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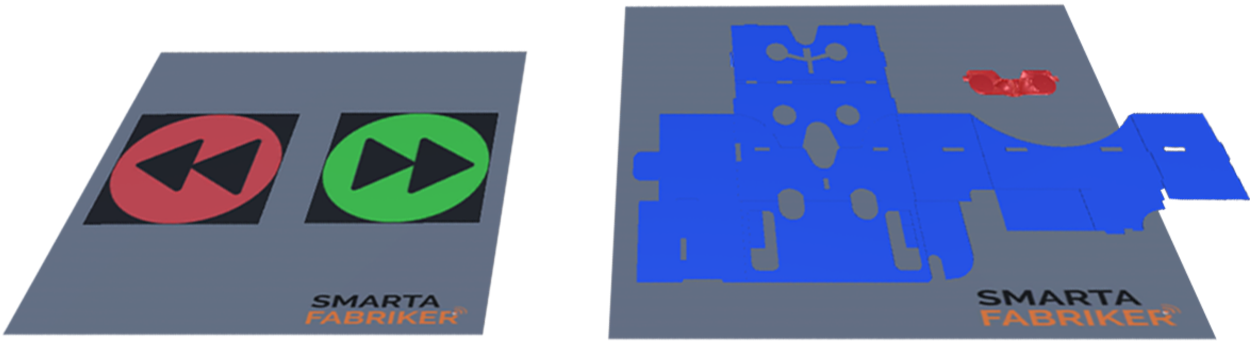

Assembly Instructions for the Swedish Manufacturing Industry of the Future

Designing and comparing effective assembly instructions in line with digitalization

Master's thesis in Production Engineering

NICLAS BUSCK and FREDRIK SVENSSON

Department of Product and Production Development
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2017

Master's thesis 2017

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Supervisor: Dan Li, Department of Product and Production Development
Examiner: Åsa Fast- Berglund, Department of Product and Production Development

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Department of Product and Production Development
Division of Production Systems
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: Operator interface of a augmented reality-based assembly instruction.

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Abstract

Digitalization within the Swedish manufacturing industry is today realized in many different ways. It often involves high levels of automation, with robotics and internet of things. How digitalization can benefit the manual assembly work where simple paper assembly instructions are used for industries with fewer levels of automation is however less mentioned. This thesis work focuses on designing and comparing three assembly instructions for a manual assembly operation in line with digitalization that supports human cognitive processes. The three instructions types considered are text and picture (T&P), Video and augmented reality (AR) and they use different technologies that could be connected to the digitalization concept. These instructions are then tested in experiments to find out differences in their individual performances regarding time to complete an assembly, achieved product quality and perceived acceptability by inexperienced operators. All three instructions are effectively designed, which entails a detailed study of both planning and presentation of instructions. The instructions have also been individually enhanced by the usage of instruction guidelines from available literature to reach each of the instruction types highest potential before compared in the experiments. The results of this thesis consists of instruction pre-work (planning), three designed instructions (presentation) and an experimental study that gives industrial engineers directions on how to design assembly instructions for inexperienced operators and which type of technology to employ. The Video instruction performed overall best in the experiments and is therefore recommended to be used considering inexperienced operators. The thesis concludes that big improvements in instructions design can be reached with familiar technologies that are in line with digitalization, which could have a large impact on Swedish companies' short term production efficiency and long term global competitiveness.

Keywords: assembly instructions, augmented reality, guidelines, product design, assembly sequence, comparison, experiments, video, text and picture.

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Then, we would of course like to thank our supervisor Dan Li for his full commitment from the start and valuable feedback, which was very influential. Also, we would like to specifically thank Pär Magnusson from Stora Enso in Skene who helped and guided us in our cardboard design development work.

The thesis would not be the same if not for all the participants in our workshop and experiments, who gave valuable qualitative feedback and quantitative data. So, a very big thanks to all of the involved researchers from Chalmers University of Technology and high school students from GTG.

Lastly, we would like to thank all the other thesis workers connected to Smarta Fabriker who contributed to the interesting weekly meetings at Visual Arena, Lindholmen science park, Gothenburg.

Niclas Busck and Fredrik Svensson, Gothenburg, June 2017

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1 Introduction

In the introduction, a background to the origin of the thesis is presented with related problems and opportunities that the manufacturing industry are currently facing. Then, a more narrowed definition of the focus areas in the thesis is presented followed by a description of the purpose, which narrows down into three research questions. Lastly, an introduction to the thesis methodology, delimitations and a thesis overview is presented.

1.1 Background

This thesis is part of a project named Smarta Fabriker, run by Göteborgs Tekniska Collage (GTC) [1], which in turn is based on Sweden's new industrialisation strategy; Smart Industry [2]. The aim of the new industrialisation strategy is to boost Swedish manufacturing companies' capacity for change and global competitiveness by focusing on utilizing the potential of industrial digitalization, enhancing sustainable production and increasing the general knowledge and skills about digitalization, which hopefully will make Sweden world leader in research and development within this field in the upcoming years. Digitalization is paving the way for new ways of working and major opportunities will come as a result. It is therefore of most importance that Swedish companies are able to see the benefits of digitalization and also have the right skills to best utilize the future potential. The project, Smarta Fabriker, is aimed to focus on increasing industries and academia's knowledge about modern industrial production and digitalization. To achieve this, engineering students from Chalmers University of Technology and high school students from Göteborgs Tekniska Gymnasium (GTG), together with several companies, are building a modern miniature factory, partly founded by the government, which will display the future manufacturing potential and hopefully attract new people into becoming interested in industrial digitalization. The factory will be exhibited at Universeum in Gothenburg later this year and people who come to visit the factory will be able to order and assemble a pair of cardboard goggles suitable for virtual reality (VR)- applications. The cardboard goggles, shown to the left in Figure 1.1, will be produced in the factory by an fully automatic process part, than later assembled manually together with plastic lenses. The factory will therefore utilize a combination of modern automation and manual operations to show the suitability of digitalization for different manufacturing companies with different levels of automation.

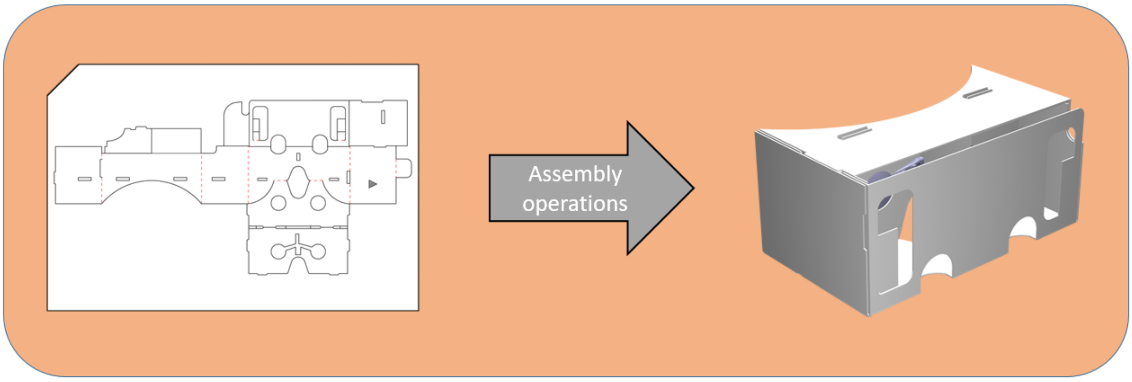


Figure 1.1: The VR-reality goggles in an unfolded cardboard sheet state, together with waste material and frame (left), and in a folded state (right), which is the desired end-state of the manual assembly operations.

This thesis will treat the manual assembly operations of the miniature factory. This entails creating solutions to how the product should be assembled in an efficient way without generating quality defects or jeopardizing exhibition visitors' safety, connected to industrial digitalization within the manual assembly field. The exhibition visitors will have no previous experience of assembling the product and will therefore need cognitive aids through effectively designed assembly instructions and fixtures. The exhibition visitor will from now on be named operator in this thesis to ease reading. The operator will be able to select which kind of instruction technology to use when doing the assembly work, this to try out all and experience the differences between each. Assembly instructions in line with digitalization often involve the usage of digital pictures, 2D drawings and 3D models, presented on screens, tablets or through Augmented reality (AR) [3]. The assembly instructions designed in this thesis include text and picture based (T&P) on paper, Video based on a touch screen and AR based on a mobile phone enclosed in a headset. These three instruction technologies will be as thoroughly and effectively designed as possible and later tested to find out differences in generated assembly time, product quality and operator acceptability.

How digitalization can benefit the manual assembly work for industries with fewer levels of automation in general is less mentioned and the focus is more towards fully automated processes [3]. Regarding instructions for manual assembly operations, industries today often use mentors to teach or instruct new assembly tasks [4], which is very resource demanding, and other information about the assembly work are often text heavy non-updated paper instructions [5] in a binder that is located far away from the operator. Digitalization offers new ways of working considering instructions, e.g. learning in virtual environments, increasing connectivity that enhances communication abilities, which keeps instructions updated for flexible production, and keeping instructions close to the operator presented on smart tables, computer screens or in viral space [3]. The increasing demand of factory resource efficiency, mass-customization with globalization [6] will make flexible and digital instructions an important asset for any industry with manual assembly work.

The manual assembly operations at the miniature factory that are being considered in this thesis work can be summarized into Figure 1.2. The manual work starts when the operator has collected a sheet of cardboard, see left image in Figure 1.1, at the end of the automated process part. The first operation to be executed is to remove waste material and frame from the cardboard sheet so that the goggles can be assembled. The next operation is to get a pair of lenses, and the final operation is to assemble the goggles and lenses together, see Figure 1.3. The designed assembly instructions does only consider the final assembly operation and fixtures are only designed for the first two operations, see Figure 1.2. The focus of this reports' research questions is on the designed assembly instructions for the final assembly and not on the fixtures, though plenty of work have been put into them. The fixtures have been designed according to Haschemi and Kang [7, 8] and validated with Kang [9]. The fixture design process, relevant theory [10, 11, 12] and results can be found in Appendix A. Also, a better overview of all manual assembly operations at the miniature factory together with interesting design suggestions for the assembly work can be found in Appendix B.

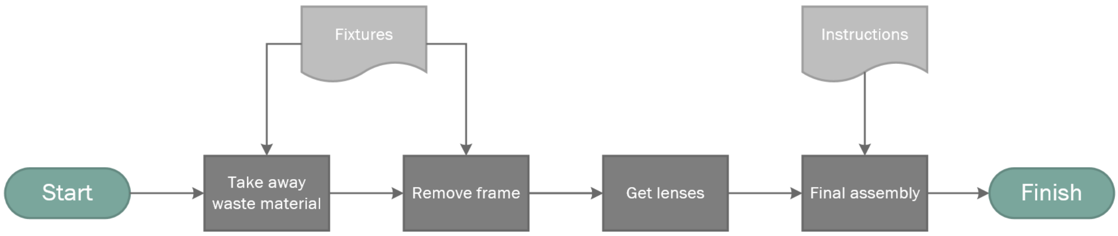


Figure 1.2: Flowchart of all manual assembly operations considered. The assembly instructions will only be constructed towards the final assembly operation and fixtures will only be designed for the first two operations; removal of waste material and frame.

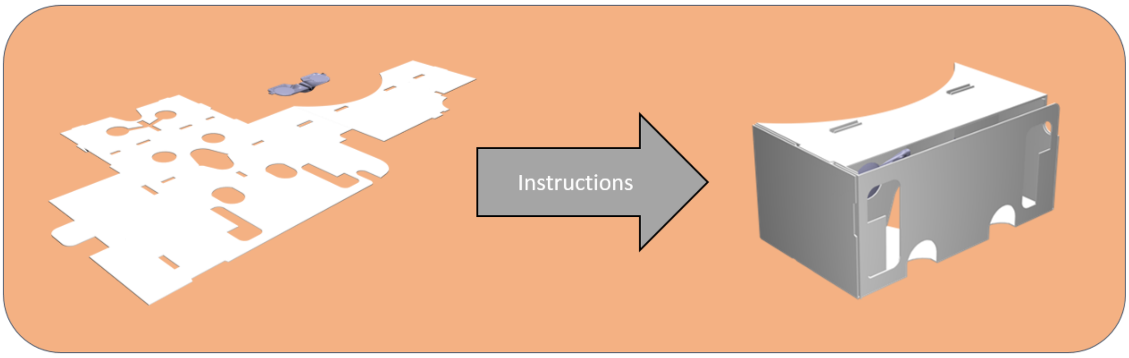


Figure 1.3: Start and finish-positions of the final assembly, which is the considered operation for the assembly instructions. To the left, the VR-cardboard goggles without waste material and frame together with lenses and the right image shows the desired end-state.

1.1.1 Purpose

The purpose of the thesis is to explore how digitalization can be applied in a manual assembly context at large, focusing towards the assembly instruction field, and formulate recommendations to the Swedish manufacturing industry regarding how to design instructions and which type of technology to employ considering the specific circumstances at Smarta Fabriker.

1.1.2 Research Questions

The first research question (RQ1) is related to finding out how to design instructions in the best way considering the specific environment.

RQ1: How can instructions be designed for an inexperienced operator in an assembly context?

The second and third research questions (RQ2 and RQ3) investigates how the three instruction designs differ in regards to important quantitative parameters, which will have an impact on factory efficiency, such as productivity.

RQ2: How do assembly instructions differ in performance regarding achieved product quality and assembly time when being used by inexperienced operators in an assembly context?

RQ3: How do assembly instruction technologies differ in perception by the inexperienced operators in an assembly context?

Perception in this research will consider the following parameters; understanding, usability, future preference, amusement and stress level.

RQ2 and RQ3 will be answered through conducting experiments. The uniqueness of RQ2 and RQ3 from previous research are the inexperienced operators, that only have one try to complete the assembly, and that all assembly instructions used in the experiments have been individually enhanced from available assembly instruction theory, so that all used technologies show their greatest potential.

1.1.3 Delimitations and Scope

The first, second and third operation, see Figure 1.2, to remove waste, remove frame and get lenses, will be aided with the help of physical fixtures. It was decided to not develop and compare assembly instruction technologies regarding these operation steps. The fourth and final operation, the final assembly, will be guided with properly designed assembly instructions based on the three different technologies; text and pictures (T&P), Video and augmented reality (AR).

The instructions designed in this thesis are intended to be used without any other help of e.g. a human instructor or mentor and since the instructions will later be used in an exhibition environment, any form of incorporated sound is not considered in the instruction design work. Thus, no solution will include the use of headphones, speakers or microphones, recording or playing sound.

The work will not be executed primarily to Smarta Fabriker, the solutions will be more general and perhaps more technically complex than what is possible to have in large crowd exhibitions. Smarta Fabriker will later be able to pick concepts they see fit in their exhibition. There will be no final manufacturing of components or fixtures from the concepts that are generated in the report. Though some prototypes may be created to facilitate concept validation.

1.2 Introduction to thesis methodology

To effectively design assembly instructions, one must according to Agrawala [6] simultaneously consider both planning and presentation of instructions. The planning of instructions regards developing and selecting the best assembly sequence that is easy for operators to understand and follow. The presentation of instructions is about conveying the selected assembly sequence in an appropriate way [6, 13]. A case study from Volvo trucks [14] confirms the view that making assembly instructions requires a lot of preparation work, in e.g. the form of gathering initial requirements, looking at the product design to improve assembly and conducting time analyses (see Figure 1.4). The thesis work have therefore been divided into two main parts inspired by Agrawala [6], pre-work and assembly instructions. One part elaborating instruction planning including relevant pre-work according to Delin [14] and one about the construction and presentation of assembly instructions.

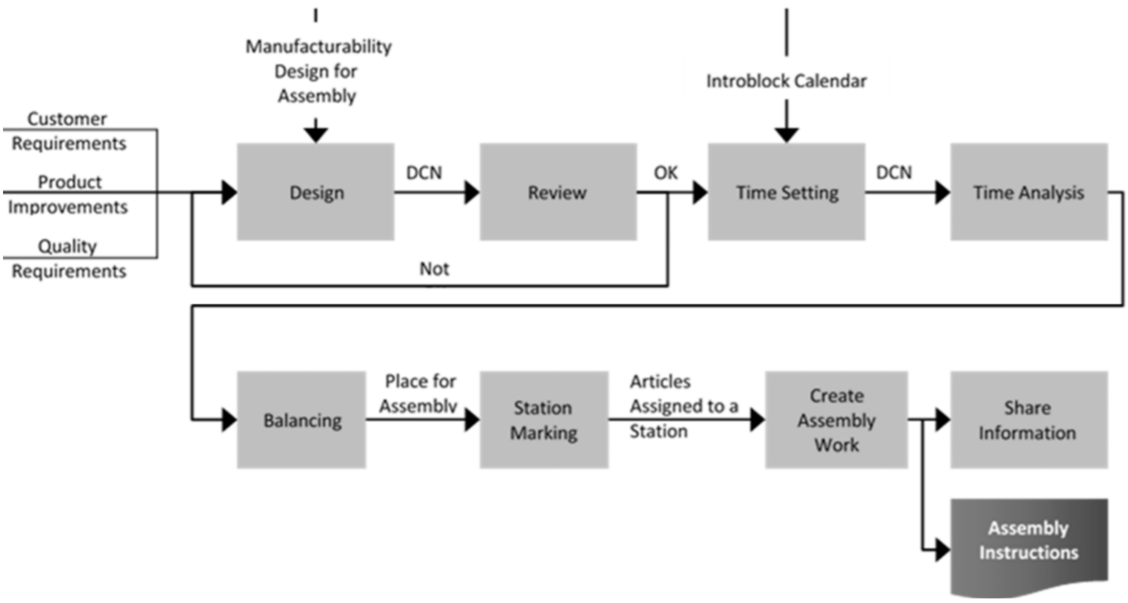


Figure 1.4: Main components of the preparation process to create assembly instructions [14].

1.2.1 The VR-product: Initial design

The VR-product design considered in this thesis work can be found in Figure 1.5 on a 600 x 400 mm cardboard sheet. The product has been stamped on the cardboard sheet. Before the final assembly, some waste material need to be removed together with the outer frame. The product will be assembled with a pair of plastic lenses to achieve the desired VR-effect. The product design in Figure 1.5 will be the starting point in the planning phase for the assembly instruction designs.

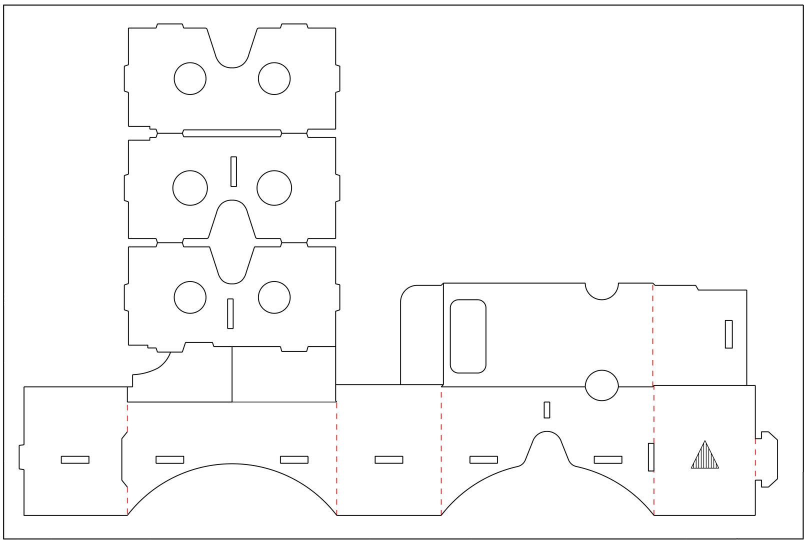


Figure 1.5: The initial VR-product design on a 600 x 400 mm cardboard sheet.

1.3 Thesis overview

The thesis is divided into six chapters, excluding appendix. First, a method chapter will be presented that elaborates the thesis methodology in a detailed way. Then, a theory chapter that present relevant theory about concepts brought up to the method. Thereafter, results, discussion and conclusion chapters follow. Answers to the thesis' research questions are indirectly incorporated in the broad discussion chapter and more directly formulated in the conclusions chapter. The appendix consists of interesting parts connected to all manual assembly operations that are not included in the results. The thesis is characterized by pre-work and assembly instructions, connected to effective instructions [6], and the division of both pre-work and assembly instructions will be throughout every thesis chapter, excluding the last conclusion chapter.

2
Methods

This section describes the method used to fulfill the thesis purpose and answer the research questions. The work is split up in the main parts; Pre-work and Assembly instructions. Figure 2.1 shows the method inspired by Delin [14] that have been used during the thesis work. The method shows a linear and sequential process, but the actual work in both Pre-work and Assembly instructions has been iterative, i.e. going back and forth between the tasks, because the process steps influence each other and changes in the later process steps effects the earlier. Since this thesis also has a lot of different stakeholders, which includes supervisors, companies and other thesis workers connected to Smarta fabriker, changes and late adjustments have been inevitable. This methods chapter will though be ordered according to the linear process of Figure 2.1. The fixture design process has been conducted in parallel to the ordinary flow and its method together with its results can be found in Appendix A.

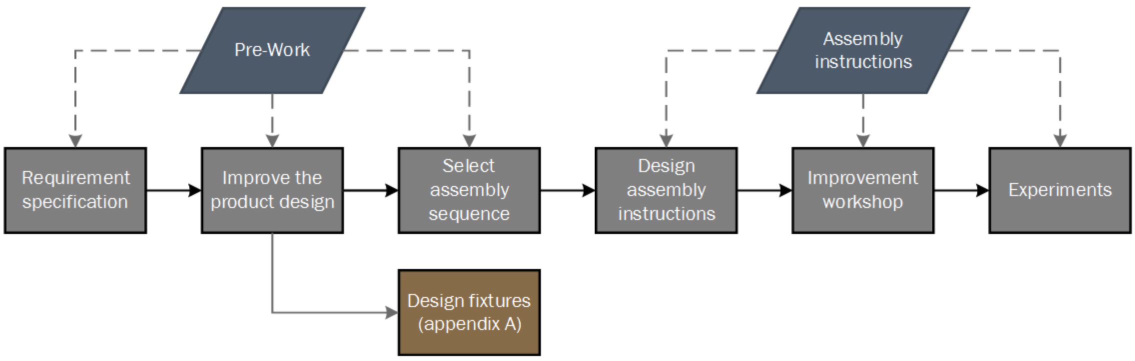


Figure 2.1: The overall thesis methodology inspired by Delin [14], with added fixture design, workshop and experiments process steps, showing the portions of the two main thesis parts; Pre-work and Assembly instructions.

2.1 Pre-work: Setting the foundation for designing effective instructions

The Pre-work part of the thesis is necessary in order to make effective assembly instructions [6]. This part implied making a requirement specification, summarizing all different requirements from various stakeholders regarding the product design and workplace design, with assembly sequence and fixture design taken into consideration. The specification acted as a guiding document in the development process and in the decision making process. The specification can be found in Appendix C. Then, the product design was analyzed with the purpose of making it more suitable for assembly, and thereafter finding possible assembly sequences considering the improved design and requirements. The sequences were later evaluated to find the most suitable sequence regarding the preconditions at the workstation. The Pre-work will lay the foundation for the later thesis part; Assembly instructions. Interviews have been conducted (semi-structured and unstructured) to guide and validate the pre-work. The interviewees in this thesis are anonymous and the interviews were recorded only if permitted by the interviewee. The recordings have only been used within the project group during the thesis work.

2.1.1 Improving the product design

The starting point of improving the product design was considering the demands and requests of the requirement specification. The specification focused on reducing hard cognitive tasks, improving the product quality, by reducing the number of assembly errors, and reducing the general time of assembly. The chosen method based on the requirement specification was Design-for-Assembly (DFA) [15, 16], in line with Delin [14]. After looking at the general guidelines in the DFA literature, an idea generating session was conducted with the purpose of finding possible product improvements that would simplify the assembly work. After generating a lot of improvement ideas, a semi-structured interview was conducted together with a senior cardboard designer at Stora Enso Packaging AB in Skene (Sweden), evaluating and validating each of the improvements found in the idea generating session. The improvement suggestions can be found in Appendix D.

2.1.2 Finding the most appropriate assembly sequence

In order to find the most appropriate assembly sequence, according to the requirement specification, all possible assembly sequences for the final assembly in Figure 1.2 needed to be studied. A precedence diagram of the improved product design was thereby constructed. Several possible sequences were eliminated because of their lack of use, which would, if used, result in unnecessary work for the operator. For example, some tasks could be executed before others but it would not add any additional value or reduce the operator's cognitive load. The generated sequences that implied extra work got screened out from the final evaluation step. The final evaluation step was executed using MTM-SAM [17, 18] looking in more detail at which sequence resulted in fewest body movements and thereby would give the fastest assembly time. The selection of using MTM-SAM was based on an unstructured interview with a production analysis researcher at Chalmers University of Technology and is also supported by Zha [19]. When the assembly sequence was determined, a Hierarchical task analysis (HTA) tree [20] was constructed to visualize and explain the inherent steps and used as a basis for the instruction layouts [6, 13].

2.2 Assembly instructions: designing, improving and experimenting

All designed assembly instructions (T&P, Video and AR) were founded on the result of the pre-work section, i.e. on the improved product design and selected assembly sequence, together with assembly instruction guidelines gathered from relevant theory [13, 21, 22, 23]. Therefore, a review of the relevant literature was conducted. All three assembly instructions were designed with the intention of reaching the highest potential of the instruction type. The generated assembly instructions were thereafter validated through an improvement workshop before tested in experiments, which were aimed to quantitatively find out differences between the instructions regarding time of assembly, achieved product quality and operator perception.

2.2.1 Method for designing the T&P instruction

To make the T&P based instructions, a camera[1] was used to take realistic assembly pictures, showing each step of completing the assembly. The product was positioned on a brown table with a brown background as well. The idea was to only show details in the pictures that are relevant to the operator. The pictures were then put together in the software Microsoft Word[2] to generate the instruction layout. Adobe Photoshop CS5[3] was used to crop and remove backgrounds in some of the pictures. It was decided to fit all of the necessary instructions in one page only, so the operator can get a better overview of all the assembly steps. An alternative would have been to use more pages to describe the sequences in more detail, but it might have also made the instructions as a whole more complex to comprehend. The page with the instructions was designed to be around A3-size. The pictures of the assembly steps have sufficient size to fit the A3 paper format. Several alternatives of instructions have been tested, to have the paper horizontal or vertical, using numbered pictures instead of sequences, having the instructions structure oriented in a number of ways etc.

2.2.2 Method for designing the Video instruction

When the Video instruction was made, the same camera was used as in the T&P instructions to capture the studied assembly sequence in video. The video of the whole assembly sequence was thereafter divided into six parts, between 4 and 12 seconds, in Videopad Video Editor[4] and converted into .gif-pictures. These pictures were then imported into Microsoft Powerpoint[5], one gif-picture per slide, to increase usability that ensures better operator control and prevents having to review the entire video sequence if one task is unseen [24, 25]. Snapshots of start and finish

[1] https://www.dpreview.com/reviews/canoneos500d/
[2] https://office.live.com/start/Word.aspx
[3] https://helpx.adobe.com/creative-suite/kb/cs5-product-downloads.html
[4] http://www.nchsoftware.com/videopad/
[5] https://office.live.com/start/PowerPoint.aspx

positions were thereby added as a complement to the gif-pictures on each slide, with the purpose of further minimizing non value added waiting time.

2.2.3 Method for designing the AR instruction

At first, an idea generating session was held to find plausible effective solutions that could instruct how to assembly the product. It was early established that a good solution would be to have an virtual 3D-model of the cardboard that was animated accordingly to the assembly sequence. The idea was that the operator should be able to control the animation to some extent, so that the instruction was presented according to the preferences of individual operators. This was the vision of the instruction. The next step was to find a solution on how this could be realized.

Unity3D[6] was initially a game engine but is today also a common engine to develop Augmented Reality, Virtual Reality or Mixed Reality with software development kits (SDK). SDK's can be used for many purposes, for example to build projects to different platforms, like Android, Playstation 4 or Samsung SMART TV. Unity3D was used together with Android SDK to be able to test the project on an Android phone with Virtual Reality glasses. This enabled a simple way to test solutions, without the need for additional hardware, like Microsoft's Hololens[7].

When Stora Enso were finished making the final product design, based on our improvement suggestions, it resulted in a 2D PDF drawing. This was imported into Google Sketchup[8] to make a 3D-CAD model of the product. The 3D model was therafter imported into Blender[9], an open-source 3D creation software, to animate the assembly sequence and lastly imported into Unity3D.

To make Unity3D function as intended, additional SDK was necessary to build augmented reality projects. Because of the research team's lack of experience with Augmented reality or Unity3D, all of the following SDK's might have been up for the task, thus had to be tested. It should be noted that the team did not have any experience with any of the software mentioned in this section, except to a small extent Google Sketchup. First, Vuforia SDK[10] was tested, then Google's Cardboard SDK[11] and they were tested combined. Finally, Vuforia SDK and Vuforia's AR/VR sample[12] was used to successfully build a solution that was aligned with the vision. Trackers to the instructions was designed in Adobe Photoshop CS5.

[6]https://unity3d.com/
[7]https://www.microsoft.com/en-us/hololens
[8]https://www.sketchup.com/
[9]https://www.blender.org/
[10]https://developer.vuforia.com/downloads/sdk
[11]https://developers.google.com/vr/unity/
[12]https://developer.vuforia.com/downloads/samples

2.2.4 Improvement workshop: Improving the assembly instruction designs

After the draft versions of the assembly instructions were completed, a workshop was made with the purpose of finding instruction improvements and set the final instruction design before conducting later experiments. The workshop participants consisted of six researchers from Chalmers University of Technology within different fields related to production (e.g. cognitive/physical ergonomics, human-machine-interaction and productivity), to reach a wide range of interrelated perspectives. The participants were divided into three separate groups and each group was assigned a specific instruction. The task was then to assemble the product with the help of the specific instruction and thereafter give feedback (positive and/or negative) on perceived instruction effectiveness and suggest future instruction improvements. Then, each participant got the chance to try all the other instructions and compare those with the first one in a joint discussion, to see if they agree with the first feedback round and/or comes up with other improvement suggestions.

The first round of feedback is very valuable, because the participants have then only assembled the product one time, which will generate as realistic assembly conditions compared to the exhibition setting as possible. When the participants try the other instruction-types in the second round, they will have cognitively remembered motion patterns and work sequences on how to perform the assembly, which will reduce operators need of using the instructions thoroughly and will increase the risk of not receiving as thorough feedback as possible.

2.2.5 Experiments: Evaluating assembly instructions

The experiments were conducted to answer research questions two and three by testing how each designed assembly instruction perform regarding assembly time, achieved product quality (RQ2) and perceived usability by operators (RQ3). The participants in the experiments consisted of students and teachers from GTG in Gothenburg, ranging from 15-55 in age, who had no previous experience of assembling the VR-cardboard product and they were in total 30 people. The participants were equally divided, so that 10 participants tested each assembly instruction. The T&P instructions was printed on a A3 paper and the Video instruction was showed on a laptop screen. The AR instructions was run on an Android OS with an Sony Xperia Z5[13] and used with an HMD called Homido Virtual Reality Headset V2[14].

The experiment procedure was designed according to the following agenda; three participants at a time were placed in a prepared room (LAB-environment) and assigned an instruction each at random. All participants are anonymous in the thesis and they were thoroughly informed of their anonymity before the experiments started. The participants were guided to separate stations containing the instruction, which were shielded from each other to prevent seeing other participants. They

[13]https://www.sonymobile.com/global-en/products/phones/xperia-z5/
[14]http://www.homido.com/en/shop/products/homido-hmd-v2

were also not allowed to talk or leave the station during the experiments. After being placed at a station they got to try out the specific instruction type by doing a tutorial consisting of a small LEGO assembly before doing the VR-cardboard assembly, where the functionality of the instruction types were explained continuously by an instructor. The purpose of the tutorial was to level out the participants' different previous experiences with the instruction type. Some participants may be very familiar with e.g. augmented reality related technology and other might not, and the research group wanted to reduce the effect of those individual preferences [23]. Thereafter, they were given the VR-cardboard product as the next assembling task and measurements of time to complete the assembly and related quality errors were taken and summarized in Microsoft Excel[15]. Lastly, they were given a questionnaire made in Google forms[16] with related questions regarding how they perceived the assembly task in general and the specific instruction. This experiment procedure was repeated 10 times until all 30 participants had assembled the VR-cardboard product once.

During the assembly of the VR-cardboard product, the experiment leaders used stopwatches to measure the time of assembly. All participants started at the same time and when they were done assembling they raised a hand to signal the experiment leaders to stop measuring the time. To asses the achieved product quality, each finished assembled product was examined between every experiment procedure, looking for assembly errors. An assembly error could be e.g. misplacement of lenses, folding the cardboard the wrong way and thereby damaging the product functionality or poorly folding cardboard parts resulting in unused interstice function. All types of assembly errors were equally weighted in the later analysis.

The questionnaire consisted of six questions, one yes/no question regarding their previous experience of assembling products in an industry context and five likert scale [26] questions with a seven-point-scale about perceived amusement, stress, if the instruction type was simple to understand and use and if the participants would like to assemble products with the related instruction type in the future. The analysis of the questionnaire answers consisted of calculating mode (the most frequent answer), median and studying the variation of answers in histogram diagrams, which are common practices when doing analyzes of likert scale data [27].

[15]https://products.office.com/sv-se/excel
[16]https://www.google.se/intl/sv/forms/about/

3

Theory

This chapter presents the theory that has been used during the thesis work, which has been brought up in the thesis methodology. The chapter is divided according to theory related to pre-work and theory related to assembly instructions, excluding the workshop and experiments, see Figure 2.1. The Theory chapter is built to first give a small introduction in each section regarding the specific subject and gradually go into more details related to the thesis topic.

3.1 Pre-work

This section describes the necessary theory related to pre-work. This includes Design for assembly (DFA), related to improving the product design, and assembly sequence planning together with MTM, related to selecting the most appropriate assembly sequence for the final assembly operation.

3.1.1 Design for Assembly

Design for assembly (DFA) is a method used when designing products with the purpose of facilitating the products assembly work [28], aiming to reduce assembly time and quality errors resulting in lowering the total manufacturing costs. The DFA analysis is often made manually but can be incorporated with computer algorithms [29]. There are general design guidelines to be followed when conducting a DFA analysis considering manual assembly [15, 16]. The most relevant of these guidelines are listed below with relation to the VR-product in parentheses:

- Reduce the number of parts (reduce the amount of cardboard pieces).
- Get parts to fit more easily (easy folding cardboard construction reduces assembly time).
- Design parts with self-location features (prevent operators making quality errors).
- Minimize reorientation of parts during assembly (reduce unnecessary body movements).

3.1.2 Assembly sequence planning and MTM-SAM

Assembly sequence planning is a method to find the optimal assembly sequence [30] regarding e.g. cost, assembly time or other parameters. It can be conducted manually or with help of computer algorithms and programs, depending on product part amount and part complexity [29, 31]. In general assembly sequence planning, the first step is to determine which parts that are included in the assembly [29, 30]. Thereafter, an analysis of the connections between parts is made, which will be the input to graphs and diagrams such as AND/OR graphs and precedence diagram. The precedence illustrate the constraints between part connections and will show all possible assembly sequences, see Figure 3.1 for a precedence of the old VR-product design. Though, it needs to be analyzed further with the help of the initial parameters (e.g. reducing assembly time) in order to find the most appropriate sequence for the assembly work [31]. Looking at the parameter; reducing assembly time, a calculated MTM- time (from e.g. MTM-SAM) could be used as a quantitative factor when determining the most optimal sequence out of all possible [19].

MTM is an abbreviation of "Methods-Time Measurements" which constitute of several methods (MTM-1, MTM-2, MTM-SAM) [17]. All methods are used to objectively calculate the time a specific operation (e.g. assemble the goggles) in an manual assembly should take, called norm time [18]. The norm time is calculated in the unit time factor, where 5.6 factors equal to 1 second. Each manual work operation is divided into the basic movements required to perform the work operation. Each of these basic movements is assigned a certain time value, which is determined by the way the human body moves and the conditions under which the movements are performed [17]. The difference between MTM-1 and MTM-SAM is that an MTM-SAM analysis is not as detailed as an MTM-1 analysis. Thus, the MTM-SAM analysis takes shorter time to perform than MTM-1, with enough precision needed to correctly analyze assembly methods in production settings [32].

3.2 Assembly instructions

This section describes relevant theory for designing assembly instructions, from a presentation of instructions point of view [6]. The chapter is divided into sections related to assembly instructions theory in general and to specific assembly instruction theory (T&P, Video, AR). At the end of each section, guidelines will be summarized, which were considered in the assembly instructions design process.

3.2.1 In general

In this research an assembly instruction is defined as a set of standalone procedural instructions that structurally shows how parts in certain predefined positions are assembled. Standalone in this case means that the instruction technology by its own, and not with the help of i.e. an instructor, is needed. When constructing assembly instructions it is important to arrange the information in a way that suits human cognitive processes [33]. The cognitive processes include perception, through vision and hearing, memory and attention [34]. When using the cognitive processes, the operator experience differences in cognitive load (intrinsic, germane and extraneous load) that effects assembly performance [21], depending on how the work instruction is created [35]. Intrinsic and germane cognitive load is affected by the complexity of the assembly task and depending if the task is new or have been learned before

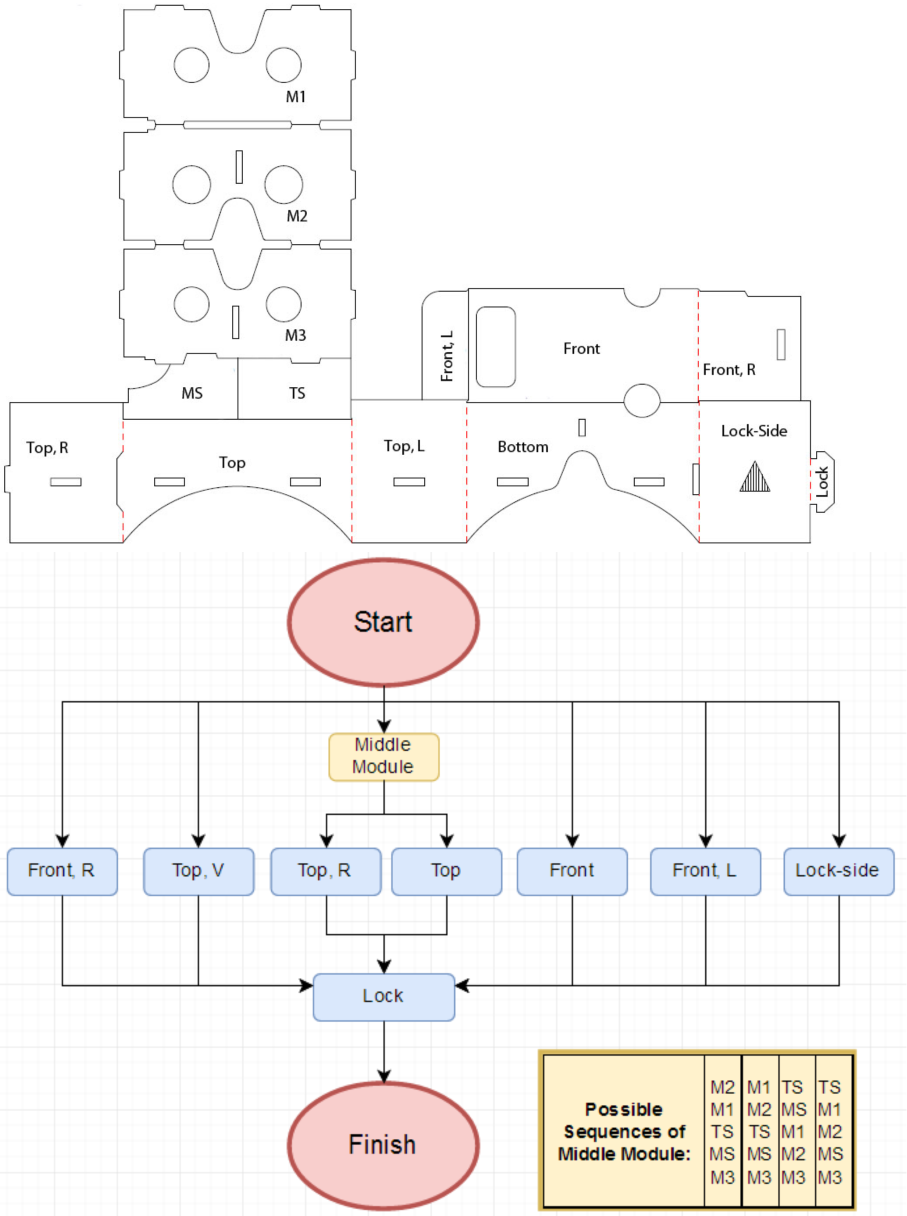


Figure 3.1: Precedence diagram of the initial product design.

from previous experiences, whereas extraneous load is unnecessary cognitive load that have no positive effect on the assembly performance [13].

Some general guidelines to help assembly instruction designers to effectively support operators are the following [21]:

- Support active cognitive processes (i.e. not too much information, focus on the most important and consider operator experience)
- Support operators mental models (how a person perceives a situation affects his/hers behaviour)
- Support cognitive abilities and limitations (memory and attention is limited,

thus take away redundant information)
- Support individual preferences (humans might want different information)
- Support perception through correct placement of information and the usage of pictures.

Instructions can be presented in many different ways. It could be in a descriptive form, e.g. text-based, or depictive form [21], e.g. pictures and video, animation. It can also be a combination of both descriptive and depictive, e.g picture- and text-based (T&P). The type of technology used (information carrier) also differ between instructions and will highly impact operators' active cognitive processes [21].

3.2.2 T&P instructions

Text instructions, often combined with pictures, are the most common type of assembly instruction in a manufacturing setting [21]. One big issue with only having text is the delimitation regarding communication. Production operators often speak different languages and have limited knowledge in other languages, thus pictures can be used instead as a compliment [36]. Combining both text and pictures makes the assembly information more easy to understand [34]. It has been shown in several studies that mixed information formats increases performance [37]. Several other case studies show that depictive work instructions (e.g. picture and video) outperform descriptive instructions (e.g. text only) when it comes to achieved product quality and assembly time [21].

When designing T&P instructions, one could consider guidelines from Söderberg [13] and Mattson [21], see Table 3.1. The guidelines are divided into the subcategories; structure, layout, and T&P, whereas structure refers to how to plan the instruction and layout and T&P are about presentation [6].

3.2.3 Video instructions

Video instructions are procedural instructions that are displayed on a screen. The video assembly instruction is often played from the beginning to the end, without pauses, but the operator have the chance to reverse and play back sections of the video. Previous research has been focusing on comparing video instructions and print instructions [24], and/or augmented reality (AR) instructions with remote guidance [25].

The benefits of using video instructions over print instructions are that animations in videos are useful for tasks that involve complex assembly actions or procedures, specifically those that are difficult for users to imagine [24]. Although print instruction often combines pictures and text, video instructions utilize sound, animation, images, and text to make meaning. Research have shown that operators perform better when animation is combined with sound or words [38]. Although video instructions have shown to improve assembly efficiency, problems have arisen regarding its usability and acceptance among operators. There seem to be a thin line between

Table 3.1: Guidelines for making T&P instructions [13, 21].

Guideline	Description
Structure	The structure should be based on a planned procedure of assembly, for example by the use of HTA.
	Support the instructions by adding separate presentations with pictures of the finished product.
	Depending on the space available in the instruction layout, the separate presentation can be placed either in the same information presenter or on a separate presenter.
	A separate presentation can also be added with pictures of high complex parts.
Layout	The layout should make it easy to find information and be consistent throughout the instructions.
	The instruction steps should include headings that are clear and concise, intuitive and informative (support the understanding of the task).
Text and pictures	The instructions should have a high focus on pictures and text should only be used when pictures are not sufficient.
	All pictures should be realistic, photographs are to prefer when possible.
	In order to be clear the pictures should be big, have high contrast and reduced shadows.
	Text and pictures should only include relevant information. Eliminate unnecessary details in pictures.
	Highlight the most important information and use e.g. different colors or arrows to direct attention.

the video playing too fast, which means that it has to be reviewed, or the video playing too slow so that the operator has to wait for the next sequence to show,[24, 25] which generates frustration among workers. There is a need of making the operator feel more in control when using the video instruction by making it easier for operators to find specific assembly sequences or tasks [24].

Plaisant and Shneiderman [22] have also gathered some guidelines to consider when creating video instructions, see Table 3.2.

3.2.4 AR instructions

Augmented Reality (AR) is a technology that can be used in assembly work to guide and instruct the operator with the help of combining virtual graphics (animation, arrows, text) and physical objects. The virtual graphics can be overlaid on the physical objects to enhance operator's perception of reality [23]. This is sometimes called "Mixed reality" instead and there are currently debates as to which term should be

Table 3.2: Guidelines for video instructions [22].

Guidelines	Description
In general	Coordinate demonstrations with text documentation
	Synchronize spoken narration and animation carefully
	Be faithful to the actual user interface
	Use highlighting to guide attention
	Ensure user control
	Keep file sizes small

used [39]. When using AR, a head-mounted display (HMD) with a camera is often used to capture the physical world and depict the combined reality, e.g. Oculus rift[1] or Microsoft Hololens[2], with one difference that Hololens do not completely block your line of sight, which allows for a different AR experience. Using AR with HMD, the assembly instructions becomes part of the actual assembly work and will also aid the operators by hands-free interaction [40]. Another way to use the AR technology is to employ a hand-held PC, which have been proven to be more beneficial for learning situations than the usage of HMD:s [41]. Though, the usage of hand-held PC in an assembly context is not yet fully studied since it requires at least one operator's hand to hold and steer the PC.

A lot of previous studies have been made comparing the effectiveness of different assembly instructions media. AR-based instructions and paper-based instructions (e.g. T&P) are often compared looking at objective quantitative differences, e.g. in assembly completion time and error rate, and subjective qualitative/quantitative differences, e.g. operator acceptance or usability [42]. The studies often conclude that the use of AR technology, when guiding operators in assembly work, outperforms paper-based instructions, achieving lower assembly time and fewer assembly errors [43, 44, 45, 46]. Operator acceptance and usability of AR technology regarding assembly instructions have though historically not been better than paper- based instructions [23]. Aspects summarized by Syberfeldt [23] that have a proven negative affect on operator's perceived usability regarding AR technology with HMD for assembly work consists of:

- Improper operator training of the AR functionality before usage.
- Time lag experienced.
- To low complexity of the considered product in assembly.

In Table 3.3, there is a summery of aspects to consider when designing AR-based instructions regarding improving assembly work efficiency (e.g. assembly time).

[1]https://www.oculus.com/
[2]https://www.microsoft.com/en-us/hololens

Table 3.3: Guidelines for making AR instructions.

Guideline	Description
Efficiency	Graphical information and visual features does not need to be located in the task area to be useful. But aim for no visible misalignment between the graphics (animation) and the physical object to achieve best performance [40]
	The type of visual features used (e.g. arrows, 2D sketches, text, 3D animations) should be adopted to the assembly operations relative difficulty level, since simpler visual features are easier to understand and thus faster recognized [47]

4

Results

This chapter will present the results generated in this thesis work, divided into the sections; Pre-work and Assembly instructions.

4.1 Pre-work

This section presents the results of the pre-work. The pre-work result consists of a presentation of the improved VR-product design and the selected final assembly sequence that was used as a foundation for all designed instructions.

4.1.1 The improved product design

A comparison of the new and old design of the cardboard sheet with the product design on it can be found in Figure 4.1. Appendix D discusses several feasible product improvements, including some of which have been implemented.

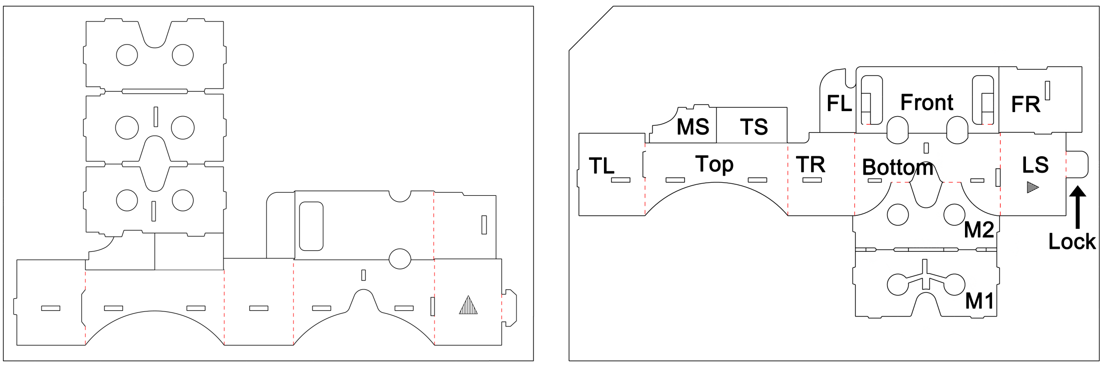


Figure 4.1: Left; Initial product design on the cardboard sheet. Right; Final product design.

The product has been through several different improvements. All demands on the product from the requirement specification (Appendix C) are being met. The product require less cardboard in the construction to fulfill its functions, without any noticeable decrease in the construction's overall strength. The cardboard sheet (around the VR-product) has the same measurements, except that one corner has been cut off, as is shown to the right in Figure 4.1. The corner is a poke-yoke[1]

[1]http://leanmanufacturingtools.org/494/poka-yoke/

solution that makes it impossible to place the cardboard sheet flat in the fixture incorrectly before the waste material are to be removed. The cardboard sheet measurements have not been reduced since the sheets will be delivered on EU pallets which is 1200 mm x 800 mm and will precisely fit four sheets per layer. The product design could not be reduced in size enough to make one pallet able to contain more sheets with products per layer. Since the VR-product require less cardboard and the cardboard sheet have roughly the same measurements it will initially result in more cardboard waste, though the reduced VR-product measurements will result in possibilities to lower the cardboard sheet dimensions.

One big change is that the whole middle-section has been optimized and moved ("M1" and "M2" in the new design). Initially there were three similar parts, but during development it was concluded that one of the parts was not necessary to fulfill the VR-product functions. The whole middle-section was moved to achieve a more natural assembly sequence. Now the product does not need to be reoriented during assembly. Before, parts of the product needed to be folded several times in order to be assembled. Now, the "Bottom" part act as a base during assembly, the other parts are folded against it. The component "M1" have also gotten a cutout according to a new lens design for the glasses.

The "lock", see Figure 4.1, has been changed as well into a simple piece of cardboard without any hooks on it. It is held in place with the help of friction and is easily assembled and disassembled. The product part "FL", see Figure 4.1, includes a small cutout, this is so the telephone can be connected to headphones when the goggles are being used. In order to be compatible with a large quantity of telephones, the product part "Front" does contain an additional hole for the camera. This way the telephone can be oriented so the headphone jack fits the cutout while the telephone's camera is in any of the camera holes.

4.1.2 The selected assembly sequence

An HTA of the selected sequence for the final assembly can be seen in Figure 4.2 and it is the sequence that resulted in the lowest assembly time when doing MTM-SAM analyses. The MTM-SAM time for the assembly sequence is 77 factors, which is 13,75 seconds. Comparing that MTM-SAM assembly time to the MTM-SAM assembly time of the old product design, which also had another sequence, it is a reduction of 20,6%, see Appendix E. The reduction in assembly time is, as said above, achieved due to both improved product design and new sequence, i.e. one aspect can not achieve the reached reduction without changing the other. The achieved reduction in assembly time of 20,6% is a significant improvement, which is solely based on the result from the pre-work.

4.2 Assembly instructions

This section will bring up the results of the three instruction designs and experiments. All instructions are based on the assembly sequence in Figure 4.2. The

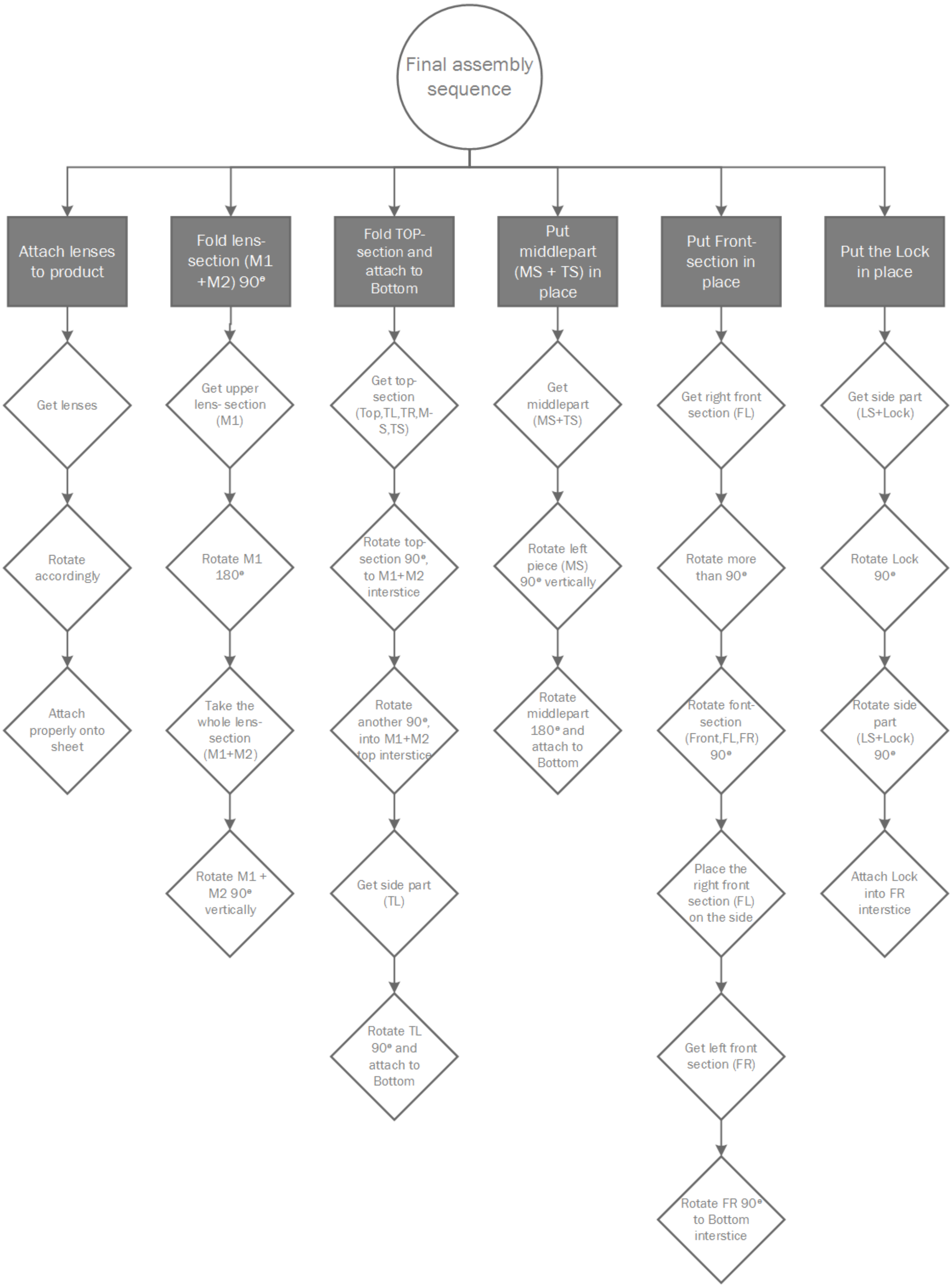


Figure 4.2: An HTA tree of the final assembly sequence. The product part- names included in the HTA is related to the part-names in Figure 4.1.

instructions have been designed with guidelines, presented in the theory chapter, taken into consideration and a sub-section is therefore dedicated for each instruction type, explaining which of the guidelines that were used. The instructions have also been improved based on what was brought up during the workshop. A summary of the improvement suggestions from the workshop can be found in Appendix F.

4.2.1 T&P instruction

The layout of the T&P instruction can be seen in Figure 4.3.

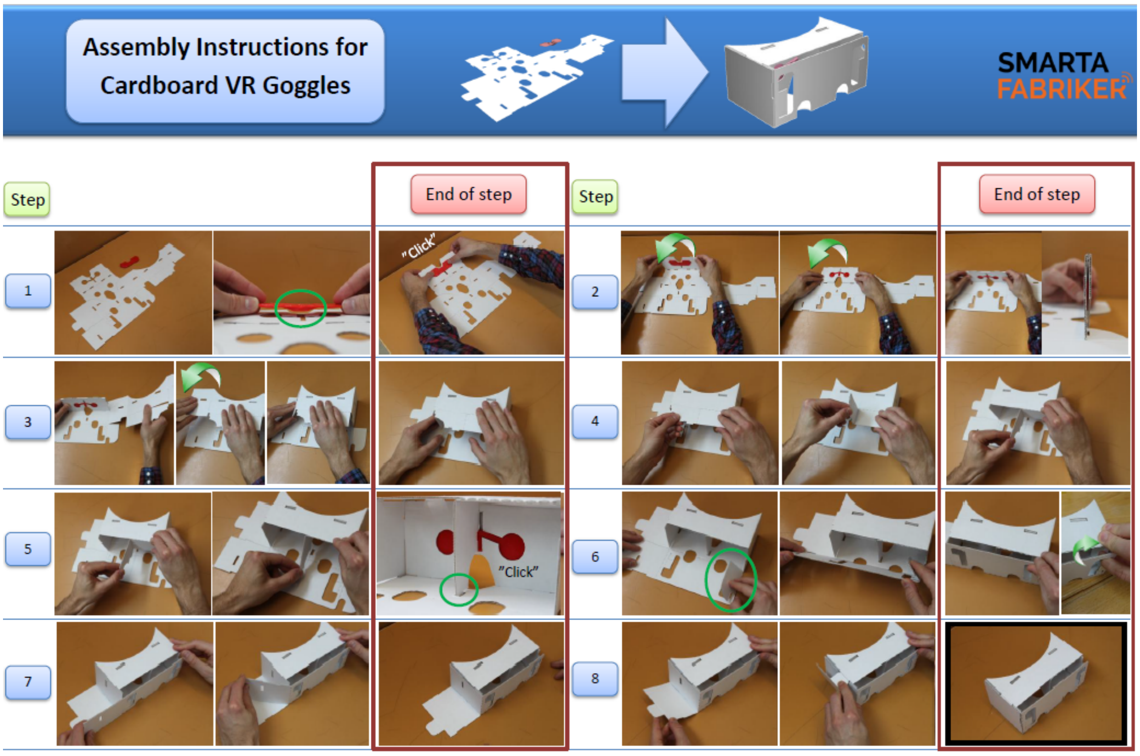


Figure 4.3: The layout of the T&P instruction.

The instruction is ordered according to eight sub-sequences which explains all assembly steps. Each sub-sequence begins and ends with an initial and final position, indicating how the product should look before and after the sub-sequence. The end positions are clearly highlighted so the operator could continuously check if the sub-sequence was carried out correctly. Between the initial and final position there are several pictures with the purpose of explaining how to carry out the sub-sequence. The images are complemented with arrows and additional highlights in the form of green circles to make details even more clear to understand. When appropriate, text has been used to indicate sound that the parts make when assembled together.

4.2.1.1 Guidelines used for the T&P instruction

Considering the guidelines from the theory chapter, the end-picture of sub-sequence eight have been highlighted with a black border, since this shows the completely assembled product. The blue border at the top contain the start position of the goggles as well as a fully assembled pair. The product itself does not contain any complex parts, it was considered one instruction for everything was enough. To minimize the extraneous cognitive load and since all steps is simply a matter of folding the product in the correct way, sub-sequences have no headings.

The instruction is based almost only on pictures. Text are used to describe how the instruction work (for example, "Step" and "End of Step"). The pictures was taken with only brown background to reduce unnecessary details in the pictures and keep a high contrast between the product and the background. The lightning was adjusted during the photo shoot to reduce shadows in each of the pictures. The pictures have been cropped and re-sized to be large and easy to understand. Some pictures only shows parts of the product, this is to reduce unnecessary details, save layout space and to have the shown parts larger instead. Arrows, colored circles and text which indicates sound have been used to highlight important details.

4.2.2 Video instruction

The interface of the Video instruction is depicted in Figure 4.4. The general concept of the instruction is that a video of the whole final assembly sequence is divided into six sub-sequences, see the grey boxes in Figure 4.2, and converted into gif-pictures, which are placed in the lower left corner, see Figure 4.4. The function of the gif-picture is that it enables the sub-sequence to be looped automatically when ended. In the instructions upper layout part, two snapshots of start and finish positions are located. These pictures are a complement to the gif-pictures, showing how it should look when a sub-sequence is completed. To switch between sub-sequences, buttons to reach previous and next sequences are placed in the lower right corner, green button for next and red for previous. The instruction is created so that it can be presented on a touch screen with interactive touch buttons.

4.2.2.1 Guidelines used for the Video instruction

In the instruction design phase, a lot of focus has been towards achieving high operator control since it has been largely documented to be one of the biggest issues towards operator acceptability. The division of the sequence into parts that are looped through gif-pictures should ensure that the operator experience less stress about missing a step or having to unnecessary wait for the next sequence. The instruction interface is built with the operator's cognitive abilities in mind, e.g. different colored touch buttons, placed in the bottom right corner and pictures of start and finish position. As for T&P instructions, the aim of the Video instruction has also been to use realistic captured video-shots, use minimum amount of text in the interface and reduce unnecessary information (extraneous load).

4.2.3 AR instruction

The final result of the AR instruction can be seen in Figure 4.5 in Unity3D's environment. The result is an app (.apk file) which can be installed on an Android device. The app works by putting the device in a HMD; in this case a pair of VR-glasses.

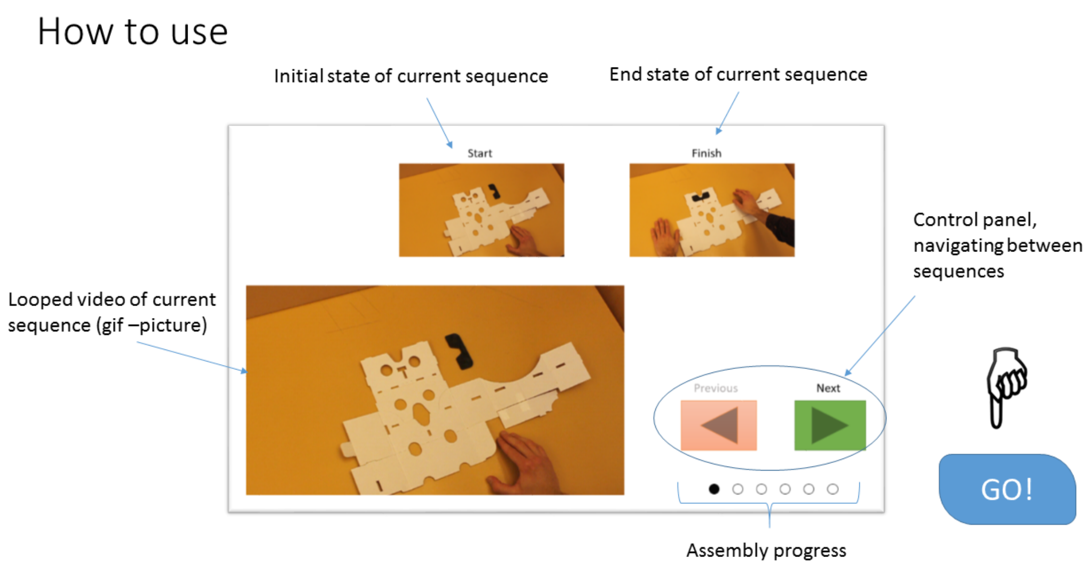


Figure 4.4: Explains the interface of the Video instruction.

The object to the top right in Figure 4.5 is a 3D model of the VR-product (blue) and lenses (red). There is a pre-programmed animation attached to the objects according to the assembly sequence. The animation is controlled by the control panel, seen to the top left in Figure 4.5. The control panel can play and rewind the animation with the green and red buttons, respectively. The 3D model of the VR-product has approximately the same size as the physical one, to mimic the physical assembly as much as possible. The instructions also need trackers so that the control panel and instructions can be displayed in the physical world. The tracker for the control panel can be seen in the bottom left and for the VR-product in the bottom right in Figure 4.5. The trackers is in the form of pictures (.PNG) that have been printed on A4 papers.

The control panel is operated with a reticle, which can be seen in in Figure 4.6. The reticle is the small blue circle that are to the left in each of the three images in Figure 4.6. The reticle is stuck in the operators view at all times, i.e it will be in the same position in relation to the HMD- screen when the operator looks around. The animation is in a paused mode when the reticle is not hovering over any of the buttons, as in the picture to the left in Figure 4.6. The animation will play when the reticle hovers over the green play button, as shown in the middle picture in Figure 4.6. The picture to the right in the same Figure shows how to rewind the animation, simply by hovering the reticle over the red rewind button instead. When any of the buttons are activated the button's image will turn blue and the arrow becomes a pause symbol, to visually indicate that the button has been pressed. Figure 4.6 also shows certain part of the product as green. These parts are the active parts in the current animation sequence; when any of the buttons are pressed the green components will move according to the assembly sequence. This is to visually guide the operator to focus on the current parts that are next to be assembled.

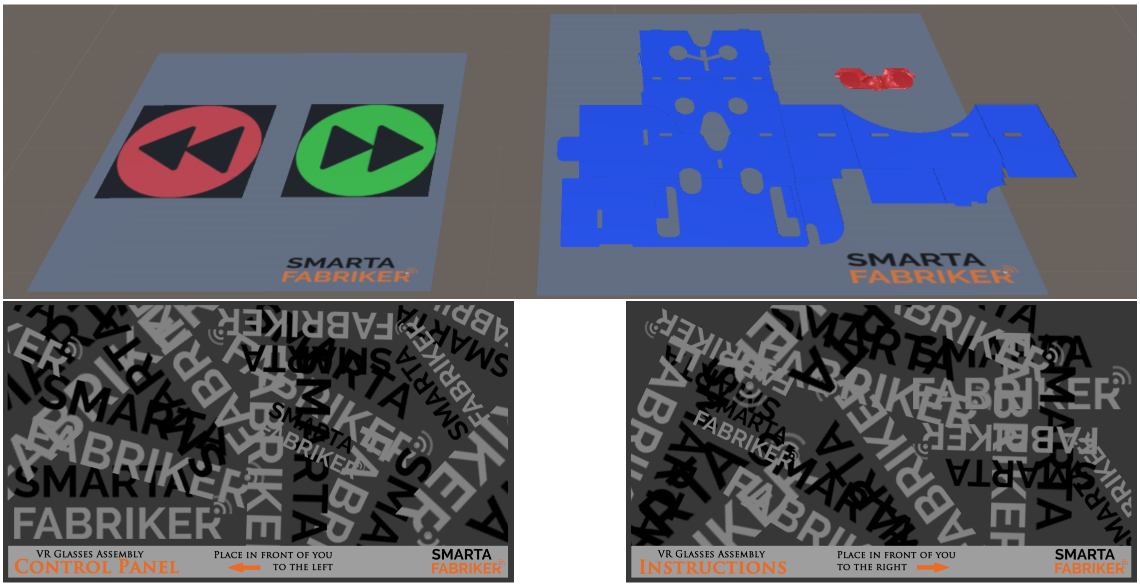


Figure 4.5: The Augmented Reality instructions viewed in Unity3D and corresponding trackers. Top Left; Control panel of the animation. Top Right; 3D model of the VR-product with embedded animation. Bottom Left; tracker for the control panel. Bottom Right; tracker for the VR-product.

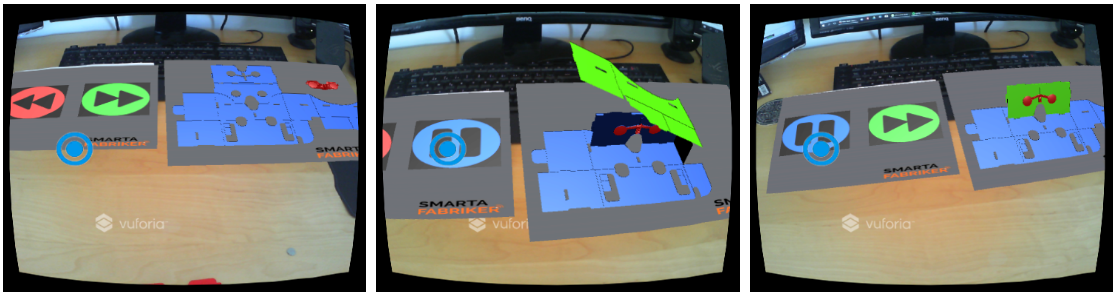
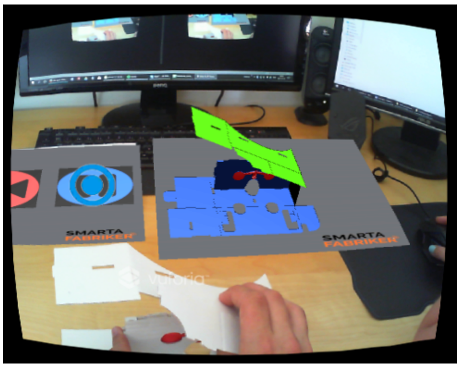


Figure 4.6: The reticle (blue circle) interacts with the control panel.

To the left in Figure 4.7 there's an operator using the animation to assemble a physical product. The idea is to have the control panel and the virtual product in front of the physical product, as the Figure shows. The operator starts by playing a comfortable length of the animation and assemble accordingly. If necessary the animation can be re-winded and played again until the physical product has been assembled accordingly. This is simply repeated with the rest of the animation until the product has been successfully assembled. The trackers displays the virtual objects at a fixed position, meaning that the trackers can be moved or rotated and still display the virtual objects. This enables the possibility to get closer to the VR-product, look at details or critical movements from different angles or simply turn the VR-product around; it is very alike a physical VR-product in terms of position and movement. There are also an YouTube video, which the QR-code to the right in Figure 4.7 links to, that shows an operator using the AR instructions' functions to assemble the VR-product.



https://youtu.be/WTdKCr1l-I0

Figure 4.7: Left; An operator using the augmented animation as guidance for the assembly work, from the operator's viewpoint. Right; A QR-code that links to a YouTube video where an operator assembles the VR-product using the AR instructions.

4.2.3.1 Guidelines used for the AR instruction

The virtual product is a replica of the physical product. This means that the operator can continuously check and identify that all parts are assembled correctly. The functionality of the AR instruction is quite simple; just play, pause and rewind the animation. Since it is combined with simple visual features, for example components becoming green, it should be easy for operators to understand and use the instructions effectively. Because of the ability to play as long as preferable of the animation, the operator can adjust the instructions according to preferences.

4.2.4 Experiments

This section presents the results from the experiments. The section is divided into two parts; Time and quality measurements, which were measured during the experiments, and survey responses, from the survey that the participants filled in after the experiments.

4.2.4.1 Assembly time and quality measurements

Figure 4.8 shows box-plots of the measured assembly time. There are three plots, one for each instruction type. The plots shows the interquartile range, mean and median values as well as the maximum and minimum assembly times. The AR instruction-plot has one sample that is an outlier, i.e. it is located above 1.5 multiplied by the interquartile range of the third quartile. This sample can be seen as a black dot above the AR box-plot. Detailed statistics of all the box-plots can be found in Table 4.1.

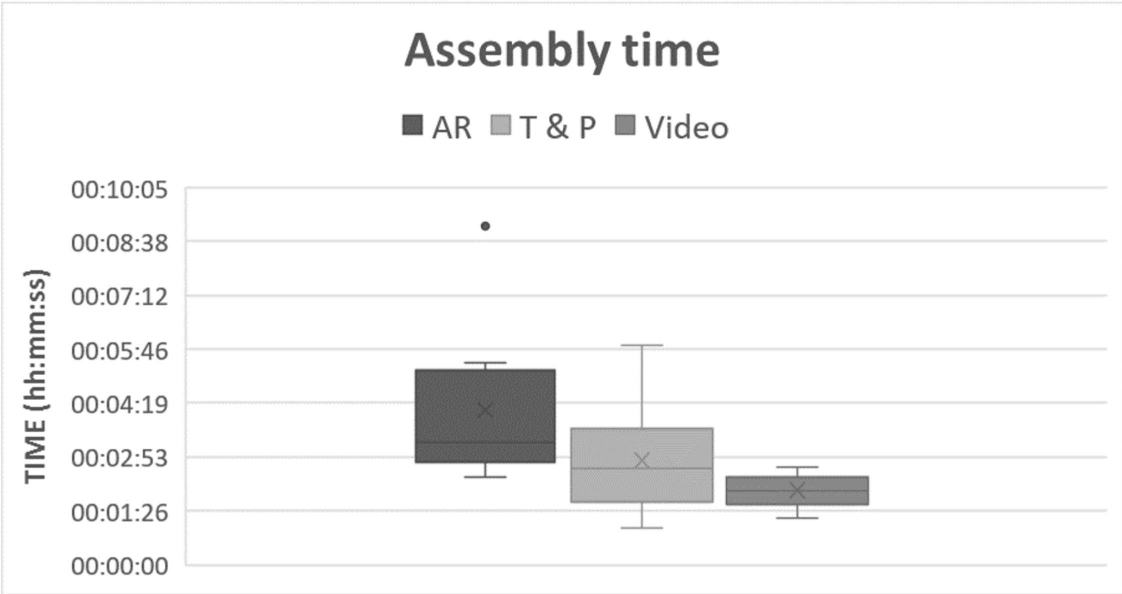


Figure 4.8: Three box-plots of the assembly time results with incorporated median-time (with a line), mean-time (with an cross), interquartile range and max/min values for all considered instruction types. The dot above the AR plot is an outlier.

Table 4.1: Assembly times statistics (minutes:seconds).

	T&P	Video	AR
Lowest	00:58	01:14	02:21
Quartile 1	01:52	01:42	02:52
Median	02:34	01:59	03:17
Mean	02:47	01:59	04:08
Quartile 3	03:46	02:12	04:59
Highest	05:52	02:37	09:03

It should be noted that the T&P instructions have the overall lowest assembly time at 00:58. The highest T&P time was 05:52 and the median time was 02:34. The AR box-plot stretches from 02:21 to 05:23 or to 09:03 with the outlier included, have a median time of 03:17 and a mean of 04:08. The Video box-plot has the shortest range between min and max- time. The mean and median is also the lowest, both at 01:59. Since the mean and median times in the T&P and AR differ, their individual distributions are skewed. The Video instruction on the other hand have the median equal to the mean, and therefore it does not have any skewness.

Figure 4.9 shows a bar-chart of the measured quality errors. The x-axis displays the number of errors per assembly for each instruction type. The y-axis shows how many products that yielded the specific amount of errors. No observation had a perfect score of zero errors, thus each instruction type is represented ten times in the chart. When the assembly errors exceeded 3 errors, the product was seen as unusable since the lenses position or the cardboard was so out of place that the VR-product's functions was significantly affected.

The Video instruction has the smallest range, between 1 and 3 errors per assembly. 60% of all Video assemblies have only one error and no VR-product is unusable. T&P generated 1, 2, 3 or 5 errors per assembly, 20% of these products is regarded as unusable. The AR instruction resulted in everything between 1 and 5 errors, where 40% is considered unusable. The T&P and AR instructions have, to some extent, a similar error distribution since both stretches over 1 to 5 errors. However, the T&P median error is 2 while the AR median error is 3.

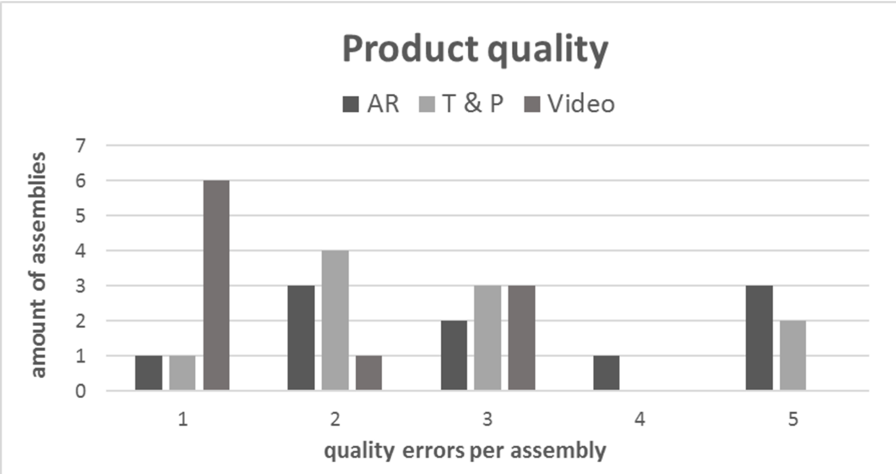


Figure 4.9: A bar-chart of the achieved product quality. The number of quality errors per assembly is shown in relation to its frequency for all considered instruction types

4.2.4.2 Survey responses

This section presents the results from the survey the participants filled in after the experiments. The first question was if they had any experience with assembly in work or school assignments. This was a yes or no question and 23 people (77%) responded yes. The rest of the questions were to be responded with a Likert scale ranging from 1 to 7. The questions was constructed so a low number in the Likert scale indicated a negative opinion and a high number indicated a positive opinion to the stated question. The questions are presented in Figure 4.10 - 4.14 as bar-charts with the Likert scale and type of instruction on the x-axis and the number of responses on the y-axis. All questions have also been compared in Table 4.2 in regards to their median and mode responses for each instruction type. The table will be explained continuously when the results from each question is presented.

In order to rule out technical misconceptions of the instruction types the participants was asked how well they understood the instruction after they had completed the LEGO tutorial. A bar-chart of the responses can be seen in Figure 4.10. Generally, the participants seem to have understood the technologies well, since most responses is a five or higher. The exception is the AR instructions which 20% scored as a 3.

If the instruction types were to be ranked according to the Likert scale's median or mode, the ranking would be;

Rank Median or Mode (Q1): 1. Video 2. T&P 3. AR

Table 4.2: Comparison of the instruction types in regards to mode and median of the Likert scales for each survey question. The Likert scales are from 1 to 7, where 1 indicates a negative response and 7 a positive response.

Question	Median			Mode		
	AR	T&P	Video	AR	T&P	Video
How well did you understand the instruction after the LEGO-assembly? (Q1)	6	6.5	7	6	7	7
How easy was the instruction to use during the VR-product assembly? (Q2)	5	4	6	5	4	6
How much would you like to assemble products with the instructions in the future? (Q3)	4	5	5.5	2	4	7
How amused were you by the assembly task? (Q4)	6	5	5.5	6	5	6
How stressful was the assembly task? (Q5)	5	5.5	5	5	6	6

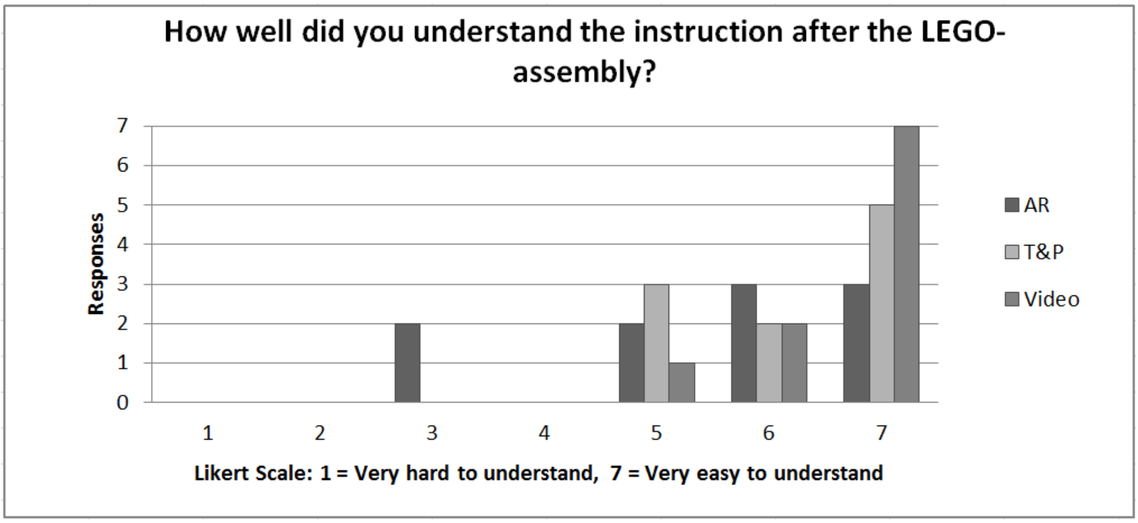


Figure 4.10: Results to the question regarding how well the participants understood the instruction type after the LEGO tutorial (Q1).

The participants were also asked how easy they thought the instruction was to use during the VR-product assembly, see Figure 4.11 for results. This was to see differences in understanding a technology versus its perceived usability. This time the responses varied more greatly, ratings were from 2 to 7. The Video instruction was similar as to how well they understood the instruction during the LEGO tutorial, still ranging from 5 to 7. The AR instruction ranged from 2 to 7 and was therefore perceived as harder to use. The same development goes for the T&P instructions, but the range was from 3 to 7. The median or mode of the responses would result in the following rank for the instructions;

Rank Median or Mode (Q2): 1. Video 2. AR 3. T&P

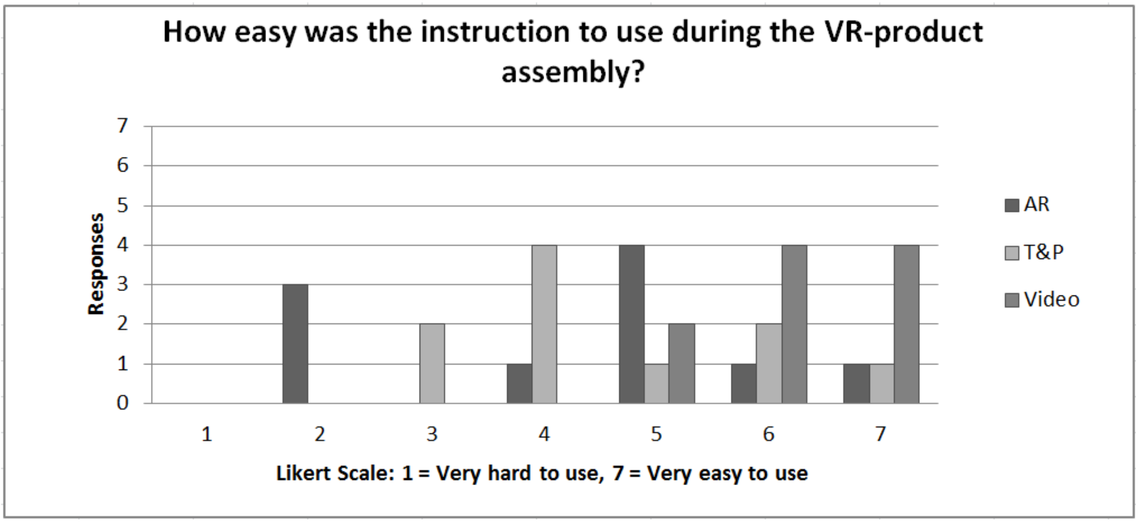


Figure 4.11: Results to the question regarding how easy the participants thought the instruction was to use during the VR-product assembly (Q2).

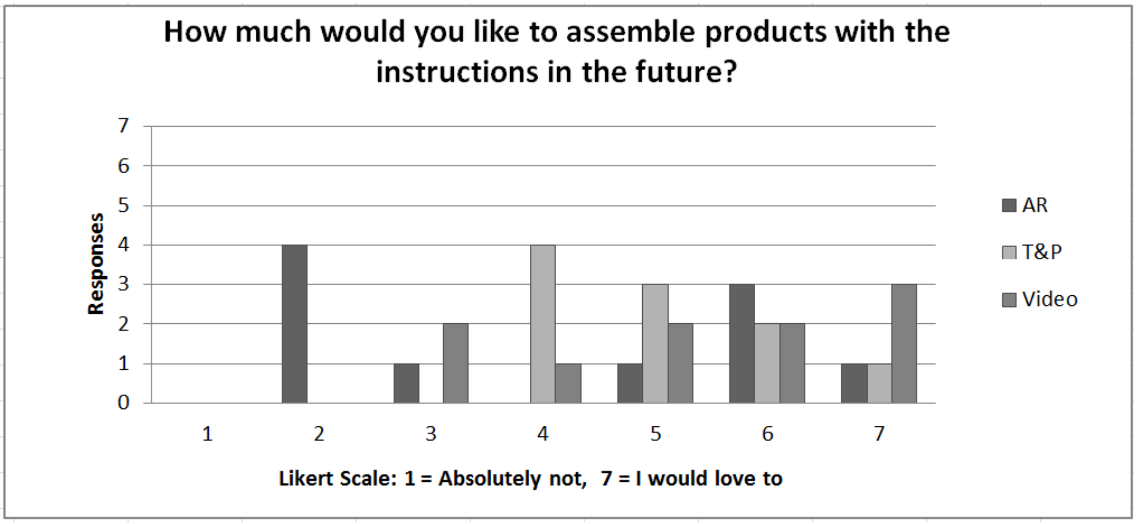


Figure 4.12: The results on how much the participants would like to use the instruction types for assembly tasks in the future (Q3).

The next question was related to how much they would like to use the instructions for assembly tasks in the future, Figure 4.12 presents the responses. The responses ranged from 2 to 7, and have a wide spread for all technologies. AR ranged from 2 to 7 and had 40% responding a 2, which indicate that many people did not like to use the technology. On the other hand, 30% responded a six indicating that several participants liked to use the technology. The T&P instruction is ranging from 4 to 7 where 40% scored it as a 4, while the rest of the responses is trending towards 7. The Video instruction is ranging from 3 to 7 and 30% scored it as a 7. The rest of the response distribution was almost uniform towards the score of 3. The ranking according to either median or mode would be;

Rank Median or Mode (Q3): 1. Video 2. T&P 3. AR

The participants was then asked how much they liked the assembly task, results can be found in Figure 4.13. The reason was to see if any technology could be more appreciated to use in industry for assembly tasks. The responses ranged from 4 to 7 and all instruction types had similar distributions. The T&P instructions ranged from 4 to 7 and peaked at 5 with 40% of the responses. AR peaked at 6 with 50% of the responses and ranged from 5 to 7. Video ranged from 4 to 7 and peaked at 6 with 40% of the responses. The ranking using median or mode resulted in two different rankings, where using mode resulted in two first places. The rankings are;

Median (Q4): 1. AR 2. Video 3. T&P

Mode (Q4): 1. Video
1. AR 3. T&P

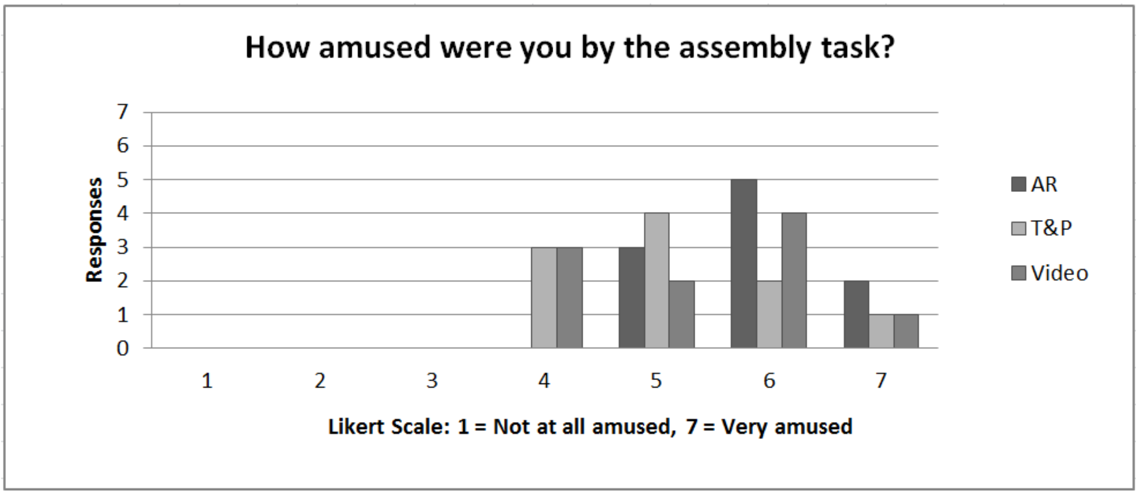


Figure 4.13: The results when the participants were asked how amused they were during the assembly task (Q4).

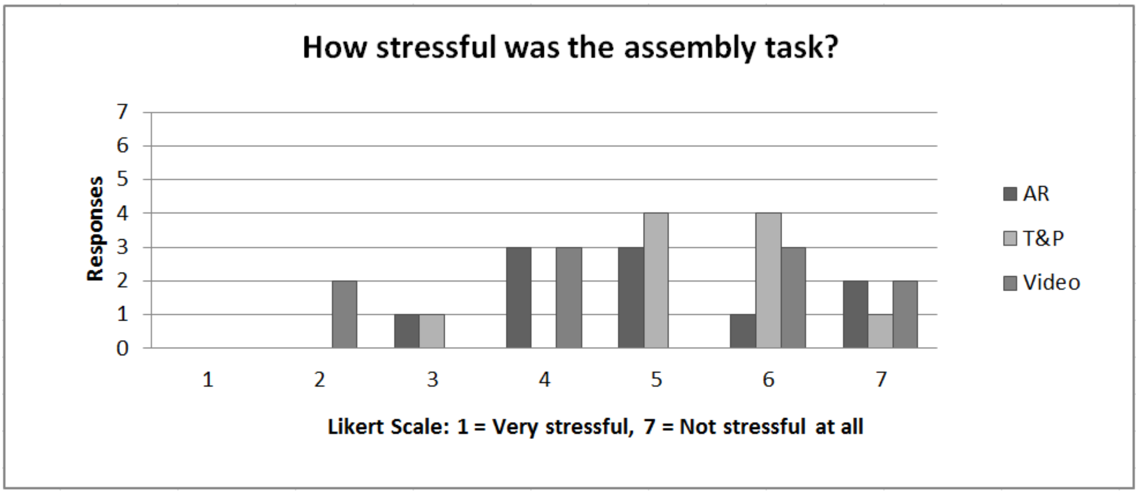


Figure 4.14: The results from the participants when they were asked how stressful the assembly task was (Q5).

The final question the participants was asked was how stressful they perceived the assembly task. The results can be found in Figure 4.14. This was to identify if there existed any differences on perceived stress between the instruction types. All responses ranged from 2 to 7. The AR and T&P instructions ranged from 3 to 7 while the Video instruction ranged from 2 to 7. The distributions of the responses for the instruction types does not seem to indicate any significant findings. If ranked to mode or median the rankings would be different and some would have several first and last places. The rankings according to mode and median would be;

Median (Q5):	1. T&P	3.Video 3. AR
Mode (Q5):	1. Video 1. T&P	3. AR

5
Discussion

This discussion chapter will comment on the methods used in the research, as well as on the results connected to theory, and future research.

5.1 Methods

To consider both planning and presentation of instructions to produce effective work instructions is an interesting method [6]. It implies to look into and optimize several areas (elements in pre-work) that at first glance can seem to not affect the assembly instructions too much. Doing so changes the content the instructions need to present and should, in theory, result in effective and advantageous work instructions. The methods used have been iterative because the methods affect each other, changing one might affect previous steps. The development phase has been an on-going process where several previous steps has been reevaluated or adjusted. It has however worked well and the final results should be extensively optimized given the certain circumstances.

The VR-product does differ quite a lot from a traditional product that are to be assembled in industry. There are often several parts that need to be assembled and nuts, screws and tool that need to be used in a certain order. The VR-product is simple, it is a single part that needs to be folded in a specific way to be assembled where no tools or similar is necessary. The assembly complexity of the VR-product could be considered much lower than a traditional product in assembly. The results might therefore be very product specific in that sense.

The research methodology was designed with research quality in mind. The purpose was to compare the instructions in a fair way by using theoretical guidelines and validate with an improvement workshop to fix any misinterpretations. The experiments have not been triangulated since the methodology itself should ensure experiments with a high amount of trustworthiness.

5.2 Pre-work implications

The pre-work results sets the foundation of the assembly instructions. It also makes sure that the instructions will be more effective than to just develop instructions of a specific type or to simply change instruction type to another. Properly executed pre-work might reduce the number of components, screws, assembly steps or similar needed which in turn will make the instructions simpler. It implies less work to execute for the same added value which raises not only productivity but also sustainability. Digitalization offers a lot of opportunities to efficiently integrate departments with systems that can connect the steps that affect instructions. The construction department could be fully integrated with digital instructions and therefore make changes in the instructions instantaneous when constructions are changed.

The product design has been optimized according to the product requirements. One large factor during the product development was that every product would automatically indicate a lot of waste. It is though better in one way than the initial design from a sustainability accept since more cardboard of the sheet are waste and can be guaranteed to be recycled, instead of trusting the visitors to recycle the product after its life cycle. The poka-yoke solution on the other hand does require an additional manufacturing step (to cut away the corner) but result in a lighter product to deliver and therefore less environmental impact. The cut corner can also be immediately recycled in the production plant and does not need to be transported back for the same purpose. On top of all of those things, it will of course make the waste removal operations easier and more intuitive.

The improved product design together with the assembly sequence have indicated 20.6% lower assembly time based on MTM-SAM compared to the initial product design with the most appropriate assembly sequence. The reduced MTM-SAM time should make it easier and faster for operators to assemble the product, which would raise the economical and environmental sustainability since the same resources can be used for higher productivity.

5.3 Assembly instructions

The assembly instructions have been designed according to guidelines from available assembly instruction theory [13, 21, 22, 23]. The intention was that each assembly instruction would be designed according to every guideline found in the theory, but some of the guidelines could not be incorporated into the design. This apply mostly to the AR instruction, where resources were lacking to employ the latest hardware and also knowledge in related software technology. The designed AR instruction could therefore e.g. not use graphics incorporated with the physical assembly object (object recognition) [40], instead all graphics were placed away from the assembly object, and the time lag generated from the mobile device could also not be reduced [23]. The instructions themselves does contain an animation of the VR-product showing the assembly sequence with the active folded parts highlighted in green. The instructions could however perhaps become more clear if more critical steps were highlighted with arrows, circles or similar during the animation. This was not done because of time issues. Time lag is, and will always be, an issue when devices with an ordinary camera and corresponding display are used. That is because the camera's detection of the physical world needs to be processed and the virtual objects need to be laid over onto the detection before everything can be displayed.

This could be solved or at least be reduced by using devices that uses optical see-through video, where only the virtual objects are displayed on top of the physical world which demands less computations and therefore also generates less time lag. Microsoft's Hololens[1] is an example that uses optical see-through video in AR experiences.

The research group also observed from the experiments that some of the participants felt uncomfortable using the AR-instruction. They did not appreciate being in-closed within a HMD, largely limiting their field of view, losing depth-vision and sometimes causing dizziness afterwords. Using technology similar to Microsoft Hololens would enable better integration of available guidelines from theory and could also offer solutions to the HMD related problems because the see-through video device retain the user's depth sense, which probably is a large factor causing nausea and similar. The AR instruction is sensitive to lights, sometimes the trackers is lost and the virtual objects disappears from the operator's view. This is solved by getting closer with the HMD to the trackers until it is recognized again by the camera. This was also observed to be an issue during the experiments, sometimes the trackers were lost and the operator needed to come closer to let the app find the tracker before the assembly could continue, which did affect the quantitative measurements. It was also observed that some participants had a hard time to properly understand the functions and how to use them during the assembly. It would be interesting to extend the tutorial to several minutes to see if it would affect the AR instructions performance. Another factor that might have affected the results that became evident during the experiments was that several participants had ordinary glasses (due to refractive errors) and the HMD did not support that. The HMD did have a functionality to change the focus of the lenses, but several participants mentioned they could not change the focus to become clear enough. Having glasses might affect this further and therefore a future recommendation would be to use an HMD that supports wearing glasses or have a large focus range that removes the effect of refractive errors.

Regarding the T&P and Video-instructions, almost all of the guidelines from theory were used, which means that they are both nearly complete solutions in relation to theory and therefore very interesting to further study and compare. The layout of the T&P instruction was designed to be easy for operators to understand and thus let operators experience low amount of extraneous cognitive load. The research group however observed an issue regarding the way in which the eight subsequences were presented on the A3 page. Some participants did not find the layout appropriate and it thereby caused confusion, which resulted in assembly errors. It is therefore suggested to design the T&P instruction with a book layout, if using landscape A3 format. It would also be beneficial if the instruction was presented on a e.g. computer screen instead of using paper-printed instruction. This would fully utilize the positive effects of digitalization.

The Video instruction were designed according to the guidelines with the high focus

[1]https://www.microsoft.com/en-us/hololens

to enhance operator control, since this has been the main reason bringing performance and operator acceptance levels down according to previous studies [24, 25], and the observations from the experiments were very positive. Participants mentioned that they felt comfortable and in control during the whole assembly. Some participants mentioned that the Video instruction really facilitated the assembly process by showing how to place and adjust hands during the assembly. Seeing the hands moving in the video should not be underestimated since it is the participants first time assembling the VR-product and they otherwise have to fully or partly guess were to best place them, regarding the AR and T&P instructions respectively.

5.4 Experiments

The experiments consisted of 30 participants, which were divided into three equal groups managing an instruction technology each. It is very important to notice that the experiment group were in total as a sample group to low to draw statistical conclusion, though the results from the measurements with observations and surveys show a good indication of the real underlying quantitative values and perceptions. The age difference, ranging from 15-55, between the participants may also have distorted the data since the sample group is low and the division into the three smaller groups were made using randomization, resulting in low chance of equal age distribution among the groups. The age may affect results with technical complex instructions, such as the AR instruction. It would thereby be interesting to for future studies to see if age have a impact or looking into the performance of specific age groups.

5.4.1 Assembly time

The measurements of assembly time from the experiments showed that the Video instruction had the lowest average assembly time values in comparison to the other instruction types. The range (distribution) between measurements is also the lowest for the Video instruction in comparison to the others. One possible explanation to the lower values of the Video instruction could be that it showed the operator how to place its hands during assembly, which made the inexperienced operator feel more comfortable and sure that the assembly was made correctly. The technology used for the Video instruction is also more familiar then e.g. AR technology. The AR instruction had the largest time values and largest statistical distribution between measurements. An explanation may be that it may take some time of practice before reaching proper usage of the AR technology, especially if you are not familiar with using AR before. The research group believes that age may have a big impact on these results and that this impact will be minimized in the future along with the technology development currently happening in the AR field. AR technology is probably more accepted in lower age groups, which will drive related technology development considering the demographically challenges industries are currently facing.

The T&P instruction also had a large distribution regarding the assembly time measurements. Surprisingly it had the lowest measured assembly time, but also the longest (if disregarding the AR outlier). These measurements could be a result of the, for some, confusing layout of the pictures in the instruction. If the participants understood the layout directly, it generated a relatively low assembly time, otherwise quite poor performance in our experiments. These related observations show that there is a good underlying potential of the T&P instruction medium to perform well, if accurately designed. Good news for companies that utilize the paper instruction format and do not want to switch instruction technology into more digital solutions.

5.4.2 Quality errors

Considering the measurements of the quality errors, similar pattern as for the assembly times appear. The Video instruction had fewest assembly error in total and non of the completed assemblies generated any severe damage to the VR-product's functionality. The AR instruction had the largest amount of assembly errors and 40% of the completed assemblies had large quality damage, related to functionality. T&P instruction generated 20% serve quality assemblies.

The results from the assembly time and quality errors are quite surprising considering previous studies, which often concludes superiority of AR technology over text-based instructions regarding both assembly completion time and amount of quality error [43, 44, 45, 46]. Previous studies show that Video instructions are often slow or causes irritation among operators. However, no previous study have taken into consideration designing effective instructions that follow proven guidelines from available theory and applying this to all studied instructions. It seems that many studies often design one instruction appropriately and then test it against an improperly designed instruction [45, 46], often only in text form, which do not support human cognitive processes very well. These studies often miss the underlying inherent potential of the individual instruction medium/technology. Since the AR instruction in this thesis could not utilize all available guidelines from theory in its design, it is possible that the AR instruction is improperly designed, like some instructions from previous studies. Thus, industrial engineers must bear this in mind when considering AR technology in general for assembly work.

5.4.3 Survey results

The results from the survey follow the same pattern, that the Video instruction overall perform most positively regarding the asked questions and that the AR instruction least positive. Not surprisingly it seems that the Video instruction and the T&P instruction are easy to understand, this because of the fact that they utilize familiar technology and need therefore not much practice before using it. During the VR-product assembly, Video instruction is most preferred to use regarding usability, followed by AR. The T&P had problems with the layout and it showed when the participants stress level raised. Regarding stress and amusement levels during the assembly, participants experienced approximately the same level amount of stress and amusement. The result that showed the most distinct differences between the instructions was the question about the future of the instruction technology, where the AR instruction seems to have divided the participants into two groups of different opinions. Some seem very optimistic regarding the AR instruction in assembly work and would like to use the technology again in the future and some thought the other way around. This could be due to the mentioned points in previous sections, regarding e.g. the non-used guidelines in the instruction.

There seems to be a connection between all results from the experiments. If one reach a low assembly time, one probably prefer and understand the instruction. The connection between assembly time and quality errors is interesting because one might think that if one assemble at a faster pace, one would make more errors than if the pace was slower. This thesis experiments show that this is not always the case and that the instruction technology have a large effect on the performance from inexperienced operators.

5.5 Future Research

In this thesis work, studies of comparing assembly instructions have been made regarding three different instruction technologies, where two out of the three were designed close to their full potential considering guidelines from theory (T&P and Video). It would be therefore be very interesting to make a similar study with an AR solution that have greater potential, e.g. with Microsoft Hololens, to utilize all design guidelines. It would also be very interesting for a future similar study to use a different product that is more similar to what manufacturing industries assemble today, which probably means a larger part amount and higher complexity. It would also mean a more realistic research area since AR instructions is beneficial in complex assemblies [23].

There have been studies showing that an handheld PC is better to use for learning purposes than an HMD in AR instructions [41]. The PC could be handheld or mounted in front of you or to the side of the assembled product instead where animations are displayed. It could also be beneficial for long term use, since HMD solutions seem to often result in nausea and similar. A study within this area would be interesting and might imply different results.

Using incorporated sound into the instruction technologies; AR and Video, during the assembly to give feedback during critical movements could increase the perception and understanding even more [38]. Also looking into the way which sound from the operator, e.g. voice command, can be used and how these sound-related aspect would impact regarding a similar study.

The participants were given a short LEGO tutorial before the experiments, but since some people had a hard time to use the AR instructions anyways, it would be interesting to drastically extend the tutorial period. An idea would be to let operators use AR instructions for a long period of time, say an hour or a whole work day. This would probably prepare the participants more on how the instructions can be used for support, not only how they work. The operators would become experienced, as opposed to the scope in this research, which would better mimic real-world operators in industry.

Research could investigate if age have any affect on the results since this research did not take it into consideration and the distribution (15-55 years) can be considered large enough that it should be needed. As mentioned earlier, there is a high probability that the three sample groups did not consist of similar age groups either, so if age does matter it could have affected these results. Together with the fact that younger people often are more comfortable with using new technologies, makes this an interesting topic to research.

Finally, it would be interesting to see what type of instruction types that is common in industry and what a change of instruction type would indicate on sustainability aspects. By doing this in an effective way with quantitative parameters, it should be possible to design a model or formulas that can estimate social-, economical- and environmental benefits of switching instruction types for a specific company. The results should work as an incentive for companies to implement instructions that are aligned with digitalization.

6
Conclusion

Considering how industries instruct inexperienced operators today regarding manual assembly tasks, it is often expensive, time consuming and involve lots of personnel. Especially when toady's products become more complex and customized, the need of operators learning new manual assembly tasks increase when having more product variants in production. If they utilize instructions, which do not involve humans, they often use improperly designed paper instructions consisting mostly out of text, which is not the most appropriate way of designing assembly instructions considering human cognitive processes. Instructions could be designed by using many different technologies, but it is about how you design the instruction that is of most importance (RQ1). To fully reach the most benefits, instructions should be effectively designed, considering both planning and presentation of instructions, and be designed according to assembly instruction design theory that takes human cognitive processes into account. The technology used for designing instructions should be digital, using screens or smart tablets, to fully utilize the benefits of digitalization.

Regarding instruction performance (RQ2), assembly time and achieved product quality, of the three instruction types (T&P, Video and AR), it can be concluded that differences between the instructions are small. The Video instruction seem to have better performance then the other regarding both assembly time and product quality based on our experiments. The most impressive result of the Video instruction was its low variation in both quantitative parameters, which is reliable and consistent.

Connected to the results from the objective quantitative measurements from the survey, the perception (RQ3) of the three instructions types by inexperienced operators are nearly equal, with a trend of slightly more positive results towards the Video instruction regarding understanding the instruction technology and usability during assembly. It is therefore recommended, based on our experiments, that industries use a properly designed Video instruction on a screen for inexperienced operators, since it guides the operator how to accurately place the hands and the technology is familiar, easy to understand and use. Looking at the future of manual assembly, technology within AR-field will be developed at a rapid pace and will therefore be interesting to follow within the upcoming years. Switching instruction technology into more digital solutions is not a large investment for companies in general, though it may have a large impact on future business and it constitute an opportunity for Swedish industry to reach higher competitiveness globally and become a leader within the digitalization field.

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A

Fixture design process and results

This appendix chapter will summarize the design process of the fixtures. First, a brief introduction to relevant fixture theory and thereafter, the methodology of the design process is presented. Lastly, the results with suggested fixture designs for facilitating removing waste material and removing frame are presented. Figure 1.2 show which manual operators the fixture design concerns and how they are located in relation to other operations. All generated fixture designs are based on the improved product design.

A.1 Theory introduction

A fixture is adapted, or adjustable to be able to be adapted to the design of the product in the operation [10]. It is used to support manufacturing, inspection and assembly operations. The purpose of fixtures is to keep the product in a appropriate position in the operation; to keep it stable and minimize unwanted movement, which minimizes the time needed to perform the operation [7]. The costs of designing and produce fixtures is typically 10-20% of the total manufacturing system costs, which is good to take into account to determine if fixtures should be used in the operation [11]. Computer aided fixture design (CAFD) enables much work to be executed digitally, which enables the costs of fixtures to become even lower [12]. There are typically five stages during fixture design, which can be seen in Table A.1 [7, 8].

Table A.1: Stages to design a fixture [7, 8]

Stages	**Steps**
Setup planning	• Identify setups • Determine locating datums
Fixture planning	• Define fixturing requirements • Determine fixture layout plan
Unit design	• Conceptual unit design • Detailed unit design
Verification	• Verify fixture against fixturing requirements

Fixtures can typically be designed in many different ways, and even be generated by CAFD-software from the workpiece design (CAD) and the manufacturing machines settings (CAM). The generated solutions can be verified by Computer-aided fixture design verification (CAFDV), to see how well the solutions fit the users requirements. One system does this based on five function modules, which can be seen in Table A.2 [9].

Table A.2: A fixture verification system [9]

Function Module	Explanation
Geometry constraint analysis	How effective the fixture minimizes the degrees of freedom and how efficient this is done.
Tolerance analysis	Predicts the tolerances that can be expected to be able to be achieved with the fixture.
Stability analysis	An analysis which calculates how stable the fixture will be.
Stiffness analysis	How stiff the fixture will be.
Accessibility analysis	Determines the availability to reach surfaces in the fixture.

A.2 Design methodology

The first step in the development process was to consider the fixture requirements, see Appendix C, and thereafter have an idea generating session to find possible fixture solutions. Possible or interesting ideas were firstly verified against the fixture requirements and by comparing to the fixture verification system [9], see Table A.2. Another screening session was held with Johan Bengtsson, one of Smarta Fabriker's project managers. The final fixture design was thereafter decided and 3D modeled in Google SketchUp [1] and lastly tested and further evaluated by generating 3D printed real scale- prototypes in plastic.

The fixtures are specifically designed to fit the VR-goggle product, so no flexible features are attached or considered in the design process. The focus have been towards fulfilling stakeholder requirements, see Appendix C, thus making a stable, robust and product specific fixture with accurate dimensions. The design process have therefore been a bit different from the stages presented in Table A.1.

A.3 Design results

This section will present the fixture design suggestions for the waste removal, frame removal and combined solutions including both.

A.3.1 Removing waste material

The waste material are cardboard material that needs to be removed in the beginning of the assembly process in order to generate the VR-goggle design, see Figure A.1.

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

The removed material will free up space for e.g. lenses and eyes so that exhibition visitors can use the goggles as intended. The problems with this process step are that visitors might remove other material than waste which are vital for the goggle construction, and also taking away the intended waste material without damaging other parts. Thus, solutions must be easy cognitively for the operators to identify the waste, and thereafter be assisted in the removal process with appropriate support, to ensure no damage occur on adjacent cardboard parts.

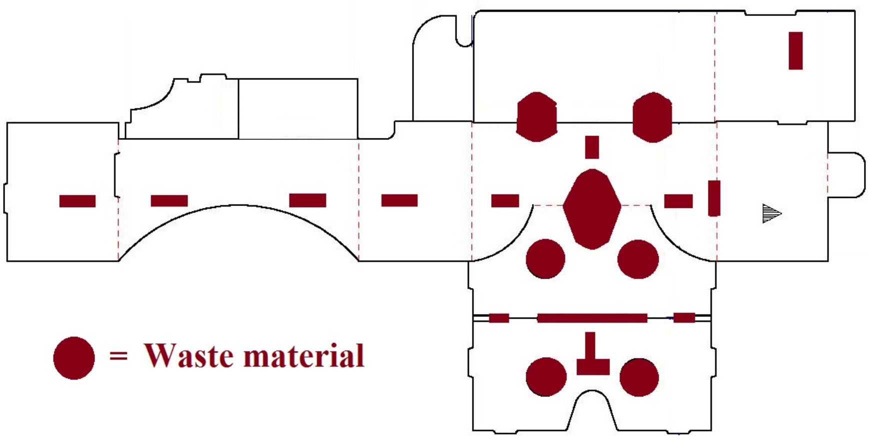

Figure A.1: Overview of the waste material (in red color)

A.3.1.1 "The Box"

The first solution is called "The Box" (see Figure A.2), because it will act as a box collecting the waste material by gravity after been removed from the cardboard sheet. "The Box" construction consists of 3 parts: a sheet metal frame with waste-specific holes and an indentation, a wooden construction with a handle and a box underneath. The suggestion is that a visitor slides the cardboard sheet in the indention of the metal frame exposing only the waste from above, which will cognitively help the visitor removing the correct material. A finger or a small tool is thereafter needed to push the waste material into a box which is placed underneath, enclosed in a construction made out of wood. This process efficiently removes the right material from the cardboard sheet and separates it from the final assembly area, keeping the workstation clean. When the waste-box underneath is full of waste material, the handle is used to open up the fixture and empty the box. Things to consider regarding safety and efficient usage are to not have any sharp edges on the box, have an opening to facilitate taking out the cardboard sheet from the indentation, having a lock on the handle and not using a sharp support- tool in the removing process.

A.3.2 Removing sheet frame

Removing the sheet frame, which is attached around the product outline, is also a critical step because of the chance of damaging adjacent cardboard parts is large if

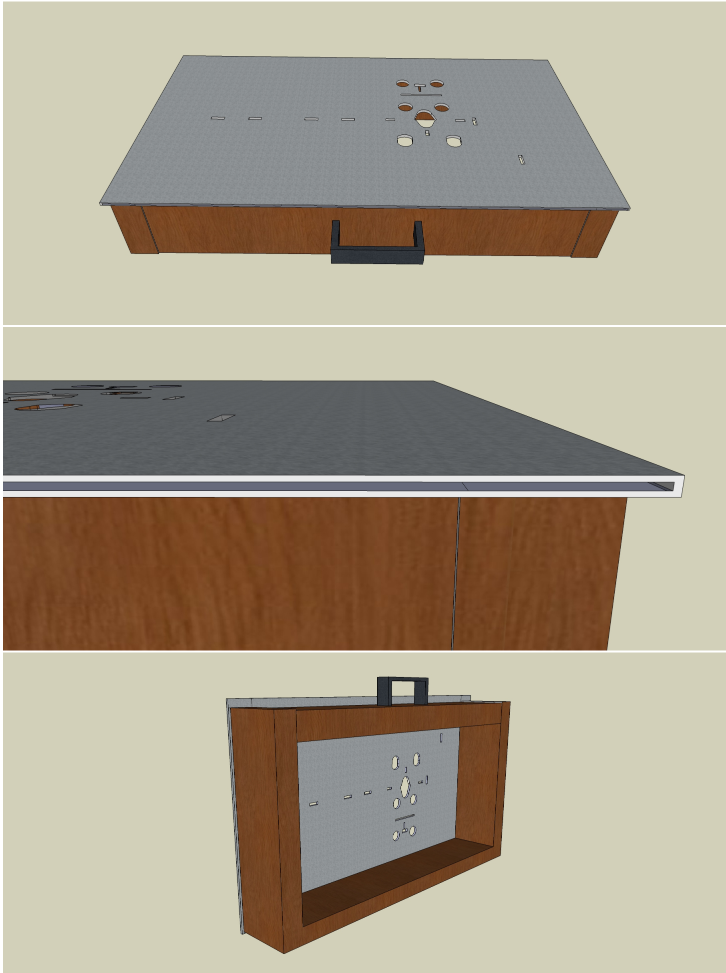

Figure A.2: "The Box" suggestion. From upper to lower picture; showing the front view, the indentation and the space underneath.

not performed properly. Thus, the process should be supported with some fixture that efficiently removes the frame with no generated damage to adjacent parts, which would lead to quality errors in the later final assembly.

A.3.2.1 "Frame a'la nose"

This fixture suggestion (see Figure A.3) is intended to help frame removal and also assist the VR-goggle final assembly. The fixture is a one- piece robust construction that can be fixedly positioned on top of a workbench. The operator places the sheet, with no waste material, on top of the fixture, following the contours of the product. The fixture will fill up the spaces from the previous waste material and thereby hold the sheet in place. Thereafter, the visitor will simply press with one hand on the frame (close to the fixture contours) and keep the other in the center of the fixture, which will generate a cutting force close to the fixture contour. The frame will be pushed down and when finally fully detached placed on a pallet specified for recyclable cardboard. The cardboard material that constitute the VR-product is then laying on top of the fixture ready to be assembled. The assembly will be supported by a "nose" construction. The nose construction will keep the lens- parts upright in a vertical position, without any hands, which would result in a more ergonomic final assembly.

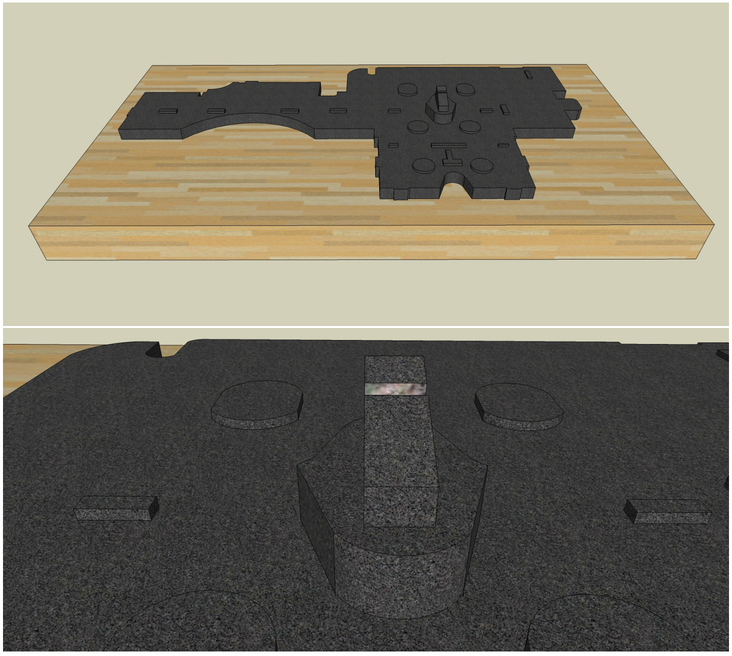

Figure A.3: The "Frame a'la nose" suggestion. From upper to lower picture; showing the whole fixture on a workbench and a focused image of the nose

A.3.3 Combined solutions

The fixture; "Combined 1", is designed as a combined solution to aid removing both the waste material and the sheet frame, see Figure A.4. The general concept of the fixture is to place the paper sheet on top of it and then, with the help of a small hand tool, push out the waste material that will fall through the top of the fixture down into a waste-bin placed underneath, similar to "The box" suggestion. Thereafter, the frame removal is aided with the help of the product contour and height difference that generates a cutting force, similar to the "Frame a'la nose" suggestion.

The fixture is designed as two solid pieces, though consists of four distinctive parts with different functions, highlighted with different colors, see Figure A.4. The green part has the contour of the VR-product and holes corresponding to position of the waste material, allowing the waste to fall downwards into the yellow bin. The brown part creates the critical height difference that aids frame removal and it also have holes corresponding to position of the waste material. The black part is a rim that keeps the cardboard sheet fixed when performing the removal steps in the y- translation and z-rotation directions, see axises in Figure A.4. It also prevents the operator to place the sheet in the wrong direction. The poka yoke [2] solution

[2] http://leanmanufacturingtools.org/494/poka-yoke/

in the upper left corner will constrain the cardboard sheet to only fit in the right way.

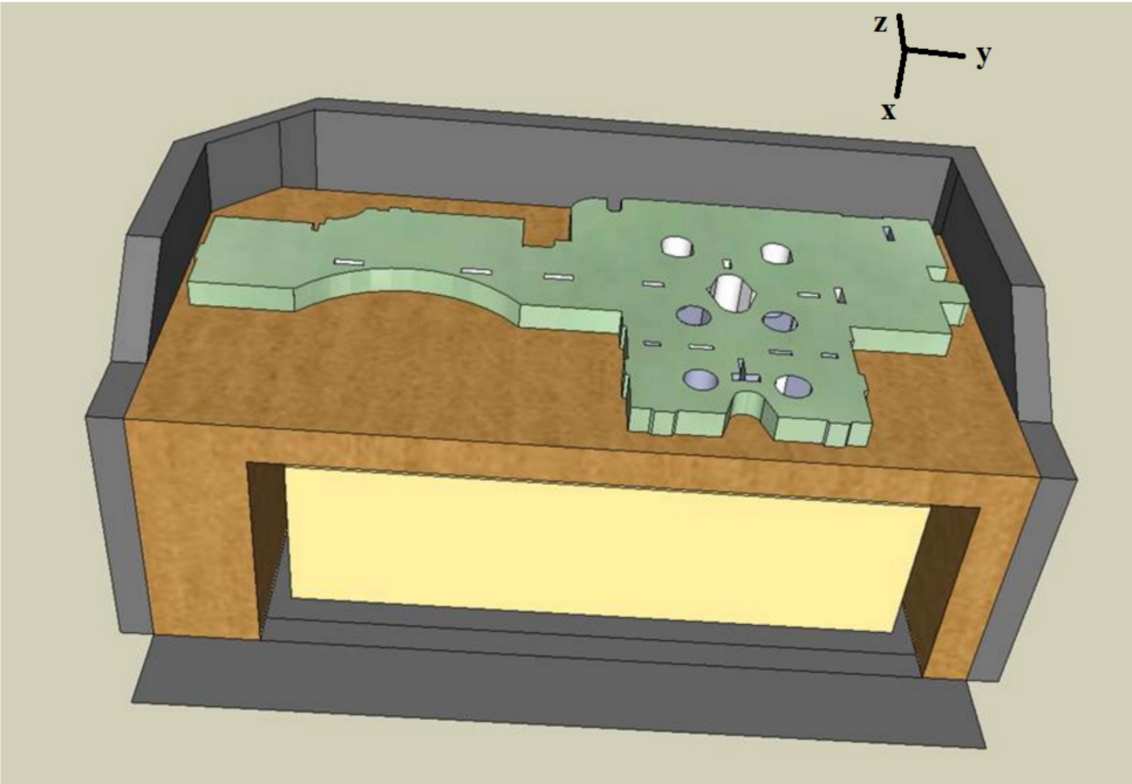

Figure A.4: A combined solution to the waste material- and frame- removal steps called "Combined 1".

The fixture; "Combined 2", is designed as a combined solution and is an updated version to the "Combined 1" suggestion, see Figure A.5. The functions of the fixture "Combined 2" are the same as the "Combined 1" suggestion, though the appearance is different, making it possible to mount on a sheet-metal framework, see bottom picture in Figure A.5. This suggestion have been chose to be 3D-printed and used in the exhibition, thus the dimensions of the "Combined 2" have been more carefully made. The product contour piece have been made 2mm smaller and waste material holes 2mm larger and conical, so that the waste do not get stuck inside the fixture or that the product will get damaged when removing the sheet frame. All edges have also been rounded to prevent any injury due to sharp edges. The 3D-printer that will be used can print with the tolerances ± 0.2 mm, which have been taken into account in the design. The fixture reduces the degrees of freedom, but not as much as "The Box" suggestion in Figure A.2. However, it has the advantage that the frame can be removed in the same process, which is one of the trade-offs between these alternatives. A stability analysis have not been made since the material that will be used in the 3D printer is not known at this point. Regardless, the stability itself should not be an issue since the VR-product is very light and there are no high force demanding operations the fixture need to support. A recommendation is that the 3D-printed fixture is printed with a high percentage of infill[3] to increase the stability, robustness and stiffness. The workbench in Figure A.5 have been designed with ergonomics in mind, considering the height and width of the bench. The VR-glasses have a fixed position on the cardboard sheet. The fixture is designed to position the sheet as close as possible to the operator, to ease accessibility when the waste are to be removed.

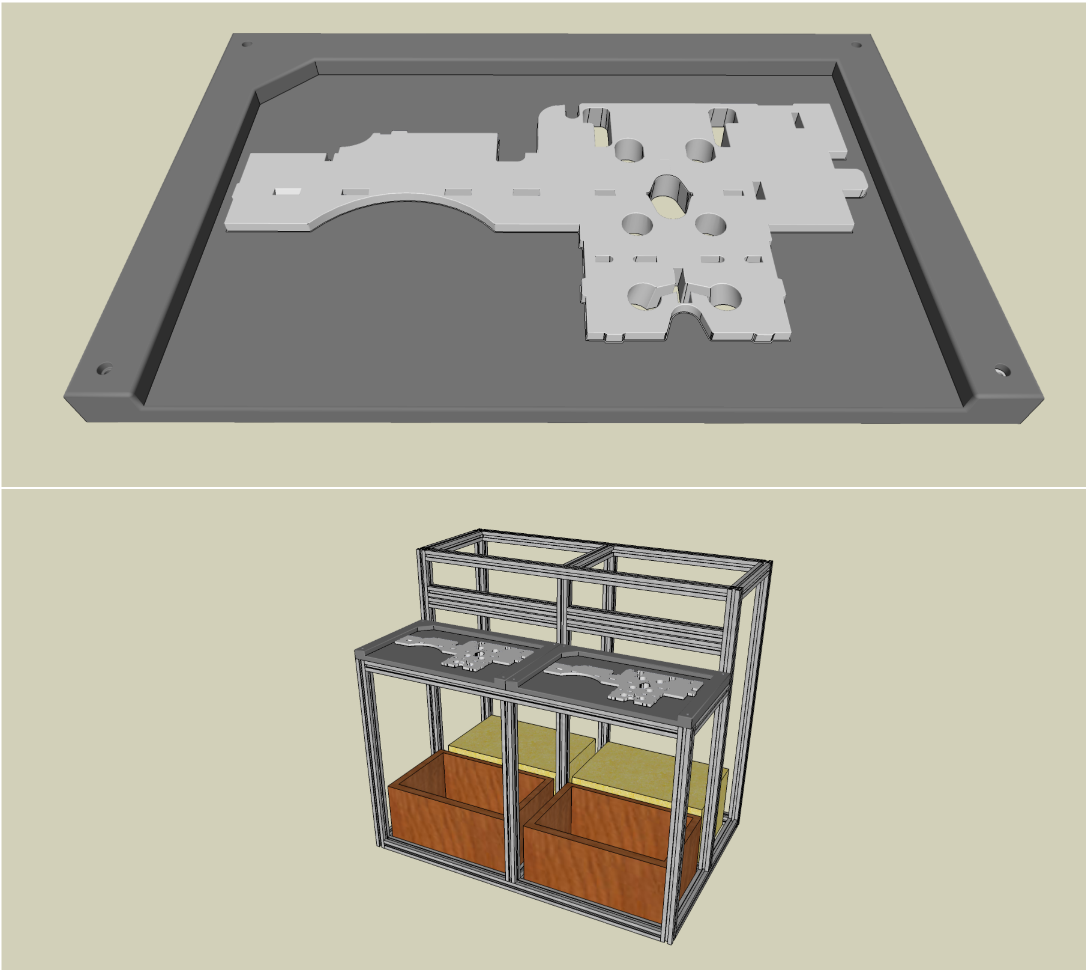

Figure A.5: A combined solution to the waste material- and frame- removal steps called "Combined 2". From upper to lower picture; showing a focused image on the fixture and a image of two fixtures attached to a sheet-metal framework.

[3]https://ultimaker.com/en/resources/16528-infill

B

General Idea Generation for the Assembly Work

This appendix chapter presents some of the ideas for possible use in the assembly work. Figure B.1 depicts the whole studied assembly process, from one large cardboard sheet to an assembled and folded VR-product. Ideas are presented for specific assembly operators, e.g. waste material removal or final assembly, or for the whole manual assembly process in Figure B.1.

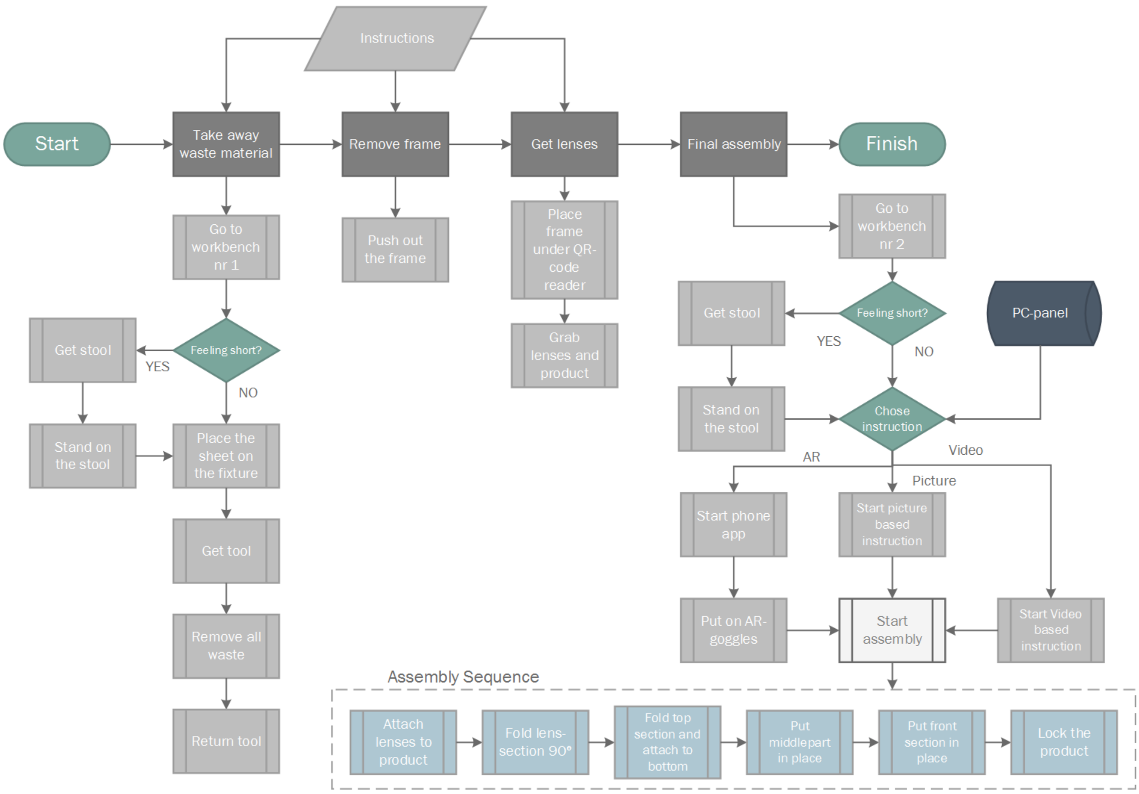

Figure B.1: Flowchart of the entire manual assembly work.

B.1 QR-Code

When the operator in the start receives the cardboard sheet at the end of the automated process part, a QR-code have been printed on the back of the cardboard sheet. The code enables the product to contain specific information for that specific product, thus the product becomes the information carrier. A possible concept for a beneficial usages of the QR-code would be to have information about the operators specific preferences, which could be added in the ordering phase. Interesting preferences would be e.g. his or her body height and possible eyesight problems. When the operator later scans the QR-code from the cardboard at the final assembly workstation with a QR-scanner, the workstation could adjust its workbench height and light settings to fit for specific operators individual needs. Solutions, as to how to design/build the workstation in practice, can be generated from CGM[1] adjustable workbenches.

B.2 Guidance by light and vision control

To facilitate removing the waste material from the cardboard sheet, see Figure B.1, a light guidance system could be implemented influenced by "pick by light" concept. This system would light up the contours of the cardboard sheet where material should be removed, waste material, when placed onto the workbench and scanned (e.g. QR-code). The system would thus cognitively help the visitor to find which material to remove and reduce the risk of accidentally removing the wrong material, damaging the product functionality.

A vision system could also be implemented after previous step, to control if the operator successfully removed all waste material and notify to start carry out the next assembly step. A vision system could also be used as a last step in the entire assembly process, to get feedback on whether the product have been assembled correctly or not.

B.3 Gamification

The work at the workstation could consist of elements from Gamification to make the assembly work feel more like a game. This is one of the recent trends in production since it should make the work more attractive and less monotonic, i.e. increasing the intrinsic motivation.

When the operator starts to assemble the product a timer could start and measure the whole assembly time. This could be constructed into a competition game where visitors could compete and compare their times. The times could also be divided into segments for each assembly step, so the operator could see in which steps they lack behind or in which steps they excel. The standard time, or the time to strive for, mimicking ordinary work-pace for a fully experienced operator could be based on MTM speed. This could be an interactive and informative part of the learning process that would enable the operator to understand a bit on how it is to work in production.

[1]http://www.cgm.se/products/

Another option for the operator would be to adjust the instructions according to preferences. This could be to enable subtitles of the instruction, get instructions via headphones, or to change the speed of the presented instructions (to get a better time in the game). If the operator feels a bit experienced the instructions could be less detailed and therefore faster to comprehend. Or, an inexperienced operator could select a very detailed set of instructions in order to be able to assemble the product correctly.

Another possible option would be to guide a operator at the workstation with Augmented Remote Guidance technology from XM Reality[2]. Consider the following example, you assemble your own glasses and feel you really understands what to do in an efficient way. Your friend is next to assemble the product, and you feel you can instruct in a better way than the instructions available. To get a better time for your friend you use the Remote Guidance technology to guide your friend and to get a much lower time.

B.4 HMI with YuMi robot

If the workstation would have access to a YuMi[3] robot several different concepts could be possible. The robot can help in the assembly to hold the product in critical movements during the final assembly, and therefore different alternative assembly sequences might be possible that could improve the efficiency and product quality.

Another concept is to make YuMi hold the product in different positions for the operator to assembly. When a assembly step is finished YuMi rotates the product (vertically and horizontally) into an ergonomically optimal position where the next assembly sub-sequence can be executed. This would greatly improve the ergonomics and probably result in higher efficiency as well. It would depend on how well YuMi can perform such a task, though this Human-machine-collaboration suggestion would be very interesting to try out.

B.5 Continuous Improvement

When the assembly is completed and the visitor is ready to leave the workbench, there can be a short feedback system where the visitors tell why they did not complete the assembly on the expected time. The MTM-time is considered optimal and everything longer should have a reason as to why it took so long time. Examples can be that they did not properly understand the instructions, they felt stressed and made several errors along the way or that something regarding the instructions was not taken into consideration and resulted in several adjustments along the way. This information could be saved and analyzed to find if something is not working as planed and could improve the overall work needed. This could be connected to Big

[2]http://xmreality.com/our-solution
[3]http://new.abb.com/products/robotics/industrial-robots/yumi

Data which definitely is something the factories in the future are going to use for improvement purposes. This system could continuously be used to find improvement areas and will in the long run adopt to the general operator preference.

C

Requirement specification

This appendix chapter will go through the requirement specification. The specification is a summary of requirements placed on the product, assembly work and fixtures suggested by the involved stakeholders and ourselves. In Table C.1, the letters D and R represents demand and request respectively.

Table C.1: Specification of requirements for the product, assembly work and fixtures.

Product Requirements:	
Consist of 100 percent cardboard (except the lenses)	D
The whole cardboard sheet must be white (e.g. no printed instructions)	D
The construction will hold the phone in place, without the user's hands	R
The maximum cardboard sheet measurements are 400 x 600 mm	D
The product needs to support the weight of a cell phone (min 200g)	D
Fits for all phones which supports VR technology	R
Should be able to be operated with ordinary glasses	R
The product should be easily disassembled	R
The product volume should be minimized, without damaging its functions	R
The phone should be fixed when using the product	R
The product must fit the dimensions of the plastic lenses	D
Assembly Requirements:	
The assembly should should be aided with well designed instructions	D
The assembly should be ergonomically designed (cognitive and physical)	R
The assembly method should ensure high quality of the product	D
The assembly should avoid potential safety hazards to operators	D
The assembly method should be time efficient	D
The assembly time should be below 1 min	R
Fixture Requirements:	
The fixture(s) needs to be stable on the workbench	D
It needs to be designed for the products tolerances	D
It needs to be robust	D

D

Product design improvement suggestions

This appendix chapter will bring up design improvement suggestions brought up from brainstorming sessions. The improvements are connected to the requirements from involved stakeholders, DFA theory and assembly sequence theory. The chapter is divided into sections based on solution suggestions that originate around specific areas from the initial product design (See Figure D.1). Each part of the design in Figure D.1 is given a specific name to facilitate describing the improvement suggestions in text form.

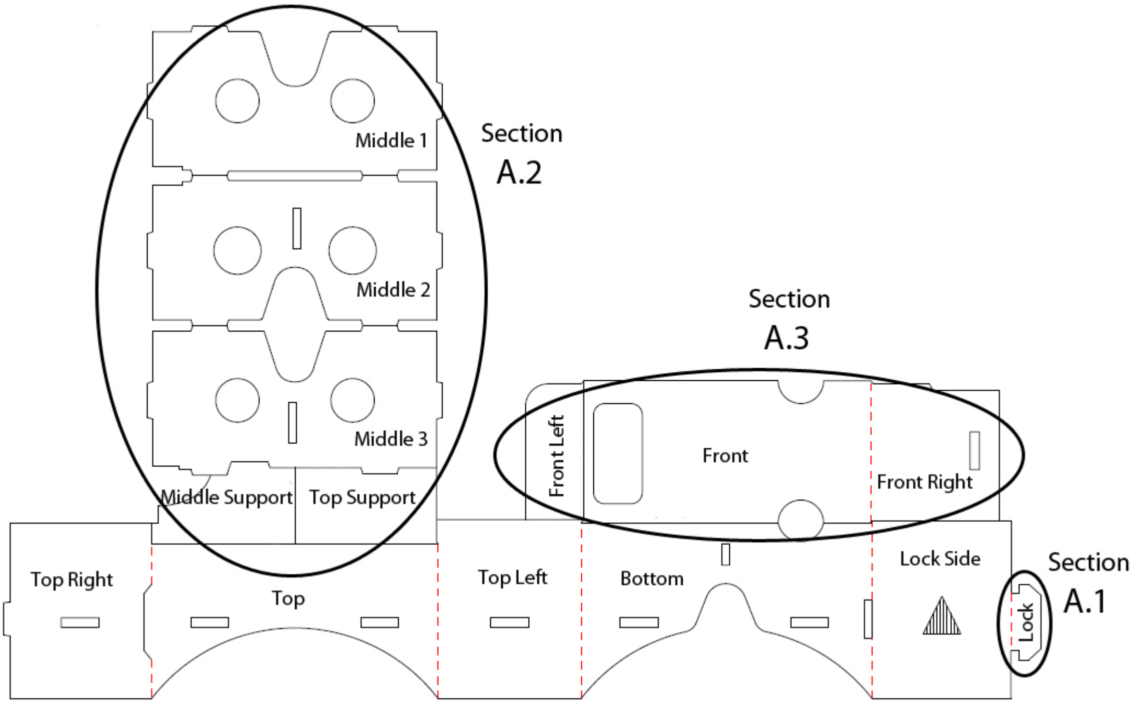

Figure D.1: Initial product design with part-names.

D.1 Lock mechanism

When the initial product design (Figure D.1) was tested and examined, the lock was considered to have improvement potential. The existing solution was a bit hard and time-consuming to assembly, since it was based on "hooks" that needed to be inserted into the product, and became easily deformed in the process. Therefore, solutions were proposed with the intention to reduce the forced insertion into the product.

D.1.1 Lock solution A

Figure D.2 show the first suggested lock solution. It is based on a small tab that is rotated 90° downwards from its horizontal position and pushed through a pocket with matching dimensions. When the whole "lock-piece" is pushed into position, the small tab is rotated back 90° to its initial position, which acts as the locking mechanism. This concept could also be developed further by having another tab on the other side, creating lock symmetry, which the two triangles in the left image in Figure D.2 represents.

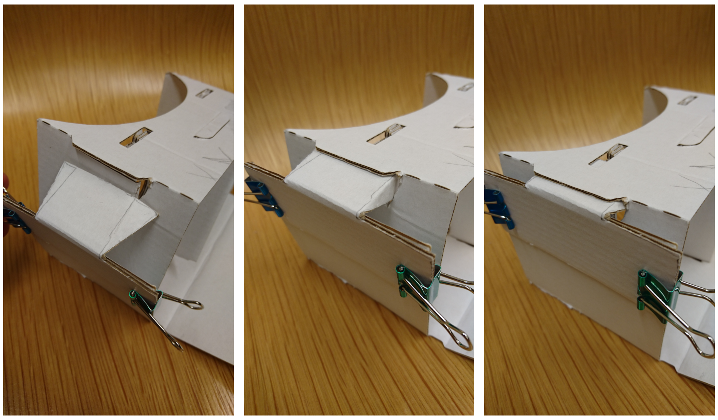

Figure D.2: Lock solution A. Left to right shows how to close the lock

D.1.2 Lock solution B

Figure D.3 shows another concept for achieving the lock mechanism. This is a very common solution for cardboard boxes in general to have and is based on two tabs that slide through each other.

D.1.3 Lock solution C

Lock solution C can be found in Figure D.4. This solution is very simple, it consists of a simple straight tab that are to be inserted in a whole with a corresponding size. The lock mechanism is based on the friction between the tab and the pocket edges, but also to some extent from the small curved deformation of the tab.

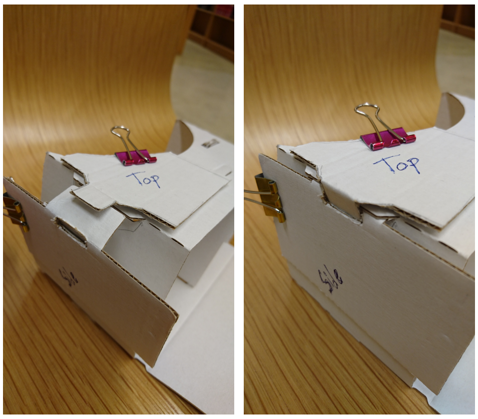

Figure D.3: Lock solution B. The left image shows the open state and the right shows the locked state.

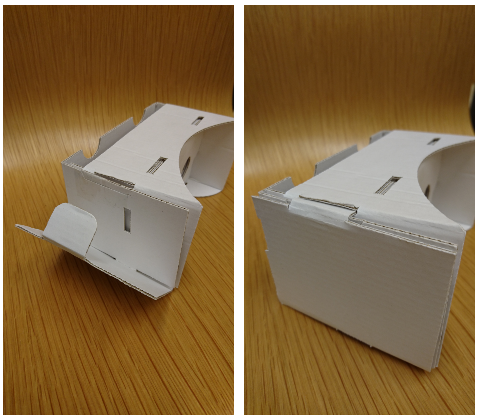

Figure D.4: Lock solution C. Left image shows the open state, and image shows the locked state.

D.2 Lens- and support- section

The lens- and support- section, section A.2 (see Figure D.1), have several different kinds of improvements. They can roughly be divided into Support parts and the Middle Section.

D.2.1 Support Parts

One issue when the part "Middle Support" (see Figure D.1) is assembled , is that it will always be misplaced if it is not repositioned before putting it in place. The reason is that the "Middle Support" has a tab that is placed in the middle hole which keeps it in place. The middle hole is so large, which will naturally position "Middle Support" outside of the bottom hole. This is shown in the left image in Figure D.5. The right image in Figure D.5 shows how it is supposed to be assembled.
This issue could be resolved by making the middle hole a bit smaller than the one in the bottom. Unfortunately, the machine that manufacture the cardboard sheets can not decrease the dimensions of the middle hole. Another solution is to place

the middle hole a bit closer to the "Bottom", since it will result in a longer distance to the "Top". Basic trigonometry logic tells us that the misalignment will therefore decrease, as the left image in Figure D.5 illustrates.

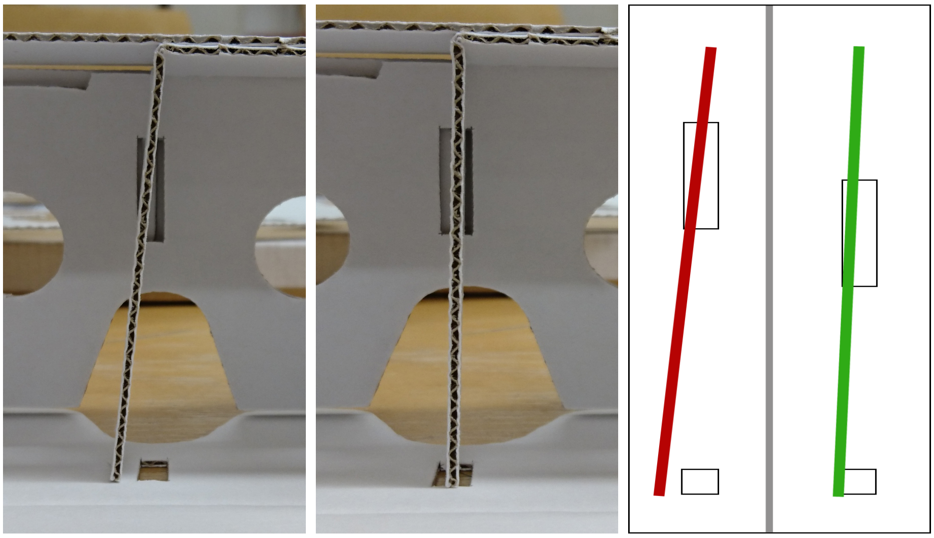

Figure D.5: Shows how the part "Middle Support" is assembled, to the left incorrectly, and middle correctly. The right image shows how the red "Middle Support" assembled incorrectly while the green "Middle Support" is assembled with a smaller misalignment by moving the middle hole closer to the part "Bottom".

D.2.2 Middle Section

The middle section consists of three parts; Middle 1-3 (see Figure D.1). The purpose of these parts is to be folded together, hold the lenses in place and act as a support construction for the whole product. It was concluded that to be able to hold the lenses in place it is enough to have two middle sections, and have the lenses between them. In other words, Middle 1 is completely unnecessary for its function, but it might have some value for the product's stability and robustness. From an assembly perspective, the main benefit is that one assembly sequence step is eliminated.

The middle sections final position is to be between the parts "Top" and "Bottom" (see Figure D.1). One sequence to assemble is to first assemble the middle section and place it on the "Top", and fold the "Bottom" section over the middle section. The problem comes to assemble the "Front", it is hard to assemble this section by having it in the air. It is easier to have it onto a flat surface for support.
Another possible sequence is to assemble the middle section, and turn the middle section with the "Top" onto the "Bottom" and then assemble the "Front". This is an easier sequence, except for rotating the assembled middle section. To come around this whole issue, the middle section can be moved and attached to the "Bottom" part instead. This would result in an natural and easy way to assemble the product. Another benefit is that the operator do not need to reposition and adjust hands during parts of the assembly sequence, all essential movements will be within the "Bottom" area.

D.3 Front Section

This section consists of the parts: "Front", "Front Left" and "Front Right" (see Figure D.1). When assembled they form a pocket the phone is to be inserted into.

D.3.1 The Pocket Size

One of the first issues connected to these parts was that the product did not fit all cellphones. The approximate maximum size are phones with a screen of 5,5". A bigger phone will not fit in the pocket these parts create when assembled. A smaller phone will always fit, but it will move around in the leftover space when the product is being used. If the parts were scaled up, bigger phones would fit, though the leftover space for smaller phones would increase instead. Since the glasses needs to be centered for optimal performance, the leftover space does result in reduced VR-experience for the user of the glasses. Therefore, a of trade-off needs to be taken into consideration to match both of these criteria. One solution could be to use an additional material to fill up the leftover space, keeping the small phones centered. Another would be to add a construction of the cardboard that can be adopted to the leftover space and force the phone to be kept in place. A third would be to add a module that are to be inserted in the pocket, with the phone inside and adapted to its size. However, at the current time there are not many phones bigger than 5,5", so this issue might not affect too many people, but considering the high speed of technological development, a bigger problem may arise in the future.

D.3.2 The hole for the phone's camera

In the part "Front" D.1) there is a large hole for the phone's camera. The reason is that the camera can be used with Augmented Reality or Mixed Reality. The problem with the hole is that it currently do not fit for all phones' cameras and it considerably weakens the structure for the whole product. If the hole's size was increased to fit all phones the cardboard structure would be weaken. At current time, there are not many apps that support Augmented Reality in VR-glasses, so it does not add much value for the product. Also, it is a critical step in the assembly since it is very easy to deform the "Front". It is suggested that it is removed to increase the strength of the product instead. If this is done, another identical hole as the one between the "Front" and "Bottom" can be placed. This will aid when the phone is taken out from the glasses, since the operators fingers can be used in both holes to push the phone out. If it is only one hole, there will be an unbalanced applied force that will generate opposite friction forces between the phone (or the phone's additional protection) and the cardboard, which could cause the phone to become slanted and get stuck in the pocket.

D.3.3 Unnecessary Cardboard

The parts "Front Right", "Lock Side" and "Top Right" are to be assembled directly parallel to each other. From the function's perspective (to lock the construction in place) it is only necessary for two sides to be locked together to form a seal. In other words, one of these parts can be eliminated without affecting the function to lock the construction. It might result in a weaker construction, but small tests show there is no significant effect. In order to not change the overall product design too much, it is suggested that the "Top Right" should be cut off directly below the hole that the "Lock" is to be placed into. This will not affect the function in any way and will save material in the process.

E

MTM-SAM calculations

This appendix chapter presents MTM-SAM calculations of the initial and improved product designs.

Old Product Design	SAM Analysis Form																											
Object								Date	#							DWG No.												
Operation								Issued by	FS							Page of												
	GET						PUT						USE				RETURN		PUT						Summing up Factors			Reg.nr
Method description	Step	GS			Add. for Handful	Weight >5 kg	Step	PD			Add. for Precision	Apply Force	No. of strokes, grip	No. of places	Time of stroke, pri		Apply Force	Weight > 5 kg	Step	PD			Add. for Precision	Apply Force	Bend+Arise			
	3	5	4	2	6	2	3	5	4	2	3	3	f	n	t	=	3	2	3	5	4	2	3	3	12	F	f	Total
Attach the lenses (two parts)	3	5	4	2	6	2	3	5	4	2	3	3					3	2	3	5	4	2	3	3	12			
			2						2		2															22	1	22
Fold lens-section 90º	3	5	4	2	6	2	3	5	4	2	3	3					3	2	3	5	4	2	3	3	12			
			1						2	1																14	1	14
Put middlepart in place	3	5	4	2	6	2	3	5	4	2	3	3					3	2	3	5	4	2	3	3	12			
			1							1	1															9	1	9
Roll-around top section and	3	5	4	2	6	2	3	5	4	2	3	3					3	2	3	5	4	2	3	3	12			
attach to bottom			2	1					2	2	2															28	1	28
Put front section in place	3	5	4	2	6	2	3	5	4	2	3	3					3	2	3	5	4	2	3	3	12			
			1						1		1															11	1	11
Lock the product	3	5	4	2	6	2	3	5	4	2	3	3					3	2	3	5	4	2	3	3	12			
			2							1	1															13	1	13
	3	5	4	2	6	2	3	5	4	2	3	3					3	2	3	5	4	2	3	3	12			
Calculation:																			Total net time (factors)									97
																											sec	17,321

Figure E.1: MTM-SAM calculation of initial product design.

New Product Design	SAM Analysis Form	Reg.nr
Object	Date #	DWG No.
Operation	Issued by FS	Page of

Method description	GET					PUT							USE					RETURN PUT									Summing up Factors		
	Step	GS			Add. for Handful	Weight >5 kg	Step	PD			Add. for Precision	Apply Force	No.of strokes, grips	No.of places	Time of stroke,prip		Apply Force	Weight > 5 kg	Step	PD			Add. for Precision	Apply Force	Bend+Arise			
	3	5	4	2	6	2	3	5	4	2	3	3	f	n	t	=	3	2	3	5	4	2	3	3	12	F	f	Total
Attach lenses to product	3	5	4	2	6	2	3	5	4	2	3	3					3	2	3	5	4	2	3	3	12			
			1						1		1															11	1	11
Fold lens-section 90°	3	5	4	2	6	2	3	5	4	2	3	3					3	2	3	5	4	2	3	3	12			
			1	1					1	1	1															15	1	15
Fold top section and	3	5	4	2	6	2	3	5	4	2	3	3					3	2	3	5	4	2	3	3	12			
attach to bottom			1	1					1	2	2															20	1	20
Put middlepart in place	3	5	4	2	6	2	3	5	4	2	3	3					3	2	3	5	4	2	3	3	12			
				1					1	1	1															11	1	11
Put front section in place	3	5	4	2	6	2	3	5	4	2	3	3					3	2	3	5	4	2	3	3	12			
			1						1		1															11	1	11
Lock the product	3	5	4	2	6	2	3	5	4	2	3	3					3	2	3	5	4	2	3	3	12			
			1							1	1															9	1	9
	3	5	4	2	6	2	3	5	4	2	3	3					3	2	3	5	4	2	3	3	12			
Calculation:																			Total net time (factors)									77
																											sec	13,75

Figure E.2: MTM-SAM calculation of improved product design.

F

Improvements suggestions: Workshop

This appendix chapter presents the improvements suggestions brought up by the participants from the workshop. Not all of the improvements were applied to the final instruction designs, see result chapter for the final instruction designs. The improvements that can be connected to the use of sound have not been taken into consideration, since it is beyond the scope of this research as stated in the introduction.

Table F.1: Generated improvement suggestions from the workshop.

Instruction type	Suggestions
T&B	The component "FL" in Figure 4.1 should be highlighted when assembled to make sure it is noticed by the operator.
	More important details overall should be highlighted.
	Remove text that could be too complicated for the intended user, for instance "180°".
	Use more arrows to facilitate the sequences.
	The columns which displays the starting position every sequence can be green instead of red.
	Use short descriptions/headings for steps that can be hard to understand.
	The layout of the T&B instructions should be changed from a "book format" into a single page format, since operators usually read that way.
Video	Replace the first "How to use" page with animations showing how the instructions work, instead of using fixed text and arrows.
	It should be more clear when a new animation sequence is displayed.
	The sequences can use headings that shortly explains the sequences.
	Sound could be used to explain how the sequences work
	The buttons in the instruction should work using a touch screen.
	The progress bar could be bigger and positioned closer to the center of the screen.
AR	Re-position the reticle to avoid accidental activation of the control panel.
	The VR-product should be bigger on the tracker
	The trackers should be positioned further away from the operator.
General	The operator should get some kind of feedback when a sequence are assembled correctly, for example with the help of sound or text explaining how it would sound.
	An alternative assembly sequence of the parts "MS" and "TS" in Figure 4.1 was found that was considered an better alternative.