Aalto University
School of Electrical Engineering
Master's Programme in ICT Innovation

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Evaluating the utility of multi-user VR in product development

Master's Thesis
Espoo, 13 July 2020

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ABSTRACT OF
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Verifying the design of a mechanical product typically requires a physical mockup. Virtual reality can avoid this by letting workers experience real-size design inspections avoiding to waste time and money to produce physical and potentially still faulty assets. Multi-user environments have been studied to verify the utility of virtual reality in performing design reviews for maintainability. The main features required in such software have been determined. A systematic literature review on the state of the art usages of virtual reality for design inspections and industrial training completes the thesis.

Keywords: Virtual reality, industry, maintenance, product design, training

Language: English

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DIPLOMITYÖN
TIIVISTELMÄ

Tekijä: Alberto Gabriel

Työn nimi:
Monen käyttäjän virtuaalitodellisuusympäristöjen hyödyllisyys tuotekehityksessä

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Mekaanisen tuotteen suunnittelun tarkistaminen vaatii tyypillisesti fyysisen prototyypin valmistamisen. Virtuaalitodellisuuden avulla voidaan tuotekehityksessä säästää aikaa ja rahaa validoimalla luonnollista kokoa oleva virtuaalinen prototyyppi sen sijaan, että tuotettaisiin kallis fyysinen prototyyppi mahdollisine suunnitteluvirheineen. Tässä opinnäytetyössä on arvoitu usean käyttäjän virtuaalitodellisuusympäristöjen hyödyllisyyttä huollettavuuden suunnittelussa sekä määritelty tärkeimmät tällaisilta ohjelmistoilta vaaditut ominaisuudet. Lisäksi on esitetty systemaattinen kirjallisuuskatsaus virtuaalitodellisuuden nykyaikaisesta käytöstä suunnittelutarkastuksissa ja teollisessa koulutuksessa.

Asiasanat: Virtuaalitodellisuus, teollisuus, ylläpito, tuotesuunnittelu, koulutus

Kieli: Englanti

Aalto University
School of Electrical Engineering
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ESTRATTO DELLA TESI

Autore:	Alberto Gabriel		
Titolo:			
Valutazione dell'utilità della realtà virtuale multi-utente nello sviluppo del prodotto			
Data:	13 luglio 2020	**Pagine:**	100
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Verificare il design di un prodotto meccanico richiede tipicamente la produzione di un modello fisico. La realtà virtuale permette di evitare questo passaggio, consentendo di effettuare ispezioni del prodotto in scala reale evitando di sprecare tempo e denaro nella realizzazione fisica di prodotti potenzialmente ancora difettosi. Sono state studiate piattaforme multi-utente per verificare l'utilità della realtà virtuale nel compiere controlli del design per la manutenibilitá e determinate le principali caratteristiche richieste in questo tipo di software. Una revisione sistematica della letteratura sullo stato dell'arte degli utilizzi della realtà virtuale per controlli del design e addestramento per mansioni in capo industriale completa la tesi.

Parole chiave: Realtà virtuale, industria, manutenzione, design del prodotto, formazione

Lingua: Inglese

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I wish to thank prof. Jan Blech from Aalto University and Dr Sanni Siltanen from KONE for their constant support, and prof. Francesco Pilati for having supervised me from the University of Trento. I want to thank also EIT Digital, offering me a life-changing experience and 3DTalo and Glue for their availability during these months.

The greatest thanks goes to my family and friends, for bearing me during my whole academic career. A tutti, grazie.

Espoo, 13 July 2020

Alberto Gabriel

Relation to KONE

The author conducted this research inside the KONE Technology and Innovation unit, to which he was related by a contract as thesis worker. In particular, he belonged to the Next Generation Maintenance (NGM) team, where new ways of maintaining elevators are conceptualized and developed with the help of the latest technologies. The colleagues directly involved in the process described in this document are experts in innovative maintenance methods and XR technologies, maintenance method development, engineering and product development.

About KONE

KONE is a global leader in the elevator and escalator industry. The company provides elevators, escalators and automatic building doors, as well as solutions for maintenance and modernization to add value to buildings throughout their life cycle. Through more effective People Flow®, KONE makes people's journeys safe, convenient and reliable, in taller, smarter buildings. In 2019, KONE had annual sales of EUR 10 billion, and at the end of the year approximately 60,000 employees. KONE class B shares are listed on the Nasdaq Helsinki Ltd. in Finland.

Covid-19

This thesis was written during the Covid-19 pandemic, which had consequences on how the work proceeded. In particular, I want to thank KONE for allowing me to complete this research regardless of the situation. Employees in general were strongly advised to work remotely, preferably from home, and asked not to meet other people belonging to the same work group. This resulted in having delays in obtaining the VR equipment needed to perform the tests and issues in downloading the 3D models via the network that was overloaded by too many accesses from people having similar needs in all the countries in which the company is present.

Abbreviations and Acronyms

AR	Augmented reality
CAD	Computer aided design
CAE	Computer aided engineering
CAM	Computer aided manufacturing
CAx	Computer aided technologies
DMT	Digital manufacturing technology
HMD	Head mounted display
KTI	KONE Technology and Innovation
OEM	Original equipment manufacturer
OST	Optical see through
SLR	Systematic literature review
VR	Virtual reality
XR	Extended reality

Contents

Chapter 1

Introduction

Since more than forty years ago, industrial design has always been moving towards digital visualization techniques, allowing for a fast and efficient design, check and simulation of products. From pen and paper technical drawings, to two and then three-dimensional representations visualized on flat displays, now there is the willingess to add the third dimension to how a person perceives and interacts with the virtual environment. In other words, digitalization and Virtual Reality (VR) grew in parallel in the last decades, but such improvement in the visualization required new hardware that seems now to be reaching a sufficient level of maturity for enterprise applications, and software that needs to be powerful to interface smoothly with industrial applications and, at the same time, easy to use to help its entrance on the market. Nowadays, the adoption of VR technologies in industry is increasing. This thesis wants to investigate the utility of multi-user platforms in the fields of product design and maintainability following an approach that gives both a theoretical framework to the subject of the research and chosen methods, and also reports on experimental tests that the reader is able and invited to repeat. This would allow to extend or correct the validity of the results, offering more insights for future investigations. In particular, this work has a twofold validity: a first block contains a systematic literature review on the state of the art, and it aims to be useful both for the scientific and technical communities. Secondly, the experimental part carried out together with experts in maintenance method development and product design offers findings that will be interesting especially for people working in the company itself. However, a correspondence in the findings from literature and the experimental part may suggest a broader validity of the results and encourage future research.

1.1 Problem statement

Verifying the design of a mechanical product typically requires a physical mockup. This is both time consuming and expensive. Industries 4.0 want to get rid of such unnecessary time and money losses and, therefore, are looking for faster and more efficient solutions. Besides this, even a correct product design, in the case of elevators, can lead to huge money expenditures if it does not consider maintainability. In fact, the money flow related to maintenance is by far larger than production costs in the lifespan of an elevator. At the moment, sometimes it happens that, when a project is in its very last phases and some real-size prototypes are already produced, design errors reducing the maintainability and making the life cycle more expensive due to maintainability costs are noticed. In this work, we explore how VR can be used in early product design to enhance maintainability of the final product. Besides this, the same technology can be used to train maintenance operators without the need to be on site, with no limitations on the physically available machines, both in terms of numeric and geographic availability. In a multinational company, it is often the case that some parts are produced in a different country than others that contribute to the final design of a product.

This work is meant to offer an overview of what is the state of the art of industrial applications of virtual reality for design review and training. Moreover, experiments carried out will try to answer the following research questions:

1. Which features are needed in a virtual reality platform to allow an efficient design review for the maintainability of products?
2. What is the readiness of virtual reality to enter industry?
3. What is the effectiveness of multi-user collaboration?
4. What are the main critical issues users find that can prevent the adoption of the technology?

1.2 Context: the mixed reality continuum

Recently, Industry 4.0 has cast more attention than ever to VR and immersive visualization techniques. Typically, they are referred to as the reality-virtuality continuum, following a taxonomy that was proposed by Milgram et al. [36], and is now widely accepted (see Figure 1.1). In particular, considering the real world and a totally virtual environment (i.e. an environment which is completely artificial) as extrema of a continuum, all what is in between is called mixed reality (MR) or, more recently, extended reality (XR). Traditionally, a couple of more definitions are given to situations in between the extrema. Augmented reality (AR) refers to the case in which most elements come from the real world and the user can see them directly, and they are enriched with other artificial information. Augmented virtuality (AV), in a similar way, refers to a mostly virtual world where some additional data coming from the real world can be shown on the screen.

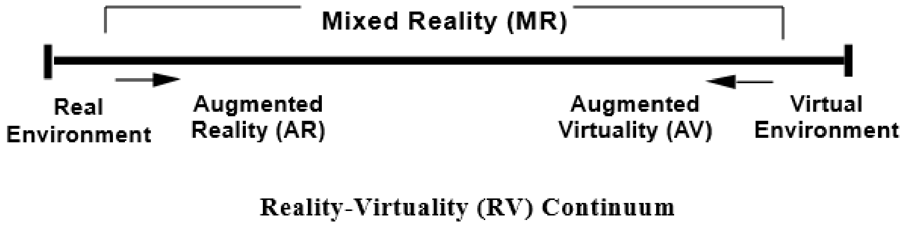


Figure 1.1: The Mixed Reality continuum by Milgram et al. [36]

Of course, different levels of virtuality require different visualization approaches and thus different hardware. Leaving aside the completely real world, that might be conceptually associated to wearing transparent glasses, the other extreme of the continuum is often visualized either with desktops or blind headsets, isolating the user from reality. Augmented reality is often obtained with some optical see through (OST) devices. These can be either head mounted displays (HMDs) with a transparent screen on top of which the additional information is projected (Microsoft Hololens - like products) or with video-see-through devices, i.e. blind HMDs allowing to record and re-project the real world on the inner display (HTC Vive Cosmos - like products). Even though it is reasonable to see the latter kind of hardware as overprocessing some information that should not even be touched to return the highest fidelity in reality, it is actually the one allowing the highest flexibility in tests, since turning off the cameras results in having a blind HMD that can also be used for VR tests. Finally, augmented virtuality is obtained by adding some stimuli or information to a completely virtual world. This augmentation is provided by devices sensing, for example, real motions of the user, and returning physical feedback in the virtual scene. LeapMotion is one of the most known 3D sensing devices in this field and is capable of performing motion tracking of hands. When paired with additional hardware, for instance with tactile gloves, tactile feedback can be also returned.

1.3 Lean startup methodology

This thesis is focused on trying to understand if and how VR can improve and speed up product development by reducing the number of prototypes to build before the finished product is ready. Ideally, this goes together with time and money savings, two essential factors constituting a matter of survival or bankrupt for startups. Similarly, projects in large companies have to deal with budgets and deadlines, and optimization of resources is always a must. The following lines will give the reader a background on the principles behind how this work has been carried out. Section 1.3.1 offers the reader some historical remarks of where the methodology adopted in this thesis comes from, and Section 1.3.2 illustrates how such approach can be used in large companies.

1.3.1 Background: Toyota and Lean Manufacturing

Even though the idea of trying to maximize the profit by reducing all what is not strictly necessary may seem obvious to the reader, it is worth mentioning that this approach was introduced in the 30s by Eastern companies dealing with continuous production lines, Toyota in particular. Before then, and still for many businesses today, the industrial approach to production was to have loads of buffer raws waiting to be processed *just in case* they were needed. Of course, this implied having large stocks that, money-wise, means capital that is not flowing. Some Asian companies, of which Toyota represents the best known example, adopted a completely different approach. Material to be processed was pulled to the production line by the downstream operations *just in time*, thus reducing the need for stocks to the bare minimum [45]. In particular, Toyota adopted a system of kanbans (the Japanese for "cards") to manage the production flow indicating which part had to be processed and consequently which actions were needed in the upstream to keep the flow working. In the 80s, John Krafcik called this approach a *lean production system* [29].

1.3.2 The approach in startups and large companies

Born as an optimization approach for continuous production, the lean methodology is often the only way small businesses like start-ups have to survive in their early phases, especially when trying to identify the product-market fit upon which building the company itself. This section aims at giving the reader some essential knowledge of the phases involved in the process that became popular and formalized by the work of Eric Ries [44]. Essentially, the lean startup methodology is based on constant self-criticism, analytic mindset, and readiness to abandon a product or method in favor of a rationally more promising one. This leads to a constant search for improvement done via rapid testing, so as to gather as much data as possible to understand whether to continue developing what as been done so far or "pivoting", that is the term used to refer to a change of direction in the project, leading to another beginning of the cycle. Figure 1.2 summarizes the typical phases of the lean startup method.

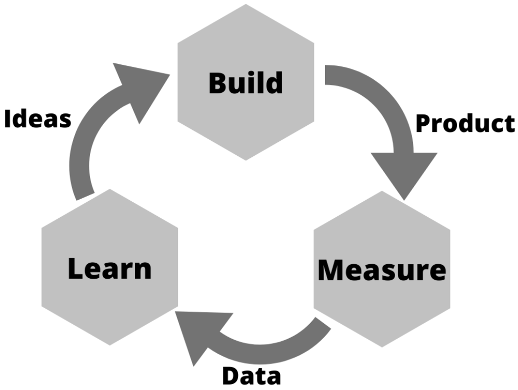


Figure 1.2: Lean startup cycle by Ries [44]

In particular, what happens is that startups rise from an idea, either a problem to solve or a product (often referred to as the solution) that satisfies target customers. In order to make tests or convince investors, a minimum viable product needs to be built. This can be defined as a version of the product that implements already the core features of what the final version should be, but requires the least effort to be developed and allows to obtain (measure) the largest amount of information as possible. From the analysis of the collected information, the product is either developed further or abandoned in favor of something new. Then other tests are made and the cycle is repeated until the problem targeted by the product or service is solved [34]. The reader will now understand that the cycle never ends as long as some margin of improvement is found.

While for startups cutting all the unnecessary out from the development of an always improving product is needed to save money that, if spent, could lead to bankruptcy, large and well established companies can use the same approach to optimize the budget in projects carried out in single departments to obtain a desired improvement faster than using other methods. This is especially true and feasible in innovation and R&D departments where development choices can change faster than in production since the later changes happen, the more expensive they are [8]. Figure 1.3 shows a graph reporting the rise of the cost of fixing errors in design published by V. Bhargava, former director of engineering at Motorola.

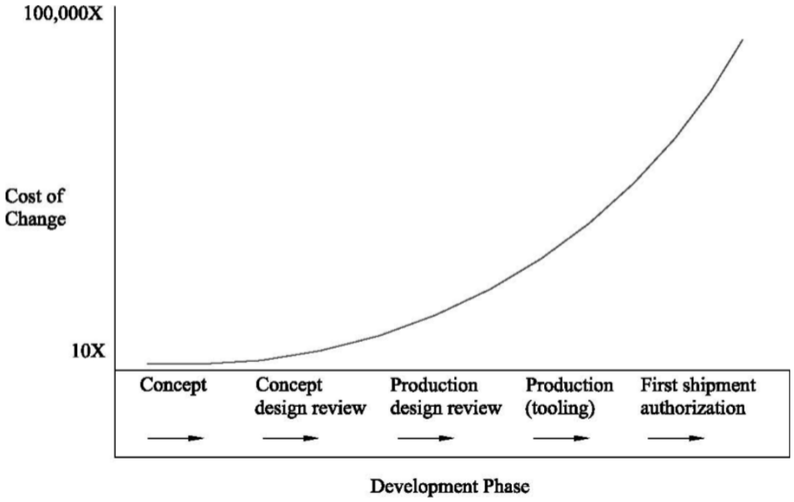


Figure 1.3: Cost of fixing design errors according to Bhargava [8]

1.3.3 Case study: multi-user VR for maintainability review

Lean startup methodology is also applied in this work, and the experimental activities conducted correspond to more cycles of the process. In particular, after the *idea* of using VR for maintenance review and the hypothesis of improving maintainability making the process faster and better thanks to the virtual collaboration, selecting two existing softwares and designing user tests represented the *build* phase. Here, a smaller cycle started with the author testing the platforms (i.e. the *product*) alone to *learn* the technology, practice, and *ideate* how to instruct others on how to exploit the available functionalities during tests. Then, back to the main cycle, we carried out such tests (*measure*) and collected *data*. The following data analysis returned as a result which features should be preserved, what should be added and what to change. This is what is called the *learn* phase in this cycle, and allowed to draw new *ideas* for the following one.

1.4 Structure of the thesis

This first chapter gave the context for which the present research is relevant, offering some background on VR and the lean startup methodology. The rest of the work is organized as follows. Chapter 2 contains a systematic literature review on the state of the art of VR technologies for design review and training of workers, and is followed by chapter 3 describing which hardware and software was used throughout the thesis. A brief discussion on the most common data formats of CAD and VR software is also contained here. Chapters 4 and 5 are about the methods and their implementation, respectively. In particular, the former explains the research design, the procedures and how data analysis has been conducted, while the latter offers a deeper description of tests and data collection. Chapter 6 contains the raw results of the research that are discussed in chapter 7. Here, research questions are answered, and this part is closed by the limitations of the work and suggestions for future improvements. Finally, chapter 8 contains the conclusions.

Chapter 2

Systematic literature review

In order to support the experimental work carried out in this thesis, a systematic literature review has been carried out. This chapter is organized as follows: Section 2.1 presents the other literature reviews that have been consulted, Section 2.2 illustrates the review methodology, Section 2.3 contains the results of the review that are also discussed, Section 2.4 explains the limitations of this systematic literature review. Finally, Section 2.5 is about what can be concluded from the review.

2.1 Related works

The identification of literature reviews related to the use of virtual reality to ensure design for maintainability of industrial products and for the training of maintenance workers in industry has been carried out by searching in Google Scholar, ACM, IEEE Xplore, Scopus, Science Direct and Springer Link libraries. The search has been conducted in May 2020.

A total of 3 works including reviews was found. Aziz et al. wrote an extensive review part mentioning the fields of application of VR (and AR as well) for industrial training, reporting that, overall, the technology is bringing benefits to the industry and is welcomed by workers [4]. Some additional review on VR applications in design review is contained in a work by Lukavcevic et al., reporting that VR did not enhance the performances of users in understanding the working principles of mechanisms starting from their 3D model [50]. The only work properly classifiable as literature review, also being closer to the purpose of this thesis, is the one by Hoedt et al., in which an analysis of experiments carried out between 1999 and 2015 on the use of VR for industrial assembly task is reported. A framework for the evaluation of the outcomes of VR tests is also proposed [25]. In a sense, this systematic literature review continues such an analysis, including also design review tests done with VR from 2015 to present days.

To the best knowledge of the author, what follows is therefore the only literature review focusing on VR applications in industrial training and design review to assess the maintainability of products.

2.2 Review methodology

Following the general guidelines given by Brereton et al. [13], a three-steps procedure has been used. In particular, after having determined the purpose of the research (in this case aligned with the aim of the thesis), the true study is conducted by determining the research strings and the libraries to look into. Extraction of the information relevant for the chosen scope is also part of this phase. Finally, the last step of the procedure consists in finalizing the work, i.e. drawing the conclusions.

2.2.1 Planning phase

This chapter is intended to provide a detailed report of what the state of the art of virtual reality technology is as for its application in the training of maintenance workers and to evaluate the maintainability of a product by analyzing its design without having a physical prototype. More formally, the review should answer the following research questions:

1. What is the direction of research in VR usage for industrial maintenance training and design review?
2. Which industries are promoting the research?
3. What are the features workers would like to have to be willing to adopt the technology?
4. What are the current limitations of VR technology to be used for reviewing product development?
5. What is the economic value of the implementation of VR in assessing or improving the maintainability of industrial products?
6. What is the perceived value of multi-user approaches to VR?

7. How does VR training perform with respect to traditional approaches?

that are needed for the following purposes, respectively:

1. Understanding possible fields of future research.
2. Understanding how other industrial companies are innovating in the field of maintenance.
3. Determining a set of minimum requirements for an ideal VR software in the field of industrial maintenance.
4. Understanding what future research and development should focus on.
5. Depicting quantitative benefits of the technology.
6. Assessing whether academic research is aligned with the needs of companies adopting similar technologies.
7. Understanding if, material and time costs apart, such technology is also at least as effective as traditional training methods.

2.2.2 Search strategy

The strings used in the research are the following:

S1: "virtual reality" AND "maintenance training"

S2: "virtual reality" AND "training" AND "maintenance" AND "industry"

S3: "virtual reality" AND "design" AND "maintainability"

S4: "virtual reality" AND "maintainability"

S5: "virtual reality" AND ("product design" OR "product development") AND ("maintenance" OR "maintainability")

S6: "virtual reality" AND ("maintenance" OR "maintainability") AND ("industry" OR "industrial")

In particular, the research has been conducted using Google Scholar (`https://scholar.google.com/`), ACM (`https://dl.acm.org`), IEEE Xplore (`https://ieeexplore.ieee.org`), ScienceDirect (`www.sciencedirect.com`), Scopus (`www.scopus.com`), and Springer Link (`https://link.springer.com`). Reason for this choice is that, while Google Scholar is likely to offer a comprehensive search of the results also appearing in other libraries, some specific papers, either old or new, might not be properly indexed, so this approach helps avoiding to miss relevant results. Access to those libraries has been done via institutional login provided by the University of Trento, where the author is also enrolled. The strings have been searched inside title and abstract of the papers, as looking for the same words in the entire documents would have led to a lot of results whose content is far from the target topic of this thesis. The research was conducted on papers published from 2015 to May 2020, so as to focus on the state of the art. In particular, since the different libraries have slightly different settings in the advanced search, Table 2.1 reports the detailed settings used for each one.

Code	Database	Search in
D1	IEEE Xplore	All Metadata
D2	ACM	Abstract
D3	Science Direct	Title, abstract or author-specified keywords
D4	Scopus	Article title, Abstract, Keywords
D5	Springer Link	Everywhere
D6	Google Scholar	Abstract

Table 2.1: Search engine settings

It is worth noting that the research on Springer Link has not been restricted on the sole abstract as such library does not allow to narrow down to some kind of metadata. Moreover, the reader should be aware that performing a research on Google Scholar restricting to the abstract returns only papers published in the last year. This choice has been made to be consistent with the restrictions applied to all the remaining databases, from which most of the results indexed by Scholar itself are taken.

2.2.3 Inclusion and exclusion criteria

First criterion that has been considered is the language. In particular, only articles written in English have been considered.

Second criterion is the year of publication: articles and papers published before 2015 were excluded from the review.

Third criterion is the manual analysis of the abstract of the papers: papers having an abstract reporting use cases unrelated to the research questions have been excluded from the analysis.

2.2.4 Selection procedure

Searching for the listed strings led to the number of results in Table 2.2, for a total of 1117 papers.

String	D1	D2	D3	D4	D5	D6	Tot
S1	0	1	3	31	0	9	44
S2	7	0	3	35	7	10	62
S3	11	1	28	37	1	7	85
S4	13	2	91	55	1	7	169
S5	1	0	5	29	414	2	451
S6	47	11	17	179	9	43	306

Table 2.2: Distribution of string search results

Where the total refers to the cumulative results that each string returned for all the libraries.

However, after removing the results appearing multiple times, a total of 809 different papers remained. Then, after an analysis of the abstract, the number of papers to be considered was reduced to 88, 2 of which contain review work and one is a proper literature review. The most recurring reason leading to this sharp cut has been the fact that many papers referred to the maintainability of software, and many others inserted "virtual reality" among the keywords even if the work was not strictly focused on it.

2.2.5 Quality assessment

A series of quality parameters has been used to evaluate the clarity and value of the studies analyzed in this literature review. In particular, these were adapted from Budgen et al. [13] and Villela et al. [55]. The same approach was then adopted by Cardozo et al. [15]. Quality criteria that are used follow:

C1. Are the goals of the research clearly explained?

C2. Is the approach followed throughout the paper easy to follow?

C3. Is the experimental environment clearly described?

C4. Are data collected according to a well described approach?

C5. Is the analysis of data carried out rigorously?

C6. Are the results reasonable?

C7. Are the results explained and discussed?

C8. Does the author remark eventual weak points of the study?

C9. Are the conclusions interesting for the purpose of this literature review?

C10. Is the paper relevant for industrial professionals?

C11. Does the author provide a clear description of related works?

C12. Is there a clear logical path joining data, discussions and conclusion?

The former questions are evaluated according to a 3-value basis. Possible values are *yes*, *no*, *partially*, and they are assigned after examining the papers. It follows that some subjectivity is involved in the rating. As for data analysis assessment (C4 and C5), *no* is also assigned to those papers in which no data were collected at all and/or data analysis is completely missing.

2.2.6 Data extraction

The analysis of literature has been carried out by storing all the relevant findings for each paper in a Google Sheet.

As for the quality assessment of the reviewed articles, results are summarized in Table 2.3.

Criterion	Yes (%)	Partially (%)	No (%)
C1	93.1	6.9	0
C2	86.2	12.6	1.1
C3	60.9	24.1	14.9
C4	41.4	12.6	46.0
C5	34.5	13.8	51.7
C6	79.3	20.7	0
C7	66.7	25.3	8.0
C8	24.1	18.4	57.5
C9	48.3	32.2	19.5
C10	42.5	31.0	26.4
C11	56.3	28.7	14.9
C12	73.6	24.1	2.3

Table 2.3: Quality assessment of the results

Moreover, articles have been analyzed as for the nature of their content (theoretical, experimental or both), the nation in which research was conducted,

the year of publication, the industrial sector in which research was carried out, and the eventual development of a multi-user VR application.
Results are shown in Tables 2.4, 2.5, 2.6, Figure 2.1.

Content	Yes (%)	No (%)
Theoretical	47.7	52.3
Experimental	94.3	5.7
Company involved	48.3	51.7
Multi-user VR app	4.6	95.4

Table 2.4: Type of content in analyzed papers

Issuing nation	Relevant works (%)
China	36.0
France	11.2
USA, Germany	6.7
Italy, Mexico, Netherlands	3.4
Finland, Australia, Portugal, Canada, Austria	2.2
Ireland, Kuwait, Belgium, Croatia	1.1

Table 2.5: Nations producing relevant work

Industrial sector	Relevant works (%)
Mechanics	24.7
Aerospace	23.3
Energy and power generation	15.1
Automotive, electronics	5.5
Buildings, healthcare	4.1
Railways, nuclear, oil	2.7
Mining, quality certifications, particle physics	1.4

Table 2.6: Industrial sectors involved in the research

2.3 Results and discussion of the SLR

Starting from the quality of the works that have been considered, Table 2.3 shows that, for the largest part, the extent of the research is easy to understand and follow in its description (C1, C2, C3, C6, C12). However, it is quite common that only a qualitative description of the results is reported

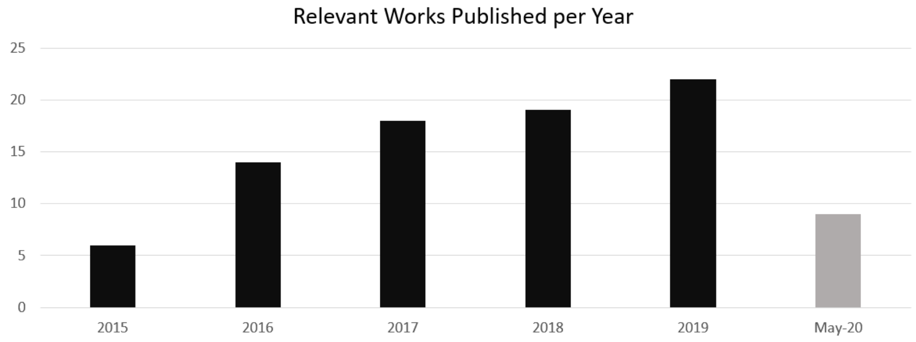


Figure 2.1: Publication trend up to May 2020

(C4, C5). It is arguable that, given that the focus of this literature review is on industrial applications of VR, when significant data are obtained, companies are not willing to make them public in order to keep a competitive advantage. Most of the times author discuss their results (C7), but rarely the limitations of the works are stated (C8). Statistics (C9) report that not every work gives a contribution that is completely aligned with the purpose of this research, most of them report some useful findings but the experiment slightly deviates from the target idea of understanding how VR is contributing to design review for maintainability of products and training of workers for industrial maintenance. Similarly, less then half of the works seem to be relevant for on-field workers (C10), this meaning that either they have not been involved in the research process or the findings will not have a significant impact on their work life. Interestingly, most of the works refer to previous publications (C11) to give evidence for their findings, denoting an interest in proving the quality of the work being produced.

Table 2.4 shows that nearly all the works that have been considered in this systematic literature review contain some practical implementation of VR, which is reasonable given the industrial context of this research. Less interest seems to be given to the theoretical explanations of concepts behind methodologies and algorithms running behind the same works. On the one hand, being often the purpose of the experiment the determination of how VR can be industrially useful, *why* things work can have a minor relevance than how to implement a working solution. On the other hand, it is a fact that nowadays, thanks to free libraries and plug-ins such as SteamVR for Unity3D, very little to no understanding of what is behind VR is needed to start coding an app. Small to no interest has been found on VR applications allowing multi-user interactions. This might be due to the complexity in the development of such a feature that is kept away from concept studies, but it is good to mention that some companies are already selling software allowing such kind of interaction capabilities (Glue, DesignSpace, ImprooVR).

Table 2.5 shows that, while it is clear that China seems to be pushing more than every other country on industrial VR, European countries all together are producing a similar amount of research in this field with respect to Asian countries. Again, the reader must take these statistics cum grano salis, given that important industrial findings are likely not to be published.

More interesting is Table 2.6, reporting the fields to which companies publicly contributing to research belong to. Apart from the distinction between the industrial sectors, all of them deal with expensive hardware which takes both a lot of time and money to be produced. It is then reasonable that an interest in using VR to perform design reviews and train maintenance workers comes from these industry.

Coming to the research questions formulated in Section 2.2.1, the following can be stated.

What is the direction of research in VR usage for industrial maintenance training and design review?
The widest type of VR application to train workers in maintenance is based on the idea that a single worker enters the virtual scene, eventually receives on-screen instructions on the action to perform and simulates the required task [58] [33] [68] [11] [1] [18] [3]. Other applications also calculate the most convenient (dis)assembly sequence [32]. It is worth mentioning that a Mexican company for power supply is currently training their workers for maintenance using a non-immersive VR application [40] saving 33% of the training time.

In the field of VR to check the maintainability of products starting from their design, most of the studies involve the use of the commercial software DELMIA (`https://www.technia.com/software/delmia/`), that allows to create virtual models to simulate factory processes and evaluate the ergonomics of the designed solution in order to understand the (dis)comfort workers will experience as for visibility, reachability, posture and other parameters [16] [20] [22] [56] [64] [57] [65] [54] [41] [62]. Mitrouchev et al. developed with Python programming language a similar application to evaluate the ergonomics during disassembling procedures, focusing on visibility, neck posture and trunk bending [37].

Interesting training applications have been tested by Zhou et al. [66] and Ciger et al. [14] in simulating emergency operations, Martinetti et al. [31] pointed out that VR can be used to train workers in operations that would normally require to stop a machine (in this case a train), making the real cost of the traditional practice huge. Neges et al. [38] showed that VR can also be used to allow workers to train in stressful situations with no real risk at all. Wolfartsberger et al. [60] showed a 3D recorded animation that any worker can access and use to learn a maintenance procedure having the same look-and-feel of a tutorial in computer game. A similar idea of recording an expert to allow others to train at their convenience was conceptualized also by Shroeder et al. [47]. Xu et al. [63] developed a VR web-application showing assembling instructions that is accessible by any device with a browser.

Which industries are promoting the research?
Table 2.6 reveals that VR is interesting for those companies having to deal with expensive prototyping and time-consuming training, i.e. companies in the automotive, mechanics, aerospace and power generation sector.

What are the features workers would like to have to be willing to adopt the technology?
Wolfartsberger [61] obtained an answer to this question asking to the employees of an engineering company (not explicitly mentioned) which features they wanted in a VR software. Their answer mentioned with high priority the need to break an assembly in its sub-parts to select, highlight and move them. High priority was also given to the chance to move parts of assembly according to their geometrical constraints to simulate those motions that would happen when the product works. Lower priority was given to hiding and scaling parts, while the lowest to the implementation of sectional views and measuring tools and other instruments such as displaying a screwdriver instead of the default controller.

What are the current limitations of VR technology to be used for reviewing product development?
When also hands are tracked with LeapMotion, users report that the alignment of the virtual and real hand is not perfect [39] [48]. To the same consideration, Barkokebas et al. wrote that a representation of the body would increase self-awareness [5]. Experiments reported that, especially when the scene is messy, spacial awareness decreases and motion sickness can still be experienced despite the progress of HMDs [7]. Similarly, Bucarelli et al. reported that during tests requiring to look to the ceiling with an HMD, workers experienced a fear to fall [12]. Tests carried out by Akanmu et al.

[2] revealed that workers are rarely familiar with VR and, unless they receive incentives to train for it, they will not do it. Users involved in the experiments carried out by Andaluz et al. highlighted that the quality of the VR application is a key factor for the perceived experience and willingness to adopt the technology [3].

What is the economic value of the implementation of VR in assessing or improving the maintainability of industrial products?
This question still represents a challenge as for gathering accurate data from real companies. On the one hand, of course companies are not expected to reveal their financial successes or failures after adopting a new technology, on the other hand VR is still in a research phase and companies are starting to adopt it in these years. It follows that available data is very little. However, some insights have been collected in the reviewed papers. Bhonde et al. [9], referring to Li and Taylor [30], report that errors in the design phase can lead to expenses amounting up to 7.36% of the project cost. Guo et al. reported that 70% of the costs related to the entire life cycle of a product depend on the first design stages. For an aircraft, roughly 11% of the operating costs is represented by maintenance [21]. The reader will agree that having products designed with an eye on maintainability is likely to lead to large savings. As for expenses due to bad cable routing, Tu et al. [54] refer to a report by Zhu [67] stating that, before 1991, the US navy spent 180 man-hours per year in maintenance of flexible wires. Matos et al. reported that VR technology to guide maintenance operations in civil aviation could help solving faster interruptions of service costing EUR 2.8 billion per year in Europe only, with such disruptions occurring in 5.8% of the flights [33]. Gallegos et al. [18], referring to Hills et al. [24], report that, after adopting digital manufacturing technologies (DMTs), Toyota cut by 33% both its lead times and design variations, while the product development costs were cut by 50%. With the adoption of DMTs - in particular, making virtual simulations to assess the ergonomics - Ford improved the design of their workstations leading to less injuries and improving the quality of new cars of 11% [53]. Using a non-immersive VR platform, a Mexican company for power supply reduced the training times of its workers by 33% giving also the advantage to practice in safe conditions [40]. Moreover, Ducker et al. proposed a method to evaluate costs and benefits of adopting VR solutions in small and medium enterprises (SMEs), starting from the definition of the requirements the VR solution should satisfy, its implementation and economic evaluation [17].
After mentioning how much VR and DMTs can help to save, the cost of implementing different immersive VR setups has been reported by Borsci et al., mentioning that, while a CAVE environment (a cubic-shaped room in

which immersivity is obtained by projecting the virtual scene on the walls) can cost more than EUR 50.000, a station with a powerful laptop and HMD is below EUR 6.000 [11].
The previous numbers suggest that it is worth exploring VR to improve the maintainability of industrial products thanks to a better design and to train workers, at least partially, with digital tools.

What is the perceived value of multi-user approaches to VR?
Table 2.4 show that recent literature does not offer many case studies. In addition to this, the few available papers either do not report the opinion of users [52] or, when they do, they state that the application is poor in quality [3]. In a sense, the analyzed literature seems not to offer a precise answer to the research question. However, the rise of multiple companies offering multi-user VR tools - Glue , DesignSpace , ImprooVR, IrisVR, EditorXR, CAVRNUS, MonsterVR, STAGE, mindeskvr - might suggest that, even if academic research is not going in that direction, from an industrial point of view the technology is interesting.

How does VR training perform with respect to traditional approaches?
Regarding this question, different studies comparing the performances of groups of workers trained with VR against traditional (typically video, presentations, or paper-based) instructions have different answers. However, even if He et al. reported that VR is faster than other training systems [23], it is a more common finding that training workers with VR takes longer than traditional approaches [1] [18] [19]. When it comes to evaluate the performances of a training, the most common metrics are the completion time of the assigned task and the number of errors done in completing it, both for design review and assembly procedures. Research is not going in a sole direction, with studies reporting that immersive VR training is, to the best extent, as effective as other methods, such as non-immersive VR and traditional training [50] [19]. Schroeder et al. and Kato et al. report that training with HMD does not result in improving a feeling of immersiveness [46] [28]. As for the effectiveness in transferring knowledge, Winther et al. show that, even if VR training transfers knowledge, it is still less effective than other approaches [58]. The same result was obtained by Barkokebas et al. that compared VR to paper-based instructions [5]. More encouraging results are also reported by many researchers. In particular, Belter stated that immersive VR enhances the spacial awareness in training [7]. Randeniya et al. together with Borsci et al. and Basset et al. showed that VR leads to faster workers committing less errors while completing a task [43] [11] [6]. Not only, the more complex the task, the larger the benefit given by VR [1]

[18]. Besides this, studies carried out on Opel workers, not only gave good results with VR, but also resulted in workers explicitly willing to use it [3]. VR benefits were also reported by Guo et al. evaluating design review procedures [22]. Bhonde et al., instead, suggest that the best result in perceiving spaces to inspect is obtained by combining both 2D and 3D instructions [9]. Promising results have also been obtained by Hou et al. that, training workers to inspect and watch over new work areas, found that those trained with VR walk along more efficient paths [26]. The reader will therefore notice that a variety of results makes an attempt to answer the research question, with a majority of studies bringing forward promising results and justifying the interests of new businesses rising in these years. However, it is also a fact that an irrefutable conclusion cannot be drawn at the moment. More studies are likely to come together with an improvement of the technology itself, and this will certainly lead to clearer evaluations of the performances of VR for training and design evaluations.

2.4 Limitations of the SLR and directions of future research

First of all, it is arguable that some relevant research is being conducted inside R&D departments of companies, but not being published. Besides this, all the experimental works considered in this review inevitably refer to VR apps having different quality, and this is likely to have influenced the perceived value of the technology to users involved in the tests. One more mention regards the way in which performances of workers are evaluated. Time of completion and number of committed errors are definitely relevant, but the reader will agree on the fact that many other rarely considered factors have an impact on the results of a research. For instance, the experience with VR of trained workers is different in the various papers. Quality assessment of the papers in Section 2.2.6 involves some subjectivity and this is due to the fact that there is currently no standard to evaluate VR works and research, as also complained by Hoedt et al. [25].

Future work should aim at proposing a framework for a uniform evaluation of VR application and tests in industrial context. Moreover, tests on multi-user VR environments will give a contribution in justifying or contradicting the rise of companies offering such a product. Not by chance, they will also be part of this same thesis. Future work should also put more focus on the opinion of workers who will eventually have to adopt VR in everyday worklife.

Actually, most of the analyzed papers did not mention either interviews or feelings from their side. Measuring how many users experience discomfort in using HMDs and haptic devices during VR sessions of various length can provide insights on the needs for better VR equipment starting, for instance, from the adoption of wireless HMDs.

2.5 Conclusions of the SLR

This systematic literature review extends previous analysis on industrial VR applications constituting a unique case as for the focus on design review for maintainability and training of workers. Every research question received a satisfying answer with the partial exception of collecting economic insights. The number of publications on this field is growing every year, testifying a general interest especially from the side of companies dealing with heavy hardware that is also very time and money consuming in production and prototyping phases. Hand tracking with LeapMotion needs some improvements before being satisfying for users also requiring a more realistic representation of their own body in the scene to have a better self-awareness. DELMIA is the most common tool to evaluate the ergonomics of maintenance processes and evaluation of the maintainability of the design of products. Multi-user platforms are rarely described in the literature, but a greater interest is shown by new businesses, even though the financial benefits of the adoption of VR for the declared applications are difficult to evaluate from literature. Training workers with VR has shown promising results in most of the case studies, suggesting to keep experimenting while the technology advances.

Chapter 3

Environment

This chapter contains a description of the software and hardware that was needed during the experimental part of the work reported in Section 5.2. In particular, Section 3.1 introduces the reader to the software used in this research, while Section 3.2 gives a short introduction to the hardware. Finally, Section 3.3 is about the data formats used in CAD and VR platforms.

3.1 Software

This section contains a quick description of the applications that were used in this work with a focus on those enabling multi-user VR collaboration. It is meant to give the reader a general understanding of the environment in which the author and his colleagues worked. For further details the reader may want to have, reference to the websites of the respective software houses is offered when details are omitted. Other platforms used for ordinary communication between users involved in the process (i.e. Office packages, Microsoft Teams) are purposefully not mentioned.

3.1.1 Glue

Developed by FAKE (`http://www.fake.fi/`), Glue is a platform allowing multi-user collaboration in VR environments. Its core feature is allowing an infinite number of users to be active on the same scene. Real limits are given by the quality of the available internet connections and how heavy the files to be streamed are. Tests have been conducted by the developers of the company with up to 20 participants.
Written in C#, the platform is designed to run both on desktops and HMDs. It requires the installation of both Steam and SteamVR, presented in Section

3.1.3. Once the user has downloaded the latest version of Glue, he/she is required to log in into his/her account. Then, navigating to `https://collab.glue.work/`, a window displaying how to manage *scenes*, *files* and *members* is offered, as shown in Figure 3.1.

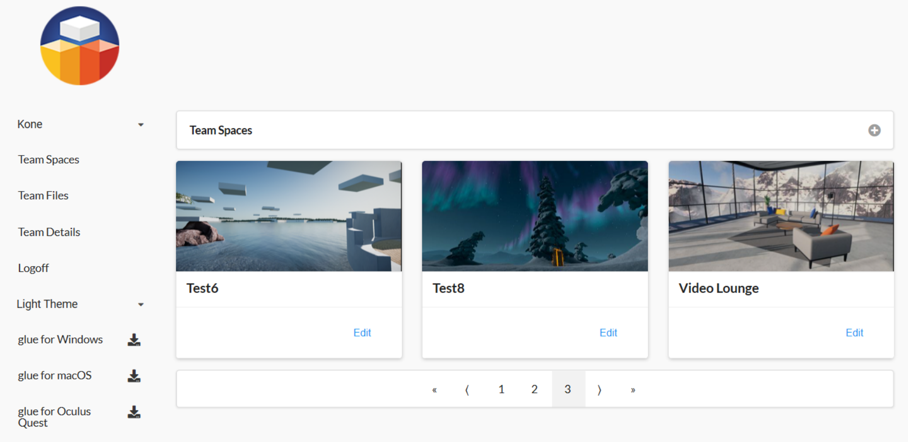


Figure 3.1: Glue - WebPortal

In particular, scenes are the virtual environments where users can meet, communicate and collaborate. Files is a menu where all the documents that will be accessible inside the scenes must be uploaded, while the Team menu allows to manage the list of users allowed to access a scene. Members can be added as guests or administrators, with the relevant difference that administrators can add and remove both scenes and other members.

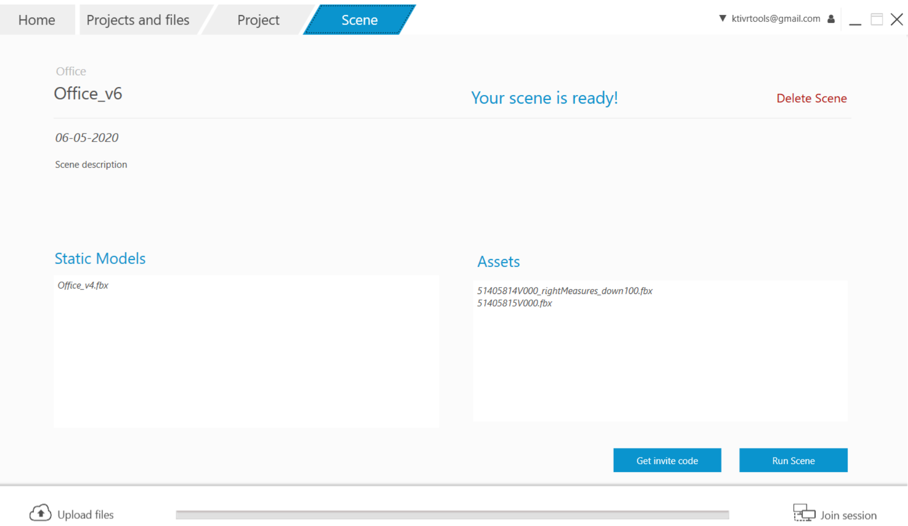
Once Glue is launched, a menu with the available environments is displayed. It is advisable to download on cache the desired scene before launching it, so as to reduce loading times. Unless they are deleted, scenes need to be downloaded only once. After launching a scene, it is opened in Desktop mode, i.e. the HMD is not set as default option. This also makes Glue independent from such hardware. Most of the actions are still possible using the desktop menu that appears on the bottom of the screen. The only exceptions are those tools that require some 3D interaction. For instance, the *camera* and the *whiteboard*. One of the buttons available in desktop mode starts the HMD. In immersive mode, the most relevant action the user can perform is *teleporting*, i.e. moving instantly from the current location to another one by pressing and holding a button of the controller, pointing at the desired destination and finally releasing the button. A distinction is made between reachable and non-reachable points: the former are displayed in blue, the latter in red. Second category of action is the manipulation of objects: the

user can grab and release items on the scene. Some more tools can be utilized, and they are selected by accessing a menu that is always available on the back of both virtual hands. A quick description of them follows.
The *whiteboard* can be recalled and moved inside the scene if the user is wearing the HMD. Like a real one, it allows to write and draw with virtual markers on it. The *notes* tool generates post-its where the user can write notes using a keyboard. *3D draw* generates a pencil that, once the user grabs it, allows to draw free hand making sketches that float in the air. The *camera*, only available in VR mode, allows to take screenshots of the scene that are saved locally. Pictures can be taken with both a front and a rear camera, so that the user can also take shots of himself. Only available in VR mode, the *laser pointer* casts a red ray in the direction of the controllers. Presentations can be done by importing the slides as .pdf file and recalling it from the team files in a scene containing a projection screen. A console to control the flow of the slides will appear visible only to the user making the presentation. In the same way, *videos* can also be played. A *web browser* can be used by each single user inside the scene, but webpages cannot be shared as slides and videos. Finally, a *clock* can be placed on the scene integrating also a stopwatch and a timer. Some more actions can be done, such as scaling the 3D models imported in the scene and moving all or some of the participants of a meeting from one scene to another, as well as grouping them all together in a place (e.g. close to where a presentation is given).

3.1.2 DesignSpace

Developed by 3DTalo (`https://3dtalo.fi/`), DesignSpace is a platform allowing multi-user collaboration, 3D model editing and exporting, and VoIP communication among users. Being the software rich in features, these will be described using different paragraphs. The reader will notice that no reference to the commands and buttons needed to perform any action is made, for which the most updated documentation should always be consulted at `https://ds.3dtalo.fi/learning`.

Once DesignSpace is installed, the user can login to the platform. This done, from the main panel one can create a project and then multiple scenes inside it, as shown in Figure 3.2. While creating a scene, it is possible to select models among the imported ones and set them as static elements or 3D assets. The difference is that the former will constitute the fixed and unalterable part of the scene, while the latter will not appear directly, but will be available to be added and manipulated in the scene via an *Add Custom Object* menu. On a side note, point clouds (.e57, .ptx and .pcd) are also supported. They can be uploaded as models thanks to a built-in tool that allows the user to choose the point density to appear in the scene once the model is placed. Models can be imported to DesignSpace in different formats: the reader can find a more detailed description about this in Section 3.3.2. The selection of the starting position of the user concludes the setup of the scene. Scenes can be accessed by one or multiple users as well. For the latter case, after creating a scene, an invitation code can be generated and sent to other users to allow them to join the scene simply by inserting it in the proper field in the home screen. The client will download and launch the scene automatically.



Office
Office_v6

Your scene is ready!

06-05-2020

Scene description

Office_v4.fbx

51405814V000_rightMeasures_down100.fbx
51405815V000.fbx

Figure 3.2: The control panel in DesignSpace

Moving, tools panel, scaling and hiding As for most of VR environments, the movement inside the 3D scene can be achieved through *teleport*, so as to cover large distances instantly. Reachable points will appear in blue, while those on which you cannot land will turn the ray cast from the controller in red. For finest movements, or to reach some places where there is no visible landing spot for teleport, the user is also allowed to *fly* in the scene. All the actions that the user is allowed to perform inside the environment are accessed through the tools panel, which is always visible on top of the left hand of the user, when he/she is wearing a HMD. In case of desktop mode utilization of the software, such panel will not be visible at all, and the user can only resize static models of the scenes but no other interaction is allowed. In short, desktop mode should be chosen only to follow what someone else is doing in the scene.

Among the many, a *scaling* function is implemented. This literally means that the user can scale his/her own size in the environment, so as to be able to have a different perception of the surroundings and be able to explore narrower spaces. In order to inspect complex 3D models that can be composed of different subparts, the user can choose to *move* or *hide* (and unhide) an entity from the environment. These two actions can also be applied at the same time to multiple objects after highlighting them with the *select* tool.

3D modeling, adding custom objects and file exporting DesignSpace allows to draw simple 3D models on the scene starting from cubes or cylinders. Cubes are drawn by defining four vertexes, while cylinders require ray and height. This elementary modeling feature helps in the understanding of the encumbrance of possible new equipment to be inserted in an existing plant, or similar applications. All the 3D objects can be placed on existing surfaces. Moreover, solids can be aligned to the principal cartesian axes. Drawing free lines as with a pencil is also allowed both on surfaces and in the air (3D sketches). A discrete tool is present to draw pipes in a drag-and-drop fashion. More complex 3D models designed with other software can be imported in the scene via the *Add Custom Object* menu, that gives access to the files that, at the moment of creating the scene, have been inserted as *assets*. Before placing them in the virtual environment, DesignSpace allows to change their scale.

Camera, measures and environment change The *camera* tool allows to take a picture, that is saved on the computer of the user, as one would naturally do with a real camera. Besides simple shots, the camera can also remove perspective from the view and align automatically to one of the cartesian axes. Moreover, surfaces can be hidden so that the camera only shows corners and edges of models. This is what is called the *wireframe mode*. Taking *measures* is also possible in DesignSpace. This tool works as a virtual ruler that can be used for quick design reviews inside the scene. Once two points are selected, it returns the x, y and z difference in coordinates, together with their linear distance. For the sake of completeness, it is worth saying that the default background of the scene is greyish, but it can be changed to look like a sunny horizon if the user wants to have better looking screenshots of the work. Given that it is not relevant from a functional point of view, no additional details will be given on this.

Saving the scene, exporting objects By default, if a scene is not used for more than 20 minutes and no users are inside it, all the edits that have been done are canceled, so that it is ready for a following session. In case the user wants to keep working on a previous session, saving the scene is allowed. Not only: every time the scene is saved, a file is generated creating a versioning of the scene itself. This means that it is possible also to go back to previous savings of the same environment. Moreover, 3D models generated inside the scene can be exported in .obj, .stl and .fbx.

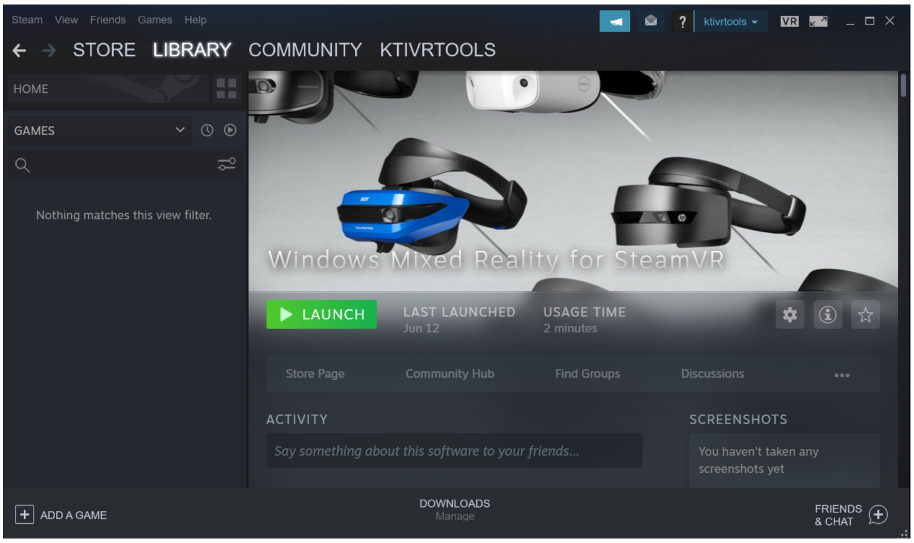
The snaps Most of the tools and commands in DesignSpace can be used in different ways according to the settings of the single command. For instance, while placing or moving objects on the scene, they can be aligned to some axis or kept vertical. The camera can remove perspective if needed, pipes can be generated making smooth or sharp bends, and so on. All these additional settings for each command can be activated or changed any time each tool is recalled. The buttons to deal with such settings are called the *snaps*.

3.1.3 Steam and SteamVR

Steam and SteamVR, developed by Valve, are platforms for distributed games and room-scale VR experiences, respectively. They are required for the HMDs that have been used during the tests reported in Section 5.2. Anyway, despite being needed for the workflow, they are not the key software on which the focus of the reader should be. Therefore, only a brief description is provided. For more information, the reader can refer to the respective official websites: `https://store.steampowered.com/` and `https://store.steampowered.com/app/250820/SteamVR/`.

Steam Steam is a platform mainly known for the distribution of games that the customer can keep in his/her own library and download any time after the purchase. The management of such a library is allowed both from a web interface and via a downloadable client. Since a Windows 10 laptop has been used, the corresponding version of Steam has been installed on it.

SteamVR SteamVR is an extension of Steam. It gives the user the chance to move and interact in a virtual environment once he/she is inside a confined space, typically a room. Initially developed with HTC, and therefore compatible with its VR devices, compatibility was then extended also to HMDs produced by other original equipment manufacturers (OEMs), such as Oculus Rift by Facebook. Despite being the enabler for most of the headsets, SteamVR is not enough to run applications that are not downloaded from Steam, such as Glue and DesignSpace. To do this, Windows Mixed Reality for SteamVR needs to be also installed from Steam. Then, when the user wants to launch any VR app, all what is needed is opening Steam, connecting the HMD, launching Windows Mixed Reality for SteamVR and then the application can be run. Otherwise, third party platforms will not be displayed in the headset. Figure 3.3 shows the control panel of Steam.



Nothing matches this view filter.

LAST LAUNCHED Jun 12

USAGE TIME 2 minutes

Say something about this software to your friends...

You haven't taken any screenshots yet

Figure 3.3: The control panel of Steam

3.1.4 Creo, Windchill and Blender

Developed by PTC, Creo is a CAD suite allowing design and simulations of mechanical products. Windchill is a platform that Creo integrates and allows to create common workspaces in which users can add and manage their files, making them accessible to others. However, these tool have been used for the only sake of accessing the models needed in the virtual scene and exporting them in a format that could be then easily imported in VR, as described in Section 3.3.2. Therefore, a detailed introduction on Creo is not needed for the full understanding of the thesis. For all the details on the software, the reader can refer to `https://www.ptc.com/en/products/cad/creo`. Similarly to Creo, Blender was also used to have the models in a suitable format for Glue and DesignSpace. In short, all the reader needs to know is that it is an open source and free modeling tool that is more focused on 3D modeling for animations rather than creating professional physical simulations of components to be manufactured. Once more, every information and a better overview of Blender is offered by the official website `https://www.blender.org/`.

3.2 Hardware

The hardware on which software was installed consists of commercially available laptops and HMDs. Therefore, they will be listed with their specifications to give a complete idea of the setup, but no other descriptions are added.

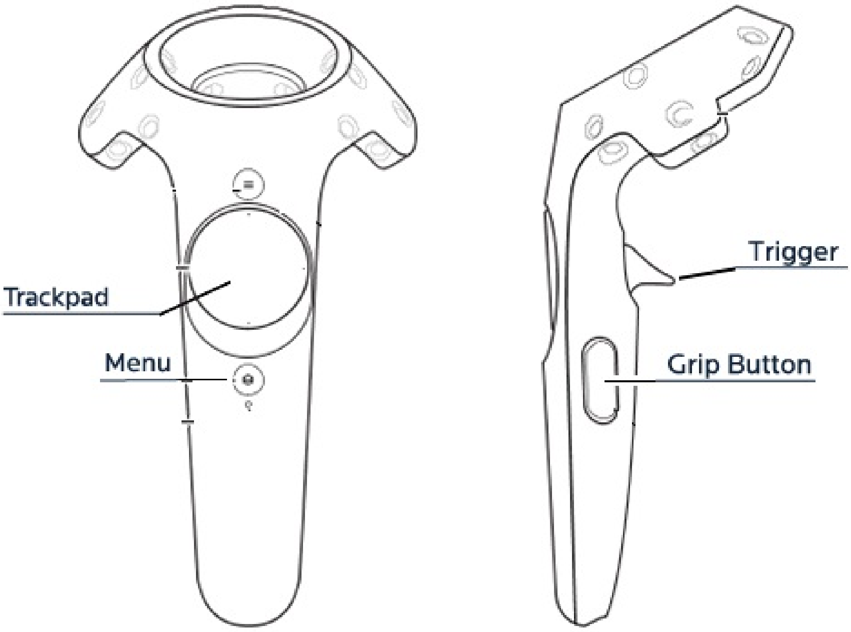


Figure 3.4: VR controllers - image adapted from wiki.orbusvr.com

Computers The author conducted the research using an msi GS65 Stealth Thin 8RF with 16Gb RAM GDDR4, CPU Intel Core i7-8750H @ 2.20GHz, integrated GPU Intel UHD Graphics 630, discrete GPU Nvidia Geforce GTX 1070 Max-Q, 8Gb VRAM GDDR5. It is worth mentioning that, since the integrated GPU was set as default for VR applications, graphics settings had to be changed to use the Nvidia during all the tests. Other users participated to the test using either their office laptops, typically equipped with 8Gb RAM, integrated Intel GPU only, CPU Intel Core i5, or more powerful devices with very similar features to the laptop of the author.

Headsets The author was equipped with a Samsung Odyssey HMD, while participants to the test had access to HTC Vive and HP Reverb headsets.

Controllers Every VR headset has slightly different controllers, but they all have a similar setup as for the available buttons, whose conventional naming follows. The *thumbpad* button (or trackpad) is a round and large touch-sensitive button placed on top of the controller. It can either be pressed or brushed according to the actions to perform. Above the thumbpad, a smaller round button with no conventional name is always present, and below the thumbpad a button to access the Windows menu is located. On the side of the controller an elliptical button is present: this is called the *grip* button. Then, behind the controller, a lever is present, this is the so-called *trigger*. Finally, some controllers also integrate joysticks. Figure 3.4 shows the standard shape of controllers.

3.3 Data formats

This section discusses format-related facts and issues that are faced when it comes to transform a CAD model into its VR counterpart. Section 3.3.1 contains a compendium of the main formats that are currently used in industry, both for modeling and VR visualization purposes, with a focus on those formats that have been used more in the tests carried out during this thesis. Credits for an exhaustive list of formats go to McHenry and Bajksy [35], whose work contains a very informative table of 3D formats that led the author to investigate more on these. Then, Section 3.3.2 will then explore the consequences related to the current lack of a standard for conversion from CAD to VR models in industry, the reasons for such a need and the drawbacks of this lack.

3.3.1 Common formats in 3D CAD and VR

This section aims at describing briefly the main features that different file formats can store, so as to give the reader a better understanding of which one can be used for certain applications. File types that represent assemblies and parts are mentioned all together as distinguishing by commercial producer would add no value to this thesis. A focus will be done for Creo formats as they are used in this work. For more detailed information, the reader can refer to [35], the webpages of the specific CAD softwares and to [27], where more insights can be found.

.FBX Standing for *FilmBoX*, this format is currently owned by AutoDesk, after buying the company MotionBuilder that had commissioned its creation to Kaydara. No public documentation is available, but some reverse engineering conducted by people in Blender allowed to discover how this file format is structured [10]. Blender apart, the only way to access data in .fbx is to use the official SDKs. This format allows to store 3D models, their materials and lights, scenes, hierarchies (parent-child relations in parts) and non uniform rational basis-splines (NURBS), which are currently seldom used. .fbx also stores position, UV (standing for x and y) and normal (depth) data. This is how 3D information is converted into flat matrices. This format is currently the standard de facto for animations and game engines. Being coded in binary, it is very fast.

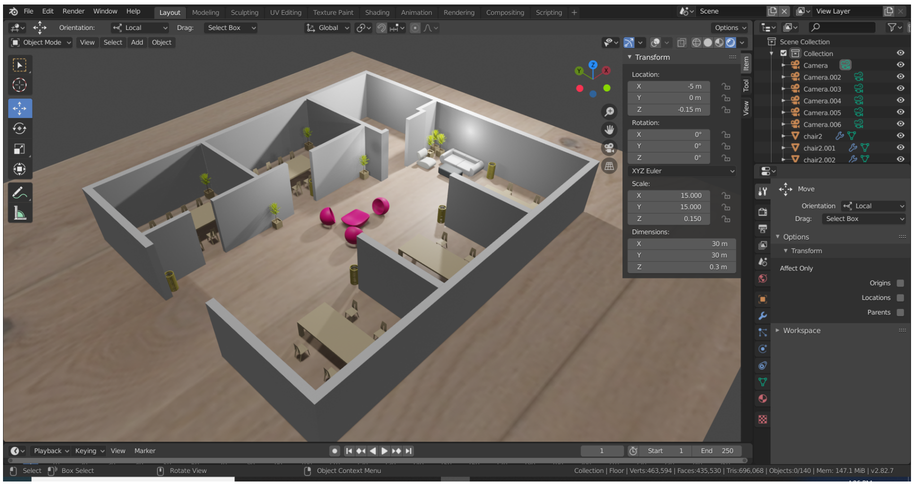
.OBJ and .MAT These formats stand for *OBJect* and *MATerial*. .obj allows to store UV and normal data. Being written in characters, it is easier to deal with for humans, but slower than .fbx. No hierarchy, light, scene with multiple models or animation can be stored. It is worth saying that, despite having a huge compatibility with commercial software, it has never been updated since the 80s.

.STL Standing for *STereoLithography*, this format is developed by `https://www.3dsystems.com/` and contains only the surface representation of the surface of 3D objects. Both binary and ASCII representations are available but, given the data it stores, is not really useful for the purposes of this thesis.

.STP Standing for *STeP*, it is an international standard, ISO 10303-21. It follows that all the most used 3D CADs provide support for it. 3D models are represented with mathematical precision using non uniform rational basis-splines (NURBS). Therefore, even after file transfer among different softwares, the exact precision is preserved. It does not store materials or visual properties: neither lights, nor scenes, nor animations etc. In short, it is great for industrial design, but should be avoided for graphical purposes.

.DXF This *Data Xchange Format* is mentioned here only as it often appears among the importable and exportable file formats in Section 3.3.2, so the reader might want to have a quick reference for a better understanding. It was developed by AutoDesk for the sole purpose of having a format to exchange AutoCAD files, typically written in .dwg, with other CAD tools, without releasing its internal documentation. Anyway, with time, .dwg became more complex and the documentation of .dxf was not updated deeply enough to allow others to exploit the new features. Anyway, this format is not used in the tests related to this thesis.

.BLEND It is the data format that is used by Blender to save the scenes before exporting them. Since this software has been used to draw and export (in .fbx) environments to make tests in DesignSpace, this format appears here. Figure 3.5 shows a scene while still being edited in this format.



Orientation: Local
Drag: Select Box
Global

Location:
X -5 m
Y 0 m
Z -0.15 m
Rotation:
X 0°
Y 0°
Z 0°
XYZ Euler
Scale:
X 15.000
Y 15.000
Z 0.150
Dimensions:
X 30 m
Y 30 m
Z 0.3 m

Orientation Local
Drag: Select Box
Affect Only
Origins ☐
Locations ☐
Parents ☐

1
Start 1
End 250

Collection | Floor | Verts:463,594 | Faces:435,530 | Tris:696,068 | Objects:0/140 | Mem: 147.1 MiB | v2.82.7

Figure 3.5: A scene edited in Blender

Part and assembly formats In Creo saved as .prt and .asm, they respectively contain the information related to the design of single parts so that they can be edited and, in the case of the assembly files, information regarding the part files constituting the final product with its properties and relations among parts. Other commercial 3D CADs have different file extensions, but the underlying logic is exactly the same.

3.3.2 From CAD to VR: reasons and consequences

First of all, there are plenty of formats in CAD industry (.iam, .ipt, ...), while only a couple of widely used in VR (.obj and .fbx). The reason is mainly historical. CAD formats are the way in which engineering platforms such as Creo by PTC store information. Being these software commercial, it follows that almost every company developing a drawing or simulation tool, also has its own format. On the contrary, being VR a relatively recent approach to visualization that can be interesting for any of the previous industry, it makes no point in developing another multiplicity of formats. This said, then it comes to understanding why there is a need for VR-specific formats and, above all, why these need to be different from their CAD counterparts.

Some general introduction

CAD formats are meant to store *all* the features that can be useful in the definition and simulation of a product. Geometry, material, physical properties, parent-child relations among parts, kinematic constraints, manufacturing procedures are only a few. On the other hand, VR is only meant to visualize and interact with the objects. Thus, many of the previous features such as the physical properties might not be needed any more.

The reason why VR formats need to be lighter lays in the fact that, while the CAD development of a product needs to be as accurate as possible, even if this implies dealing with loads of features, VR visualization must satisfy, first of all, another requirement: running at high frame rates. It follows that, the lighter the model to handle, the smoother the animation will be.

Following this logic, it all then comes down to understanding how to choose which features are essential for VR and, eventually, how to make them also lighter than their CAD counterparts. In general, the features preserved when converting modeling formats to VR are geometry and the logical structure (parent-child). While the latter allows to manipulate in the virtual environment sub-assemblies as they have been thought and grouped by the designers, the former typically consists of thousands, if not millions, polygons that need to be displayed. From here the consequent need to start an optimization process to reduce such number.

As reported by Tang and Gu [51], there are many different algorithms, but they all follow the same structure. Given the constraint that the outer surface of a product must be preserved to grant a good appearance, some of the inner polygons, typically triangles, are collapsed. This is done by selecting a vertex, sliding it towards one of its neighbours following an edge and then, when they overlap, removing it from the data, together with the edges that were sliding with it. The difference between most of these algorithms lays in how to choose the points to collapse. Figure 3.6 shows graphically the described process. Iterating multiple times allows to simplify the model until the desired complexity is reached.
Generally speaking, the previous description covers what happens when a

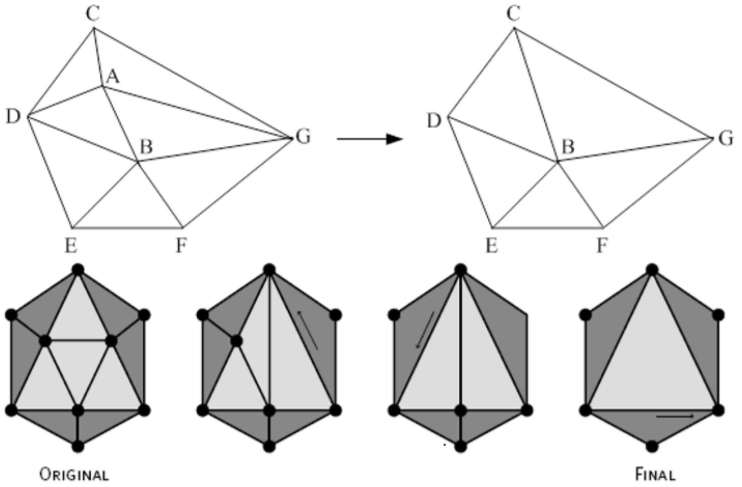


Figure 3.6: The process of reducing polygons. Credits: Tang and Gu [51]

CAD project has to be converted to VR formats. Now, it is interesting to see what the state of the art of this process in commercial software is.

The current situation

Given that, as described above, the idea underlying model simplification is nearly always the same, and being VR a main interest in Industry 4.0, it would be reasonable to think that conversion between CAD and VR formats has been standardized. Unfortunately, this is not yet true. The following question to ask is why. The answer is more qualitative than technical, and it deals with the industries working with the different formats. On the one hand, CAD formats are related to traditional industry and manufacturing. On the other, VR was improved by game development companies, and only later on became interesting for a broader spectrum of businesses. Since the two fields were, and somewhat still are, independent on each other, creating a cross-industry standard format, tool, or approach to bridge the two worlds is likely to take time.
Anyway, whatever the reason, today, to the best knowledge of the author, the only approach to visualize in VR a model designed with industrial software, a third party application has to be used as pointed out by Wolfartsberger [59], and this is not painless in terms of loss of features.

Consequent approach

The content of this section mainly refers to tests that have been conducted with software, models and file formats that are used in this work. However, given that such formats and softwares are widely used in industry, it is arguable that the impressions and conclusions deriving from these tests have a more general validity.

As mentioned in Section 3.1.4, the 3D CAD models used in this work were created with Creo. Therefore, some more attention has been paid to the formats that can be generated as an output from there. Then, as for the VR, Glue and DesignSpace are the programs to be tested. It is relevant to say that these are developed with the Unity game engine, and from here they derive the models that can be given as input.
In order to choose which process to follow to move a model from Creo to either Glue or DesignSpace, it is useful to summarize which formats can be exported by Creo, and which ones can be taken as input by Glue and DesignSpace.

- Input to Glue: **.fbx**
- Input to DesignSpace: **.fbx** (native), .ifc, **.obj** and **.dxf** (both internally converted to .fbx)
- Output from Creo: .asm, .pvz, .igs, .vda, **.dxf**, .neu, .stp, **.stl**, .iv, **.obj**, .slp, .unv, .wrl, .dwg, .emn, .idx, .eda, .gbf, .asc, .asc, .facet, .sat, ._ps, .x_t, .pdf, .u3d, .amf, .tif, .png, .jpg, .eps, .tif, .png, .pic, .zip

Please note that the formats exportable from Creo include some that generate 2D documents, such as .pdf or .png: they have been listed for the sake of completeness of the analysis, but are not useful for it.

From the list above, the reader can note that there is no straightforward compatibility with Glue and, as for DesignSpace, it is possible via .obj and .dxf. Anyway, given that both Glue and DesignSpace accept .fbx as an input, a practical approach was followed. In particular, a free software has been chosen to act as a bridge between the exportable formats of Creo and .fbx. The chosen software to perform the conversion is Blender. The formats it can handle are:

- Importable: .dae, .abc, .bvh, .svg, .ply, **.stl**, .fbx, .glb, .gltf, **.obj**, .x3d, .wrl, .blend

- Exportable: .dae, .abc, .usd, usdc, .usda, .bvh, .ply, .stl, **.fbx**, .glb, .gltf, .obj, .x3d

The reader can see that it is reasonable to export from Creo either in .stl or .obj and export in .fbx. Exporting in .stl is not adviseable, since this format only includes information about the geometry of the surface of the object. It is therefore used for 3D printers and similar applications where no other properties are needed. But in this case study, the more information of the model are preserved granting inspectionability and a good interaction with the user (i.e. exact values of dimensions, mechanical constraints, materials, parent-child relations among parts and assemblies), the better.

From the information above, it follows that the conversion process that has been used to move from a part designed in Creo to its visualization in Glue and DesignSpace has been the following:

1. Open the 3D model of the part in Creo;
2. Export from Creo in .obj format;
3. Import the .obj file in Blender;
4. Export from Blender in .fbx;
5. Import the .fbx in Glue or DesignSpace

Of course, this repetitive format conversion, has its drawbacks.
A first, clearly visible, fault happening in the conversion process, is the loss of textures in the 3D models, either appearing in both Glue and DesignSpace as question mark symbols, as reported in Figure 3.7.
Given that this thesis aims at verifying the concept of usability of VR in a well defined industrial context, this minor technical issue is reported but does not constitute a real impediment to the progress. For completeness, it is also worth mentioning that the version of Creo that has been used to open and export the model is also much more recent than the file itself, and this is likely to have contributed to the generation of minor bugs.

Another obstacle in the usability of DesignSpace has been found in setting the proper scale and orientation of models when building a scene (please note that in Glue you cannot create fully customized scenes, so this problem is not present, and the 3D models, textures apart, are always imported correctly). In particular, DesignSpace, at the moment of importing a model, asks for the up-vector that has been used in the modelling software, as well as its unit

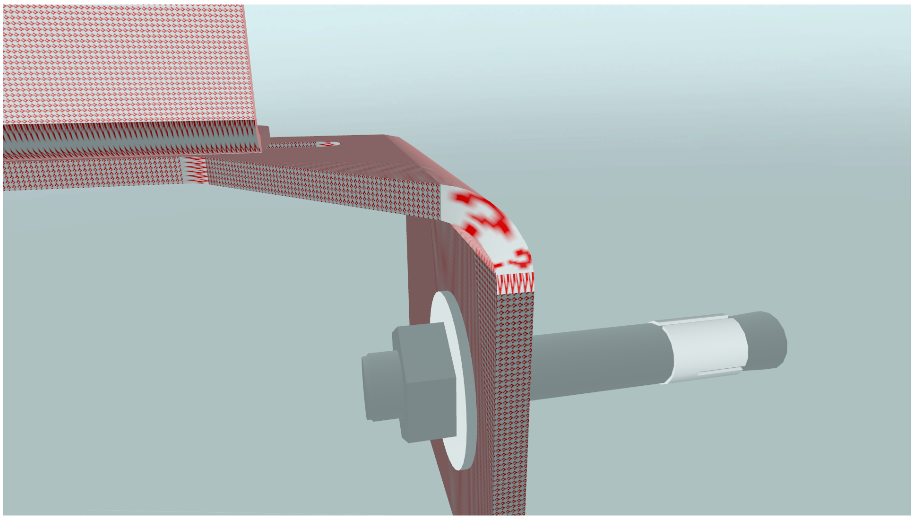


Figure 3.7: Texture loss in DesignSpace

of length. In practice, this feature resulted to fail multiple times, with the consequence that the practical rule is to make multiple tests with the different softwares in use and take note of the settings giving the best results. As for Blender, that was used to design a scene from scratch using the xy-plane as ground, the positive z-axis as up vector, and metres as the length unit, the same settings in DesignSpace resulted in having the scene rotated of 90 degrees in virtual reality and magnified by 100 times (this was checked with the "measure" tool). Consequently, multiple trials have been done to find the proper parameters in Blender to obtain the desired result in VR. The best configuration is reported to act as a guide for eventual further uses:

- Blender: draw using xy-plane as ground, up: +z axis, front: +y axis, unit: m. Before exporting in .fbx, select all the objects in the scene and rotate about the x-axis of +90 degrees. Rescale everything to 0.01;
- DesignSpace: import the model generated as above with unit: m and up vector: z

One more issue, only detectable in DesignSpace since Glue does not offer the recognition of subparts of the models, lays in how such parts are selectable and movable in the virtual environment. This is not a problem by itself but, given that designers often group together components like screws etc, what happens is that trying to move a single screw to simulate an unmounting procedure, actually results in moving undesired parts, as shown in Figure 3.8.

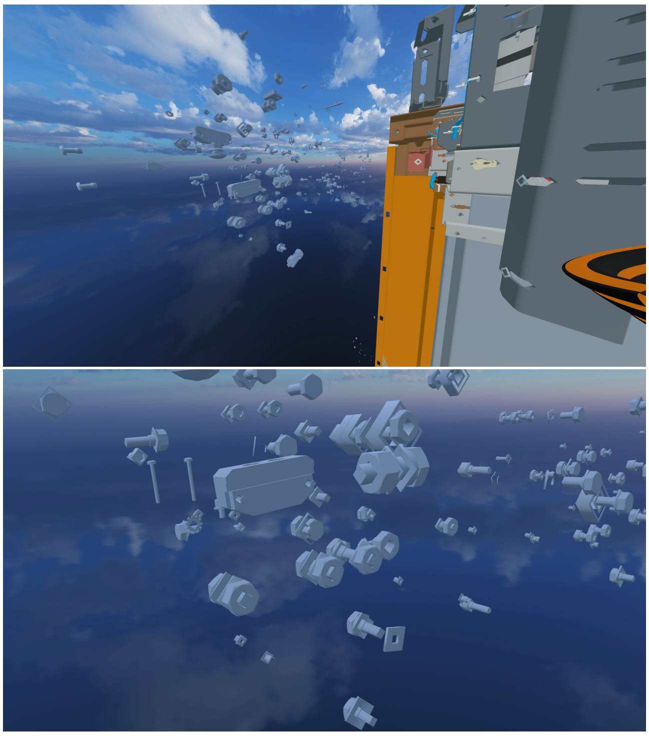


Figure 3.8: All the screws of the upper part of a 3D model moving together

This could be fixed in two different ways. On the one hand, it is theoretically possible, in the long run, to adapt the logic of the CAD to take into account this need, but the effort would probably overtake the benefit of such a change. On the other hand, an "explode" feature could be implemented to break on demand the logic relations among subparts to make each one independent on each other.

The bottleneck

Finally, a comment on the general situation should be done as for the information content of the formats that are used in the conversion process described to move from CAD to VR. As said, CAD models contain the maximum amount of features, and they are converted into .obj which is way simpler. Then, .obj is converted into the VR-compatible .fbx, which is capable of storing more information than .obj. This means that .obj is acting as a bottleneck causing unnecessary compressions and feature losses in a process that is therefore sub-optimal. It follows that whenever Creo will allow to export directly into .fbx will certainly lead to better results.

Chapter 4

Methods

This chapter explains the purpose, context and choices taken on how to perform the work carried out. In particular, Section 4.1 describes the research design and the groups of participants, Section 4.2 explains the procedures followed and Section 4.3 summarizes how data have been analyzed.

4.1 Research design and participants

Section 1.1 has shown which research questions guide the entire process covered by this thesis. The reader has probably noted that all of them are *what*-questions aiming at describing the state of the art of virtual reality utilization in industrial contexts as for design reviews and maintenance training. As reported by Shields et al. [49], this is the typical structure of a *descriptive research design*. In other words, this thesis wants to collect, analyze and show data comparing the results to what previous literature has found. This, together with the limitations reported in Section 7.3, will give new insights and directions for future research.

This thesis involved two different groups of participants: those who were asked to compile a questionnaire which required no experience at all with VR (the reader can find it in Appendix B), and those who took part to the tests and provided comments also on the software under evaluation. The latter reached the former via email on an field-of-work basis: those who took part to tests were encouraged to forward the questionnaire to colleagues, even belonging to different departments, who might have been interested in sharing a thought on the topic.

4.2 Procedures

This paragraph contains information about how participants were reached to take part to the tests, fill the questionnaires and allow to collect data. In particular, the author was first introduced to maintenance methods developers in R&D. This allowed to be in touch with User 1, User 2 and User 3. An employee of 3DTalo had been met before, in the Office of 3DTalo, for an introductory session with DesignSpace. Then, after pre-experimental activities carried out by the author that the reader can find in Section 5.1, tests with both Glue and DesignSpace were made. During these tests, the author encouraged a think-aloud approach and took notes. Participants agreed verbally that such notes would be used to write this thesis. In particular, the general workflow of each test session was reported together with unexpected events, relevant phrases and comments of users, what they found easy and difficult.

After these were concluded, the author sent the questionnaires and some reminders followed. In particular, the survey about DesignSpace and the optimal features of a VR platform to be used for design reviews and training of workers has been sent first to the participants to the test immediately after it. Then, a copy of the second part (asking which features should be implemented with highest priority) was sent to users who work with maintenance method development, having few to forty years of experience, and also to people with several years of experience in engineering. All were encouraged to forward the questionnaire to anyone could be interested in expressing his/her opinion about VR for design review and maintenance training. The questionnaire about Glue was sent only to the participants after the last test with that platform because of the specificity of the questions.

4.3 Data analysis

First of all, since the questionnaire about Glue and the first part of the questionnaire about DesignSpace were only compiled by few users (those who actively took part to test sessions), the related answers were considered qualitatively and were not subject to any analysis that would lead to statistically irrelevant outcomes. Therefore, more attention was given to the second part of the questionnaire about DesignSpace, which allowed to retrieve some quantitative metrics. Open comments have been collected and revised together with the detailed reports of all the test sessions. Given the nature of most of the data collected, meaning Likert values, the chosen approach was to compute mean, mode, median and variance. While the mean is typically the easiest to understand, it is actually the less reliable of the group since it treats as numbers opinions which, in reality, are qualitative. On the other hand, mode and median do not suffer this issue, since the former represents the most frequent opinion and the latter states if the overall response is closer to a positive or negative value. In addition to this, median is way less sensitive to peak values out of an eventual trend than the mean. Finally, variance simply measures how different the answers were from each other. Once mean, mode and median have been computed, the evaluated features can be sorted by each metric obtaining three lists ordered by urgency of development that can be compared to the results found by Wolfartsberger [61].

Chapter 5

Implementation

This chapter illustrates how the methods described in Chapter 4 have been implemented in practice and is structured as follows: Section 5.1 describes the activities done to frame and give theoretical foundation to the purpose of the research. It also reports preliminary activities carried out by the users to be able to use the required VR equipment and to give the author an understanding of how maintenance of elevators works. Section 5.2 describes the tests conducted with Glue and DesignSpace and Section 5.3 is about the approach followed to collect data.

5.1 Pre-experimental phase

This research began on Tuesday, February 25 with a meeting with the thesis supervisor at KONE, expert in innovative maintenance methods and XR. Purpose of the meeting has been informing the author about the current way prototyping, design reviews for maintainability of products and training of maintenance operations are done. From this, the consequent need to explore VR as a way to reduce the number of issued prototypes and the time to market was explicitly declared and the purpose of the thesis clearly set. This meeting also allowed to draft the research questions reported in Section 1.1. The related systematic literature review with its additional research questions was done in parallel to the other activities described in this chapter.

After receiving an explanation of the need for this work, the author was allowed by the aforementioned expert to see the VR training modules KONE had already realized for some of their assets. This quick trial was conducted while constantly being monitored by the expert so as to be ready to intervene in case any motion sickness or safety issue occurred to the author while experiencing the tool for the first time.

Once a basic understanding of what was needed and what the technology was ready to do, the author was allowed to take part to a real maintenance session. The activity occurred inside a building in the city center of Hyvinkää and supervised by a senior engineer. It consisted in performing an overall check of the status of the elevator and show to a peer colleague how to tighten properly a screw determining the friction with which a component rotates. Interestingly, he recorded a video to be shared with his colleagues to supplement and to add clarity to existing paper maintenance instructions.. This confirmed once more the need for a better way of sharing instructions with workers for maintenance operations.
Last activity that has been done before starting to experiment with the multi-user VR software has been a training to learn how to supervise other people while using VR. The author received instructions on how to setup a room for VR activities, how to warn users about sickness and what to do in that case and, finally, on how to pack VR equipment for transportation. This concluded the preliminary activities that allowed to proceed with experimental work.

5.2 Experimental phase

This section describes how tests on VR platforms have been conducted. In particular, focus is given to the overall purpose of the process. Section 5.2.1 reports about the tests carried out by the author alone, while Section 5.2.2 is about the sessions that followed involving more users.

5.2.1 Individual tests

The author received licenses for two different multi-user platforms, namely Glue and DesignSpace. An overview of these can be found in Section 3.1. First thing to do, in order to have a degree of understanding of such softwares that allowed to setup tests for experts coming from the field of maintenance, was to get familiar with them. Therefore, the author spent some time to understand the optimal use cases for each platform and get confident enough with the different interfaces. Given that both Glue and DesignSpace are still under constant development, this phase included giving numerous feedback to the respective software houses. Results on the optimal use for each of them are discussed in Section 7.1.

5.2.2 Multi-user tests

After reaching a satisfying understanding of the potentialities of each platform, the author arranged meetings with experts in maintenance methods and maintenance method development, so as to have their opinion on the usability of such tools in their actual state of development and, above all, determining which are the needed features that they should implement to be optimal for design review and maintenance training. Tables 5.1 and 5.2 report the days in which tests sessions were held and when questionnaires and reminders sent. The last answers were collected on June, 12 for DesignSpace and June, 16 for Glue.

Date	Software tested	N participants
30/03/2020	Glue	4
01/04/2020	Glue	4
06/05/2020	DesignSpace	2
08/05/2020	DesignSpace	2
13/05/2020	DesignSpace	4
25/05/2020	DesignSpace	4
01/06/2020	DesignSpace	5
12/06/2020	Glue	3

Table 5.1: All the test sessions

Date	What
01/06/2020	Questionnaire about DesignSpace sent to participants of test held on this day
05/06/2020	Second part of the questionnaire about Design Space sent to experts in maintenance method development and engineering
08/06/2020	Reminder for questionnaire about DesignSpace
12/06/2020	Questionnaire about Glue sent to participants of test held on this day
15/06/2020	Reminder for questionnaire about Glue

Table 5.2: Questionnaires and reminders

Participants Participants to the tests were selected in KONE Technology and Innovation (KTI). Two of them were experienced with maintenance method development, while each one had a different degree of expertise with VR. Tables 5.3, 5.4 and 5.5 give relevant information on the users, the hardware at their disposal, and to which activity they took part. Values for questionnaires only report effective respondents, while those on the tests the total number of participants, even if not present during all the sessions. Please notice that the author is inserted in the tables for completeness in reporting all the people inside the VR scenes during the tests, but the data collected do not refer to him. The same goes for the 3DTalo employee, that was allowed to attend only the test sessions with DesignSpace to let him collect feedback for the development of their platform. Finally, by VR-Ready laptop the author refers to a Windows pc having at least 16Gb RAM, 15-inch display, discrete GPU and Core i7 processor.

Activity	Participants	N
Tests with Glue	Author, Users 1, 2, 3	4
Tests with DesignSpace	Author, 3DTalo employee, Users 1, 2, 3	5
Questionnaire on Glue	Either User 2 or 3	1
Questionnaire on DesignSpace (Part 1)	Users 2 and 3	2
Questionnaire on DesignSpace (Part 2)	Experts in maintenance method development and engineering	16

Table 5.3: Activities and participants

Choice of the model For all the tests, the model of the doors of an elevator was used. Reason for the choice of such a part lays in the fact that it is complex enough to inspect its internal components (e.g. gears and screws) during a maintainability review and, at the same time, to verify if the space in which workers can move while installing or repairing it in a real site is sufficient. This latter situation assumes that the model of some walls with a hole to install the elevator is designed and placed in the VR scene.

On the one hand, while Glue does not allow to draw custom scenes but only

User	Role or experience	Previous experience with VR
Author	Facilitator	Experienced with both VR, and Glue and DesignSpace
3DTalo employee	Observer	Experienced with VR and DesignSpace
User 1	Experienced with innovative maintenance methods and XR	Experienced with VR, had some previous experience with both Glue and DesignSpace
User 2	Experienced with maintenance method development	Never used VR
User 3	Experienced with maintenance method development	Never used Glue or DesignSpace. Had completed the VR training modules available in KTI

Table 5.4: Participants to the tests

User	VR-ready laptop	HMD
Author	Yes	Samsung Odyssey
3DTalo employee	Yes	HP Reverb
User 3	Yes	HTC Vive
User 2	Yes	HP Reverb
User 1	Yes	HTC Vive

Table 5.5: Hardware used in the tests

to import any 3D model inside predefined environments, DesignSpace allows to create entirely customized scenarios. Therefore, DesignSpace was chosen to perform most of the tests. In particular, the model of an office was drawn in Blender. In order to allow maximum flexibility in the tests, a wall was purposefully left with a hole where any model of doors could be inserted and an entire room was also left empty. Moreover, the floor was extended also outside the office itself so that there was enough space for any extra activity that could be done, especially during tests aimed at teaching how to use DesignSpace. The reader can refer to Figure 3.5 to understand the shape of the virtual office used in the tests.

Structure of the tests As for tests made inside Glue, every meeting started in Microsoft Teams to agree which scene should be entered. Then, once inside the VR, either the audio in Glue or Teams was muted to avoid echos. Meetings had different purposes and duration and, whenever the latter exceeded one hour, a break was taken. Given the few possible interactions with 3D models, there has been no final test to evaluate how much users had learnt. On the contrary, sessions were focused on getting familiar with the interface at first, and then in understanding the optimal use case of Glue. In particular, the last session held in Glue simulated a workshop in which User 2 and User 3 had to group post-its reporting some features that VR platforms can implement according to the priority of development. The reader will probably notice this is the same purpose of the second part of the questionnaire about DesignSpace. However, in this case, focus was on the feasibility of a workshop in Glue rather than on its outcome. Finally, after the last session, Users 2 and 3 were asked to fill a questionnaire that the reader can find in Appendix A. Table 5.6 illustrates all the sessions held in Glue with participants and purpose of the test, while Figure 5.1 shows a participant wearing an HTC Vive headset during a test. Figures 5.2 and 5.3 are taken from a workshop held in Glue.

Date	Users	Reason
30/03/2020	Author, User 1, User 2, User 3	Setting up Glue and introducing participants to the software
01/04/2020	Author, User 1, User 2, User 3	Showing all the commands and potentialities of Glue
12/06/2020	Author, User 2, User 3	Evaluating Glue for workshops and collecting feedback

Table 5.6: Practice and test sessions in Glue

In the case of DesignSpace, all the tests followed a similar flow. In particular, every meeting started with a call in Microsoft Teams, where the author could share the string allowing the remaining participants to join the VR session in DesignSpace. When all the users were inside the scene, audio in DesignSpace was muted and Teams was used for voice communication. This was done to avoid echos. Meetings had various durations. Therefore, a break was always taken roughly after 40 minutes from the beginning of the sessions. Users have been asked to express their opinions on the features they were testing, both as for what they were finding difficult to do, what they appreciated and what they felt was missing. In general, the author encouraged a think-aloud approach. When any sickness due to VR happened, participants immediately

Figure 5.1: A participant attending a test session with HTC Vive

Figure 5.2: A user writing on a whiteboard in Glue

Figure 5.3: A workshop held in Glue

interrupted the session to take a break.
During those meetings whose purpose was to introduce users to DesignSpace, the first part of the session was always meant to teach them how to move around the scene and get familiar with the controllers. This has been necessary since most of the users were not experienced or confident enough with VR, and even those who had already tried VR applications preferred to revise the basics. The second part of the sessions focused on the commands and actions that can be performed in DesignSpace. In particular, one by one, the author showed the tools to the other users so that they had time to follow the instructions and were then let free to experiment by themselves for some minutes. After four practice sessions, a test was carried out one week after the last training. Here, the author described orally some actions that the remaining users were then required to perform autonomously. In case a participant needed help, another was encouraged to offer support. This also allowed to evaluate the effectiveness of DesignSpace as a collaboration tool. In case none of the participants felt confident enough with the task to complete, the author provided support. No time limit was given, and no metrics such as time of completion or number of errors have been noted down. Reason for these rules is that the purpose of the test was not to collect quantitative metrics, but rather understanding the actual value of DesignSpace as for design reviews and either validating or correcting the knowledge acquired from the literature. One more reason for the test has been having the users express their opinions as for which features they felt are needed in a multi-user VR platform to be optimal for their needs. During all the sessions, both trainings and test, the author collected notes reporting relevant phrases by the participants, difficulties that arose and any other relevant fact regarding what they liked or not and found easy or difficult. The reader will find a detailed presentation and discussion of results in Chapters 6 and 7. Finally, participants were required to fill a questionnaire after the test session that allowed to collect their opinions. Users participating to the survey belonged to different groups. First of all, User 2 and User 3, taking active part in the final test session, received the full questionnaire immediately after the test was concluded on 01/06/2020. User 1 received only the second part as she could only follow the session in desktop mode. Such reduced questionnaire was then sent also to people working with maintenance method development and experts in engineering on 05/06/2020, as they have an understanding of what needs to be checked to assess the maintainability of products. Table 5.7 reports an overview of all the sessions held in DesignSpace, with the purpose of each one and the users involved, while Figures 5.4 and 5.5 shows users collaborating and inspecting a model during a test in DesignSpace.

Date	Users	Reason
06/05/2020	Author, User 2	Introducing User 2 to VR and DesignSpace
08/05/2020	Author, 3DTalo employee	Reporting feedback to 3DTalo
13/05/2020	Author, 3DTalo employee, User 1, User 2	Teaching the basic commands of Design Space to User 2 and User 1
25/05/2020	Author, 3DTalo employee, User 1, User 3	Teaching the basic commands of DesignSpace to User 3 and improving confidence in DS of Users 1
01/06/2020	Author, 3DTalo employee, User 1, User 2, User 3	Test to collect feedback from users

Table 5.7: Practice and test sessions in DesignSpace

Figure 5.4: Users collaborating in DesignSpace

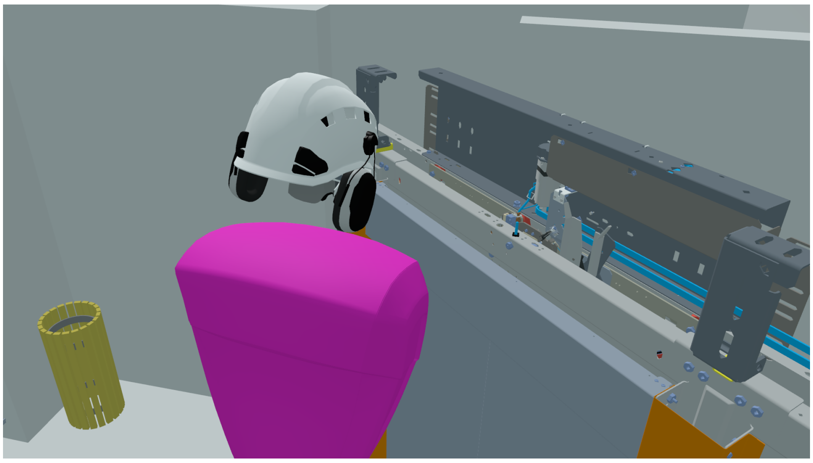


Figure 5.5: A model inspection in DesignSpace

5.3 Measures

This paragraph reports which approach has been followed to collect data. First of all, during all the test sessions, both on Glue and DesignSpace, the author took notes including any issue encountered and relevant comments made by users during the tests. These, together with all the other findings of the research, are also reported in Chapter 6. Second main tool used to collect data have been questionnaires. In particular, one was sent after tests with Glue, and another after the sessions with DesignSpace. Starting from the former, that the reader can find in Appendix A, this was designed with the only intention of understanding the possible use cases of Glue itself in R&D or if, on the contrary, such tool has some drawbacks requiring further improvement. Therefore, it was filled only by the participants to the tests and included questions asking to evaluate the effectiveness of the platform in different scenarios using a Likert scale and, in the end, open fields to suggest other possible use cases and free comments were added. The questionnaire started with a declaration of the purpose of the questions. A broader discussion is needed for the questionnaire following DesignSpace. The purpose of this questionnaire was threefold: providing valuable opinions of maintenance method development experts about DesignSpace, understanding which features should be included in a VR platform for design review and maintenance training, and either confirming or going against results found in literature. Such a questionnaire, that the reader can find in Appendix B, was built so that it could be compiled both by the users who had taken part to the test and other workers involved in product development. In particular, the questionnaire is divided in two parts. The first one contains questions specifically referred to DesignSpace, while the second is structured to understand which features users think are needed the most. Therefore, those who did not participate to the test sessions in DesignSpace described in Section 5.2 were only asked to fill the second part. Moreover, fields allowing to express free thoughts followed the multiple choice questions of both parts.

A disclaimer at the beginning of the questionnaire explicitly informed about the purpose of the survey. The only personal data collected were age and the professional role. As for the questions, while those in the first block have been written from scratch, the second part followed a different approach. Since this thesis aims at extending and either validating or going against previous findings in literature, the features mentioned by Wolfartsberger [61] have been included among those to evaluate. Others have been added as they were mentioned by free comments of participants during the test sessions. Moreover, insights on a broader spectrum of features are likely to bring more value to the research and clearer directions for future development.

As for the tool adopted for both questionnaires, Google Forms was used. Reason for the choice of this platform lays in the fact that it automatically displays the results of each questions with graphs and generates a spreadsheet with all the answers, making further analysis quite simple. Moreover, questions in both surveys belonged to three categories: 5-point Likert-scale, binary answer (yes/no etc.) or open questions. The first have been chosen to obtain a degree of preference allowing to sort qualitative impressions otherwise difficult to analyze, the second when a sharper opinion was required and the last to allow anyone to express any view that could bring some value with thoughts that the author might not have considered.

Chapter 6

Results

This chapter contains the uncommented results of the research, including the surveys and free comments by participants during the tests. In particular, Section 6.1 contains the results of the questionnaire about Glue and Section 6.2 those about DesignSpace.

6.1 Questionnaire about Glue

This questionnaire was sent to User 2 and User 3, only compiled by one of them. Questions are reported in italics and compulsory questions marked with an asterisk.
Your Age Answer: 5-year wide age slots.* Answer not shown for anonymity.

*What is your role?** Answer not shown for anonymity.

Do you think Glue can be useful in KONE? Answer: Yes / No* Yes

If yes, which use case would you suggest? share the information, keep collaboration meeting and going through eg. explain the outline when working to documents.

If no, why? No answers.

Then users were required to evaluate how useful Glue can be in different situations on a Likert scale from 1 (not useful) to 5 (very useful). Evaluating all the features was compulsory. Table 6.1 shows the answers.

Do you think KONE should explore more the potentialities of Glue? Answer:*

Situation	Answers
Product showcases	4
Virtual meetings	4
Virtual workshops	4
Design inspections	4
Training for maintenance operations	4

Table 6.1: Use cases for Glue

Yes / No Yes.

If yes, what do you suggest? For the wide use.

Any additional comment you want to share? I think we should open the project for deeper investigation in how many possible the use in this program.

6.2 Questionnaire about DesignSpace

The first part of the questionnaire was only compiled by two participants, User 2 and User 3. Questions are reported in italics, answers are separated by a slash. Compulsory questions are marked with an asterisk.

Age Answer: 5-year wide age slots.*: 56-60 / 36-40

How expert were you with Virtual Reality before these tests? Possible answers: I was totally new to Virtual Reality / I knew about it but I had never tried it personally / I was somewhat familiar with it, but used it rarely / I was an expert* Same answer for both: I knew about it but I had never tried it personally

If you took part to the test session on Monday, June 1st, please share a quick thought. There will be more specific questions, but any direct feedback on that session, regarding anything, is more than welcome. Only one answer: Actually there was still quite many starting problem.

Did the remote work of these days affect the effectiveness of working with virtual reality? Please, explain. For my side no. / Getting access to VR equipment was more difficult due to restriction to office access (note of the author: due the Covid-19 situation office access was restricted).

Have you ever experienced any sort of discomfort with VR? Answer: Yes / No* Yes / No.

If yes, what? Seasickness.

Do you think the cables of the headset are annoying? Answer: Yes / No Yes / No.

Please state which headset you are using. HP Reverb / Do not know.

How satisfied are you with your headset? Did you experience any issue? Please explain. Headset itself not so much, but handset (note of the author: controllers) is not so good for me. / Headset was OK. Getting goggles sitting correctly in front of my eyes to have clear image was a bit challenging.

How would you define the ease of use of placing objects in DesignSpace? Answer: Likert scale from 1 (very easy) to 5 (very difficult)* 2 / 3

Any free thought on the ease of placing the objects? Maybe if better handset is available then maybe then is better, but not big issue. / Some kind of indication when object is contacting to other would be good. Also when trying to make "model" with objects there should be indicator when items are aligned or centered to each other.

How precisely do you think you can set measures of the objects you create in DesignSpace, for example the sizes of a cube or the diameter of a cylinder? Answer: Likert scale from 1 (not accurately) to 5 (very accurately)* 2 / 4

Any free thought on selecting the dimensions of the objects you create? I do not see any big issue for that, maybe need in future test the different handset. / Somekind of set value would be helpful. Other option is to make "steps" bigger when creating item so the dimension does not change so fast and easily but requires bigger hand movement. Perhaps "autostop" to suggest even dimensions? (even tens, hundreds..)

Did you find it difficult to learn how to move in DesignSpace (teleporting and flying)? Answer: Likert scale from 1 (very difficult) to 5 (very easy)* 4 / 5

Any free comment on moving inside DesignSpace? Only if we get more logistical handset maybe but not big issue only need more practice. / Flying might cause nausea.

Do you think taking measures inside the environment is useful for design review and maintenance training? Answer: Likert scale from 1 (not useful) to 5 (very useful)* 3 / 5.

Any free comment on taking measurements in Design Space? In maintenance we need more measurement for space and access. / Automatic "pick" to edges or corners would help. At the moment it is very "close enough" to take measures for example from edge to edge of one surface.

The built-in camera allows you to take pictures from inside the scene also including measures and with the chance to remove the perspective effects and also to display only the wireframe making up the objects (the lines you would see in a CAD program). The screenshots taken are saved into your laptop. Do you think this feature is useful? Answer: Likert scale from 1 (not useful) to 5 (very useful)* 3 / 5.

Any free comment on the camera? No answers.

The "hide object" tool allows to inspect parts that are inside the model. Please rate how useful you think this tool is. Answer: Likert scale from 1 (not useful) to 5 (very useful)* 3 / 5.

Any free comment on the "hide object"? we need better model, then we can remove smaller parts, no so big assemblies. / Structure of the model caused most of the issues using this feature.

Scaling yourself allows to make closer inspections of small details and parts. Please rate how useful you find this feature. Answer: Likert scale from 1 (not useful) to 5 (very useful)* 4 / 5.

Any free comment on the scale feature? Only one answer: Good option.

DesignSpace allows to create cubes, cylinders and tubes inside the scene. Do you think it is a useful feature? Answer: Likert scale from 1 (not useful) to 5 (very useful)* 2 / 4.

Any free comment on drawing cubes, cylinders and pipes? I think not needed for creation the method. / Setting dimensions and "attaching" item to other items needs work.

Saving changes to the scene, including any modification to the models, at the moment is a bit buggy and is not reliable. How urgent do you think a fix to this feature is? Answer: Likert scale from 1 (not urgent) to 5 (very urgent)* 5 / 5.

*Adding external objects, such as models of elevators, is possible. However, if you want to move some subparts (maybe you want to move apart some screws or the doors to simulate an assembling procedure) the subparts are grouped together as in the CAD model. This means, for example, that all the screws of a part will move together and so on. How do you think this affects the usability of DesignSpace in maintenance training and design reviews?** This affect the lot of. / It completely demises the purpose and advantage of the feature.

When you want to move subparts of objects like screws, you cannot grasp them. Instead, a ray is cast from the controller and that acts as a manipulation tool. Do you think it is a good way of interacting with the objects? Answer: Yes / No* Yes / No.

Any free suggestion about how to move objects? Not so important feature. / Using ray was confusing sometimes. Object jumped very far and it was very difficult to get it back near. Turning and rotating objects takes a lot of practice since controller reacts to wrist and arm movement.

DesignSpace does not have any collision detection system when the user moves and hits objects. This means, for example, that you can go through walls and your hands will not receive a feedback when you try to perform any action in a space which, in reality, is not available. Do you think it would be important to have this collision detection? Answer: Likert scale from 1 (not important) to 5 (essential)* 1 / 5.

If you want to elaborate a bit your answer, please write your thoughts here. This is good option. / Placing object to each other to make constructions would be a lot easier.

Please rate how user friendly you found the interface and commands in DesignSpace in general. Answer: Likert scale from 1 (very difficult to approach) to 5 (very user friendly)* 3 / 4.

At the moment, DesignSpace only supports the real-time synchronization of objects that are created inside the scene. This means that cubes, cylinders *and pipes can be added and edited contemporarily by more users. On the contrary, external models like those of the elevators can be added, but all the modifications that anyone does inside the scene, the others will not see them. Please write your opinion on how much you think this lack of synchronization affects the usability of DesignSpace and its multi-user feature.** A lot. / Not seeing changes others made to model kind of takes the whole idea of using VR as design meeting tool away.

*DesignSpace currently has no way to display either written or video or voice instructions on how to perform an action. How do you think this affects the applicability of the application in training maintenance procedures?** Not so much. / This makes good training and facilitation even more important. It can be managed if person with good knowledge and skills is available to support meetings or at least give training sessions.

The picture represents how DesignSpace could be used for layout planning and routing (making drafts of where to place machineries and where cables should go). Do you think this could be a useful application of the software? And in which other contexts do you see a potential for DesignSpace? Only little for method creations, more for choose the tool. / System mechanical engineering meetings to check and design interfaces, components of system.

Do you think DesignSpace is effective in simulating cable routing? Answer: Likert scale from 1 (not at all) to 5 (yes, a lot)* 3 / 4.

Do you think DesignSpace is effective in layout planning? Answer: Likert scale from 1 (not at all) to 5 (yes, a lot).* 3/5.

Which of these is closer to your opinion? Possible answers: Design Space requires some training to be used proficiently / Design Space can be used with no training* Both answered: Design Space requires some training to be used proficiently

Which of these is closer to your opinion? Possible answers: If I did not use Design Space for a while, I feel I would forget how to use it. / I think I could use Design Space well even every once in a while.* If I did not use Design Space for a while, I feel I would forget how to use it. / I think I could use Design Space well even every once in a while.

Do you think DesignSpace is ready to be used inside KONE? Answer: Yes / No* Both answered: No.

The second part of the questionnaire, that reached more people, was filled by 16 participants with the following characteristics:

age: average: 42.7, standard deviation: 9.4

How expert are you with virtual reality? 9 (56.3%) I am somewhat familiar with it, but use it rarely, 6 (37.5%) I know about it but I never tried it personally, 1 (6.3%) I am an expert.

Then participants were required to evaluate the need for some features using a Likert scale from 1 (not necessary) to 5 (essential). Each one was required to be evaluated compulsorily. Synthetic results are shown in Table 6.2, where the results of the work of Wolfartsberger [61] have been included, whenever available.

Feature	mean	mode	median	st. dev.	Wol.
Select parts to interact	4.75	5	5	0.45	A
Break an assembly into parts	4.31	5	5	0.95	A
Highlighting parts	4.50	5	5	0.63	A
Resetting position of objects	4.44	5	5	0.73	-
Move parts following constraints	4.56	5	5	0.89	A
Camera	4.44	5	5	0.81	-
Alternatives to teleport	3.87	5	4	1.15	-
Scaling	3.94	5	4	1.24	B
Group parts into an assembly	3.94	3	4	0.85	-
Measurement tool	4.13	5	4	0.96	C
Set precise dimensions of objects	3.69	4	4	1.01	-
Set precise pose of objects	3.69	4	4	0.87	-
Show tools instead of controllers	3.63	5	4	1.50	C
VideoCamera	3.88	4	4	0.96	-
Importing documentation	3.44	4	4	1.15	-
Audio instructions	3.56	4	4	1.09	-
Text instructions	3.94	4	4	1.06	-
Sectional view of parts	3.56	3	3.5	1.09	C
Haptic feedback	3.06	3	3	1.06	-

Table 6.2: Features to implement, sorted by median

Additional comments left by participants follow:
It would be helpful in the virtual world to add the possibility to do wrong.

This would act as a safety learning feature. So if not done correctly it would brake down, it would not function correctly, a danger indication that something would go wrong if continue.. etc. /
I think we are in good path but need still development work, with models and design space should work better together. /
Lots of potential for our industry where there is a lot of human interaction during assembly and maintenance. /
Usability and need for different features depend on the actual use-case, e.g. training´, fault finding, method development, etc.

Interestingly, no metric has been below 3. However, given that the work of Wolfartsberger [61] did not describe if and how priority of development was evaluated before grouping features into three different demand levels, the only reasonable comparison that can be done is between his ranking and the features of Table 6.2, sorted by median. Mean is given little relevance as explained in Section 4.3.

Chapter 7

Evaluation

This Chapter is organized as follows: Section 7.1 discusses the results presented in Chapter 6, Section 7.2 answers the research questions and is followed by Section 7.3 explaining the limitations of this thesis. Finally, Section 7.4 suggests directions for future work.

7.1 Discussion of results

Given the amount of topics to comment on, this section is structured to follow the same sequence of the tests conducted. In particular, Section 7.1.1 reports about what was understood already after pre-experimental work, while Section 7.1.2 is focused on what could be concluded thanks to the tests carried out with experts.

7.1.1 Comments on pre-experimental work

Trying the training modules already available in KONE gave a first important result: VR is mature enough to be used for design inspection, training of workers and, in general, for industrial and professional use. Moreover, the limitations experienced in using paper instructions for maintenance by the senior engineer mentioned in Section 5.1 suggest that VR could, in the future, be also used to substitute traditional documentation by, for instance, implementing a database of 3D recorded VR sessions of maintenance experts performing maintenance of machines. These sessions, if accessible from mobile devices and integrating the chance to orbit around the part to change the point of view, would allow to avoid ambiguity given by the 2D visualization of paper manuals. Finally, receiving a training to supervise the usage of VR allowed the author to focus on what can go wrong during a session as for the safety: it is often the case that users, especially if beginners with VR, can get hurt in different ways. This happens especially if VR is used while standing in a room and moving in the scene by walking instead of teleporting. A first thing that may go wrong is the user hitting the real walls of the room he/she is in, or trying to jump to reach virtual objects that would require other actions, for instance a light bulb pending from the virtual ceiling to be substituted. Secondly, it is quite common that who is in the virtual scene forgets about the cables connected to the headset, making the risk of stumbling into them significantly higher. Finally, if the HMD is not calibrated, it may occur that the virtual scene starts to tremble, leading in short time to motion sickness. Therefore, it is important to be aware that the only safe solution is to take off the headset.

7.1.2 Comments on experimental work

A first consideration can be done regarding *how* this research has been conducted. While, as pointed out in Section 2.3, the majority of the studies on VR applications for industry does not consider the opinion of final users, this work is widely focused on the thoughts of experts in the fields of maintenance and product development.

Individual sessions Section 5.2 mentioned that the author spent some time to get familiar with Glue and DesignSpace before choosing how to structure the tests that followed. As a matter of fact, Glue immediately proved to be more graphically appealing than DesignSpace which, on the contrary, allows a much deeper interaction with 3D models. Therefore, despite the fact that both integrate multi-user capabilities, their optimal use case is inherently different, and the author chose to investigate the potentialities of the former especially for virtual remote meetings and workshops and the latter for design inspections. Moreover, since both platforms are still under development, the author has often been in touch with the technical support of both software houses.

Tests in Glue and questionnaire Similarly to the sessions held in DesignSpace, participants were professionals in maintenance with no expertise in VR. During the tests in Glue, they appreciated how well models and scene are rendered in VR, but complained about the little interaction that can be done with 3D objects. However, a user commented that *for workshopping this works quite well and this seems a very good place to present and discuss visually things*, but mentioned the lack for a tool to take private notes during a meeting and underlined that having the chance to open a web browser in the scene that cannot be shared with others reduces significantly its utility. Moreover, during the last virtual workshop, comparing the desktop mode of Glue with respect to the one of DesignSpace, a participant said that *from laptop it is not utterly awful. Let's say it is 80% good.* In short, tests showed that Glue is appreciated as a workshopping tool. The only answer to the questionnaire suggested that the use of Glue should be further investigated, especially to hold meetings where to discuss the outline of projects.

Tests in DesignSpace and first part of the questionnaire Users involved in the tests were both experts in maintenance method development, but none of them had tried VR before. One of them said that he found it challenging to place the HMD properly in front of the eyes, and later also experienced seasickness caused by fast movements inside the scene. This seems to suggest that hardware can be further improved, as confirmed by the fact that it was also reported that cables were annoying and the controllers not much appreciated.

Moving the focus to DesignSpace, users reported that the way in which objects are placed on the scene can be improved. For instance, they wished to be notified when you try to place a model that is colliding with something else. Having the chance to snap the position to relevant locations (i.e. centered, aligned to something) is also something users were missing. In particular, during the fourth session and referring to a 3D model, a user said that *it was quite difficult to place the elevator because it was too close to me. [...] I almost just dropped it, I could not place it where I wanted.* Similarly, they complained about lacking the chances to set precise dimensions of objects in the scene and having a measurement tool that snaps to edges and corners. For the latter feature, one commented *this is something I am really missing here. Now it is like a more or less thing.* The camera to take screenshots was overall appreciated together with the option of scaling the size of the virtual user: a participant, during a test, commented that *it is quite nice to see inside the doors. [...] This is how we can use it (DesignSpace) when we plan to replace some parts.* Again, one of the users, during the fourth session, after shrinking himself spontaneously started to take measurements, confirming that, if the measurement tool is improved, DesignSpace can be effective for design reviews. Other criticisms went towards how parts of assemblies often reflect the hierarchy of the CAD drawing, causing, for instance, all screws moving or being hidden together. In addition to this, during the last session, participants complained about an excessive simplification in the rendering of custom CAD models in the scene: referring to a known component, they com-

mented that *this part is supposed to be round but looks squared.* Moreover, not being able to save the work on the scene caused large disappointment together with the fact that synchronization between users only works for some actions. However, adding elementary geometry and custom 3D models was generally appreciated. Simulating layout planning and cable routing was also judged positively.
When asked about their willingness to have audio, video, or text instructions to guide someone on how to perform an operation, users had very different opinions. One showed almost no interest in the feature, the other underlined that this would make DesignSpace an effective training tool. In particular, at the end of the first practice session, one commented that multi-user capabilities not only are valuable to collaborate in the scene for industrial purposes, but also facilitate the learning of the platform itself if one of the participants is an expert.
As for the user interface and experience, the overall opinion was positive. A user remarked that displaying the buttons of controllers with different colors made it easier to refer to them when asking for help, but he also said that adding the chance to move with joysticks would be better. Anyway, in the questionnaire one of the users reported that casting a ray to select, move and rotate objects is an ineffective approach. Users agreed on the fact that DesignSpace requires some training to be used proficiently, and one also added that he feels that he would forget how to use it if not practicing often.
Finally, both users concluded that DesignSpace still requires some development before its potentialities are fully reached. More comments were made regarding other features but, since an evaluation was required to more participants in the second part of the questionnaire, the reader will find them discussed in the next paragraph.

Second part of the questionnaire The second part of the questionnaire, aimed at understanding which features should be included in an optimal multi-user VR platform, was answered by 16 participants, aged 42.7 on average with a standard deviation of 9.4 years. Of them, only one is an expert of VR, 6 had heard about VR but have never tried it, while the remaining 9 use it rarely. Therefore, a good spectrum of relevant users took part to the survey.

Commenting first on those features that were also found in previous literature [61], Table 6.2, in which they are sorted according to the median of the answers to the questionnaire, shows that the features mentioned in previous literature also appear in descending order of priority of development. This is true regardless of the logic behind the sorting of Wolfartsberger. In

particular, features he marked with an A, appear in this research with both median and mode being 5. Then, features marked with either B or C correspond to features having at least one value less or equal than 4 in this study. Concluding the comparison, while the most desired features (selection and highlighting of parts, breaking and assembly and moving parts according to constraints) and least required (sectional view of parts) features have a direct correspondence between this and previous work, what is in the middle of preferences varies as for how much users require it: scaling, measurement tool and showing tools instead of the default controllers all resulted with a mode of 5 and a median of 4, but for Wolfartsberger they received priorities of B, C and C, respectively.
In particular, highlighting parts is required with the highest priority considering both previous studies, mean, mode and median. The same goes for the chance of moving parts according their mechanical constraints. Surprisingly, none of these is currently implemented in either Glue or DesignSpace. The survey seems to suggest that haptic feedback is not considered an urgent need, and this goes in contrast with both what Users 2 and 3 reported during the test sessions and previous literature illustrating the benefits of such implementation [1] [18]. This unexpected result may be due to the fact that most of the participants to this survey have little experience with VR. The author argues that if they had had more experiences with the technology, this answer would have been different.

Looking at the values of standard deviation in Table 6.2, the reader can notice that the highest values correspond to showing tools instead of default controllers (1.50), scaling the size of the virtual avatar (1.24), having alternatives to teleport (1.15) and importing documentation to be consulted on the scene (1.15). This means that participants had very different opinions with respect to each other. The author believes that, even though each feature was explained in the questionnaire (fully available in Appendix B), this is because of the degree of specificity of these features that one who has never tried VR probably struggles to understand. On the contrary, the highest level of agreement (i.e. low standard deviation) was obtained by selecting and highlighting parts (0.45 and 0.63, respectively), followed by resetting the position of moved objects (0.73). Not surprisingly, the first is essential to interact with anything, the second has been required by everyone to better interact with other users on the scene showing what someone is referring to when talking, and the last one places back items that, for instance, could be removed from an assembly to inspect them. However, both the second and the third one are not present in Glue and DesignSpace.

After mentioning those features that were also discussed in the previous literature, some comments can be made on the entire set listed in Table 6.2. Here, the focus will be on mode and median of the opinions of the interviewees, while the mean is left apart for the reasons discussed in Section 4.3. In particular, while breaking an assembly into its subparts is required with the highest priority, its converse, meaning grouping parts into an assembly is not considered urgent, and received a mode of 3. Setting precise values for pose and dimension of objects was judged of average importance, but previous literature not even mentioned it. The same is true for having a videocamera and audio / video instructions or importing documentation on the scene. The feature receiving the worst evaluation in this study, i.e. haptic feedback, was not mentioned by Wolfartsberger. Interestingly, the camera is very appreciated but did not appear in previous literature, and the same goes for resetting the position of objects and having alternatives to teleport.

Finally, some words about the comments left in the questionnaire. One of the interviewees suggested, probably referring to training applications, to add the chance to do wrong. This approach was followed by Zywicki et al. [68], who built a the prototype of a VR platform allowing to learn by trial and error. Similarly, Qu et al. realized an application in which, if the user repairs a faulty system ineffectively, he/she is required to fix it again to restore normal working conditions [42]. Another user pointed out that the set of optimal features is likely to vary among different use cases but, in general, VR seems welcome among the interviewees.

7.2 Answers to research questions

This part concludes the study answering the research questions formulated in Section 1.1 and offering hints for future work.

Which features are needed in a virtual reality platform to allow an efficient design review for the maintainability of products?
Referring to Section 7.1.2 and Table 6.2, it is clear that some features are desired more than others. In particular, the development of a multi-user VR platform for design review and training for maintenance procedures should start from implementing the chance to select and highlight assemblies, parts and sub-parts, that should be movable according to their real mechanic constraints. On the same level of priority, resetting the position of items that have been moved is desired as much as a camera to take screenshots of what is happening inside the scene. The chance to notify a user when making er-

rors in a procedure has been suggested but would require further studies. On a lower level of priority, experts wish to have alternative ways to move other than teleport, breaking and forming assemblies into / from parts, scaling the size of the avatar, measuring tools and showing realistic instruments when simulating industrial procedures. All the other investigated features are required with less urgency. These include setting precisely size and pose of objects created on the scene, a videocamera, importing documentation and having audio and text instructions on how to complete a procedure. The least desired features are haptic feedback and sectional views of parts.

What is the readiness of virtual reality to enter industry?
Overall, both literature and experiments reported in this thesis showed that users are enthusiastic about the adoption of VR in industry. However, this willingness to adopt the technology is often based on either demos or sharp software whose quality is not high enough to match industrial standards. Andaluz et al. reported that the quality of the application shown in tests has an impact on the perceived value of the technology as a whole [3]. In particular, as for the platforms that have been tested in this thesis, DesignSpace showed to require improvements but still allowed to carry on the research proficiently determining which features are missing. On the other hand, Glue appeared more ready to enter industry, even though with optimal (workshop-like) use cases slightly different from those analyzed in this thesis. Summing up, industry is ready and waiting for stable platforms to be integrated in the daily operations.

What is the effectiveness of multi-user collaboration?
While Chapter 2 investigated literature to find previous studies on the perceived value of multi-user collaboration, actually providing little results, tests conducted allowed to have first-hand feedback that, to the best of knowledge of the author, constitute a unique case in the publications of the last five years. However, all the tests and workshops conducted in VR gave very positive feedback as for the multi-user potentialities. As reported by one user at the end of the first practice session in DesignSpace, this also helps those who are new to a platform to learn it quickly if someone else with a higher expertise is on the same scene. Moreover, the unlucky conditions forced to test these softwares also in a remote working context. The outcome has been positive, considering that most of the participants had no previous expertise with VR and they had also to be trained on the very basics of the technology from remote. It is therefore arguable that, in the context of a multinational company, where different parts of the same products are designed in different countries, these tools allowing to collaborate in immersive 3D environment

are likely to be more and more present in the upcoming years. The most common drawback, at the moment, is the availability of HMDs coupled with the limiting capabilities of the desktop modes of the software.

What are the main critical issues users find that can prevent the adoption of the technology?
Leaving aside the optimal features required by experts that are not yet implemented, some improvements seem to be possible in the hardware, since during one of the tests a user suffered seasickness, while another complained about the ergonomics of controllers. This is not uncommon and similar findings come from literature [61]. Adoption of VR would be considerably accelerated by the development of plugins that natively integrate with computer aided technology (CAx) software. This would allow simply to wear the HMD and check and discuss the model with other users without the need to create scenes, importing files in specific formats and so on. User experience would be undoubtedly smoother. In addition to this, from the perspective of a company willing to make VR training modules, to the best knowledge of the author, there is currently no available platform that allows to create scenes for training. Finally, users expressed the need for a rendering of 3D models causing no simplification of the shapes. In addition to these findings coming from direct tests, all the previous results arising from literature mentioned in Section 2.3 must be mentioned. These include the reluctance to adopt new technologies in general unless some kind of incentive is offered [2], not perfect motion tracking of hands when LeapMotion is used and, once more, the quality of the application [3]. In contrast with Barkokebas [5], during tests conducted for this thesis, none of the participants mentioned the need for the representation of the full body. This might suggest the need for further investigation.

7.3 Limitations

The largest limitation of this study is in the number of participants to tests and surveys. It is arguable that a higher participation would have led to a better reliability of the research. Reason for this limitation may be due, at least in part, to the remote working conditions following the Covid-19 pandemic. The same event made it more difficult for the author to collect the impressions of users experiencing VR during the tests, consequently worsening the quality of the notes.

7.4 Future work

Given the results of this study, the author suggests to explore VR as a way to have 3D maintenance manuals that would allow to learn a procedure by looking at it from different positions. If, for instance, every maintenance technician could have access to a virtual library with such content, there would be significantly less need for paper instructions that have already proved to have limitations. Moreover, given that a list of optimal features to include in VR software has been determined, the following step is to look if the market already offers a platform including, if not all, at least most of the characteristics required with the highest priority. Then, more tests should be made starting a new cycle of the lean startup method. As for design review applications, DELMIA seems a valid candidate also giving a good representation of the entire body of a person. However, one must also consider the need for the compatibility between any new VR platform under test and the CAD software used. In addition to this, users suggested to study the chance to develop training modules allowing to learn by trial and error.

Chapter 8

Conclusions

This thesis evaluated the utility of multi-user VR applications in product development, investigating the state of the art of the technology and determining the optimal features that such platforms should implement to satisfy the needs of engineering companies. The study also investigated the readiness of VR to enter traditional industry and what may represent an obstacle to its adoption. A first part, containing a systematic literature review, is expected to be useful both for the scientific and technical community by offering results coming from industrial experts in maintenance and product design. For the experimental part of the thesis, the lean startup methodology was adopted, of which the thesis represents an entire cycle. Even though the study is affected by the declared limitations, results cast the bases for new research in the use of VR to improve the design and maintenance of industrial products. However, given the good correspondence of results with previous findings in literature, it is arguable that technical professionals coming from other sectors will find the research interesting. All the research questions stated both in the introduction and inside the systematic literature review found an answer. Therefore, the study can be considered successful, and the author hopes this may constitute a solid starting point for future investigations, both from the technical and scientific communities.

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Appendix A

Questionnaire about Glue

This appendix contains the questionnaire used to collect feedback on Glue. The questionnaire follows, and an asterisk marks compulsory questions.

This questionnaire will collect your feedback about Glue.
There will be open text fields to have your open comments. None of them is compulsory, but it would be of great help if you could take some extra minutes to write down your thoughts explicitly.

Compiling everything will probably take less than 5 minutes.

Please note that:
1. Your email address will NOT be collected
2. Your name will NOT be collected
3. The more honest your answers, the better
4. Your answers will be used to determine whether the software
under testing is ready for the needs of the company.

Thank you!!

1. Your age.*
2. What is your role?*
3. Do you think Glue can be useful in KONE?* Answer: Yes/No.
4. If yes, which use case would you suggest? Answer: open question.
5. If no, why? Answer: open question.

For the following suggested use cases, please state how much you think Glue can be effective

6. Product showcases (e.g. Glue used by salesmen with potential customers)*. Answer: 5-point Likert scale from 1 (not useful) to 5 (very useful)
7. Virtual meetings (e.g. instead of Microsoft Teams).* Answer: 5-point Likert scale from 1 (not useful) to 5 (very useful)
8. Virtual workshops (where a higher degree of interaction is needed).* Answer: 5-point Likert scale from 1 (not useful) to 5 (very useful)
9. Design inspections.* Answer: 5-point Likert scale from 1 (not useful) to 5 (very useful)
10. Training for maintenance operations.* Answer: 5-point Likert scale from 1 (not useful) to 5 (very useful)
11. Do you think KONE should explore more the potentialities of Glue?* Answer: Yes/No.
12. If yes, what do you suggest? Answer: open question.
13. Any additional comment you want to share? Answer: open question.

Appendix B

Questionnaire about DesignSpace

This appendix contains the questionnaire used to collect feedback on DesignSpace and the needed features an optimal multi-user virtual reality platform should implement to allow to make design reviews and maintenance simulations successfully. The questionnaire follows, and an asterisk marks compulsory questions. In the second part, questions from 1 to 19 were all answered with a 5-point Likert scale from 1 (not necessary) to 5 (essential) and therefore the available answer has not been reported explicitly for each question.

First part

This questionnaire will collect your feedback about DesignSpace, a collaborative virtual reality environment. There will be open text fields to have your open comments. None of them is compulsory, but it would be of great help if you could take some extra minutes to write down your thoughts explicitly.

Compiling everything is likely to take some time if you share detailed thoughts, but they are highly appreciated.

Please note that:
1. Your email address will NOT be collected
2. Your name will NOT be collected
3. The more honest your answers, the better
4. You answers will be used to determine whether the software is ready for the needs of KONE.
5. If not, it will be useful to understand what are the most important features that such software should have.

Thank you!!

1. Your age.*
2. How expert were you with Virtual Reality before these tests?* Answer: I was totally new to Virtual Reality / I knew about it but I had never tried it personally / I was somewhat familiar with it, but used it rarely / I was an expert.
3. If you took part to the test session on Monday, June 1st, please share a quick thought. There will be more specific questions, but any direct feedback on that session, regarding anything, is more than welcome. Answer: open question.
4. Did the remote work of these days affect the effectiveness of working with virtual reality? Please, explain. Answer: open question.
5. Have you ever experienced any sort of discomfort with VR?* Answer: yes / no.
6. If yes, what? Answer: open question.
7. Do you think the cables of the headset are annoying? Answer: yes / no.
8. Please state which headset you are using. Answer: open question.
9. How satisfied are you with your headset? Did you experience any issue? Please explain. Answer: open question.
10. How would you define the ease of use of placing objects in DesignSpace?* Answer: 5-point Likert scale from 1 (very easy) to 5 (very difficult).
11. Any free thought on the ease of placing the objects? Answer: open question.
12. How precisely do you think you can set measures of the objects you create in DesignSpace, for example the sizes of a cube or the diameter of a cylinder?* Answer: 5-point Likert scale from 1 (not accurately) to 5 (very accurately).
13. Any free thought on selecting the dimensions of the objects you create? Answer: open question.

Now there will be some more generic questions related to DesignSpace.

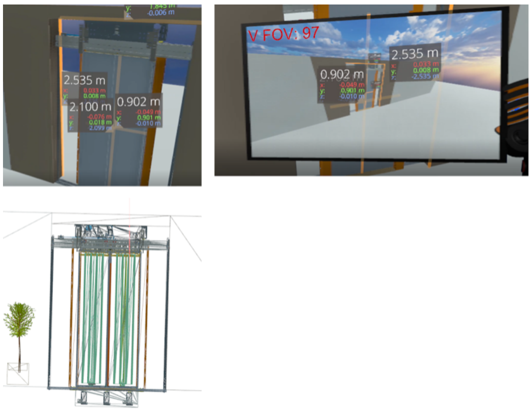
1. Did you find it difficult to learn how to move in DesignSpace (teleporting and flying)?* Answer: 5-point Likert scale from 1 (very difficult) to 5 (very easy).

2. Any free comment on moving inside DesignSpace? Answer: open question.

3. Do you think taking measures inside the environment is useful for design review and maintenance training?* Answer: 5-point Likert scale from 1 (not useful) to 5 (very useful).

4. Any free comment on taking measurements in Design Space? Answer: open question.

5. The built-in camera allows you to take pictures from inside the scene also including measures and with the chance to remove the perspective effects and also to display only the wireframe making up the objects (the lines you would see in a CAD program). The screenshots taken are saved into your laptop. Do you think this feature is useful?* Answer: 5-point Likert scale from 1 (not useful) to 5 (very useful).



6. Any free comment on the camera?

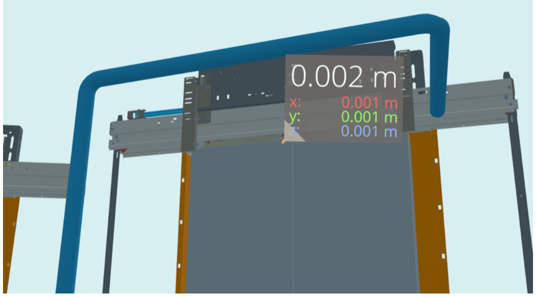
7. The "hide object" tool allows to inspect parts that are inside the model. Please rate how useful you think this tool is.* Answer 5-point Likert scale from 1 (not useful) to 5 (very useful).

8. Any free comment on the "hide object"? Answer: open question.

9. Scaling yourself allows to make closer inspections of small details and parts. Please rate how useful you find this feature.* Answer 5-point Likert scale from 1 (not useful) to 5 (very useful).

10. Any free comment on the scale feature? Answer: open question.

11. DesignSpace allows to create cubes, cylinders and tubes inside the scene. Do you think it is a useful feature?* Answer: 5-point Likert scale from 1 (not useful) to 5 (very useful).

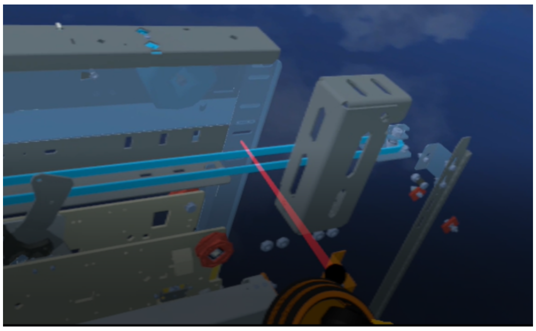


12. Any free comment on drawing cubes, cylinders and pipes? Answer: open question.

13. Saving changes to the scene, including any modification to the models, at the moment is a bit buggy and is not reliable. How urgent do you think a fix to this feature is?* Answer: 5-point Likert scale from 1 (not urgent) to 5 (very urgent).

14. Adding external objects, such as models of elevators, is possible. However, if you want to move some subparts (maybe you want to move apart some screws or the doors to simulate an assembling procedure) the subparts are grouped together as in the CAD model. This means, for example, that all the screws of a part will move together and so on. How do you think this affects the usability of DesignSpace in maintenance training and design reviews?* Answer: open question.

15. When you want to move subparts of objects like screws, you cannot grasp them. Instead, a ray is cast from the controller and that acts as a manipulation tool. Do you think it is a good way of interacting with the objects?* Answer: yes / no.



16. Any free suggestion about how to move objects? Answer: open question.

17. DesignSpace does not have any collision detection system when the user moves and hits objects. This means, for example, that you can go through walls and your hands will not receive a feedback when you try to perform any action in a space which, in reality, is not available. Do you think it would be important to have this collision detection?* Answer: 5-point Likert scale from 1 (not important) to 5 (essential).

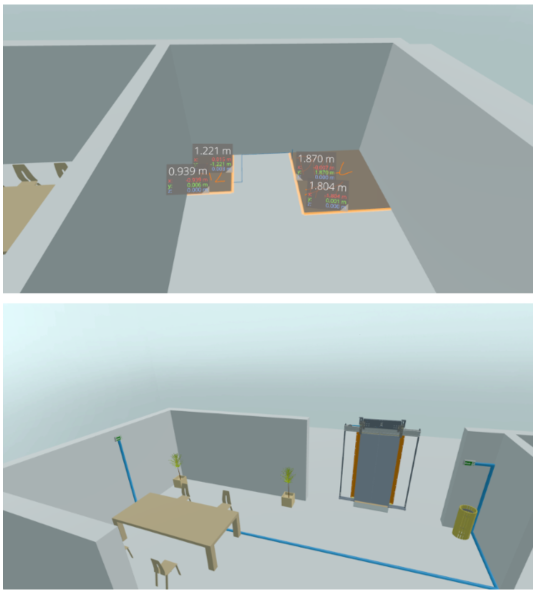
18. If you want to elaborate a bit your answer, please write your thoughts here. Answer: open question.

19. Please rate how user friendly you found the interface and commands in DesignSpace in general.* Answer: 5-point Likert scale from 1 (very difficult to approach) to 5 (very user friendly). Credits for the image: `3dtalo.fi`.

20. At the moment, DesignSpace only supports the real-time synchronization of objects that are created inside the scene. This means that cubes, cylinders and pipes can be added and edited contemporarily by more users. On the contrary, external models like those of the elevators can be added, but all the modifications that anyone does inside the scene, the others will not see them. Please write your opinion on how much you think this lack of synchronization affects the usability of DesignSpace and its multi-user feature.* Answer: open question.

21. DesignSpace currently has no way to display either written or video or voice instructions on how to perform an action. How do you think this affects the applicability of the application in training maintenance procedures?* Answer: open question.

22. The picture represents how DesignSpace could be used for layout planning and routing (making drafts of where to place machineries and where cables should go). Do you think this could be a useful application of the software? And in which other contexts do you see a potential for DesignSpace? Answer: open question.



23. Do you think DesignSpace is effective in simulating cable routing?* Answer: 5-point Likert scale from 1 (not at all) to 5 (yes, a lot).

24. Do you think DesignSpace is effective in layout planning?* Answer: 5-point Likert scale from 1 (not at all) to 5 (yes, a lot).

25. Which of these is closer to your opinion?* Answer: Design Space requires some training to be used proficiently / Design Space can be used with no training.
26. Which of these is closer to your opinion?* Answer: If I did not use Design Space for a while, I feel I would forget how to use it / I think I could use Design Space well even every once in a while.
27. Do you think DesignSpace is ready to be used inside KONE?* Answer: yes / no.

Second part

What follows is independent on DesignSpace. Please state for the following features if and how much you think are needed for a Virtual Reality tool that would allow to perform design reviews and train workers in maintenance operations.

1. Having the chance to move in different ways other than teleport (e.g. flying). Teleporting means: moving instantly to a desired spot.*
2. Scaling either yourself or the model.*

3. Selecting an assembly group, part, or sub-part (to interact with it).*
4. Breaking an assembly group into parts and sub-parts (to be able to interact with each single part).*
5. Grouping into an assembly some different parts (to be moved together etc.).*
6. Highlighting an assembly group, part, or sub-part (to allow others to see what you are referring to when talking).*

7. Placing objects back to their original position after they have been moved somewhere else.*

8. Having a measurement tool with the chance to snap on edges and/or corners.*

9. When creating objects on the scene, having the chance to insert precise values for the dimensions.*

10. When placing objects on the scene, having the chance to insert precise values for their location and rotation with respect to some coordinates or reference points.*

11. Having the chance to move mechanically constrained parts (for instance, doors) only according to the allowed movement (for instance, doors only sliding as would do in reality).*

12. Show tools (e.g. a hand holding a screwdriver) instead of the default controller in the scene.*

13. Displaying sectional views of parts. (Sectional view means that you can see what is inside a part, like if it was cut with a plane).*

14. Having a tool (e.g camera) to take screenshots in the scene.*

15. Having a tool (e.g videocamera) to take videos in the scene.*

16. Having haptic feedback (controller vibrates) when the user touches some model with the hands.*

17. Importing various documentations to be consulted inside the scene. (e.g. visualizing .pdfs, videos, etc.)*

18. Having audio instructions on what to do that can be recalled on the need.*

19. Having text instructions on what to do that can be recalled on the need.*
20. Any additional comment you want to share? Answer: open question.