in German. In the first part, the application and instructions were tested by seven people in maintenance-related roles without physically performing the maintenance task. In the second part, maintenance experts used the system for a real complicated maintenance task (replacing a drive component). One user performed the actual maintenance task and other maintenance experts followed the work. One extra pair of smart glasses was available, so one maintenance expert was able to follow the instructions on glasses while the other performed the maintenance task (Figure 8).

Figure 8. A maintenance expert is performing maintenance task using ODG R-7. Another one is following the work and instructions on ODG R-7.

User observation and the think aloud method were used in both parts of the user evaluation. After the second part, the maintenance experts gave their feedback in a group discussion, and notes were taken. When the content was displayed on ODG, the instructions occupied a total of 126 pages.

Test was combined with an AR remote assistance user test. At the end of the maintenance task, another application was used to get remote assistance for parameter settings. However, description of that part of the experiment is out of scope for this publication.

3 Results

The user tests were carried out by a diverse team of experts in field maintenance, industrial XR, technical documentation, and extended team of IT backend systems and software development. Three different smart glasses were used (Vuzix M100, HoloLens, and ODG R7) in four different experiments. Proof-of-concept applications were tested by a total of 22 different people as some users were involved in several experiments. Three user tests were carried out in a real or realistic environment by real maintenance experts. Figure 9 shows maintenance expert working with HoloLens in experiment 1.

Figure 9. Maintenance worker using smart glasses (Experiment 1).

General attitude among the test groups was positive towards using technical information in smart glasses. Many users commented that they would prefer XR-based guidance to traditional paper manuals, provided that the information is usable, the application intuitive to use, and devices technically advanced enough. They showed general enthusiasm to utilizing XR-based guidance, especially to check a short task or a technical detail related to it. Some users still preferred to use their mobile phone to read technical information, and, to overcome the hands-busy issue, to "use a piece of gum to stick it somewhere and watch a video".

3.1 Devices and user interfaces

Test users gave much feedback regarding devices. As a general remark we can conclude that **the hardware still needs to be improved before it really is applicable for this kind of industrial use**. A see-through display is in some occasions too opaque, and the user cannot see the real environment. On the other hand, sometimes it is difficult to see the display in bright light. With a small monocular display, many users need to close the other eye to see the display, and changing the focus between the working environment and the display is unergonomic and inconvenient. Very small displays such as Vuzix are not well-suited for reading a large amount of information, and it seems that these kinds of devices are suitable for checklist type of information. Battery life is also an issue as an external power source complicates smart glass use: The cable connected to e.g. power bank cannot hang freely, but must be under clothes for safety reasons. Large, heavy devices such as HoloLens are not suitable for field use because of the weight and the fact that the device blocks the user's field of view.

User experience and user interface design for smart glasses is needed. In the first experiment, some of the instructions were retrieved directly from the web portal and viewed with the device default browser. The view was cluttered with navigation-related toolbars and very little room was left for the actual instruction texts (see Figure 3). Users commented that it was difficult to understand and follow the instructions as a very small amount of text was visible at one time. Therefore, for further experiments the viewer applications were developed to maximize the amount of text visible in the smart glass view.

Users also gave feedback regarding the viewer application UX and UI design (Experiments 2-4). For example, with HoloLens they would have liked to easily position windows and move them in the desired position. Some users also desired the possibility to "wipe application windows away" and easily "recall them back to the view". Users also commented on application features. Especially in Experiment 2, the users were asked to give feedback on technical details of the application and to test the functionality.

Non-native English speakers had problems using voice commands in English. In addition to unclear pronunciation, the commands were also not recognized due to background noise and echo. There was some lag with sound commands, which frustrated users. Many users preferred gestures to voice, but commented that this is due to voice commands not working as they expected. Users also commented that the UI user interface should support hands-busy type of actions, and voice commands, if working properly, would support this.

3.2 Technical information

As the content was not designed to be displayed on a small screen, most topics were too long and step lists were difficult to follow due to the large number of steps. Topic length resulted in content not fitting on the screen and frequent scrolling was required from users in Experiment 1. Scrolling is necessary when the information to be displayed does not fit on the screen and overflows from immediate view. Table 2 defines the number of words and task topics for the content that was analyzed in these experiments. Even though the average number of steps is reasonable, the longest step list contained 49 steps, which was extremely difficult to follow. Admittedly, this step list would be difficult to follow even on paper.

Table 2. Average number of words in topics and number of steps in task topics. Same content was used in Experiments 1 and 3.

Experiment	Average number of words in topics	Average number of steps in task topics
1	65,3	6,7
2	134,4	7,3
3	65,3	6,7
4	158,5	13,7

In the first experiments, users had problems in understanding where they were within the instructions (position inside the current document and location in the documentation hierarchy). Users also noted a need for bookmarking. These problems were taken into account in application development in Experiments 2 and 3. To avoid the scrolling problem, users could browse by pages and had the possibility to go by chapters or move to next chapter or section title. A simplified bookmarking functionality was also built into the application. From the menu icon, the user could always return back to the main menu.

The test content included a large number of tables. Tabular data fit poorly on small screens and required horizontal scrolling. In many cases, test users just scrolled past the tables without reading them, looking for tasks and step lists.

In the first experiment, videos and animations were not clearly distinguishable as something that can be started. They were indicated with a grey box only, and users did not know that they could start video playback. This was improved in Experiment 2 by adding a clear play icon to playable objects. When users knew how to start an animation, stopping it proved problematic. The users had problems in understanding where they were within the video, if the video was going to end soon, or if there was still a long part to be seen. As a solution, a progress bar was added.

Both English and German content was used in the experiments, and both languages worked in a similar manner from the delivery point of view.

4 Discussion

General attitude towards using technical information in smart glasses was positive in our user evaluations. However, to utilize smart glasses in industrial maintenance, further development is needed for devices, their user interfaces, and in the design of technical information.

4.1 Devices

The best way of utilizing smart glasses in industry depends on the field of industry and the type of operations. If we compare smart glass use cases on assembly line and in equipment maintenance, there is one fundamental difference. On an assembly line, the location is fixed and the same tasks are performed frequently, whereas in equipment maintenance, the worker is constantly moving from one equipment to another in geographically different locations, and the tasks to be performed vary considerably. Therefore, the smart glass concepts are different. On an assembly line one can have a dedicated application on glasses. The glasses can be in kiosk mode where only that specific application is running. When the assemblers enter the specific spot on the assembly line, they grab the glasses and follows instruction on glasses. When they complete the task, they put the glasses back on the charging station, and this way the glasses are always ready for the next user. As the worker is moving from one location to another in equipment maintenance, the charging of the devices has to be considered. Probably an external battery, i.e. power bank, is needed to ensure that the device is enabled during the whole work shift. As the need for information is not always predictable, the device should always be ready for use at once when the need arises. Current battery life and UIs do not support this.

With many maintenance tasks, the technician's both hands are holding tools and parts while they are performing the task, and in this situation hand gestures cannot be used. On the other hand, operating the device UI, launching the application, and selecting menu items can be performed with gestures. **As the use situations vary and users have individual preferences, multi-modal user interface is advisable.** Prilla et al compared handheld touch device and head gestures in hands-busy type of health care context. They show that also head gestures support this kind of use scenario. [16] Therefore, further research of complimentary user interaction methods would be beneficial.
One point worth mentioning is that the maintenance worker needs guidance or technical information only every now and then and not constantly. Therefore, **the user interface should be intuitive and easy to remember to avoid the technology cost overrunning the gains**. Businesswise one additional challenge is the cost compared to use hours: If the smart glasses are used only seldom, is the cost too high? The cost becomes more acceptable if the smart glasses are used for several purposes. One additional use case is remote assistance, and the glasses could also act as a mirror screen for the smart phone. Another possible approach would be to have the smart phone as the processing unit and have the wearable display connected to it.

Tasks vary in equipment maintenance, and the technician does not perform the same task repeatedly. Therefore, it is essential that the smart glass application provides instructions for several different tasks, and the technician can then easily select the appropriate instructions.

Developing and testing augmented reality in a real context and environment is challenging in many aspects. Perhaps two dominant questions are related to **occupational safety and costs**. You cannot compromise safety and, therefore, the testing should also be safe. Testing several devices and creating applications for all of them is expensive. One solution to overcome the problems is to **simulate augmented reality and smart glass use in virtual reality** as suggested by Burova et al. [5].

On very small displays such as Vuzix **it is important to squeeze the information in as compact a format as possible**. The application of the minimalist approach and minimalism heuristics [22] offers one way to compress the instructions, and controlled languages such as Simplified Technical English [1] generally restrict the length of sentences. Further research is needed to validate these approaches with the use of smart glasses.

IoT sensor data is used more and more in industrial maintenance to implement preventive and predictive maintenance. The core of this approach is to carry out the necessary maintenance actions only, and perform them at the optimal time. This means that the combination of tasks performed at each maintenance visit differ from each other. In order to serve the maintenance technician, the instructions need to be dynamically composed based on this combination. Contextually relevant dynamic information content is composed of relevant information topics and, and through that, tailored for each maintenance visit and task.

4.2 Technical information

Armfield et al note that “professional and technical communicators, with knowledge of visual design, minimalism, structured authoring, and user experience, are crucial for the development of content required for AR” [3]. As the mixed reality technologies develop further, **more focus needs to be put on designing the content so that it fits the users’ needs instead of automatically converting old existing content**. User-centered design is the main principle of technical communication in the more traditional delivery channels [11, 18], and this principle also holds true when the information is delivered through XR devices.

To move the content from traditional delivery channels to XR, many researchers recommend that textual elements are reduced and images and icons are used instead [20]. Some researchers suggest that there might not be a need for text at all [9]. Researchers also recommend the use of authoring templates or frameworks to create standardized content for AR applications [6, 13, 14]. While the automated process from text or 3D models to images through templates may seem like an efficient and cost-effective mode of operation, there is not much evidence that images alone carry over all the needed information. On the contrary, it has been established that language facilitates a more explicit meaning of what is being communicated than images, and leaves less room for interpretations [5]. In industrial maintenance with a zero accident tolerance policy, we cannot leave the correctness of the interpretation to the user but **ensure unambiguousness with the correct ratio of text and accompanying images**. This issue needs to be further investigated to establish guidelines.

Content and style is separated in DITA, and, therefore, information can be delivered in a scalable and responsive format, supporting devices of different sizes. However, even when content is modularized, **traditional topics tend to be too long and do not work as such in AR applications**. As already seen in the scope of our experiments, scrolling is not desirable when viewing content on smart glasses. Sanchez and Wiley have investigated the effects of scrolling on learning and concluded that especially with individuals with lower working memory capacity, scrolling affects learning negatively [19]. Studies on scrolling have focused on PCs and smart phones, but in the test setup with smart glasses, the negatives effects of scrolling were amplified for the following reasons: 1. The screen size is considerably smaller than with a PC and most handheld devices, resulting in frequent overflow of content. 2. When the used devices are controlled with voice commands, it is clear that speech recognition is not yet sophisticated enough. Many test users had problems with the commands “scroll down”, “scroll up”, resulting in content scrolling too fast past the desired point and the user having to scroll the other way again. Constant scrolling back and forth caused frustration and hindered task completion. Further research is needed to establish guidelines for the ideal length of topics and step lists and ways to overcome the scrolling issues.

As DITA topics have a standardized structure, they can be utilized in the creation of standardized content for AR. Furthermore, as information typing is also a feature of DITA, each topic type already has a specific primary objective which allows for **certain kind of information to be targeted for delivery to AR applications**. For example, it is possible to deliver only task-related information to the AR application and leave the rest of the information to other delivery channels. In this study we established that reference information, in many cases in form of tables, fits poorly on smaller screens. However, the role of reference information on smart glasses needs to be studied further. In our field experiments, we were able to use both English and German and can conclude that this is a language-independent system. Therefore, if localization is done in XML, we can use any target language to easily deliver localized content to smart glasses.

When the number of possible tasks is increased to accommodate for the maintenance of the whole equipment or equipment base, it is not viable to manually design and hardcode each set of instructions for smart glass use. Therefore, **it is of crucial importance that the instructions are delivered from a documentation repository, and the content adaptation for smart glasses is performed already in the backend system**. Consequentially, no design or configuration is needed in the smart glass application. Even though the content used in our experiments was converted from other formats (FrameMaker or PDF) to XML, the current authoring format and the industry standard is DITA XML and no conversions are needed. However, as evidenced by our experiments, the format alone does not mean that the content is suitable for smart glasses as such.

5 Conclusions

Even though smart glass devices and applications can display the instructions in more visual and interactive ways, it does not remove the need for textual information in the instructions. Instead, **the message is conveyed most reliably with a mixture of text, graphics and videos or animations**. Moreover, when the content is designed for mobile use with small displays, it does not only support use in smart glasses but also works in a variety of different devices including smart phones, smart watches or other wearable displays.

We have established that **the concept of using smart glasses to deliver maintenance instructions to technicians is well-received** and a validated concept. In a production setting, it is important that existing technical information can be utilized, but **information design and compression and shortening of topics** is needed for usability reasons. Additionally, **further development is needed on devices, user experience, and user interface design**. To advance the use of XR technologies in industrial maintenance and other similar hands-busy type of professional use, there is a need **to develop an explicit list of UI and usability heuristics for XR context.**

Industry 4.0 and new technologies are offering new and exciting ways to support the work of maintenance technicians. Smart maintenance support will help the maintenance technicians to perform their tasks more efficiently and in a safer way. Most importantly, **proper information design and well-designed information delivery support the maintenance technicians to perform their tasks by providing context-sensitive information in an easily understandable format**.

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Paper VI

Hanna Heinonen, Sanni Siltanen, and Petri Ahola. 2021. Information Design for Small Screens: Toward Smart Glass Use in Guidance for Industrial Maintenance. In *IEEE Transactions on Professional Communication*, vol. 64, no. 4, pp. 407-426, Dec. 2021. doi:10.1109/TPC.2021.3110616

Information Design for Small Screens: Toward Smart Glass Use in Guidance for Industrial Maintenance

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***Abstract*—Background:** *Smart glasses and other extended reality (XR) solutions provide new ways of utilizing technical documentation with hands-busy tasks in the field. Scaling up the use of XR solutions in industry has been difficult due to the manual authoring of content for each device and task. Therefore, authoring solutions and information design methods need to be developed to scale content automatically to different devices and applications.* **Literature review:** *Related work includes smart glasses and industrial maintenance work, categorization based on users' skill levels, and standardized guidelines in information design.* **Research questions:** *1. How should information content be designed and created to support use in smart glasses and other small-screen devices in addition to existing delivery channels? 2. How can the same information content be utilized to deliver relevant content to users based on their skill levels? 3. Are the users of technical instructions ready to accept smart glasses and XR as a delivery channel?* **Methodology:** *We describe a study that focused on designing maintenance instructions for small screens. The information was authored in DITA XML format, and a smart glass application was used in user tests to evaluate the delivery and usability of the information. We used thinking aloud and participant observation as well as questionnaires to collect data.* **Results and discussion:** *The chosen information design methods successfully compressed technical information, and automatic filtering of content supported different use cases. Participants were enthusiastic about the use of smart glasses, and the instructions helped in performing tasks.* **Conclusions:** *Information designed with the user-centered approach of minimalism works best with instructions on small screens, and filtering information using DITA XML elements is an efficient way to scale information for different user needs.*

Index Terms*—Darwin Information Typing Architecture (DITA), industrial maintenance, smart glasses, structured authoring, extended reality (XR).*

Traditionally, maintenance instructions have been delivered on paper copies, but paper delivery has proven problematic for many reasons. For example, an outdated copy of instructions might be accidentally used, and there are costs involved with printing. The trend has been, therefore, to move the delivery of information to electronic print formats—i.e., PDFs and more recently online portals. However, as industrial maintenance is often characterized by tasks that require the use of personal protective equipment while keeping the technician's hands busy holding equipment parts and tools, it is often difficult to access instructions while performing a task. Therefore, to solve this issue, the focus has turned beyond PDFs and online portals to new delivery methods, especially to extended reality (XR) solutions.

Extended reality is an umbrella term for technologies combining virtual and real elements. There are several levels of immersivity among XR applications, varying from total digital virtual reality (VR) environments, through mixed reality (MR), to augmented reality (AR), where the virtual elements are added on top of the user's view of reality [1]. In industry, VR is used, for example, in training and design reviews [2], and MR is used for many visualization purposes [3]. AR, especially when applied with smart glasses, is used in industrial settings for workflow guidance, reporting, and remote assistance [4], [5]. Solutions where information is displayed on smart glasses are sometimes also referred to as informed reality or assisted reality.

In industrial maintenance, it is not feasible in terms of resources to tailor instructions manually for different outputs and devices. Therefore, it is essential that the technical instructions displayed on XR devices be automatically retrieved from a company's repository. As demonstrated by Siltanen and Heinonen, Darwin Information Typing Architecture (DITA) XML is a good candidate for the creation of content for XR applications [6]. DITA is the technical communication standard for

Practitioner Takeaway

- Instructions displayed on smart glasses help users perform tasks in industrial maintenance, and attitudes towards using smart glasses are positive.
- Well-designed technical information can be automatically used and delivered for several use cases and in several end devices.
- Information designed with the user-centered approach of minimalism works best with instructions on small screens, and filtering information using DITA XML elements is an efficient way to scale information for different user needs.

Fig. 1. Test participants performing maintenance tasks during user tests. The personal protective equipment (hardhat, safety shoes, and cut-resistant gloves) is the same that is required for field operations.

structured writing, and it defines three main topic types: concept (what something is like or how it works), task (how something is done), and reference (information users might need when performing a task) [7]. A repository is used to store the topics, which can then be reused across publications and in different delivery channels.

However, even though we are nearing the era when XR solutions could be utilized on a wider scale in industrial maintenance, very little has been done to create any guidelines for the use of the new media and technologies in the field that specializes in designing and creating technical instructions and guidance, technical communication [8]. Even though DITA offers the technical capability to produce content for XR solutions, the focus needs to be put on designing the content so that it scales according to the media and users' needs. It is also of utmost importance that these concepts are developed and tested in real industry settings, taking into account the actual work environment and the challenges that arise from it. For example, the mandatory use of personal protective equipment (see Fig. 1) in many industrial roles has a substantial effect on how different devices and solutions can be utilized in the field [9]. For example, if safety glasses are required, AR glasses need to be compatible with them to meet the safety standards.

KONE is a global leader in the elevator and escalator industry [10]. It operates in more than 60 countries with approximately 30,000 field employees with varied levels of expertise. As new products are introduced often, even experienced field workers need detailed instructions for them. KONE publishes hundreds of new or revised instructions each year, and, therefore, single sourcing and reuse between information products and different outputs is essential. KONE has also been actively looking into novel ways of delivering technical information to field workers.

The aim of this research is to better understand how technical information content should be designed and created to support use in XR and other small-screen devices in addition to the existing delivery channels. Many industrial companies already produce instructions in DITA XML format that can be transformed into PDF or HTML formats or published to a web service for dynamic delivery to applications. However, the same content needs to be adapted to fit better in small display devices and to automatically filter content to support XR use cases. This study is a step toward creating guidelines for the design of content for omnichannel delivery, including smart glasses.

Next, we review the related work and present our research questions. Then, we explain the research methodology and the test arrangements. Finally, we describe the results and discuss future directions, and end the article with conclusions.

Literature Review

This exploratory study brings together research related to smart glasses and industrial maintenance work, categorization of users based on their skills levels, and standardized guidelines in information design. Smart glass use is a prominent area of research in industrial maintenance, and combined with information design, it offers a new way of delivering maintenance instructions to field workers. When delivering instructions to the limited space available on small screens, it is very important that the information be readable and fits the screen. Therefore, we also wanted to look into categorization of users' skills levels as a way of delivering the correct amount of information.

Smart Glasses and Hands-Busy Work in Industrial Maintenance Modern maintenance work is no longer only about using physical tools, such as screwdrivers, and getting measurements and values on physical gauges. Increasingly, technicians need to interact with digital information and information systems. Equipment information has moved to Internet of Things clouds, and technicians need to check parameters, equipment performance indicators, and measurement readings from information systems. Instructions are no longer only paper manuals but are stored in electronic format and accessed with mobile devices.

In many cases, industrial maintenance tasks require hands-busy actions and, in some cases, both hands are required most of the time [11]. Considering that the technician also needs to wear gloves that can be dirty and greasy, it is clear that a mobile phone with a touch screen user interface is not the optimal device to access information systems in these situations. For these use cases, smart glasses provide a potential solution. User interaction challenges and solutions in maintenance are very similar to some healthcare situations where both hands are needed, the hands might be dirty, and special attention needs to be paid to maintaining a sterile field. In healthcare, the use of smart glasses has also been studied to overcome these challenges [12].

Klinker et al. presented more than 20 use cases for smart glasses in maintenance [13]. One of the prominent use cases is providing workflow information for maintenance technicians. Industrial companies have experimented with smart glasses and, in several use cases, maintenance instructions are displayed using smart glasses [4], [5]. Studies show that users are able to perform faster and reduce error rates with such systems [14]–[16]. In addition, users feel more competent and satisfied [17], [18]. Adequate instructions provided with smart glasses instantly enhance the users' skills. Thus, technicians with different competence levels are able to complete maintenance tasks successfully.

Smart glass use has been often studied and tested in single-purpose use, and content has been tailor-made for each use case, a solution that is costly. Since smart glasses are still quite costly as well, especially those that meet industrial standards, the adaptation of smart glasses to industrial maintenance has been low despite the obvious benefits. However, if existing technical instructions already used for other formats can be reused for smart glasses and if the delivery is automated, the number of use cases increases drastically. Furthermore, when the work processes and practices are designed to support multipurpose use, the return on investment increases considerably. For example, smart glasses can be used to get remote assistance, read technical information, and utilize AR guidance (see, for example, SightCall [19]).

Expert–Novice People working in the field have different skill levels, varying from trainees to experts with lifelong experience. Experienced maintenance technicians know how to perform highly complex maintenance procedures [20]. In many cases, the knowledge they possess is tacit or tribal in nature. At the other end of the continuum, novice users are anxious about making mistakes and want to get started quickly with the tasks at hand [11]. Advanced users may know and remember the task sequence in general and need only to check some details. They prefer to have detailed guidance only when performing tasks that occur rarely or that are new to them [21]. Novice users, on the other hand, need more generic guidance to be able to complete the task. In short, different types of users with varying skill levels have different requirements for technical information [22].

The classification of users into categories based on their skill levels is an established concept in technical communication. Hackos, for example, classifies users into expert performers, competent performers, advanced beginners, and novices [23]. These user profiles are used when creating and delivering content to meet the needs and demands of a specific target group. A user can be an expert for some tasks and novice for other tasks. Thus, the level of expertise and the need for guidance depend on the task at hand. Funk et al. use adaptive assistance for field workers with three different expertise levels–novice, advanced, and expert–to give each group a different level of guidance [24]. A common practice with DITA XML is that the filtering is done with conditions (audience = expert/novice), which requires that each sentence or segment in the DITA XML source be defined for expert-level users, novice-level users, or both.

Traditionally, many maintenance tasks have been standardized. For example, a certain set of preventive maintenance actions is performed at a set interval, and by working with the same equipment for years, the technician learns the tasks. However, the ongoing fourth industrial revolution is also changing the way maintenance work is performed. The Internet of Things, connectivity, and digitalization are transforming even the more traditional heavy industries, giving rise to concepts such as remote and condition-based maintenance. In these settings, the tasks vary from one piece of equipment and day to another, the maintenance technicians have a unique set of tasks to be performed at each maintenance visit, and it is no longer possible even for the experienced maintenance technician to know the tasks related to a certain preventive maintenance visit, for example. Therefore, there is an increased need for guidance even for the experts.

Standardized Guidelines in Information Design

Company style guides are created to provide consistency within each technical instruction and a larger set. In addition to setting standards for writing and formatting, style guides enforce guidelines for information design. The foundations for company guidelines lay in technical communication literature, where, for example, it is recommended that the number of steps in procedures be restricted to a maximum of nine [25], or that information is chunked into meaningful pieces to help readers make lengthy text more manageable to reduce the cognitive load [26]–[29]. These guidelines are based on an established theory in psychology: the magical number seven, plus or minus two. According to this theory, most people are capable of storing between five to nine items in their short-term memory [30]. In addition to technical communication, this theory has been applied to several aspects of daily life, for example, the length of telephone numbers, or recommendations for the maximum numbers of points in oral presentations [31].

Even though these guidelines are widely used in information design, it has also been argued that users of technical instructions do not have to memorize the steps of a procedure, but they typically read the steps one by one as they are performing the related tasks [25]. But with hands-busy maintenance procedures, it is not always possible to flip the pages of a paper manual or scroll down the screen to proceed one step at a time, and the users are forced to memorize a certain number of steps or chunks. Therefore, it has been safer to refrain from writing long procedures and keep them as short as possible or meaningfully chunked, even if that ends up fragmenting the overall task.

Research Questions

As the literature is lacking in guidelines for small-screen information design, we wanted to validate the type of information design principles that should be used for small screens where the instructions are available while the user is performing tasks. Therefore, we designed our study to explore whether the established guidelines in technical communication apply when designing information specifically for small screens. We also experimented with the standard semantic structure of DITA XML to see whether it can be used to filter content based on the user's expertise level. Furthermore, since the use of smart glasses to deliver technical instructions is new,

Table I

Selected Tasks and Related Devices

Task Name	Device Used	Task Description
Install motion sensor cable	Connectivity device	Performed on the elevator car roof. The user routes the motion sensor cable through the roof into the elevator car.
Power-up Connection	Connectivity device	Performed on the elevator car roof. The user connects the motion sensor cable to a connectivity device, switches on the device, and checks that it turns on.
Replace MediaPlayer	Content streaming device	Performed in a residential building lobby. The user replaces a broken content streaming device behind a TV.

Table II

Selected Information Design Methods

Method	Description
Conventional	Based on original instructions available for the tasks. No redesign of content, but due to limitations of the test device used (the screen size and features of the application), some minor, mostly layout modifications were needed for both text and graphics. (Fig. 4, left)
Visual manual	Based on the visual manual theory of Gattullo et al. [32]. The aim is to replace text with graphics, symbols, and icons. (Fig. 4, center)
Minimalist	Based on the minimalism heuristics of van der Meij and Carroll [33]. With minimalism, be aware of what to include, but also what not include, using a user-centered approach. In practice, provide only the information that users need to perform a specific task, and omit unnecessary details. Error prevention information is also included to aid the user. (Fig. 4, right)

we also wanted to study users' attitudes toward this new delivery channel.

Therefore, our research was motivated by three key research questions.

RQ1. How should information content be designed and created to support use in smart glasses and other small-screen devices in addition to existing delivery channels?

RQ2. How can the same information content be utilized to deliver relevant content to users based on their skill levels?

RQ3. Are the users of technical instructions ready to accept smart glasses and XR as a delivery channel?

Research Methodology

Test Material Design Authentic KONE elevator maintenance and installation tasks were utilized in the study. We selected tasks for which the test participants would have to follow the instructions and would not know or guess the steps involved, but which would be simple enough to be completed in the chosen test setup and within a set timeframe. Three different sets of task instructions were created for each of the selected tasks. The selected tasks are presented in Table I and the selected information design methods in Table II.

The conventional version was chosen for this study as the baseline. Earlier research had indicated that traditional technical content is too long for small-screen delivery [6], so we used this as the reference version for the study.

Second, a visual manual version was chosen because the underlying theory considers the whole documentation production process, including the conversion of existing documents to AR (see Fig. 2). It is designed both to convert existing paper-oriented instructions to augmented reality instructions and to write new AR instructions from scratch [32], [34], [35]. The theory promotes replacing existing text with graphics, symbols, and icons [32].

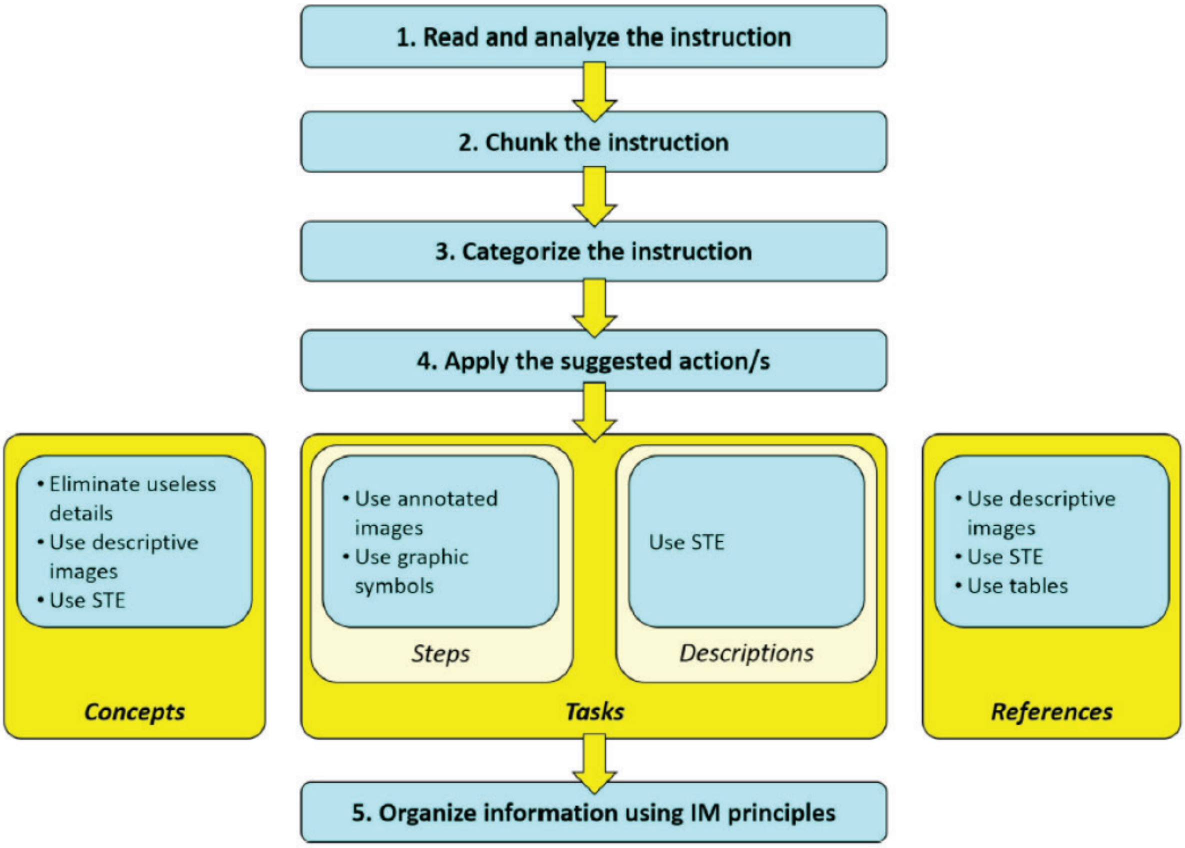

Fig. 2. Main conversion steps of visual manual theory (STE = Simplified Technical English, IM = Information Mapping) [32].

For many companies, legacy documentation must be utilized in one way or another to avoid losing their investment in it, even to the extent that the legacy and any new designs must be synchronized, since both are required by the company's field operations. As the amount of text in this version is limited, it is also cost-effective in terms of translation [34]. According to Gattullo et al., even though modern research acknowledges that more visual instructions are aligned with augmented reality (AR) and Industry 4.0 purposes, there is a lack of specific guidelines to convert existing instructions to visual manuals [32]. Most related research—for example, Knopfle et al. [36], Stock et al. [37], Engelke [38], Gimeno et al. [39], and Erkoyuncu et al. [40]—primarily discusses creating new content. Therefore, existing documentation does not reach technicians.

The third approach, using the minimalism heuristics of van der Meij and Carroll [33], was chosen because it is user-centric. It does not rely on conversion theory as such, but design principles for any technical communication content. In our test material design, the minimalism heuristics were used as a more researched counterpart to the visual manual theory. The minimalism heuristics work well on a small screen because unnecessary descriptive and transitional text is omitted.

The minimalism heuristics stress that one does not write instructions describing the full system, but includes only the steps that a user needs to perform his or her tasks. The user's goals and the tasks themselves must be known before writing the instructions. Also, error prevention information (notes, warnings) is added to save the user's time.

All the test content was authored in English in DITA XML format. DITA XML is also the standard suggested by Gattullo et al. for their visual manual theory [32]. Fig. 3 shows one of the original tasks, rendered in PDF format.

The original task explains why the cable has to be secured with cable ties, but for the target-audience, the trained maintenance technician, there is no need to include this information. As the conventional version was based on the wording of the original task, the explanation was left in that version.

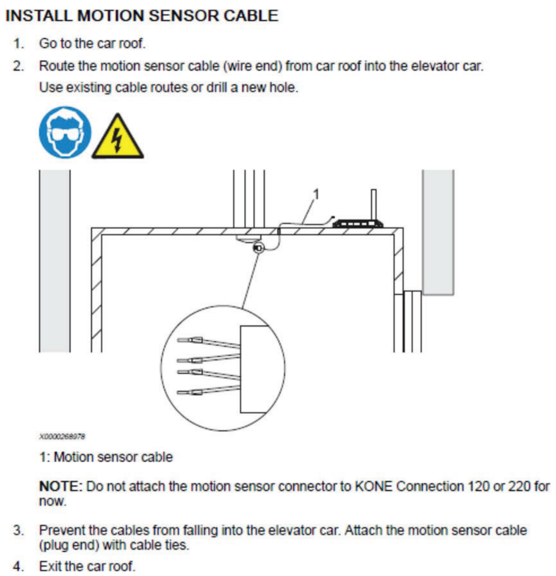

Fig. 3. Original version of the task "Install motion sensor cable."

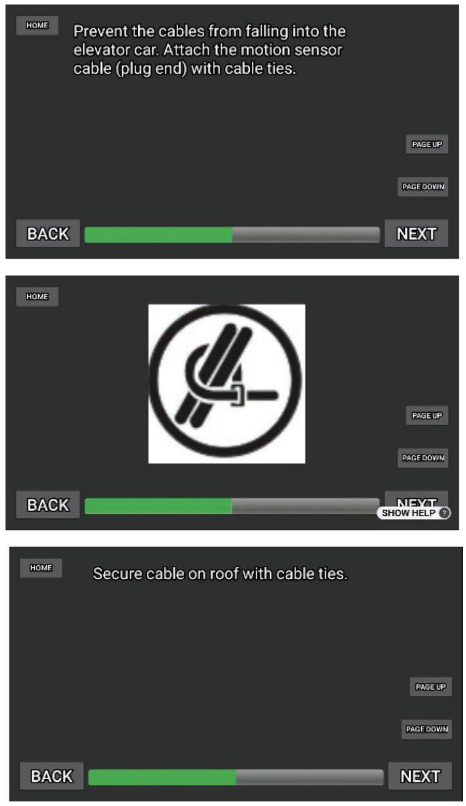

Fig. 4. Three versions of the same step in the smart glass application: conventional (left), visual manual (middle), and minimalist (right).

For the visual manual version, we created an action symbol to indicate securing the cable and replaced the textual instruction with the symbol. For the minimalist version, we removed most of the descriptive text because, based on a target-audience analysis, we concluded that the target audience does not need it. Fig. 4 illustrates the results of step 3 of the original task with different methods. Test material design is described in detail in a master's thesis by Petri Ahola [41].

Test Application To test the concepts, a simple test application was developed for RealWear HMT-1 (see Fig. 5). We selected Realwear HMT-1 as the end device because it has a quite reliable voice user interface that facilitates hands-busy types of maintenance tasks. Furthermore, HMT-1 is compatible with a hardhat and a helmet, and it is a good representative of smart glasses suitable for industrial use.

In the test application, we targeted two issues:

- Focused information for experts, showing only certain parts of the existing content to the users—checklist type of use
- Information flow and the way the information is displayed on the screen

We wanted to show checklist type of information to people who are already familiar with basic maintenance tasks—that is, only the information that the expert-lever user needs. In this research, we use the term *checklist* to indicate a simple list of items that you have to inspect or check, or simple steps that you have to perform, without lengthy explanations or descriptions of the steps. The intention was to tackle the problem that if we show all the information that a novice needs, the experts have problems finding the information that they need as the details are buried in the wealth of information. With our checklist, experts would have a reminder of what to check or do, but they could use their own expertise to perform the actual tasks.

We achieved the checklist by defining certain DITA XML elements that would be displayed; the rest would be ignored by the application (see Fig. 6). As DITA XML is based on semantic tagging of content [42], we could rely on the fact that certain elements would contain the information that we wanted to show. The approach that we utilized enables the reuse of information, and no hand-tailored expert files are needed. In other words, the same XML file can be used to resolve the full content, including the novice-level information, in another application or output. Traditionally, the expert-novice distinction is achieved with the use of conditions and conditional processing, but we wanted to explore ways to utilize

Fig. 5. RealWear HMT-1 with a hardhat.

```xml
<title>Install motion sensor cable</title>
<taskbody>
<prereq>You must have a new replacement cable before starting this task.</prereq>
<steps>
<step><cmd>Go to the elevator car roof.</cmd>
<info>Follow safe procedures for going to the car roof. Make sure you have familiarized yourself with all the needed safety instrutions.
<image href="W13.svg"></image></info>
</step>
<step><cmd>Route the motion sensor cable (wire end) from car roof into the elevator car.<image href="image1.png" placement="inline"></image></cmd>
<info>Pay attention to the ends of the cable and route it in the correct way.</info>
<stepresult>The cable is now routed properly.</stepresult>
</step>
<step><cmd>Prevent the cables from falling into the elevator car.</cmd>
<info><note>Watch out for other people working with the equipment. Always follow safe procedures when working on the elevator car roof.</note></info>
</step>
<step><cmd>Attach the motion sensor cable with cable ties.<image href="image2.png" placement="inline"></image></cmd>
<info>Make sure that the cable tie is firmly attached. Cut off extra lenght from the cable tie.</info></step>
<step><cmd>Exit the car roof.</cmd>
<info>Follow safe procedures for exiting the car roof. Make sure you have familiarized yourself with all the needed safety instrutions.
<image href="W13.svg"></image></info>
</step>
<step><cmd>Finalize maintenance visit.</cmd>
<info>Remove all the tools and waste material from the work site. Dispose of any waste according to local regulations.
<image href="image3.png" placement="break"></image></info></step>
</steps>
<result>You have now installed the motion sensor cable.</result>
</taskbody>
```

Fig. 6. Example of XML elements displayed and ignored by the application. Displayed elements are highlighted in the figure; all other fields are omitted.

the semantic structure of DITA XML and avoid adding conditioning to multiple parts of each topic. This approach saves time in the authoring phase as the conditions would always have to be manually assigned for each element.

Interface design for the test application was not in the focus of our study. However, some simple interactions were developed for the test application. The application was designed to show one step at a time, progressing with “next” and “back” voice commands.

On each screen, a progress bar was shown that indicated the progression of the total maintenance task. The aim was to avoid or minimize the need for scrolling that is a usability problem on small screens, especially with voice commands [6]. In case the content did not fit on the screen, “page up” and “page down” commands could be used to access it. For an example of a UI screen, see Fig. 7.

We produced the XML files with XML authoring tools, and they had exactly the same structure as any XML files

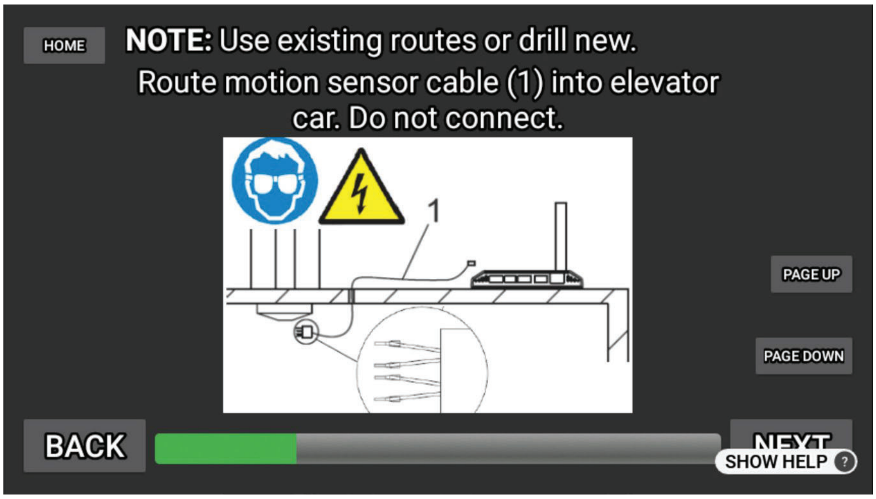

Fig. 7. Application UI showing one step, voice-activated action buttons, and the progress bar.

utilized in the company's technical instructions. For this study, the files were saved locally in the HMT-1. This allowed for the quick iteration of the different test files in the development phase as no publishing to the web service was needed. The tasks were accessible from main menu in the application. The menu was created dynamically from an XML file containing references to the XML task files.

Participants A total of 21 test participants from the elevator company participated in the user tests and evaluated the different instructions (18 male, 3 female). Most participants fell into the 30–39 (N = 8) or 50–59 (N = 7) age groups, and the rest were from 40–49 (N = 4), 20–29 (N = 1), or > 59 (N = 1) age groups. All the participants were native Finnish speakers but had at least a working knowledge of English.

Six of the participants had worked in a field position or were very experienced, two were familiar with the field environment, and six were somewhat familiar with the field environment. The rest of the participants had very limited experience of the field environment (*N* = 2) or no experience (*N* = 6). However, the participants that had limited or no personal experience of the field environment were working with field documentation, maintenance development, or related roles, and all but three can be considered expert-level users of maintenance instructions.

Most of the participants had experience in industrial maintenance (N = 10) or technical documentation (N = 5). Participants also had a background in engineering (N = 4), installation (N = 3), or IT (N = 3). One participant was an elevator maintenance student.

Test Methods We used a combination of conventional qualitative and participatory methods: thinking aloud, participant observation, and questionnaires. These methods are known to reveal the behavior and perception of users [43]. Due to the small size of our test group, the statistical results are only indicative. Instead of relying on statistical inference, the quantitative results of the questionnaire are interpreted through experts' remarks and verbal observations. This research is at the conceptual phase, and qualitative methods support this phase best.

First, we observed participants during the test. The participants were also instructed to think aloud while performing the task. They were instructed to explain what they were doing, what they liked and disliked, what they did not understand, and voice it when having a doubt. The sessions were also video recorded so that we could go back and check a detail if needed.

The participants were also asked to complete a questionnaire to find out attitudes, preferences, and opinions regarding each method, and to compare the methods. In addition to user background questions, the questionnaire contained 7-point Likert-scale questions and free-form questions. In addition, one part of the questionnaire included 7-point Likert-scale questions related to the use of smart glasses.

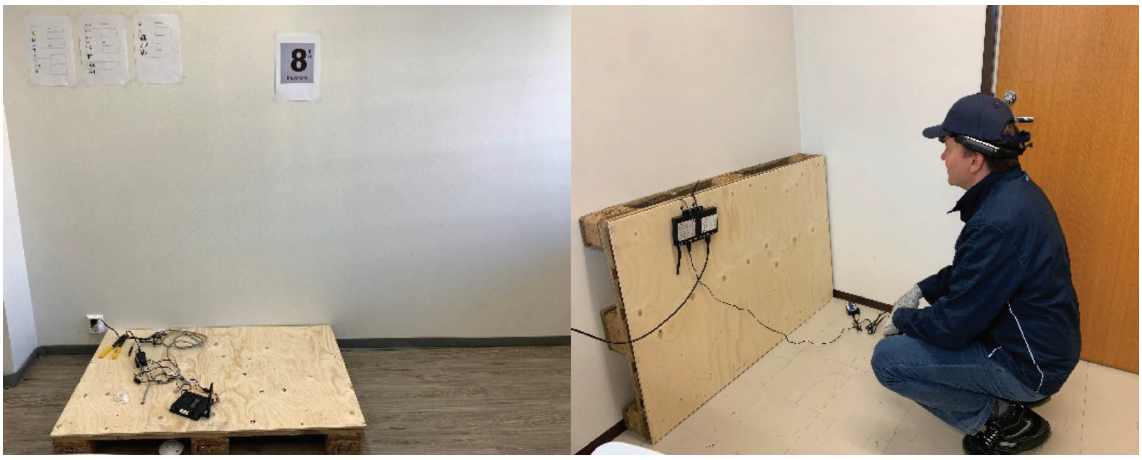

Fig. 8. Test setup: Elevator shaft and car roof simulation (left); lobby (right).

The collected data were recorded and stored in a company SharePoint database. Data storage and removal observed company guidelines and policies as described on the user consent forms. The authors grouped similar items together and analyzed the data.

Our study did not involve ethical issues that would require ethical review according to the local regulations. Therefore, the study was exempt from Institutional Review Board (IRB) review.

Test Setup Two test tasks were meant to be performed on an elevator car roof. Because the elevator car is located inside an elevator shaft, and only qualified personnel are allowed to enter the shaft, in our user study, the shaft and the elevator car roof were simulated with a pallet with a fixed plywood top in a meeting room. The test equipment was located on the pallet (see Fig. 8). This simulation allowed us to avoid any safety-related issues that might arise from working on actual equipment, yet the task mimicked performing the task in a real environment. The setup was explained to the test participants, and during the tests, when requested to enter the car roof, they stepped on the pallet. The third task was meant to be performed in a building lobby. We simulated the lobby in the same meeting room, using a monitor as the TV screen. Another pallet with plywood was used to simulate the fixing of the equipment behind the TV.

Two identical rooms with identical test setups were used in the user tests. A 2-hour timeslot was reserved for each testing session.

The comprehension of symbols was not within the scope of this study; therefore, a list of symbols used in the instructions was available for the participants during the test (see Fig. 9). Participants were encouraged to check the meaning of any symbols during the study and ask for help if they could not understand the meaning of symbols.

Each test participant conducted a series of three tasks. For each of the three tasks, we had three different versions of the instructions created according to the selected compression methods: conventional, minimalist, and visual manual. Therefore, a total of nine different instruction sets were used in the tests. We varied both the order of tasks and the order of compression methods, and different tasks were tested with different methods by different people. Each test participant used and evaluated all three of the methods during the user tests.

User Test Session Flow The user test sessions followed a predefined flow. First, as most of the participants came to the user tests directly from other work duties, they were offered some refreshments and asked to relax and orient to the user test. While each participant was having refreshments, we explained the scope and purpose of the user test, asked for research consent, and requested permission to record the session and take photographs.

Second, we introduced the test setups, devices, and tools used in the test (see Fig. 10). We explained how smart glasses function and fitted the display for the participant. In addition, we went through the symbols and their "cheat sheets" on the wall.

Third, we emphasized that we were testing technology and information compression methods, not the participant. We explained that it is important that the participants try

Fig. 9. Test participant examining the list of symbols used with the visual manual method.

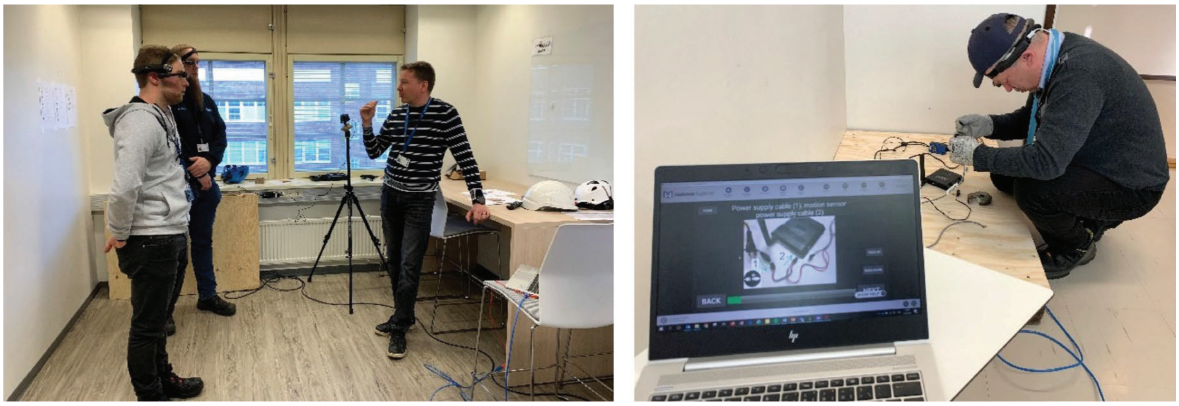

Fig. 10. Test setup and tasks being explained to participants (left). User test in progress (right). The smart glasses were connected to a PC so that we were able to follow what participants saw on the glasses.

not to please us, but openly express their thoughts and concerns. The participants were asked to think aloud, describe their actions, and express all the thoughts that they have regarding the tasks and the setup. They were also asked to think aloud when interpreting the instructions and experiencing any uncertainty.

When the actual user test began, participants performed the first task with the first method. After finishing the task, the participants answered questions regarding the first method. Two other tasks were completed, and questions were answered in the same manner.

After completing all three tasks, the participants had a short break, and were offered refreshments. The purpose of the break was to allow the participants to refresh their minds and get some distance from the previous task and method performed before answering the final part of the questionnaire. Finally, the participants answered questions comparing the methods as well as questions regarding smart glasses.

Results

First, all participants were very engaged with the user test. We did not measure user engagement per se, but we observed that all participants were focused, readily provided feedback, and showed intrinsic motivation during the tests [44]. Participants commented on other things than those primarily studied, and proposed improvements and modifications to components and products used in

Table III
Preference and Comprehension of Methods

Question	*N*	Result
Which version did you like the most?	20	Minimalist, *N* = 9 Visual manual, *N* = 7 Conventional, *N* = 4
Which version was the easiest to comprehend?	21	Minimalist, *N* = 10 Conventional, *N* = 6 Visual manual, *N* = 5

the test setup. They also gave feedback for the maintenance method used for the task and proposed alternative ways of performing the task. In addition, they discussed future maintenance guidance and proposed other areas where a similar system could bring benefits. All this confirmed high engagement and concentration from participants.

The preferred information design method among our test group was minimalist, followed by visual manual. The least liked method was conventional. Minimalist was rated the easiest to comprehend, conventional second, and visual manual last. The questions and results are presented in Table III.

As described earlier, the order of the tasks and methods was varied to avoid a bias that could be caused by participants favoring or disfavoring the method related to the task they performed first or last due to unfamiliarity with smart glasses or fatigue. This variability also addressed the bias caused by participants favoring or disfavoring a certain task.

There was a negative correlation between the method performed with the first task and the favorite method. Only two participants selected the method that they tried first as their favorite. Eight participants selected the last method as their favorite, and nine participants selected the middle one. One person omitted this question. There was also a negative correlation between the favorite method and the *Install motion sensor cable* task as only three participants preferred the one that they tested with the *Install motion sensor cable* task. Seven participants preferred the one they tested with the *Power-up Connection* task, and nine participants preferred the method they tested with the *Replace MediaPlayer* task.

Participants were requested to answer 12 questions for each method regarding the readability and understandability of the instructions on the screen, and the amount of text and number of graphics in the instructions. The results are presented in Figs. 11 and 12. In addition, participants were able to write free-form comments after each task regarding the task and the method.

Over 50% of participants agreed or totally agreed that there should be at least one graphic in each step, approximately 30% agreed or totally agreed that there should always be some text in each step, and approximately 30% agreed or totally agreed that there should always be both text and graphics in each step. Many participants commented that a combination of text and graphics complement each other especially with complex tasks: “There should always be an illustration for each step” (P1). However, with simple tasks it was not deemed necessary: “It is good that the very simple steps are not illustrated” (P2).

Participants were satisfied with the checklist type of reduced information; 48% disagreed or strongly disagreed with the question “I would like to have more explanatory text.” One third of participants were neutral, and only 9.5% of the participants agreed or strongly agreed. Participants also commented that the instructions described what was needed for task completion and that they did not need to assume or guess anything. Some participants named a specific task or detail for which they would have liked to have more explanation: “Where could I get more information about removing this part of the device?” (P3). These findings support our hypothesis of delivering reduced information and providing extra information only when the user needs and requests it.

With the visual manual instructions, people generally liked the concept but had problems recognizing when something needed to be done. For example, in deciding whether a graphic was a reference type of graphic only or whether they

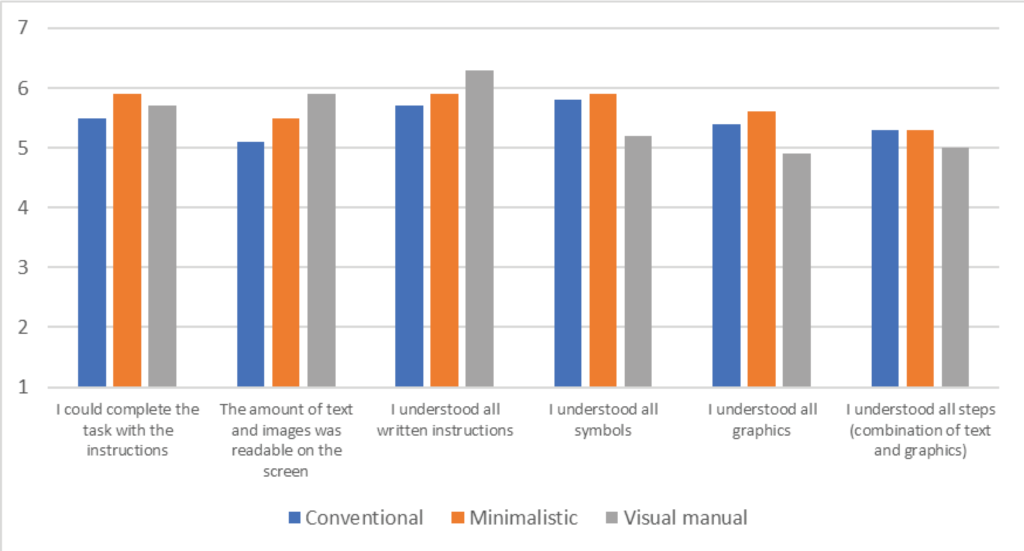

Fig. 11. Comments on methods, 1/2 (1 = totally disagree, 7 = totally agree), (N = 21). With these questions, the larger the value, the more positive the answer.

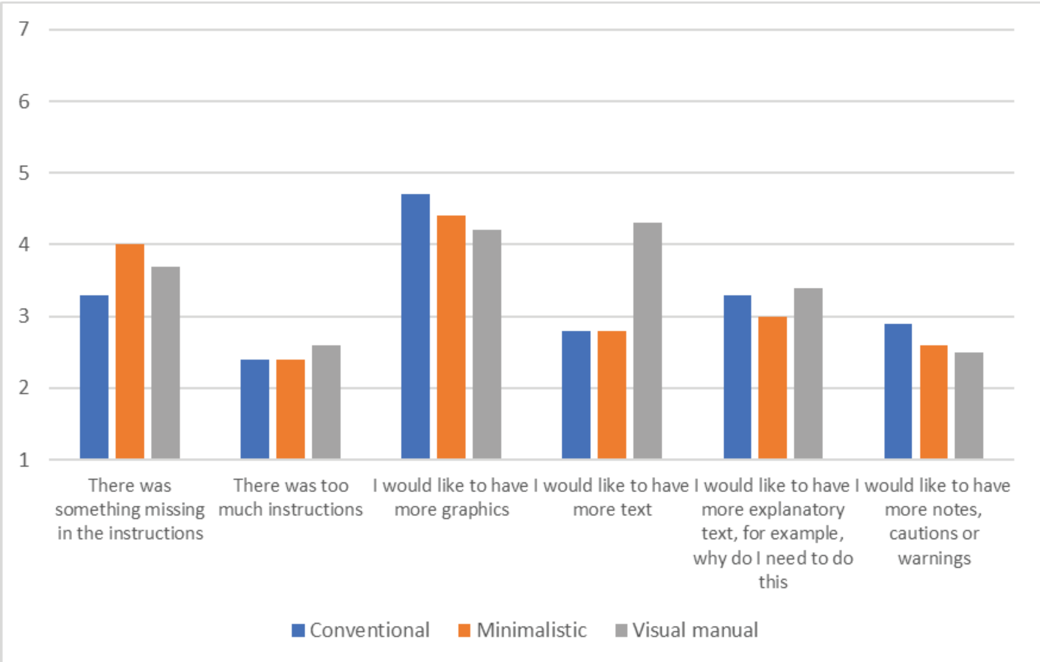

Fig. 12. Comments on methods, 2/2 (1 = totally disagree, 7 = totally agree), (N = 21). With these questions, the smaller the value, the more positive the answer.

needed to perform actions based on it, they might think aloud, "Do I need to do something now?" (P4) or "How do I know when I need to do something?" (P5). For one visual manual instruction (see Fig. 13), one screen consisted of a graphic that had several task symbols in it. The participants disliked the idea of several steps in one graphic and were also unsure whether the steps needed to be completed in a certain order: "There is so much information that I do not know where to start" (P1). This example revealed the need to clearly show one step at a time—that is, separated steps for *Drill hole* and *Route cable*.

Participants agreed that the amount of information was good for all the methods—that is, they were able to perform the tasks with the instructions provided. They felt that following the instructions one step at a time was more effective than scrolling up and down in a long list of steps that would not fit on the screen and would have required scrolling. Therefore, it can be noted that having

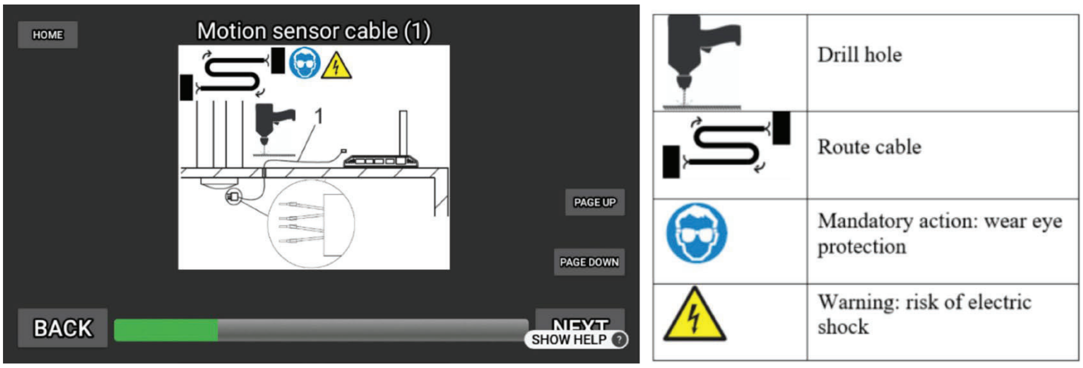

Fig. 13. Single graphic with several task symbols and legend from the visual manual (left). Symbols used in this instruction step (right).

Table IV
Questions Regarding Smart Classes, on a Scale of 1 = Totally Disagree,7 = Totally Agree (N = 21)

Question	Score	Rating Scale
The smart glass concept is something I could use in my daily work.	4.2	Neutral (3.4–4.5)
The use of smart glasses felt natural, did not hinder work.	4.2	Neutral
The use of smart glasses did not limit my awareness of the surroundings.	4.3	Neutral
The voice control operated well.	4.3	Neutral
The display was not in the way of my view.	4.8	Somewhat positive (4.6–5.7)
I was able to navigate and progress through the steps well.	5.3	Somewhat positive
The application UI was intuitive and easy to use.	5.6	Somewhat positive
The application worked well and ran smoothly.	4.7	Somewhat positive
I was able to read the text and graphics.	5.3	Somewhat positive
Instructions on smart glasses helps performing the task.	5.8	Very positive (5.8–7)

the instructions proceed step-by-step on the screen was a well-received concept. However, the progress bar by itself was not enough to give a sense of location within the process for the participants. The relationship between steps and substeps was also not clear, and some participants even checked the next step to see what was coming before performing the step at hand: “I have a feeling that I need to check the next step here before doing anything” (P6).

Even though the list of the symbols used in the visual manual version was introduced to the participants before starting the task, and the participants were encouraged to check the meaning of symbols while doing the task, the visual manual approach scored the lowest for symbol understanding. Minimalism scored the highest in this category, followed by conventional. The conventional and minimalist versions used only symbols frequently included in maintenance instructions.

Understanding all of the steps (a combination of text and graphics) followed this same logic: minimalist and conventional scored the highest, and the visual manual scored the lowest.

The visual manual scored high for the readability of text and graphics on the screen. The conventional manual scored the lowest, probably affected by the scrolling needed for some of the steps. Even though the conventional version had the most details and explanation, it scored the lowest for understanding all written instructions. The visual manual scored the highest for this category but admittedly had only a small amount of text. The minimalist scored above the conventional.

Smart glass use was generally received in a neutral or somewhat positive way (see Table IV). People were generally enthusiastic about the use of smart glasses, but as they are not yet a mature technology, that fact also showed in the evaluation of the concept.

For example, some participants had problems with the voice commands and had to repeat the same command several times, causing frustration. The small screen of the HMT-1 was also difficult to use for some participants, and they had problems either seeing the instructions properly or focusing their eyes on the small screen. Therefore, further development is needed for devices and their user interfaces to apply smart glass use to industrial maintenance. However, participants strongly agreed that the instructions displayed on smart glasses helped in performing the tasks. Several participants commented that the step-by-step instructions were easy to follow and helped them perform the steps in the correct order: “With these instructions, anybody could complete the task” (P7) and “The smart glasses seem very useful; I like the concept very much” (P8).

Discussion

The aim of this research was to better understand how information content should be created and designed to support future use in addition to existing delivery channels. Our focus was to adapt checklist-type of technical information to small screens such as smart phones, smart glasses, smart watches, and other wearables. The user tests were conducted using smart glasses.

XR offers exciting possibilities for industrial maintenance. However, as the needs of the users should be the driving force when creating the content for these solutions, the content creation cannot be automated, and information design has a central role in the development of content for XR solutions [45]. Furthermore, users are not a homogeneous group. Because the background and expertise of maintenance technicians vary, their needs also vary. Xue et al. note that to improve the usability of AR-assisted maintenance systems, the information should be contextualized, for example, according to the user’s level of expertise and skills [18].

In our case study, we investigated the possibilities of delivering expert-level information through smart glasses. With the semantic tagging of DITA XML and competent information design, we could rely on certain elements containing the expert-level information and other elements containing the information needed for novices. Therefore, a straightforward filtering process of including and excluding information was utilized to contextualize the information according to a user’s level of expertise.

This design also catered to the reuse of information because the same XML files could be used in other applications or outputs to resolve the full content, including the content excluded in our test application. As no conditions were required in the design of our materials, we could utilize the existing XML files without conditional processing.

Even though it has been argued that users of technical instructions do not have to memorize procedure steps, many company style guides set limits on step lengths or promote chunking into meaningful pieces to reduce cognitive load. Especially with hands-busy tasks, such as elevator maintenance, the delivery of maintenance instructions has been problematic. Users might need to memorize a sequence of steps if they are unable to utilize the mobile device to scroll down lengthy step lists or flip the pages of a paper manual while they are performing the task.

With XR solutions, however, the number of steps or chunks in a procedure becomes irrelevant as the users are able to follow the instructions simultaneously while performing the task. In our user tests, we utilized a design that proceeded step by step, one screen at a time. The participants were able to control the application with voice commands synchronously with the task at hand. The attitude of participants toward displaying information this way in smart glasses was very positive, and it was deemed to assist in task completion. However, the information must be carefully designed so that there is only one action on each screen; otherwise, users might skip an action or be unsure of the order of the steps.

We used different methods to compress the information. The conventional version based on the original instructions was used as the baseline version in this study. The preferred method among our test group was minimalist, followed by the visual manual approach. The baseline, conventional, was the least-liked method in the study. Even though conventional had the most description and details, it was rated lower than the other two for task completion. Therefore, it can be concluded that more details do not necessarily aid understanding or task completion if those details are not seen as relevant or necessary by the user. In contrast, with minimalism, the information is designed with a user-centered approach, and the focus is on providing the correct amount of detail that users need to perform the task.

Researchers have suggested that leaving out text altogether might be an option for XR solutions [34].

The visual manual approach is an enticing theory, especially in a global setting because of resulting low translation costs. In our case study, the basic idea of the visual manual was evaluated positively, but participants felt that leaving out text altogether made understanding difficult, especially with more complex tasks. It should be noted that in industrial maintenance, working environments pose hazardous conditions, and the unambiguousness of instructions is essential. Previous research has indicated that text leaves less room for interpretation than graphics, and that language can be used as a disambiguation tool for graphics [46]. Furthermore, as the understanding of symbols was not within the scope of our study, more research is needed to evaluate the comprehension of action symbols, specifically in a global multicultural setting.

Participants were asked to evaluate whether each step should always have at least one graphic, some text, or both. There was a considerable difference among the answers to these questions. On one hand, participants preferred visual objects, and stated that they helped in understanding the location of connectors, for example. On the other hand, unnecessary details hindered task completion, so specific guidelines about the use of graphics and text should not be enforced. Again, the user-centered approach promoted by minimalism is the best guideline for the use of text and graphics. A fusion between minimalism and the visual manual method would be worth investigating in the future, and enriching the XML content with animations, videos, and augmented reality elements would also be an interesting area for further research.

Even though the testing was done with smart glasses, the results are also applicable to other devices with small screens, such as, for example, smart watches. Correctly tagged and compressed information enables the generation of relevant content to various outputs.

Furthermore, many test participants proposed that a similar system could be used, for example, in installation, document review in product development, or training. These suggestions further confirm that there are many uses for this type of information delivery.

Conclusion

In our study, we evaluated different information design and information compression methods and the usability of maintenance guidance on small screens such as smart glasses.

We wanted to study whether users of technical instructions are ready to accept smart glasses and XR as a delivery channel, and our research confirms that instructions displayed on smart glasses help in performing tasks in industrial maintenance, and attitudes toward using smart glasses are positive.

In this case study, we also explored whether the same information content can be utilized to deliver relevant content to the users based on their skill levels. Filtering information with different DITA XML elements proved to be an efficient way to scale information for different user needs. In this study, we used this method to provide checklist type of information for expert users and leave out novice-level information. In the future, we will continue this study by implementing the possibility to get further instructions when needed to cater more to novice-level users.

Our third area of interest in this study was the design of information content so that it supports use in smart glasses and other small-screen devices in addition to existing delivery channels. Because smart glasses as a delivery channel for technical instructions is a new concept, literature is lacking in guidelines for the design and authoring of technical instructions targeted for small screens. Information created using the minimalism principles was the preferred information design method within our test group. It was also considered the most understandable. Therefore, the minimalism heuristics could be implemented more thoroughly in the future. The visual manual concept was also received well and, in general, the participants of our study wanted to have more visual content. However, the cultural understanding of symbols needs to be further studied before implementation.

Research papers very often focus on augmented reality instructions for maintenance guidance—that is, systems where the actions to be performed are animated on top of a machine. However, for a large number of maintenance tasks, the necessary information can be presented with graphics or text, and using 3-D augmentations would be overengineering. Thus, it is important to study ways to utilize more traditional instructions, based on graphics and text, in hands-busy situations. On the other hand, in some use cases, animations and augmentations would be beneficial and would bring extra value. Therefore, our proposal and area of further research is to embed augmented reality content in the XML files so that the viewer application can switch to the AR mode when the augmented content is available. In such a scenario, augmented content would be created only for complicated tasks, where the superimposed animations would help in task completion or accuracy, and the rest of the content would be derived from DITA XML files.

For industrial companies with tens of thousands of technical instruction sets, the capability to use the single source for multiple delivery formats without the need for constant tailoring would be a huge benefit. Our case study shows that well-designed technical information can be automatically used and delivered for several use cases and in several end devices, including displaying checklist-type maintenance information on smart glasses.

Appendix
Questionnaire

1. Gender
    a. Male
    b. Female
    c. Other/I don’t want to tell
2. Age
    a. < 20
    b. 20-29
    c. 30-39
    d. 40-49
    e. 50-59
    f. > 59
3. Your working experience related to maintenance field work
    a. No experience
    b. Very limited experience of field environment
    c. Somewhat familiar with field environment
    d. Familiar with field environment
    e. I have worked at field myself / very experienced
4. Field of expertise (select all that apply)
    a. Maintenance
    b. Technical Documentation
    c. Installation
    d. IT
    e. XR
    f. Engineering
    g. Student
    h. Other
5. Task/theory [participants chose the combination they had been assigned and rated statements/answered questions 6-9 separately for each combination]
    a. Install motion sensor cable
    b. Power up KONE Connection
    c. Replace KONE MediaPlayer
    —
    d. Conventional
    e. Visual manual
    f. Minimalist
6. Content [Likert scale for each question 1-8, 1 = strongly disagree, 7 = strongly agree, 8 = no opinion/cannot evaluate]
    a. I could complete the task with the instructions.
    b. There was something missing in the instructions.
    c. The amount of text and images was readable on the screen.

   d. There was too much instructions.I understood all written instructions.
   e. I understood all symbols.
   f. I understood all graphics.
   g. I understood all steps (combination of text and graphics).
   h. I would like to have more graphics.
   i. I would like to have more text.
   j. I would like to have more explanatory text, for example, why do I need to do this.
   k. I would like to have more notes, cautions or warnings.
   l. All steps should have at least some text.
7. Was there something that could be left out? [free-form field]
8. Was there something that was missing? [free-form field]
9. Do you have any other comments of feedback? [free-form field]
10. Which version did you like the most?
   a. Conventional
   b. Visual manual
   c. Minimalist
11. Why? [free-form field]
12. Which version was the easiest to comprehend?
   a. Conventional
   b. Visual manual
   c. Minimalist
13. Why? [free-form field]
14. Images and text: [Likert scale for each question 1-8, 1 = strongly disagree, 7 = strongly agree, 8 = no opinion/cannot evaluate]
   a. There should be at least one image at each step
   b. There should always be some text at each step
   c. There should always be both text and images at each step
15. Smart glasses: [Likert scale for each question 1-8, 1 = strongly disagree, 7 = strongly agree, 8 = no opinion/cannot evaluate]
   a. The smart glass concept is something I could use in my daily work.
   b. The use of smart glasses felt natural, did not hinder work.
   c. The use of smart glasses did not limit my awareness of the surroundings.
   d. The display was on the way of my view.
   e. The voice control operated well.
   f. I was able to navigate and progress through the steps well.
   g. The application UI was intuitive and easy to use.
   h. The application worked well and ran smoothly.
   i. I was able to read the text and images.
   j. Instructions on smart glasses helps performing the task.

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Paper VII

Hanna Heinonen, Jenni Virtaluoto, Tiia Suomivuori, Kristian Forsman, Tuomas Kangas, and Sanni Siltanen. Minimalism for the win - User-centered design for maintenance guidance. In *IEEE Transactions on Professional Communication*, vol. 65, no. 4, pp. 485-501, Dec. 2022. doi:10.1109/TPC.2022.3205468

Minimalism for the Win: User-Centered Design for Guidance in Industrial Maintenance

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***Abstract*—Background:** *We conducted an exploratory study to test the delivery of technical instructions built on the principles of minimalism. The aim was to investigate how we could support target users' skill levels in a context-sensitive manner.* **Literature review:** *Related work examines minimalism, user needs and profiling, and industrial maintenance and technician experience.* **Research questions:** *1. How can the semantic structure of DITA XML be utilized in delivering technical information to users based on their skill levels? 2. How would a layered system of information support the principles of minimalism?* **Methodology:** *We created material and tested the concept in user studies with maintenance personnel in three countries. We collected feedback through participant observation, interviews, and questionnaires.* **Results and discussion:** *The minimalist approach of delivering information to maintenance technicians was well received and supported users with varying skill levels.* **Conclusion:** *The context-sensitive level of expertise concept empowers users to decide on the depth of technical information that they require to complete the task at hand. The semantic structure of DITA XML works well in the delivery of technical information to the users based on their skill levels. Many of the key principles of minimalism are applicable to hardware maintenance instructions.*

Index Terms*—Darwin Information Typing Architecture (DITA), industrial maintenance, minimalism, structured authoring, user-centered design.*

The ongoing Industry 4.0 revolution is changing the world of industrial maintenance. The focus is shifting from annual maintenance plans with predefined maintenance tasks to predictive and condition-based maintenance, in which computers help humans predict issues before they are visible to the human eye. In predictive maintenance, trends, patterns, and correlations are analyzed for anticipated failures to help with maintenance decision-making and to avoid equipment downtime and callouts [1]. In short, issues with equipment are identified and fixed before breakage.

With predictive maintenance, the work of maintenance technicians is also changing dramatically. Traditionally, when maintenance technicians work with certain equipment, they build up knowledge and learn the necessary tasks, rarely needing instructions to complete them. However, with predictive or condition-based maintenance, the tasks vary from day to day and from one piece of equipment to another, and even experienced maintenance technicians need guidance on which tasks to perform. Therefore, there is an increased need to provide instructions, even for experts [2].

Naturally, at the same time, novice technicians need more detailed instructions. Consequently, it is becoming increasingly important that the needs of technicians with different skill levels are supported efficiently and flexibly in the technical instructions that support their work.

In response to these challenges, we conducted an exploratory study in which maintenance technicians performed elevator maintenance with instructions built using an interactive design mechanism. This design was based on the feedback received earlier by the company that experts did not want to see too many details; too much detail hindered task completion, and the experts would rather operate without instructions than get lost in too many details. On the other hand, novice users needed those details, so they could not be removed altogether. Our aim was to investigate the possibility of supporting different skill levels efficiently and in a context-sensitive manner with a delivery mechanism built on DITA semantic tagging.

Practitioner Takeaway

- The concept of context-sensitive level of expertise empowers users to decide on the depth of technical information that they require to complete a task.
- Filtering information using the DITA XML semantic structure works well to target information to different skill levels.
- Although minimalism has often been seen as an approach relevant only for software instructions, many of its key principles are also applicable to hardware maintenance instructions.

possibility of supporting different skill levels efficiently and in a context-sensitive manner with a delivery mechanism built on DITA semantic tagging. In this article, we introduce this mechanism and the concept of *context-sensitive level of expertise*, in which users are given the agency to decide on the depth of technical information required to complete the task at hand in a case-by-case manner.

The technical instructions used in this study were built using the principles of minimalism. They are action-oriented, user-centered, task-based, and concise [3]. Although minimalism has been a trend in technical communication for decades, relatively few reports provide advice on implementing it in practice [4].

In this study, we did not focus on the actual textual and visual content of the task topics, as this area has been studied earlier [2]. Instead, we expanded the principles of minimalism—usually applied in the content creation phase—to the delivery of maintenance instructions.

We propose that our delivery mechanism is inherently minimalist. Our approach “respects the integrity of the user’s activity” [3]: according to the principles of minimalism, help should be available as needed but not interfere with the user’s task completion. In addition, the proposed delivery mechanism allows users to act immediately and supports their actions despite their level of expertise. This is a priority in minimalism [3].

Since minimalism was created with novice software users in mind [5], it has been suggested that it might not be applicable to hardware settings or with complex enterprise products. Although our primary focus in this study is on the delivery instead of the creation of information, the documentation used in the tests was written with the principles of minimalism in mind and was aimed at expert users in hardware maintenance settings rather than novice users working with software.

Literature Review

Minimalism and User Needs Minimalism is a **user**-centered, **use**-centered, and **action-oriented** approach for creating technical documentation [6].

Minimalist instructions allow users to start working immediately on real-life tasks. The instructions encourage users to try things out on their own and provide ample error information for independent problem-solving. The focus is on providing users with the information they need when they need it and doing so as concisely as possible [3].

Although minimalism has been one of the major trends in technical communication since the 1990s [7], it has also been criticized. For example, it has been seen as applicable only to software documentation for novices [5]. One of its four principles, guided exploration, has also been seen as frustrating and inefficient for users [8]. In guided exploration, users are encouraged to explore the system independently instead of relying on detailed step-by-step instructions for completing tasks. This way, they are expected to learn the system in greater depth [6].

However, in many current contexts of use, the idea is not to get users to learn a new system but rather to allow them to accomplish the task at hand in the most efficient way. In such settings, omitting pieces of information in the instructions would be not only frustrating but also dangerous. However, the other principles of minimalism, such as providing user-centered and action-oriented information, are in line with the best practices of technical communication [4].

Modularity is also one of the cornerstones of minimalism, and present-day content management systems allow for modularity in a much more efficient way than the documentation tools of the 1990s did. Instead of merely reducing the amount of information—one of the misconceptions often associated with minimalism [9]—optimizing the information should be the focus [10]. The key is to present users with only the information they need at that specific moment and otherwise get in their way as little as possible.

The original minimalism heuristics proposed by van der Meij and Carroll [3] have recently been revised [4] to provide technical communication practitioners with a practical evaluation tool for assessing whether their content fulfills the principles of minimalism. The three main categories of the revised minimalism heuristics are as follows:

1. Core tasks and goal orientation
2. Accessibility
3. Error management

Along with troubleshooting instructions, the most typical error management information type in hardware manuals, the third category covers instructions that can help users prevent and recover from errors. It also deals with warnings and notes. Preventive maintenance instructions and checklists, typical of hardware, could also be classified as error prevention instructions. See Appendix A for a full list of the revised heuristics.

As mentioned above, minimalism originated in the context of software user instructions, but the revised heuristics are intended for hardware too. The applicability of the revised heuristics specifically to a hardware context was tested in a workshop with technical communication professionals, who evaluated the PDF of a traditional maintenance manual for industrial hardware [11]. In this limited test, the practitioners found the revised heuristics a useful tool for evaluating instructional content for heavy machinery end users. All workshop participants found several issues to be remedied during the relatively brief time allotted for the evaluation task, and participants also noted that the heuristics would work well as a checklist for content production.

Although the first and most important category of the revised minimalism heuristics concerned supporting the users in completing their core tasks, it was the second category—the accessibility of the instructions: the content, findability, understandability, and visuals—that workshop participants mainly focused on. Perhaps because they were communication experts, the workshop participants concentrated on the heuristics whose implementation and evaluation came most naturally to them.

Even though it became clear in the workshop's wrap-up discussion that the participants had, in fact, kept the users and their goals in mind during the evaluation, the findings can also be seen as indicative of a wider issue regarding user- centeredness in technical communication, especially in the context of hardware: the subject matter experts and the authors of the instructions are not the users. To produce usable minimalist instructions that enable users to begin and complete their core tasks as quickly as possible, technical communicators need to know the users. Although it is possible to improve end-user instructions by ensuring that the content fulfills the accessibility criteria of the revised minimalism heuristics, the real challenge lies in optimizing the information for different types of users in their specific use situations.

Although this type of user-centeredness is at the heart of minimalism, the approach itself does not offer any concrete methods for producing user instructions for different types of users and contexts, for example. Instead, it assumes that all users are active learners.

The revised minimalism heuristics focus on the versatile needs of different types of users and are intended as a concrete tool to be used in the content production and evaluation phase. However, rather than pre-profiling users and delivering information based on that profile, the users themselves should be empowered to decide the level of information they require in each specific context [2]. This study explores this concept as a step forward in user-centeredness as well as action orientation.

User Profiling in Technical Communication Technical communicators are familiar with user profiling based on expertise. For example, Hackos [12] categorized users into expert performers, competent performers, advanced beginners, and novices; Jayaprakash [13] classified them into experts, competent performers, and beginners; van Laan [14] talked about brand new beginners and experienced users; and van der Meij et al. [15] identified different types of needs for novice users and specialists. These profiles are then used as the starting point when creating instructions for users with different skill levels.

DITA XML supports conditional profiling as well and offers the standard attribute @*audience* for filtering content for different audiences [16]. In many cases, this attribute is used to tailor outputs for experts and novices—i.e., to filter the same content to create different sets of instructions for each group of users. This DITA feature naturally supports the reuse of content in the authoring and publishing phase.

Although user profiling is a well-established concept in technical communication and mechanisms exist for its implementation, the traditional outcome has separate instructions for different user groups—for example, a quick guide for experts and a comprehensive user guide for novice users. In practice, the users are pre-profiled for their skills and are then delivered instructions based on that profiling instead of being able to decide on their information needs themselves while completing tasks.

Industrial Maintenance and Technician Experience
During the last few decades, Industry 4.0 has transformed the way maintenance is actualized in the field and how services are implemented with remarkable developments in information technologies, cheaper sensors, and ever-increasing connectivity. Today's service businesses are driven by customer value, smart services, and sustainability [17], [18].

Sensor data are used to provide information on the behavior, use, and condition of the equipment. Data collected across time and across different pieces of equipment are analyzed with advanced data analytics methods. Artificial intelligence provides insights into the condition and maintenance needs of individual pieces of equipment [1]. With predictive and condition-based maintenance strategies, companies aim to avoid unscheduled maintenance visits, increase equipment up-time, reduce downtime and costs, and improve customer satisfaction.

Traditionally, preventive maintenance has used a time-based maintenance strategy in which specified maintenance tasks are carried out at certain time intervals. The interval can be adjusted, for example, to be shorter for high-utilization-rate equipment, but nonetheless, the activities performed during the maintenance visit are always predefined and static. On the contrary, condition- based, predictive maintenance strives to perform the necessary maintenance actions just before a predicted breakdown to prevent it. This condition-based maintenance strategy can achieve higher reliability with lower maintenance costs compared to a time-based maintenance strategy [19]. Furthermore, the aim is also to avoid over-maintenance and to perform only the necessary maintenance actions as there is a constant need for optimization and cost reduction.

At the same time, artificial intelligence solutions can predict the most probable root causes to aid in troubleshooting, and the system can offer context-relevant guidance and instructions for the technician. Previously, complex repairs were performed by experienced technicians, but with these new technologies, less experienced technicians are also able to work on such tasks.

From the maintenance technician's perspective, this means that the activities performed during each maintenance visit are different, and the tasks that the technician needs to perform vary from one piece of equipment to another. Technicians can no longer learn the task list by heart, and even an experienced technician needs to follow instructions, at least to understand which tasks to perform. In addition, some maintenance tasks may be performed very seldom with condition-based maintenance. Therefore, even experienced technicians might not remember everything and need to turn to the instructions to verify some details, such as parameter values. At the other end of the experience continuum, novice users still need very detailed instructions. This fact poses a new challenge for technical communication: How can you support the work of maintenance technicians, both experts and novices, when you can no longer rely on predefined talent profiles or standardized task lists?

Research Questions

Our research was motivated by the need to understand how the principles of minimalism can be implemented in practice. More precisely, we aim to answer the following research questions.

RQ1. How can the semantic structure of DITA XML be utilized in delivering technical information to users based on their skill levels?

RQ2. How would a layered system of information support the principles of minimalism?

As discussed above, minimalism has often been seen as applicable only to designing software documentation for novice users. Our primary focus in this study is on the delivery instead of the creation of information, but the documentation used in the tests was aimed at expert users in hardware maintenance settings rather than novice users working with software.

Research Methodology

We used the lean start-up method to develop and test the usability of the concept iteratively. The lean start-up method is based on a build-measure-learn feedback loop, where the phases of hypothesis, proof of concept, user evaluations, and adjustments are repeated as many times as needed [20]. The feedback loop allows for ideas and concepts to be tested flexibly with users with minimally viable products before going into full production mode with the product, therefore, testing the viability of the concept before any final business decisions are made.

We used both qualitative and quantitative methods in this study, including participant observation, interviews, and questionnaires. Our focus was on qualitative methods, as we wanted to gain insight into the opinions, thoughts, and feelings of maintenance personnel with different levels of experience working in the field [21]. We also obtained some quantitative results, but as our test groups were small, the results were only indicative. However, the participants in our user study were all people who performed the work described in the instructions, albeit with different levels of experience. Therefore, they represent people working in similar roles and, thus, their opinions carry considerable weight.

We tested the first iteration of the concept in Germany and Finland in late 2020, and a new, further developed and improved concept was tested in Poland during 2021–2022. For both iterations, user test participants performed tasks related to elevator maintenance using the instructions created for the purpose.

Iteration 1: Test Material Design and Test Setup for Germany and Finland

Test Material Design: We tested the first iteration of the concept in Germany and Finland with a prototype developed for Adobe XD. The content for the prototype was authored in Adobe XD. We analyzed the instructions for seven maintenance tasks and categorized each piece of information as either information for experts or information for novices. When users accessed the instructions for a task with a mobile phone, the expert-level information was shown as the default (see Fig. 1), and it progressed step by step. More detailed information was available for novice-level users for each applicable step with a *More information* button (see Fig. 2). Users who did not want to access the more detailed information could proceed without it.

This design was based on feedback received earlier by the company that instructions have too many details for the experts, but on the other hand, novice-level users need those details. Therefore, the aim was to support both user groups. With the test material design, we paid special attention to the clarity of instructions based on the principles of minimalism. We also wanted to create a clear sense of navigation within the task, related steps, and substeps. The test material was in English, and all test participants had a basic knowledge of English.

Participants: We tested the concept in Germany and Finland. For a summary of the participants, see Table I.

Test Setup: In Germany, the user tests were streamed over the Microsoft Teams platform with a USB camera. The tests were facilitated and observed remotely from Finland via Teams (see Fig. 3). An onsite assistant located in the same space as the user test participants was available in Germany for practical arrangements.

In Finland, the user tests were also streamed over the Microsoft Teams platform with a USB camera. The tests were facilitated onsite by a facilitator and observed remotely from other locations in Finland.

All user test sessions followed a predefined test flow. Before the tests, we explained the purpose and scope to the participants. Each participant signed a research consent form and gave us permission to record videos and take photographs during the user tests. The facilitator emphasized that we were not testing the participants or their skills but rather the concept and user-interface prototype that had been developed.

The participants then proceeded to perform elevator maintenance tasks based on the tasks and instructions offered by the application prototype.
The application prototype was used with a mobile phone with touch-screen functionality. Each participant completed four randomized tasks during testing. We asked the participants to think aloud and describe what they were doing and how they felt about the instructions and the application prototype user interface. If the

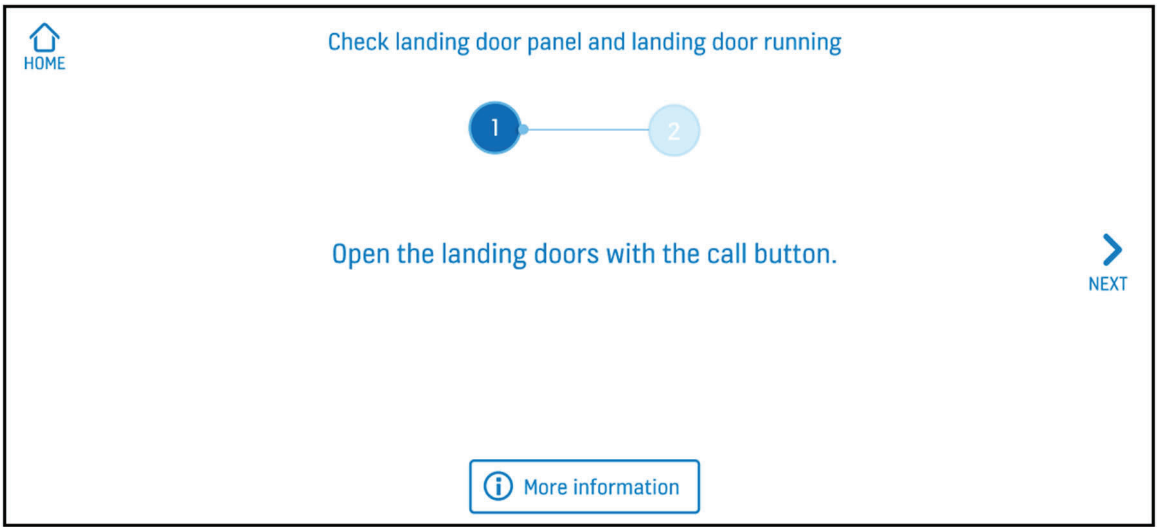

Fig. 1. Expert-level information shown for a task.

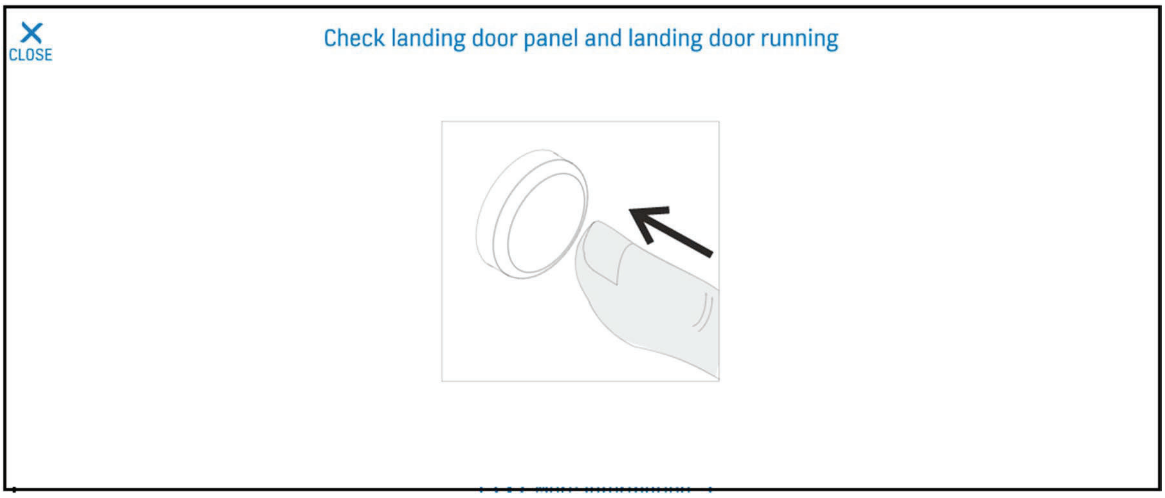

Fig. 2. Novice-level information accessed with the *More information* button.

Table I
Summary of User Test Participants in Germany and Finland

User Test Location	Number of Participants	Less Than 2 Years of Maintenance Experience	2-7 Years of Maintenance Experience	8 or More Years of Maintenance Experience
Germany	7	1	4	2
Finland	2	2	-	-

German participants had trouble explaining themselves in English, they could speak in German, and the onsite assistant then served as an interpreter for the facilitator and observers.

After all maintenance tasks were completed, the participants completed a questionnaire evaluating the concept and its usefulness with seven-point Likert-scale questions (see Appendix B). Finally, a

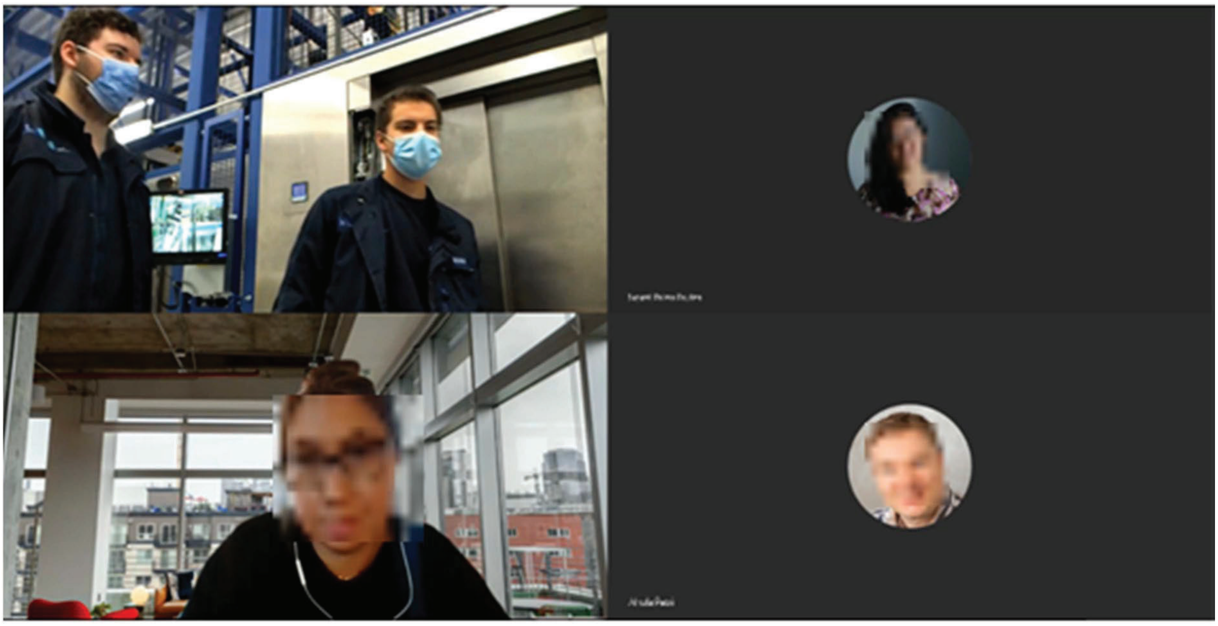

Fig. 3. Teams view of user testing in Germany.

```
<task>
<title>Check entrance and corridor</title>
<taskbody>
 <steps>
   <step>
    <cmd>Check the condition of the lights in the entrance and corridor.
      <image href="lights.svg" placement="break"/>
    </cmd>
      <info>On floor level, the entrance light must be efficient enough for a user
            to see ahead and enter the car, even if the car light has failed.</info>
   </step>
 </steps>
</taskbody>
</task>
```

Fig. 4. Example content delivered to expert (highlighted with orange), standard user (highlighted with blue), and novice (highlighted with yellow).

semistructured interview took place, with the German onsite assistant serving as an interpreter when needed.

Iteration 2: Test Material Design and Test Setup for Poland

Test Material Design: For Iteration 2, we developed the concept further based on the feedback received from Iteration 1. The content for instructions was authored in DITA XML format and stored in the company's content management system. A total of 82 tasks were created in English, of which 59 were unique and the rest reused according to DITA principles.

We used a predefined set of DITA XML elements in authoring and used specific elements to target information for three skill levels: experts, standard users, and novices. The third level was added based on the feedback received for Iteration 1. For an example of semantic tagging of a file, see Fig. 4.

The content was exported from the content management system to a dynamic delivery service. Mobile devices were then able to fetch the content from the dynamic delivery (see Fig. 5).

For this iteration, we developed a mobile-phone application to show the instructions and guide the

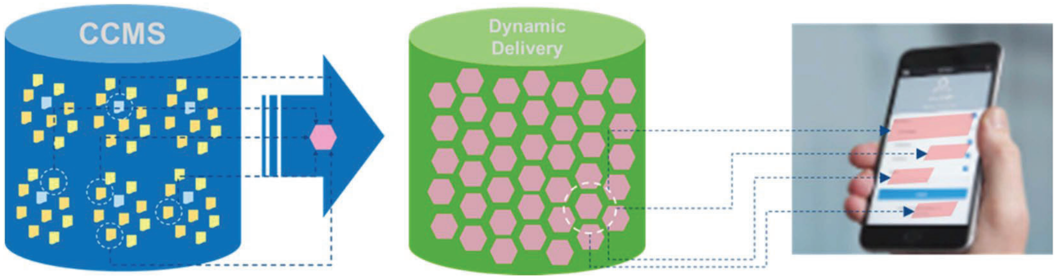

Fig. 5. Delivery of the DITA XML content from the component content management system (CCMS) via dynamic delivery service to a mobile device.

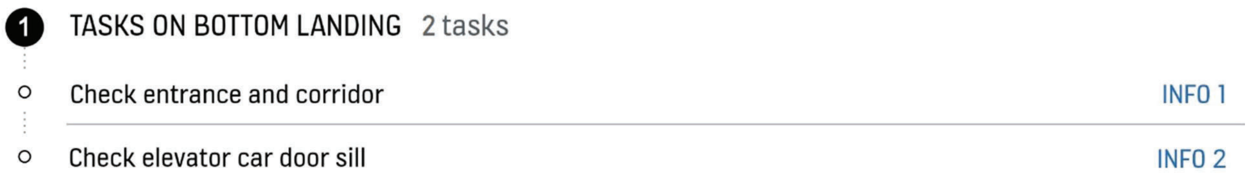

Fig. 6. Task list for expert users.

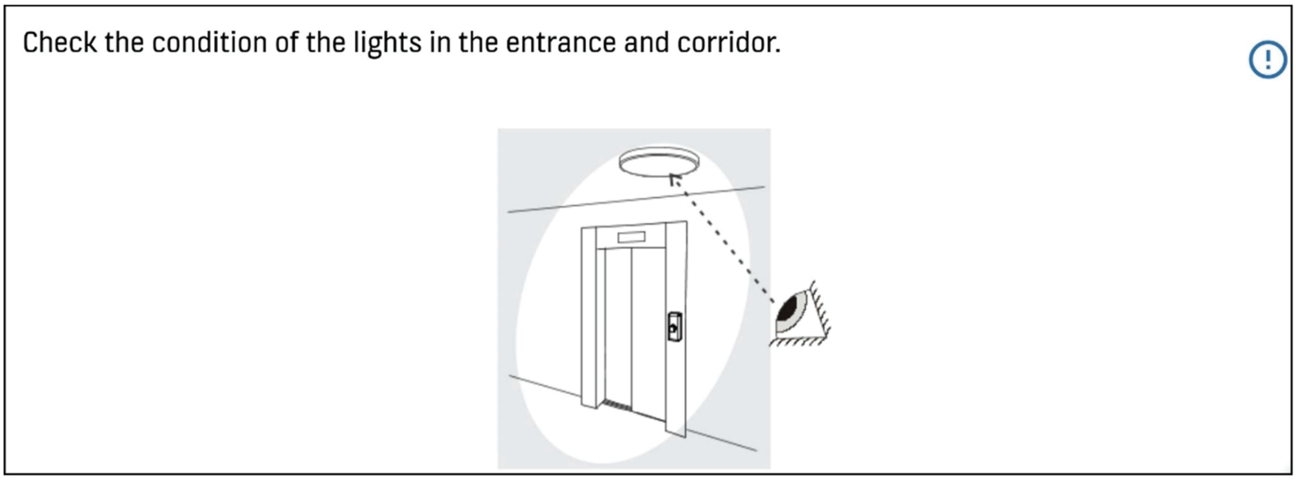

Fig. 7. Standard task instructions.

work. In the user interface, the task list and the related instructions were dynamically built with the DITA XML content so that only relevant tasks and instructions were displayed for each maintenance visit. For expert users, a checklist of tasks was created from the DITA XML titles (see Fig. 6). Users familiar with the task could proceed with just the checklist, without opening more detailed instructions. However, if the user needed instructions for any task, they were available. The standard-level instructions would then be displayed when the user opened the link (see Fig. 7). From standard-level instructions, novice users could access further details (see Fig. 8) whenever needed.

Our design allowed the users to decide how much information they needed for each task. If they were familiar with a task, they could proceed without instructions. However, if they needed instructions, two levels were available to them, and they could select information as needed.

For testing in Poland, the DITA XML content was localized into Polish. The users were able to use the application in their preferred language, either in English or Polish. From the delivery point of view, both languages worked in the same way.

Participants: We tested the concept in Poland. For a summary of the participants, see Table II.

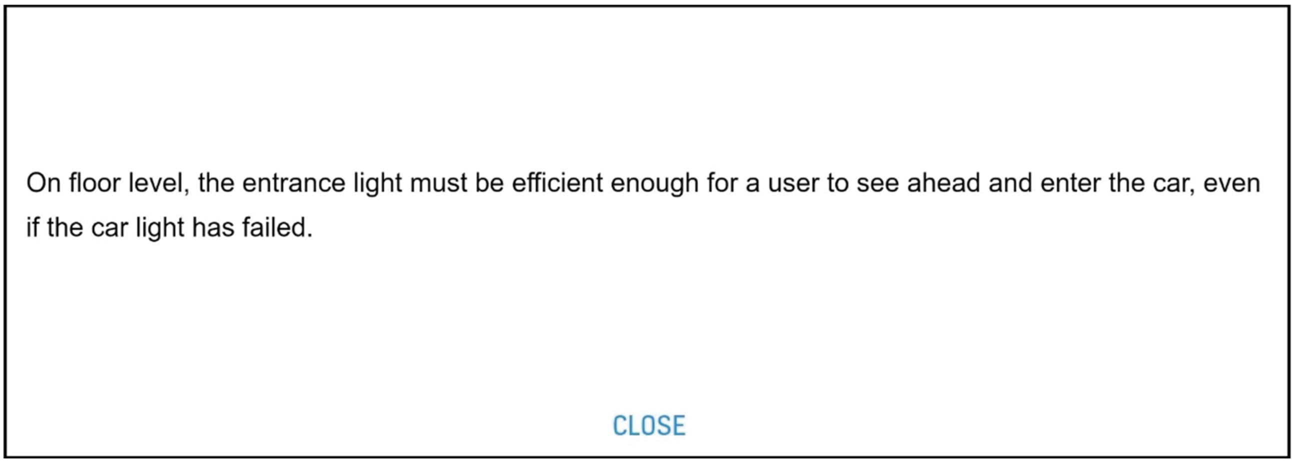

Fig. 8. More information available for novice users.

Table II
Summary of User Test Participants in Poland

User Test Location	Number of Participants	Less Than 2 Years of Maintenance Experience	2-7 Years of Maintenance Experience	8 or More Years of Maintenance Experience
Poland	13	-	4	9

Pilot Project Setup: We tested this iteration of the application and related instructions in a pilot project, a small-scale implementation used to prove the viability of the idea. The testing was integrated with the daily work of 13 Polish maintenance technicians, and it involved the maintenance of 610 pieces of equipment during a six-month period. Therefore, it was not an actual test setup but the application was used by the company's maintenance technicians as a part of their daily tasks. The selection of participants for the pilot project was made by the business line.

Due to the COVID-19 pandemic and related travel restrictions, we could not use participant observation or interviews in Iteration 2. After the pilot project was completed, the maintenance technicians filled in a questionnaire evaluating the concept and its usefulness with 7-point Likert-scale questions and open feedback (see Appendix B). We created the questionnaire in English, translated it to Polish, and made it available in both languages to the respondents. We requested research consent from each technician involved in the testing.

Data Storage and Ethical Review All the collected data were stored in Microsoft SharePoint according to company policies and principles outlined in the consent forms. As local regulations did not require an ethical review for a study such as this, it was exempt from Institutional Review Board reviews.

Results

The general attitudes toward the phone application and the instructions displayed on them were positive for both iterations. The participants were engaged in the testing and eager to share their feedback on the concept. The questionnaire response rate was 100%, further proving the engagement of the test participants. A summary of the data-collection methods for each of the iterations is presented in Table III.

Iteration 1 For Iteration 1, we collected feedback on the usefulness of the information on the screen. There were questions on both the readability of text and images and the clarity of the images (see Fig. 9). As the mobile-phone screen is rather small, the purpose of these questions was to discover whether the user interface and information design for the tasks were successful, and the users could easily read and utilize the information displayed on

Table III
Summary of Data-Collection Methods

Iteration	Quantitative	Qualitative		
	Questionnaire (7-point Likert Scale)	Questionnaire (Open Feedback)	Participant Observation	Interview
Iteration 1	x	x	x	x
Iteration 2	x	x		

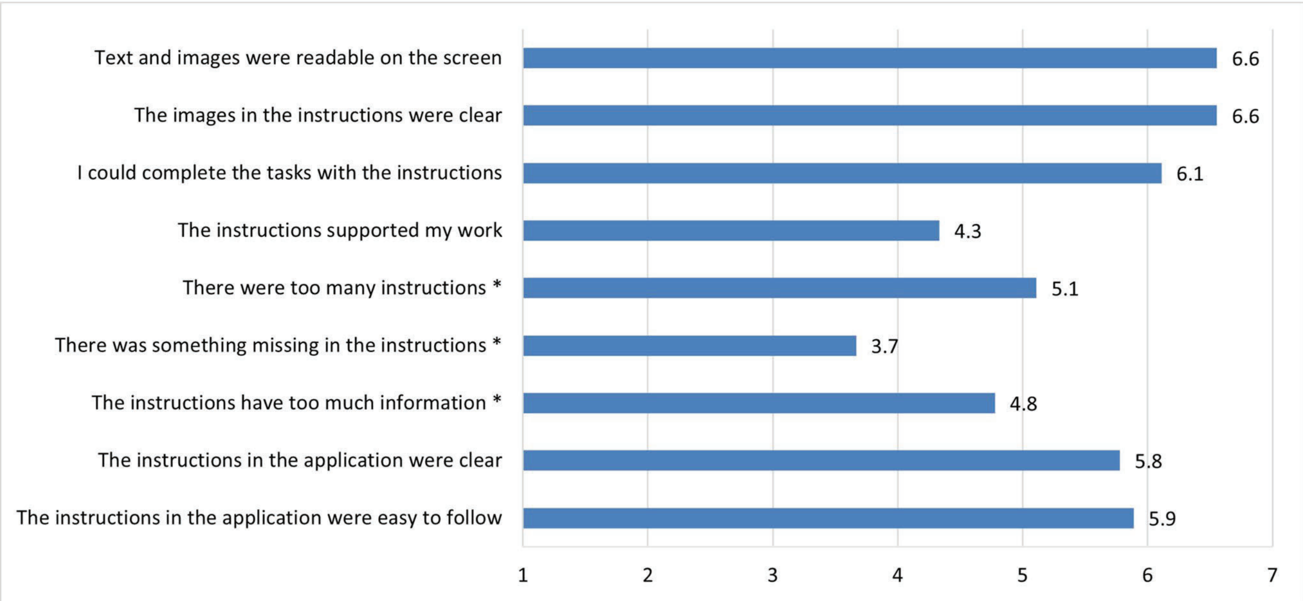

Fig. 9. Feedback for Iteration 1. The larger the score, the better the result (1 = totally disagree, 7 = totally agree). Scores marked with $*$ are reversed as the original question was negatively phrased.

the screen. The users were very satisfied with both the readability and clarity of the task instructions.

We also collected feedback on how the delivery of the instructions supported the work of the participants. In interviews, the more experienced participants commented on the need for an additional layer of instructions that would display only the title of the tasks (expert view). They noted that for an expert familiar with the tasks, it sometimes takes longer to read the instructions than it does to complete the task. They recommended a simple task name as a checklist for the experts who have no need for the actual task instructions. This can also be seen in the ratings of “there were too many instructions” and “there was something missing in the instructions” (see Fig. 9), as the two layers of information did not fully support the work of all expertise levels. Overall, however, the participants felt that the instructions were clear and easy to follow.

Iteration 2 For Iteration 2, we introduced the additional layer recommended by the test participants in Iteration 1, and the participants were able to complete tasks with the checklist only. This time, the focus of feedback collection was on the layers of information and their usefulness for the participants and their task completion. The concept of three layers of information (expert, standard, and novice) was rated positively (see Fig. 10), but open feedback suggested that task titles must be well designed to work as a checklist. In open feedback, some of the novice participants commented that they liked the idea but sometimes had difficulty understanding the task based solely on the titles given, requiring them to open the standard instructions to understand the task.

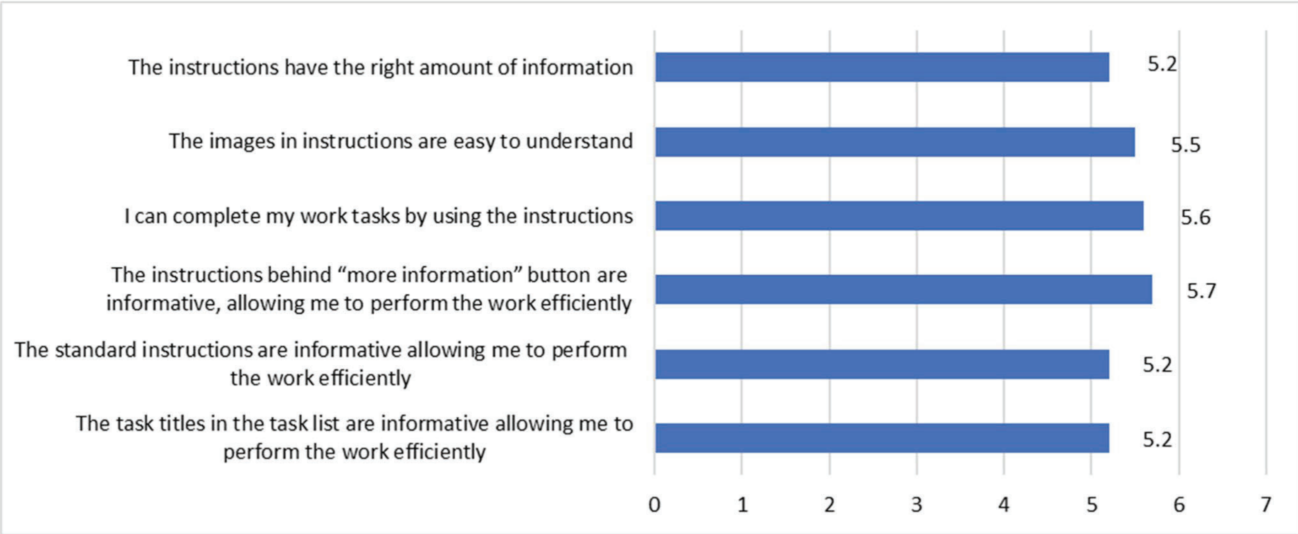

Fig. 10. Feedback for Iteration 2. The larger the score, the better the result (1 = totally disagree, 7 = totally agree).

Clear deviation can be seen in the answers, with most participants rating the concept very positively and one participant much lower. However, in the open feedback, the participants were very positive about the concept, noting that it offers them easy access to the instructions while they are maintaining equipment and effectively facilitates the needs of different users and expertise levels.

We left the clarity of the task instructions out of scope for feedback collection for the second iteration as it followed the same principles as earlier. As some modifications were made to the way images were handled, that question was included. The results indicated that images were still clear and useful for the participants.

To summarize, test participants rated both iterations positively, and adding another layer requested by Iteration 1 participants improved the concept and user satisfaction, as evidenced by ratings for Iteration 2.

Discussion

The context-sensitive level of expertise concept that we tested in this study strengthens user independence and agency, which is one of the priorities of minimalism. In the past, with separate instructions for novice and expert users, it had not been possible for users to decide on the required level of information on the spot. Traditionally, users have been classified based on their perceived skill levels, and instructions have then been targeted to these groups. This classification was done at the beginning of the documentation process, often with no access to users or user data. In this type of process, it is difficult to be truly user-centered.

Furthermore, as we are moving toward Industry 5.0 and striving to create individually personalized experiences [22], we must also start to contextualize expertise. To be able to support the users in their task completion, we should not be guessing how much information they need but empowering them to decide on their own information needs contextually on a case-by-case and task-by-task basis.

The revised minimalism heuristics suggest that immediate assistance should be available when users need it and that they should be able to get to work immediately. The context-sensitive level of expertise concept that we implemented in this study empowers the users to decide on the necessary level of information and allows them to proceed when they are comfortable doing so.

As with any new technology, there is a learning curve during the rollout of this type of new concept as the users get used to the new type of delivery.
However, as the feedback from our test participants and pilot users was very encouraging and positive, it is safe to say that the design of our concept was successful.

As discussed above, minimalism has been a trend in technical communication for decades, but there are relatively few reports on implementing it in practice [4]. Because the minimalist approach was created with novice software users in mind, it has also been suggested that it might not be applicable to hardware settings or complex enterprise products. More recent work on minimalism also seems to focus on software [23]. Based on the results of our study, however, the principles of minimalism—such as providing users with action-oriented and user-centered information—are not setting-specific and can also be applied to hardware maintenance documentation.

The world of industrial maintenance is changing with remote monitoring and condition-based maintenance programs. Traditionally, many maintenance programs have had standardized tasks. For instance, a preventive maintenance program includes a set of checks to be performed, and by working within that program, the maintenance technicians have learned to perform the checks without the need to use any instructions. However, in the condition-based maintenance programs that are becoming more common, the tasks vary from day to day and equipment to equipment, and even the more experienced maintenance technicians need guidance on what tasks to complete. Therefore, there is a need to deliver instructions that support the work of all the maintenance technicians, from experts to novices.

Furthermore, when moving from a static preventive maintenance task list to condition-based maintenance programs, decisions are made by an artificial-intelligence system. Wanner et al. [24] describe how the unified theory of acceptance and use of technology model [25] can be modified to measure the acceptance of artificial-intelligence maintenance decision support systems. A central factor in technology acceptance is users' trust in the system and the transparency of decision-making.

It is good to remember that many human factors affect how users accept and evaluate new technologies or applications. First, users belong to different categories of the technology acceptance lifecycle [26]. Second, several factors influence how users perceive technology and how easily they adopt it. For example, the voluntary nature of use and social acceptance also play a role [27], [28].

A part of the deviation in the overall rating of our concept by test participants may have been affected by their various positions along the technology acceptance curve. One participant gave extremely low ratings for most questions in the questionnaire compared to all the other participants, and that fact raises a question about this participant's position on the technology acceptance curve.

In our study, some of the novice participants gave feedback on the usefulness of the task titles and reported that the tasks could not be completed with the titles only. Even though the titles must be carefully designed and authored so that they work as a checklist for experts, they cannot include all the information that the standard or novice instructions do, and users must learn to turn to the more detailed levels of instructions when needed.

From the authoring and delivery point of view, the concept we tested in this study works well. DITA XML is a markup language, and content authored with it can be processed to extract specific information for particular use cases [29]. When the content is designed and authored carefully, and the semantic tagging is used properly, it is possible to deliver specific information to specific parts of the user interface with application design and careful coordination with user interface designers.
However, if needed, the same content can still be used to create other outputs, such as a complete PDF file of the instructions. Well-designed and authored content, therefore, enables a truly omnichannel delivery of instructions. As the structure of the DITA XML content remains the same in the translation process, this solution is also language-independent. Naturally, proprietary XML content models can also be used, but we recommend the industry-standard content model, DITA.

Van der Meij et al. point out that since 2000, research has become increasingly focused on supporting the experiences of users and fostering motivation [15]. However, very little has been done to apply this principle in practice in technical communication, even though calls for more practice-oriented and accessible academic research have been made [30]. The results of our study are, therefore, also relevant to the field of technical communication in general.

Limitations and Suggestions for Further Research
We tested our concept in two iterations in three countries. For Iteration 1, we used standard usability testing where participants used the instructions to perform tasks while thinking aloud and gave subjective feedback on a

questionnaire and in a semistructured interview (see Appendix B for Iteration 1 questionnaire). For Iteration 2, the concept was not tested in an actual test setup, but the application and related instructions were used by real maintenance technicians in the field. Due to the COVID-19 pandemic and related travel restrictions, we could not use participant observation or interviews as a data-collection method, so we collected feedback with a questionnaire only (see Appendix B for Iteration 2 questionnaire). However, as the use of the application was integrated into the daily work of the company's maintenance technicians for 6 months, the feedback received holds great significance.

As Iteration 2 was not an actual test setup, the selection of participants was made by the business line. The sample did not include any novices with fewer than two years of maintenance experience.
Therefore, this fact can be considered a limitation of this study as Iterations 1 and 2 cannot be directly compared. However, as the concept of standard and novice instructions remained the same as in Iteration 1, and the concept was positively rated by participants in Iteration 1, we can say that the concept supports maintenance technicians with different levels of expertise in their work.

In future research, the same study could be conducted with a larger number of participants from several different countries who represent all expertise levels. Such a study could examine how people choose the layers of information that they use and how the layers correspond to their information needs and experience with maintaining equipment. Technology acceptance and users' willingness to use new technologies should be considered in future research.

Industrial maintenance is characteristically a high-risk environment that is governed by safety regulations. Maintenance technicians typically wear personal protective equipment such as helmets and cut-resistant gloves, and using the touch screen of a smartphone, often with dirty gloves, is cumbersome. Therefore, there is also an increasing interest in using smart glasses to deliver technical instructions to the field. As DITA scales well to different devices and uses cases [31], it is also a solution that supports possible new delivery channels for technical instructions. Consequently, even though we tested our concept with a mobile phone in this study, the scalability of DITA means that the same information can be used on other small-screen devices such as smart glasses, wearable displays, and smartwatches. This would offer an interesting area for further research.

Conclusion

We designed our exploratory study to test the delivery—as opposed to the creation—of technical instructions built on the principles of minimalism. Our research questions were as follows.

> **RQ1.** How can the semantic structure of DITA XML be utilized in delivering technical information to users based on their skill levels?

> **RQ2.** How would a layered system of information support the principles of minimalism?

We explored how the semantic structure of DITA XML can be utilized in delivering technical information to users based on their skill levels. Since all of the available DITA XML elements in task topics are known, applications can be built on these principles, and the content is then delivered to different parts of the application. Our study shows that well-formed and well-tagged content works very efficiently for this purpose, and the solution is also language-independent because the structure of the topics remains the same in the translation process. Therefore, filtering information with different DITA XML elements is an excellent and flexible way to target information at different skill levels.

Minimalism is usually discussed in the context of designing and creating instructions for users. In this study, instead of focusing on minimalism in the content creation phase, we applied the principles of minimalism in the delivery phase. As discussed above, the literature on minimalism calls for designing instructions that allow the user to start working immediately with real-life tasks. The aim of minimalist instructions is to get in the way as little as possible and to empower users to decide on the depth of the technical information that they require to complete the task at hand. This is what the context-sensitive level of expertise concept seeks to accomplish.

We also discovered that although minimalism has often been seen as an approach relevant only to software instructions for novice users, many of its key principles—such as action orientation and user-centeredness—are applicable to hardware maintenance instructions too.

Table IV
Minimalism Heuristics [4]

1 CORE TASKS AND GOAL-ORIENTATION	
Core tasks	1.1 Does the documentation concentrate on the user's core tasks? (OH2.1)
	1.2 Does the documentation reflect the real-life structure of each task? (OH2.2)
	1.3 Does the documentation explain why the task is done, in addition to how? (OH2.2, Extended)
Getting to work immediately	1.4 Can the users start working on real-life tasks immediately? If the documentation contains general information, prefaces, or introductory information before the steps, is the information concise and necessary? (OH1.1; OH4.1 Extended)
Immediate assistance	1.5 Is the documentation available when needed? (OH1.3)
	1.6 Does the user get targeted instructions at the relevant touch points on the user journey? (OH1.3, Extended)
2 ACCESSIBILITY	
Content	2.1 Is the documentation as concise as possible in its overall selection of contents? (OH4.1)
Findability	2.2 Is the overall structure of the documentation logical and consistent? Are all topics/sections structured in the same way? (OH4.2, Extended)
	2.3 Do the users find what they are looking for? Does the documentation contain: (OH3.1, Extended) • A clear and precise table of contents • A clear and intuitive index • Clear, intuitive headings and keywords • An accessible and intuitive search functionality for online or electronic documentation?
Understandability	2.4 Is the information in the documentation easy to understand? Does the documentation contain: (OH3.1, Extended) • Long tasks broken into shorter sequences • Clear, action-oriented steps • Short, simple sentences • Verb forms relevant to the information type • Terminology that is appropriate to the user group • Clear, simple language?
Visuals	2.5 Is the documentation visual? • Have graphics, images, videos, etc., been used where appropriate? • Are the visuals relevant? • Are the visuals used consistently? • Are the visuals clear and readable both online and in print? • Are the visuals clearly labelled (titles, figure numbers, etc.)? • Are the images and text in the documentation clearly connected using callouts, for example?
3 ERROR MANAGEMENT	
Preventing errors	3.1 Have errors been prevented? (OH3.1)
Warnings and notes	3.2 Have all the applicable safety standards and legislation (e.g. the Machinery Directive) been taken into consideration in the documentation? (OH3.1, Extended)
	3.3 Are all the warnings and notes necessary? (OH4.1)
	3.4 Are the warnings and notes located next to the relevant procedure? (OH3.4)
Error recognition	3.5 Does the documentation offer error information: recognition, diagnosis, solution? (OH3.3)
	3.6 Is the error information located close to the relevant procedure? (OH3.4)
Troubleshooting	3.7 Does the documentation contain a troubleshooting section? (OH3.1, Extended) • Is the troubleshooting section clearly visible in the table of contents? • Does the troubleshooting section contain the problems most often faced and/or reported by the users of the product?

Appendix A
Heuristics

Table IV lists the heuristics used in this study.

Appendix B
Questionnaires

Iteration 1

1. How many years of experience in the field of elevator maintenance or similar do you have? [free-form field]
2. The instructions in the application were easy to to follow [Likert scale 1–7, 1 = totally disagree, 7 = totally agree]
3. The instructions in the application were clear [Likert scale 1–7, 1 = totally disagree, 7 = totally agree]
4. The instructions have too much information [Likert scale 1–7, 1 = totally disagree, 7 = totally agree]
5. There was something missing in the instructions [Likert scale 1–7, 1 = totally disagree, 7 = totally agree]
6. There were too many instructions [Likert scale 1–7, 1 = totally disagree, 7 = totally agree]
7. The instructions supported my work [Likert scale 1–7, 1 = totally disagree, 7 = totally agree]
8. I could complete the tasks with the instructions [Likert scale 1–7, 1 = totally disagree, 7 = totally agree]
9. The images in the instructions were clear [Likert scale 1–7, 1 = totally disagree, 7 = totally agree]
10. Text and images were readable on the screen [Likert scale 1–7, 1 = totally disagree, 7 = totally agree]

Iteration 2

1. How many years of experience do you have in the field of elevator maintenance? [free-form field]
2. The task titles in the task list are informative, allowing me to perform the work efficiently [Likert scale 1–7, 1 = totally disagree, 7 = totally agree]
3. The standard instructions are informative, allowing me to perform the work efficiently [Likert scale 1–7, 1 = totally disagree, 7 = totally agree]
4. The instructions behind the “more information” button are informative, allowing me to perform the work efficiently [Likert scale 1–7, 1 = totally disagree, 7 = totally agree]
5. I can complete my work tasks using the instructions [Likert scale 1–7, 1 = totally disagree, 7 = totally agree]
6. The images in the instructions are easy to understand [Likert scale 1–7, 1 = totally disagree, 7 = totally agree]
7. The instructions have the right amount of information [Likert scale 1–7, 1 = totally disagree, 7 = totally agree]
8. Please provide any additional comments on the instructions and how informative they are [free-form field]
9. Any other feedback you would like to give? [free-form field]

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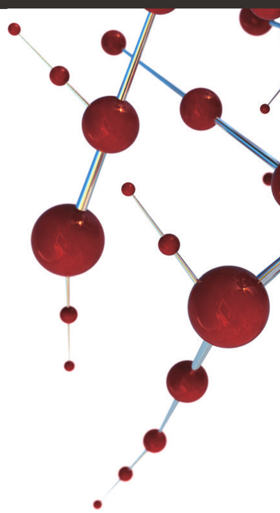

The main goal of this dissertation is to explore the benefits of extended reality for technical communication. Under the umbrella of extended reality and technical communication, this dissertation focuses on two main themes. The first part studies virtual reality as a technology to facilitate collaboration and digital content creation for technical documentation in industrial companies, and the second part explores the possibilities of augmented reality and smart glasses as a delivery channel for maintenance instructions. This dissertation shows that virtual reality offers many benefits for technical documentation creation, an area where it has not been utilized until now. On the augmented reality side, domain experts were generally enthusiastic about the use of smart glasses even though the technologies are not yet mature enough for field use in industrial maintenance. Furthermore, the results show that content created in the technical communications industry standard, DITA XML, works well when delivered to smart glasses, and the same content can be single sourced to other delivery channels. The use of DITA XML eliminates the need to tailor content for each delivery channel separately, and offers an effective way to create and update content for AR applications in industrial companies. This, in turn, can advance the use of AR technologies and related devices in field operations in industrial companies.

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