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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

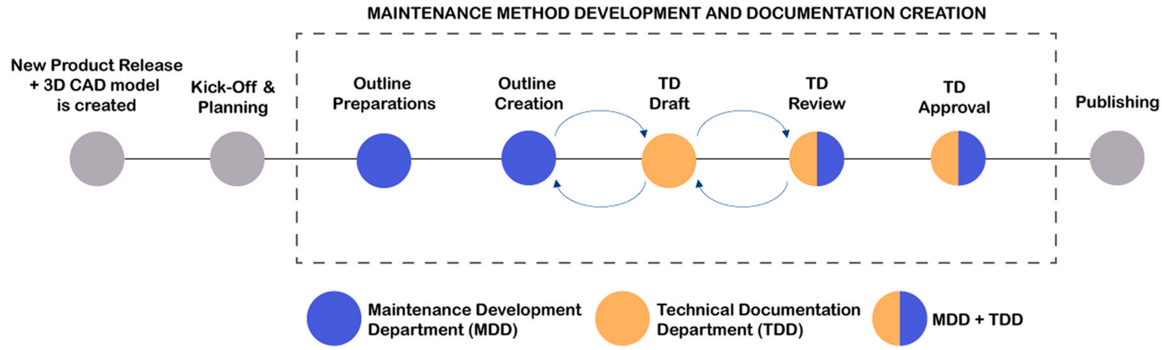

Fig. 1. The process of technical documentation creation at KONE.

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

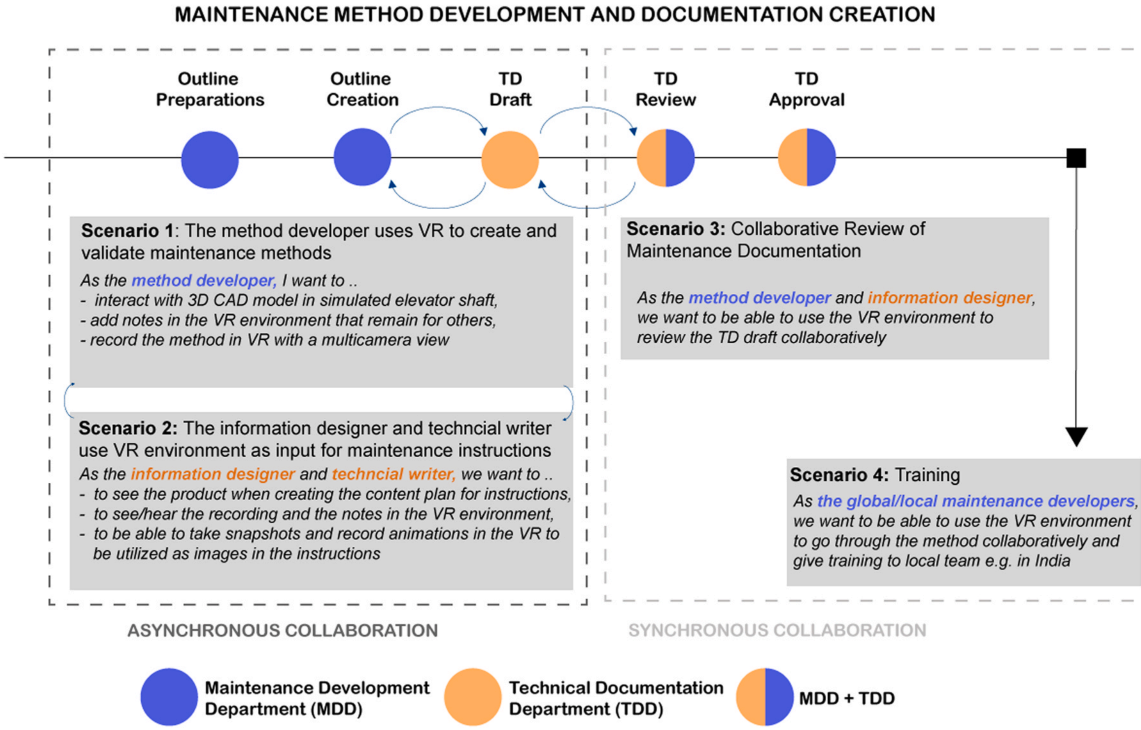

Fig. 2. Scenarios of VR application to the process of technical documentation creation.

(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

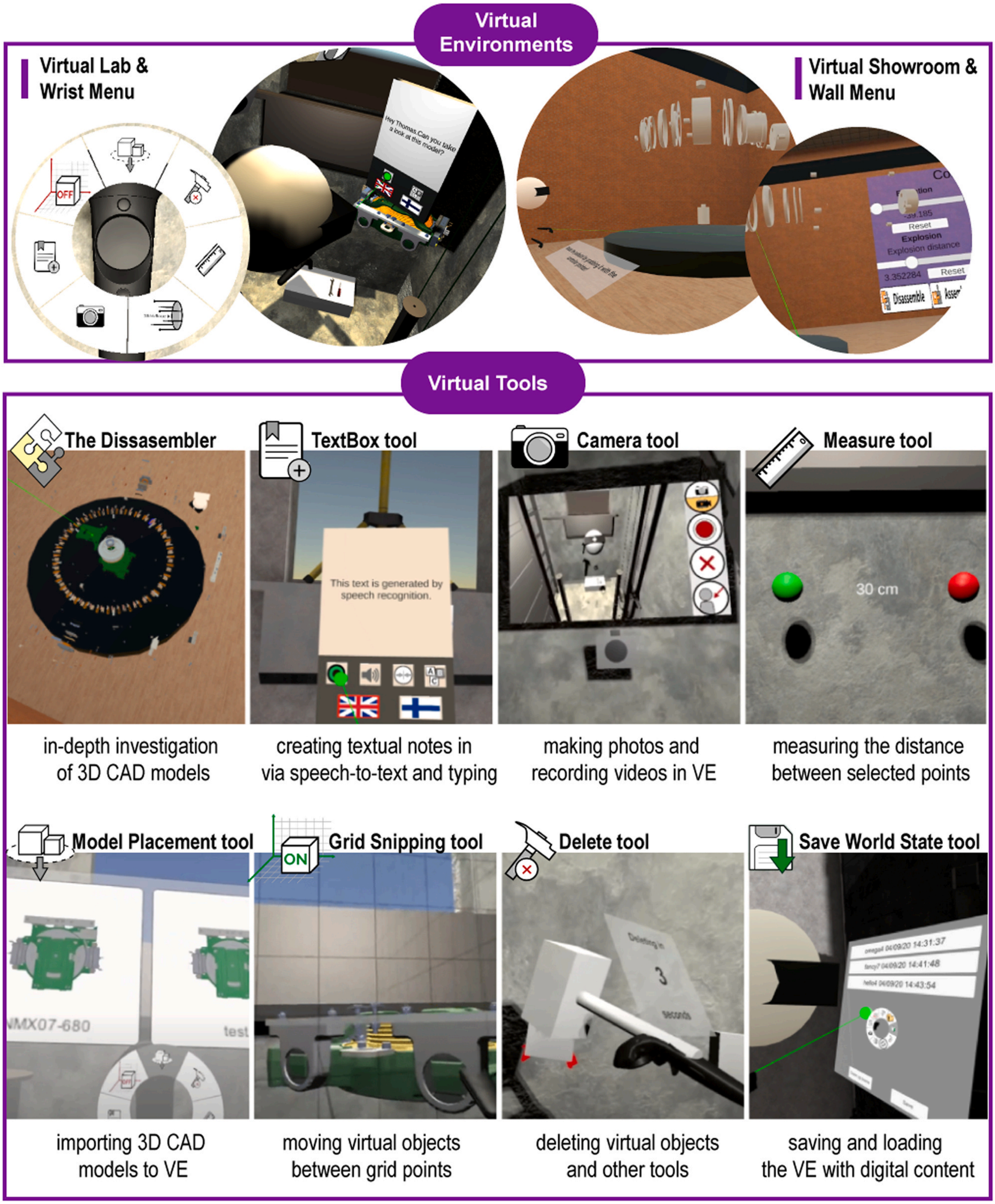

Fig. 3. COVE-VR virtual environments and tools.

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

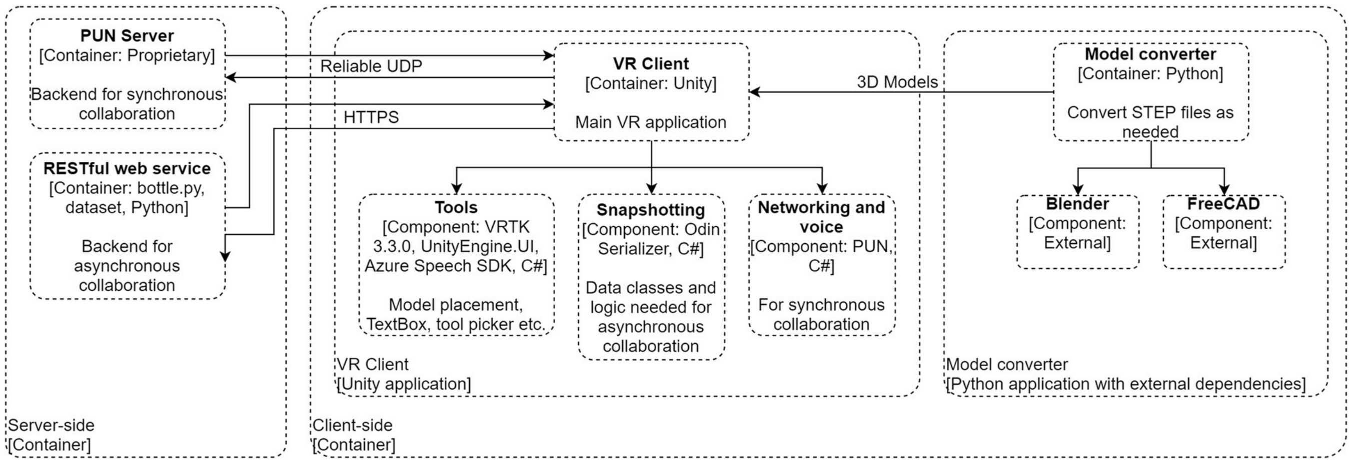

Fig. 4. COVE-VR platform architecture.

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 error-free than expected. Nevertheless, despite the moderate number of errors spotted, subject matter experts still found it to be useful, fast and would like to use it in the future.

4.1. Virtual tools evaluation

In this section, we present the evaluation of *four virtual tools* (Fig. 7)– since they were reviewed as the base for technical documentation tasks. Overall, despite several interaction difficulties, the tools were evaluated positively. Experts found the virtual tools to be useful and valuable for their working activities, which may become easier and safer. However, all tools require further development in terms of interactions and functionality, and experts expressed many ideas on how to make them better. Experts' comments, development items and the UI/interaction changes are presented in Appendix A.

The Disassembler in the Showroom got extremely positive feedback from method developers, while technical writers and illustrators were less enthusiastic and pointed out the need for more functionality. For instance, they mentioned enhancing the wall menu position and controls in addition to adding more functionality over disassembled 3D CAD models, such as labeling, components grouping, highlighting, and removing.

The *TextBox Tool* was also perceived positively, especially its speech recognition feature. All experts agreed that it was easy to use and expressed the need to attach textual notes or recorded audio messages to the 3D CAD model components. They also highlighted the importance of visualizing the author and the order of created textboxes to support asynchronous collaboration.

The Camera tool and *The Measure tool* were evaluated with less enthusiasm since most of the participants faced difficulties in using them. For the *Camera tool*, the UI elements were found to be non-intuitive – for instance, the switch between photo and video modes were not obvious. In addition, primary camera orientation (in 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

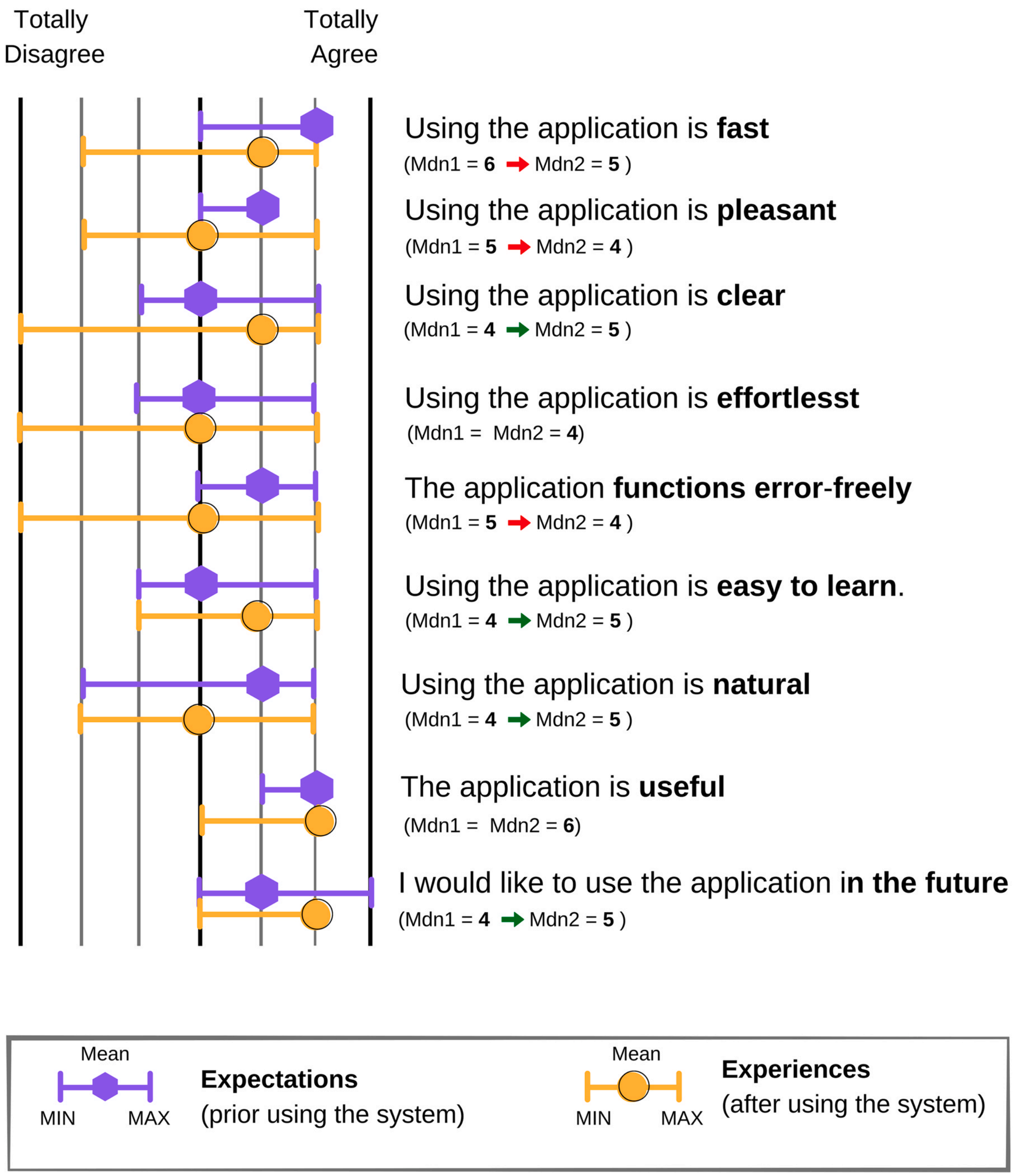

Fig. 6. The comparison of expectations vs. experiences with COVE-VR plarform.

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

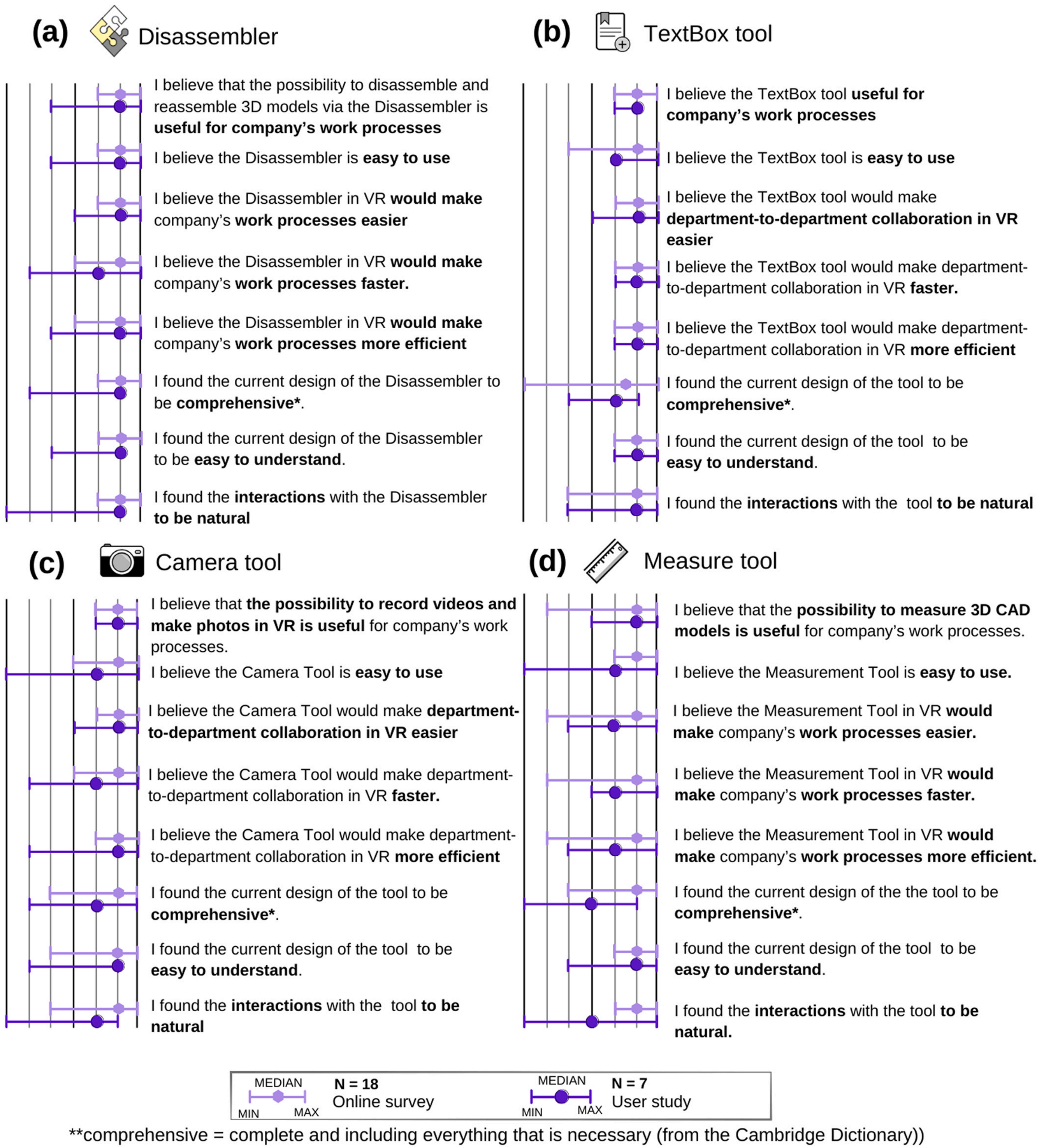

Fig. 7. The results of virtual tools evaluation.

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:

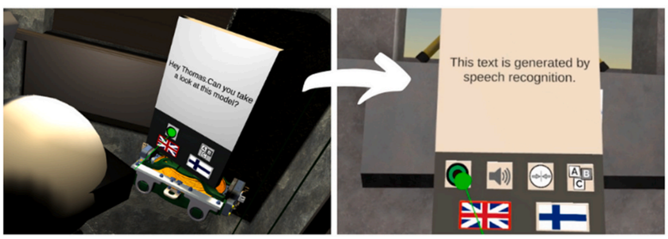
4 Note is floating, cannot be attached to a specific object.
2 Switching languages requires a button press
2 User didn't know how to start the recording

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:

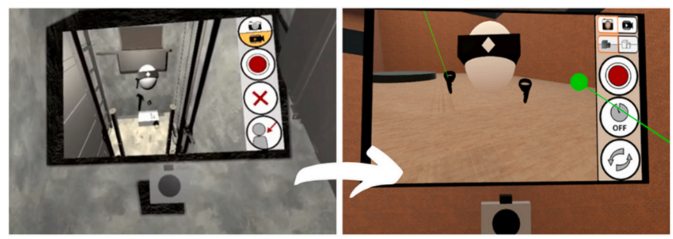
7 Back view of the camera is needed
5 Icons are not intuitive enough
3 Zoom feature
2 Camera position is too close to the user

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

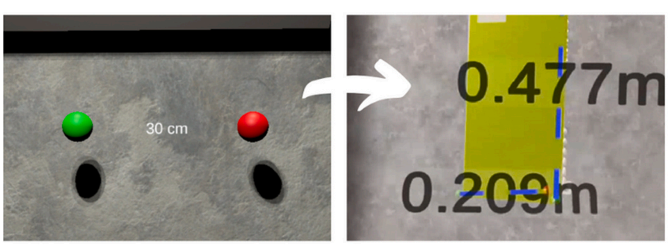
Interaction problems/ requests:

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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