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Interactive Assembly Instructions

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Master of Science in Technology.

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Abstract

Industrial products are increasingly varying, and the assembly of customized or unique products is slow, expensive, and prone to errors. Conventional static assembly drawings and instructions are suboptimal in supporting complex and dynamic assembly operations. The main objective of the study was to investigate if interactive assembly instructions could substitute the current documents instructing assembly in the case company.

Two approaches, 3D instructions and augmented reality (AR) instructions, were developed based on literature review. 3D instructions presented the assembly procedure in steps in which the assembly of the parts is animated. The instructions were based directly on the 3D model of the assembly object. AR instructions utilized the same assembly sequence as 3D instructions. AR instructions were viewed using a head-mounted display, which presented the assembly step animations spatially overlaid on the physical assembly.

The developed instructions were evaluated in a user study. The tests were observed by the author, and the participants answered to a post-study questionnaire that concerned subjective efficiency and user acceptance. Both AR instructions and 3D instructions received positive feedback and were evaluated more efficient than the currently used assembly drawings. The features of the interactive assembly drawings address directly the problems of the current assembly documents. Hence, it was concluded that interactive assembly instructions could be used instead of the current assembly drawings and work instructions. However, the complexity of the case company products require that the instructions must be configurable to enable their implementation.

Keywords assembly instructions, interactive assembly instructions, manual assembly, augmented reality, work instructions

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Tiivistelmä

Teolliset tuotteet kehittyvät jatkuvasti monipuolisemmin muunneltaviksi, ja samalla niiden kokoonpano muuttuu hankalammaksi ja kalliimmaksi. Perinteiset kuviin ja tekstiin perustuvat kokoonpanokuvat ja työohjeet ovat monin tavoin riittämättömiä ohjeistamaan monimutkaisia ja dynaamisia kokoonpanotehtäviä. Tässä työssä tavoitteena oli tutkia, voisiko interaktiivisilla kokoonpano-ohjeilla korvata kohdeyrityksessä nykyisin käytössä olevat työohjeet ja kokoonpanokuvat.

Työssä kehitettiin aikaisempien tutkimusten pohjalta kaksi erilaista interaktiivista ohjeistustapaa. 3D-ohjeet opastavat kokoonpanoa vaihe vaiheelta näyttäen jokaisen osan asennuksen animoidusti. 3D-ohjeet luodaan suoraan kokoonpanon 3D-mallin pohjalta. Toiseksi menetelmäksi valikoitui lisättyä todellisuutta (augmented reality, AR) hyödyntävät ohjeet. AR-ohjeet perustuvat 3D-ohjeita varten luotuihin vaiheistuksiin sekä animaatioihin. AR-ohjeita katsotaan silmikkonäytöllä, joka näyttää ohjeiden virtuaaliset komponentit todellisen kokoonpanon päällä.

Ohjeiden toimivuutta testattiin käyttäjäkokeissa. Testeissä havainnoitiin koehenkilöiden toimintaa, ja lisäksi he vastasivat kyselyyn. Kyselyllä selvitettiin, miten tehokkaana koehenkilöt pitivät testattuja ohjeita verrattuna heidän tavallisesti käyttämiin kokoonpanokuviin. Sekä AR- että 3D-ohjeet saivat positiivista palautetta, ja koehenkilöt kokivat niiden toimivan tavallisia kokoonpanokuvia paremmin. Interaktiiviset ohjeet ja niiden tärkeimmät ominaisuudet vastaavat nykyisten kokoonpanokuvien ja työohjeiden ongelmakohtiin. Työn johtopäätöksenä voidaankin todeta, että interaktiiviset kokoonpano-ohjeet sopisivat korvaamaan nykyiset kokoonpanokuvat sekä työohjeet. Tuotteiden monimutkaisuus kuitenkin edellyttää, että ohjeet pitää pystyä konfiguroimaan varianttikohtaisesti.

Avainsanat kokoonpano, kokoonpanokuva, lisätty todellisuus, interaktiiviset kokoonpano-ohjeet, työohjeet

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Aukusti Kankaanpää

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Abbreviations

2D	Two-dimensional
3D	Three-dimensional
AR	Augmented reality
CAD	Computer-aided design
CPU	Central processing unit
CTO	Configure-to-order
ERP	Enterprise resource planning
ETO	Engineer-to-order
GPS	Global Positioning System
HMD	Head mounted display
MD	Multidrives
OSE	Order-specific engineering
PDF	Portable document format
PLM	Product lifecycle management
RAM	Random access memory
R&D	Research and development
SAR	Spatial Augmented Reality
SD	Single drives
SWOT	Strength, Weaknesses, Opportunities, Threats
VR	Virtual reality

1 Introduction

Industrial products are becoming increasingly complex by their assembly and product variety. The drivers behind this trend are mass customization, individualization, and personalization of the products. (Fässberg et al., 2012). At the same time, fierce global competition demands companies to operate as efficiently as possible. Assembling customized or unique products is slow, expensive, and prone to errors (Salonen et al., p. 9, 2009). For assembly line operators the increased variance of the products means that they constantly encounter slight changes in the materials or work processes (Hopkins, 2016, cited in Kohn & Harborth, 2018). As a result, there is an increasing need for advanced instruction systems providing reliable information and cognitive support at the right time for the operators assembling the products. (Funk et al., 2016; Fässberg et al., 2012). High quality assembly instructions support rapid learning which helps to maintain cost-efficiency, especially in the assembly of varying products (Peltokorpi, 2018, p. 57). Poor quality work instructions result in employees having lower job satisfaction, being less efficient and making more errors (Haug, 2012).

Fässberg et al. (2012) explain that the presentation of the information consists of two parts: carrier and content. Carrier refers to the medium or device carrying the information, e.g. paper, monitors, or tablet, while content refers to the mode of the information, e.g. text, diagrams, or animations. Fässberg et al. point out, that the development of the mere system is not enough, but the content needs to be focused on as well.

The present study explores whether interactive assembly instructions could provide the needed improved support. They allow the transmission of dynamic information and representation of assembly sequences in a timely manner. In the present study, *interactive assembly instructions* refer to animated instructions based on three-dimensional (3D) computer-aided design (CAD) models, which are viewed either on a monitor displaying a virtual environment or through a head-mounted display which uses augmented reality (AR) to overlay the instructions on the real environment. Respectively, these two distinct types of instructions are referred to as 3D instructions and AR instructions. Regarding the instructions demonstrated in the present study, interactivity refers to the users' ability to control the playback of the animation. Additionally, in the case of 3D instructions, there are other interactive features available.

Despite that assembly guidance was one of the early interests of AR applications and use of AR in manufacturing has been researched a lot in the last two decades, the technology has not yet become widely adopted. This appears as a gap between the popularity of theory and practical use cases. (Kohn & Harborth, 2018). There are multiple reasons for slow adoption of the technology. Salonen et al. (2009) state that AR hardware is expensive and difficult to use in an industrial environment. However, more powerful devices with higher portability have been developed and published recently enabling industrial use. Syberfeldt et al. (2015) believe that the key to breakthrough is to attain higher acceptance of the users. According to Campbell (2018), the single largest barrier to widespread adoption of AR is cost and effort of authoring AR content. The present study extends the body of industrial experiments and demonstrates both AR and 3D instructions in the assembly of relatively large industrial products.

In the case company, there is an ongoing project to study the feasibility and possibilities of integrating different product lifecycle processes and related data into a single product lifecycle management (PLM) system. One aspect of the project is to study how the existing 3D models of the products could be utilized more widely. Now, the use of these models is mainly limited to product development, order-specific engineering, and product engineering. The PLM project was one source of inspiration for the present study, which explores from one point of view how 3D models could be utilized better in supporting the production and what requirements would this use generate for the PLM system.

The initial idea of the present study was to explore feasibility of a 3D assembly drawing. At the beginning, there was no idea of the actual realization, meaning the actual carriers and the content of the instructions which would be used in the user study. During the course of getting familiar with the literature, the vision of the realization started to form and encouraged by the selected approach described in Section 1.4 below, this shaped the study design. It became clear that AR instructions should be considered as well.

1.1 Research problem

The conventional assembly drawings are in many ways suboptimal. They do not provide all the needed information, even though most of the information needed for efficient assembly is generated already in the product development phase. Most of the assembly operations are executed in a spatial context and include complex 3D objects and actions. Therefore, conventional instructions representing complex actions in only static 2D images and descriptive text are inefficient. (Salonen et al., 2009; Baldassi et al., 2016).

Haag et al. (2011) surveyed the common state of assembly instructions in Finnish manufacturing companies. The most common work instruction is a bill of materials combined with assembly drawings. For common tasks there are more detailed work instructions, which utilize text, photographs of actual assemblies and screenshots. Usually, the responsible organizational function for creating the instructions is production. The work instructions are made with Microsoft Office tools and they are published in A4 format. Despite the instructions are in A4 format, they are usually viewed on a PC monitor rather than printed on paper. This enables updating of the instructions and ensures that the latest version is used. In the survey, Haag et al. investigated common issues related to the assembly instructions, as well. The creation of the instructions requires manual work but there are not enough resources for the job. The instructions are hard to keep up to date because of the way they are made. In addition, instruction updates are not usually linked to the product or manufacturing process. This results in that the instructions are actually not updated at all or they are updated only seldom, and the creation of the instructions is seen as a one-time job.

The current state of assembly instructions in the case company is very similar to how Haag et al. (2011) depicted the general state in Finland. The level of variation of the case company's products has increased after introducing new product families. Despite this development, the assembly instructions are made the same way as in the age of earlier product families. Back then, the products varied less, and the operators were able to memorize the process, thus the relevance of assembly instructions was lower. However, today each assembled product might differ from others due to the increased variation, and the conventional way to instruct the work has become outdated and even the experienced operators need instructions to support their work. In the worst case, the operators learn but then forget how certain products are assembled, since there might be even months between assembling a certain unit. The next time they are assembling a similar unit, they need to learn the procedure again through trial and error, since the assembly instructions do not provide the needed information. In addition, the employee turnover has increased, meaning that there is a need for more efficient training.

1.2 Objective

The main objective of the present study is to investigate whether interactive assembly instructions could be used to substitute the currently used static instructions in the case company.

There are two subobjectives which help to achieve the main goal. First, to gain an understanding of the problem at hand, the theoretical background must be formed. In addition, the findings gained by reaching this subobjective are used as the basis for completing the second subobjective. The following research questions related to the objective must be answered:

1. What is the purpose of assembly instructions?
2. What makes a good assembly instruction?
3. What is the most efficient way to deliver and present the instruction information?
4. What requirements or problems do combining interactive instructions with configurable products create?

The second subobjective is to produce a demonstration of interactive assembly instructions and evaluate their usability in the assembly of real products. Related research questions are:

5. How are the interactive instructions created?
6. What is the user experience and feedback from the shop floor?

1.3 Research scope

The present study focuses on investigating the feasibility of interactive assembly instructions only on a simple level, meaning that the emphasis of the user study is on demonstrating the interactive instructions, rather than thoroughly evaluating them. Additionally, the focus is on the instructions themselves, and the study considers only indirectly the rest of the system. The instructions used in demonstrations are created using software already available in the case company. The content of the demonstrated instructions is limited to concern only the mechanical phase of the assembly.

1.4 Research approach

The scientific approach of the present study was inspired by design-based research, which has evolved from instructional systems design. The topic of the present study is closely related to instructional design, or instructional systems design even though they concern usually educational instructions. Wang & Hannafin (2005) define design-based research as a systematic but flexible methodology with the aim to improve practices. Design-based research encourages to use multi-method approaches when conducting analysis. The researchers have an active role as both designers and researchers, collaborating with participants in order to design interventions. In the core of approaches to instructional design are a set of five principles or phases which form an iterative process. These phases are analysis, design, development, implementation, and evaluation. In addition, iteration appears in constant refining of the research design, since the initial research plan is usually not detailed enough. (Wang & Hannafin, 2005; Piskurich, 2015).

For the present study, design-based research provided a framework for developing the instructions and the system with an active role, based on both theory and practice. The main takeaways of the approach were the active role of the researcher enabling improvement of the artifact, the importance of both theory and practice as the basis of development, and the phased iterative process. The structure of the present study reflects the described process. First, in the chapters 2 and 3, the delivery methods and operator needs are *analyzed* by reviewing literature and by conducting a current state analysis, and then the practical approach is *designed* based on the analysis of the findings in these chapters. Then the content is *developed*, *implemented*, and *evaluated* in the chapter 4.

2 Literature review

This chapter addresses the first subobjective and corresponding research questions 1-4 and establishes the theoretical background for the present study. Literature review was the selected research method for investigating these research questions, since there is a well-established body of research covering the related issues. The sources used in the literature review are mainly peer-reviewed research papers published in international scientific journals and conference proceedings. The exceptions to this are Sections 2.1 and 2.5 in which research program reports and book references were used as the main sources. In addition, for Section 2.4.3 there were only web references available. The articles were searched by using Google Scholar search engine and by conducting backward search on the already found articles. The sources were selected based on their assessed relevance.

First, Section 2.1 discusses manual assembly to gain an understanding of its characteristics, what actually happens in manual assembly and what information does the operator need. In addition, this section discusses the effects of manual assembly on the product costs.

Next, Section 2.2 discusses how the operators use the instructions, and how they process the provided information. The aim of this section is to investigate what information the instructions should contain and how it should be presented to make the instructions effective.

Sections 2.3 and 2.4 discuss the theoretical background of the features of the interactive instructions. In practice, this includes the use of animations and augmented reality in assembly instructions. Their performance in comparative studies against more traditional instruction methods is investigated.

The creation, management, and storage of the instructions is very relevant regarding the efficient use of the instructions, thus product configuration, product lifecycle management and their relation to the assembly instructions are discussed in Section 2.5.

Lastly, in Section 2.6, the contents and findings of the chapter are analyzed.

2.1 Manual assembly

Assembly is a manufacturing process in which various components are attached together to form a working product or a subassembly. The components which are joined together can be standard parts, product specific parts or subassemblies. Assembling consists of tasks which are done sequentially in a step-by-step manner. (Tekes, 2001, p. 6-7; Radkowski et al., 2015). According to Whitney (2004, p.1, 11-14), assembly is more than just attaching parts together. Assembly is the process in which all upstream processes like designing, engineering, manufacturing and logistics are brought together to form a functioning product. Assembly is often done manually, especially in single and small batch production where great flexibility is required. The difficulty of different assembly tasks variate and the tasks can be complex; hence, they require mentally and physically skilled labor. Assembly has been researched only little compared to other processes in manufacturing and therefore it is one of the least understood processes in manufacturing. In some industries, like car manufacturing, companies have reverted robotic assembly back to manual due to unsuccessful attempts to automatize assembly tasks (Fox et al., 2018).

There are six common operations which operators perform during assembly (Radkowski et al., 2015; Tekes, 2001, p.7):

> **Identification:** the action to identify the parts which are assembled, for example by checking the part form and number, and the tools which are needed to assemble the part.
>
> **Handling:** this refers to all manual material moving in the production, like bringing the needed parts from storage to work area.
>
> **Alignment:** the operation to locate mating surfaces of the part and the assembly and to detect the correct position of the part to be installed.
>
> **Joining:** creates a connection between two parts, which can be either fixed or detachable. Joining methods include for example gluing or making a nut-bolt connection.
>
> **Adjustment**: the operator adjusts the location of a part or a connection. For instance, changing the torque of a nut-bolt-connection is considered as adjustment.
>
> **Checking:** the action to assess the quality of the connection, alignment, and adjustment of the parts.

In principle, joining is the only value-adding task in assembly (Tekes, 2001, p.7). Consequently, other action and movement which breaks the focus of the operator is non-productive. For example, the time which the operator uses for searching and interpreting information from the assembly instructions is non-value-adding. Same can be stated for searching and handling components, although these are necessary operations in order to execute the assembly. By minimizing the time consumed on executing other actions than joining parts the productivity of the operator can be maximized.

Assembly has a significant effect on product cost and quality. The correct assembly defines the quality of the whole product. Even if high quality parts are used, the end product may be of poor quality if it is poorly assembled. (Haag et al., 2011). Assembly may take up from 20 to 40 percent of the total work time of a product. Skilled labor needed in assembly is expensive and combined with the large amount of contributed working time makes its cost impact so large. According to Tekes' report regarding Finnish heavy and semi-heavy industry technology program from 2001, only half of the assembly time is used working and the other half is consumed on waiting, pauses and interruptions. Furthermore, only 10 to 25 percent of the actual working time is value-adding. (Tekes, 2001, p. 6-7). However, these ratios have most probably changed to positive direction. The labor productivity in the manufacture of electrical equipment, machinery, and other equipment, which are assembly-oriented industries, was 52 percent higher in 2017 compared to year 2000. Figure 1 presents the average development of labor productivity in these industries in Finland. However, it should be noted that the price development of the products affects the index and therefore the real improvement in the work efficiency cannot be interpreted with certainty. (Statistics Finland, 2019; Statistics Finland, 2008, p. 145).

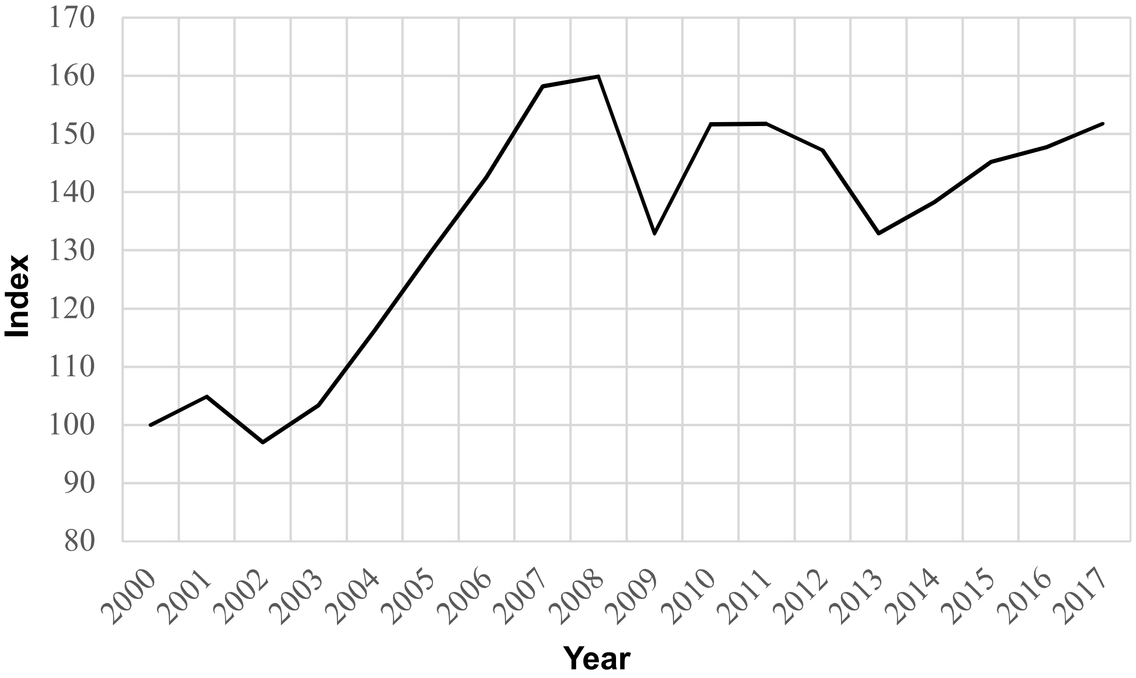


Figure 1. Labour productivity index of manufacture of electrical equipment, machinery, and other equipment in Finland, 2000=100. (Industries 27 and 28 according to Standard Industrial Classification TOL2008.) (Statistics Finland, 2019).

Assembly faults increase the assembly costs in several ways. These costs are defined as part of quality costs, more specifically they are internal and external failure costs. Internal failure costs derive from scrapping material and rework. Repairing the faulty assembly takes additional time. Parts or even an entire assembly may have to be scrapped. Valuable resources are lost as the operators and the system have been spending time on assembling the faulty product. The costs may rise even more if a time-critical product delivery is delayed due to problems in the final assembly. External failure costs result if product defects are not detected internally, but instead the product is delivered to the end customer and problems arise. Regarding the effect of a single occurrence, external quality costs have usually much larger impact than internal failure costs. It should be noted, that assembly faults are not the only source of product defects. However, external failure costs result from warranty complaints, product service, product liability, product recall and loss of reputation. (Feigenbaum, 1991, p. 110-119; Whitney, 2004, p. 436).

2.2 Assembly instructions

To successfully carry out the manual assembly tasks the operators need accurate information. Most of the information is generated in product development and the assembly instructions are the medium communicating it. For example, the operator needs to know what parts and tools are needed and in which quantity, where they are found, in which position and order the parts are assembled, and how they are joined. Checking of the installed parts might be instructed, as well. In principle, information is needed only for four of the six assembly operations: identification, alignment, joining, and checking. (Haag et al, 2011; Radkowski et al, 2015). Information for adjustment is derived from the same input as for the other four actions. For handling the operator uses non-product specific information. For instance, he needs to know where the storage areas for bulk material are located, and the location does not typically depend on what specific product they are assembling.

From a general point of view, the prevailing view in the field of cognitive research on how any information is processed, is that we construct internal representations from the information of external representations. The way of processing depends on the form of information, which can be either descriptive or depictive. Descriptive information is symbol-based, e.g. text, while depictive representations, e.g. pictures, present information similar to its referent. (Watson et al., 2010). Novick and Morse (2000) described the processing of information particularly for assembly instructions in their study. Assembly instructions help the operator to build an internal representation of the assembly which they are constructing. Each assembly step requires that the operator updates their internal model. The step is then mapped onto the actual object, and only after this the assembly step can be executed and realized. The ease of executing this internal process of building and refreshing the mental model depends heavily on the assembly instructions.

In their study, Novick & Morse (2000) compared effectiveness of three different types of assembly instructions, particularly for folding origami objects. Their goal was to explain the role of diagrams in object assembly. The three types of instructions were textual, final state diagrams and step-by-step diagrams. They found out that a set of diagrams instructing the assembly step-by-step are more effective than a single final state diagram presenting the outcome of all operations. Both step-by-step and final state diagrams are more effective than plain textual instructions, which induce errors both in updating the mental model and mapping the next operation on the actual object. In addition, they found out that the benefit of step-by-step instructions over final state diagram depends on the prior experience of the operator and the number of assembly steps. Operators with only little experience gain more benefit on the step-by-step instructions. It is easier for experienced operators to interpret the needed assembly steps from a final state diagram. Similarly, it is easier to extract the assembly steps from the final diagram if the number of steps is low. Watson et al. (2010) got related results and provide a further explanation for the effectiveness of diagrams. Diagrams provide explicit spatial information, which allows direct mapping from the external representation of the diagrams to the internal mental representation. Spatial information means information regarding position in space. Textual instructions require that the operator first establishes an internal verbal representation, then an internal propositional model and lastly an internal “situational” model.

If we now consider conventional assembly instructions, consisting of a bill of material and an assembly drawing, they are by nature like final state diagrams. They present the assembled product, and the parts to be assembled are marked with notes on the drawing. If the product has a large number of parts, the assembly process is divided in a few steps containing the installation of multiple significant parts. But this is still far from step-by-step instructions. As discussed earlier, interpreting the instructions requires experience (Novick & Morse, 2000). Simple assembly drawings do not contain all the assembly information and the operators must decide the assembly order by themselves without any guidelines, for example. However, even the most experienced operators make sometimes mistakes in the interpretation or their interpretation might not be the most optimal one. (Salonen et al., 2009).

In the study of Agrawala et al. (2003), the objective was to develop guidelines for designing effective assembly instructions based on cognitive psychology experiments and earlier cognitive research. In their experiment, the researchers had different groups of people assemble a piece of furniture. The first group had only an image of the finished product as their assembly instruction. After the task was done, the research participants created instructions for the task. Other groups improved these instructions further. The researchers analyzed the participants' instructions and improvements and measured their performance of executing the assembly tasks. As a result, the researchers identified six principles that make the assembly instructions efficient and simultaneously confirmed the Novick's & Morse's (2000) finding that step-by-step instructions are more effective than final state diagrams. Next, the six principles are presented:

> **Hierarchy and grouping of parts:** People like to group similar parts by their function and they think assemblies as a hierarchy of parts. Parts belonging to the groups are preferred to be assembled at the same time or in sequence.
>
> **Hierarchy of operations:** Similarly, as the parts of the assembly belong to a hierarchy so do the actions needed to build the assembly. Operations needed to combine separate subassemblies are considered to belong to the higher levels of the hierarchy. At the lowest level there are the actions to attach small parts and fasteners to more significant parts. In simple products there might be only two-level hierarchy consisting of significant parts, and less important parts and fasteners. More complex products may have multiple hierarchical levels.
>
> **Step-by-step instructions:** People prefer that instructions present the assembly of only one significant part at a time. However, attachment of multiple non-significant parts can be illustrated on one diagram.
>
> **Structural diagrams and action diagrams:** The researchers compared the effectiveness of structural diagrams and action diagrams in step-by-step instructions. Structural diagrams present all new parts in their final position and the operator identifies the parts which are assembled through comparing two consecutive diagrams. Action diagrams present the new parts as detached from the assembly and guidelines show where the parts should be attached. The result of this comparison was that action diagrams are far more effective than structural diagrams.
>
> **Orientation:** The assembly should be depicted in such orientation which maximizes the visibility of important features of the parts and the mating surfaces. This helps alignment and object identification.
>
> **Visibility:** All new parts that are assembled in the steps should be visible. This is the strongest principle. However, in a symmetric group the visibility is not so important. Additionally, it is important that previously assembled parts are visible.

Let us continue to discuss the step-by-step principle and its effects. In the simplest form, step-by-step diagrams could be used to depict assembling a single part at a time. However, this would make the instructions long and tiresome. Dividing assemblies into optimal number of steps can be challenging. The mental capacity and attention of an operator is limited. Too much information simultaneously may overwhelm the operator resulting in that they will need more time to understand the information and the accuracy of understanding decreases. The overwhelming is caused by informational noise; It is difficult to spot the needed information if it is surrounded with other information. But then again, too little information or too minor steps may make the operator bored, and the instructions will become long. (Radkowski et al., 2015; Agrawala et al 2003; Thorvald, 2011, p. 30).

2.3 Animations in assembly instructions

According to the literature, animations should enable more effective instructions, since they carry additional dynamic information compared to static diagrams. Static diagrams require that a mental animation is interpolated from consecutive diagrams, while from animations this information can be simply perceived. (Watson et al., 2010; Hegarty et al., 2005). Only few studies have researched the advantages of using animations particularly in assembly instructions. Additionally, there are other studies which have investigated the efficiency of animations in instructing procedural-motor tasks. Since assembly is a specific example of such task, these findings can be utilized as well to investigate the advantage of animations.

Höffler and Leutner (2007) conducted a meta-analysis of 26 studies resulting in 76 pair-wise comparisons of dynamic and static instructions in various contexts of learning. Only two of the 26 studies contained comparisons using procedural-motor tasks, yielding in total 5 pair-wise comparisons. According to the study, animations have a medium overall advantage over static pictures. The effect on learning outcome is largest when the animation is representational and realistic, and the type of acquired knowledge is procedural-motor.

Watson et al. (2010) studied efficiency of descriptive, depictive, and dynamic assembly instructions based on text, static structural diagrams, and animations, respectively. The animations were created based on the 3D model of the assembly object and exported into video format. The diagram instructions were created by taking screenshots of the animation video. All instructions were viewed using a monitor. Efficiency was evaluated through measuring build time performance of consecutive executions of the small assembly task. Figure 2 presents the mean total times for all participants in each group of the study. The advantage of both diagram- and animation-based instructions over textual instructions was found to be significant. Due to small number of participants and rather simple assembly task, the difference between animation and diagram group did not reach statistical significance. However, the results of the study suggest that animation might have an advantage over both text- and diagram-based instructions. Animation group had 21 and 35 percent lower average initial build times than diagram and text groups, respectively. In addition, animation group had notably lower standard deviation in build times for the build 1, suggesting that animations could result in less misinterpretations and more consistent build times when building an assembly for the first time. The observed number of errors supports this conclusion, as text and diagram groups both made in total seven errors during the build one, while the animation group had only one error.

Considering the findings of Agrawala et al. (2003) discussed in Section 2.2, there is one shortcoming in the study of Watson et al. (2010). Namely, Watson et al., used structural diagrams in their instructions for the diagram group, but Agrawala et al., showed that action diagrams are more effective than structural diagrams in step-by-step instructions. If Watson et al., had used action diagrams, there might have been even less difference between the diagram and the animation groups. In addition, Watson et al. decided to remove the time which the participants used on reworking the assembly after an error was made from the total build time, which changes the resulting build times. At the same time, this decision indicates that the emphasis of the study was on investigating the efficiency of perceiving the information rather than the overall efficiency of the assembly operations.

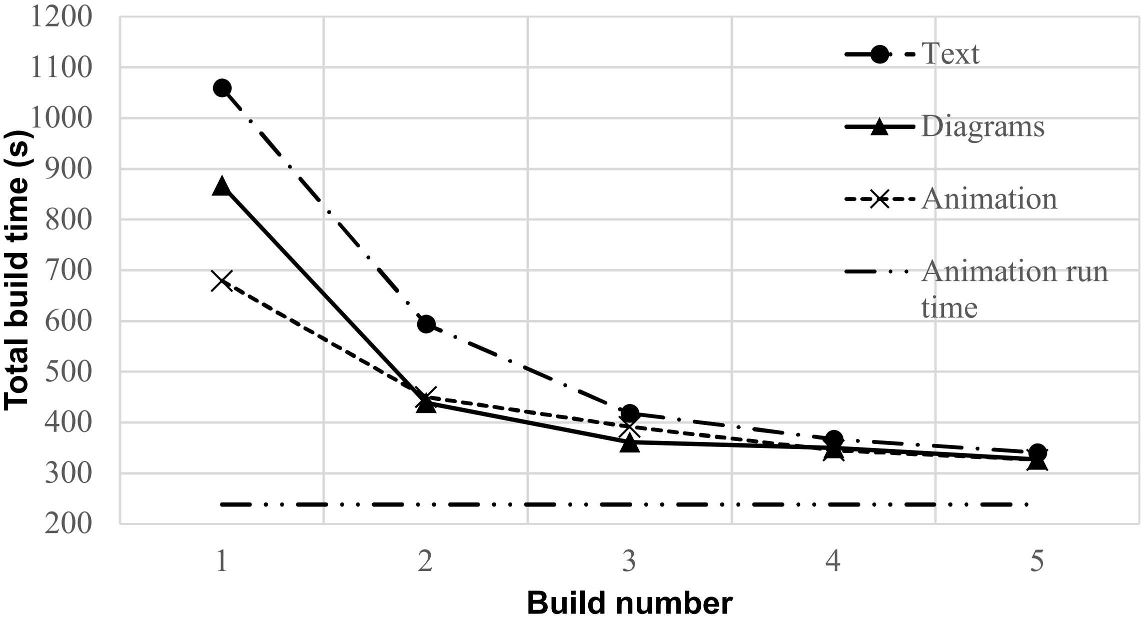


Figure 2. "Mean build times for all participants in each of the three instructional groups over the five builds. Each separate curve on the graph represents a separate experimental group, Text (solid squares), Diagrams (solid triangles) and Animation (open circles). The flat dashed line below represents the animation run time which corresponds to the minimum time it would take to build the device if participants were building in time with the animation" (Watson et al, 2010).

Lušić et al. (2016) conducted a similar study comparing dynamic and static assembly instructions which were viewed using a monitor. However, it is not defined and cannot be interpreted from the report if the static instructions used structural or action diagrams. The assembly objects were two industrial case examples. Unlike Watson et al. (2010), Lušić et al. (2016) claim that their results demonstrate an advantage of using dynamic instructions over static instructions. Dynamic instructions yielded shorter working durations. However, this result is questionable, since the researchers have not conducted any variance analysis to ensure the statistical significance of the results. In the more complex experiment 1, the resulting assembly duration for dynamic instructions was on average 16 percent lower than for static instructions, while the experiment 2 resulted corresponding difference of 4 percent. This finding suggests, that the higher the complexity of the assembly, the more advantage animation provides. Additionally, the participants needed to look at dynamic instructions less frequently, and when they had to take another look at a specific instruction step, they used less time compared to static instructions.

2.4 Augmented reality

This section introduces Augmented Reality (AR), related hardware, and discusses how AR can be used to display assembly instructions. Another related technology, which has gained attention recently, is Virtual Reality (VR) and should not be confused with AR. The main difference between these two is that AR refers to overlaying virtual objects in the view of real environment while VR immerses the user in computer-generated environment including only virtual objects without any features of physical reality. (Kohn & Harborth, 2018; Carmigniani & Fuhrt, 2011, p. 3). Both AR and VR can be placed on the reality-virtuality continuum which was first first introduced by Milgram et al. (1995) and is presented in Figure 3. Reality-virtuality continuum illustrates how AR and VR are related and how the distinctions are not clear. Third related term is Mixed Reality, which includes almost any mix of virtual and real environments augmented with real or virtual objects (Kohn & Harborth, 2018; Carmigniani & Fuhrt, 2011, p. 3).

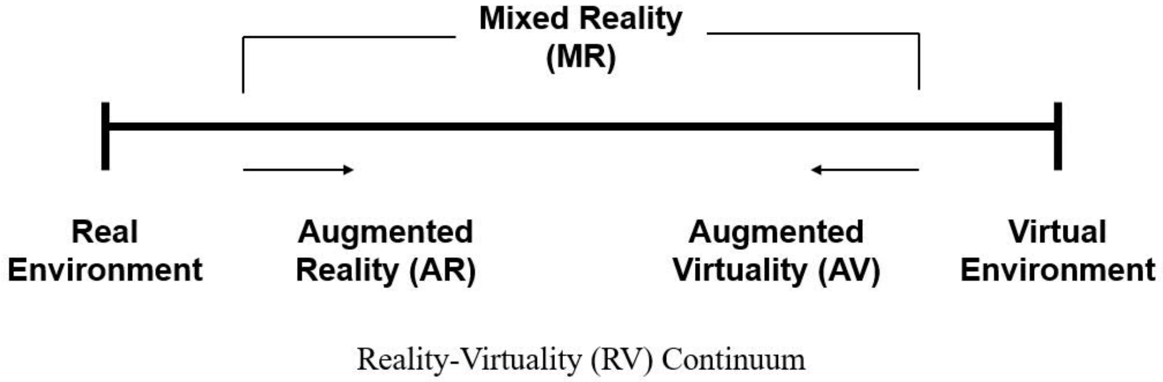


Figure 3. Reality-Virtuality Continuum (adapted from Milgram et al, 1995).

AR gained vast public attention during the end of the first decade of the 2000s. According to Gartner and their annually released hype cycle of emerging technologies, AR was on the peak of its hype in 2010. At that time, many applications and platforms utilizing AR were introduced for consumer mobile devices. Since then the hype around AR has faded, and in the latest Hype cycle from 2018 AR has reached the “Trough of disillusionment”, as seen in Figure 4. This indicates that now is the time when the providers of applications of the technology either fail or survive by improving their products. Gartner estimates that it takes still 5-10 years before AR reaches the plateau of productivity and adoption of the technology starts to become mainstream. (Gartner, 2010, 2018A, 2018B). Hence, for companies looking to familiarize themselves with this emerging technology, now is a great moment to reflect on how this could affect their businesses.

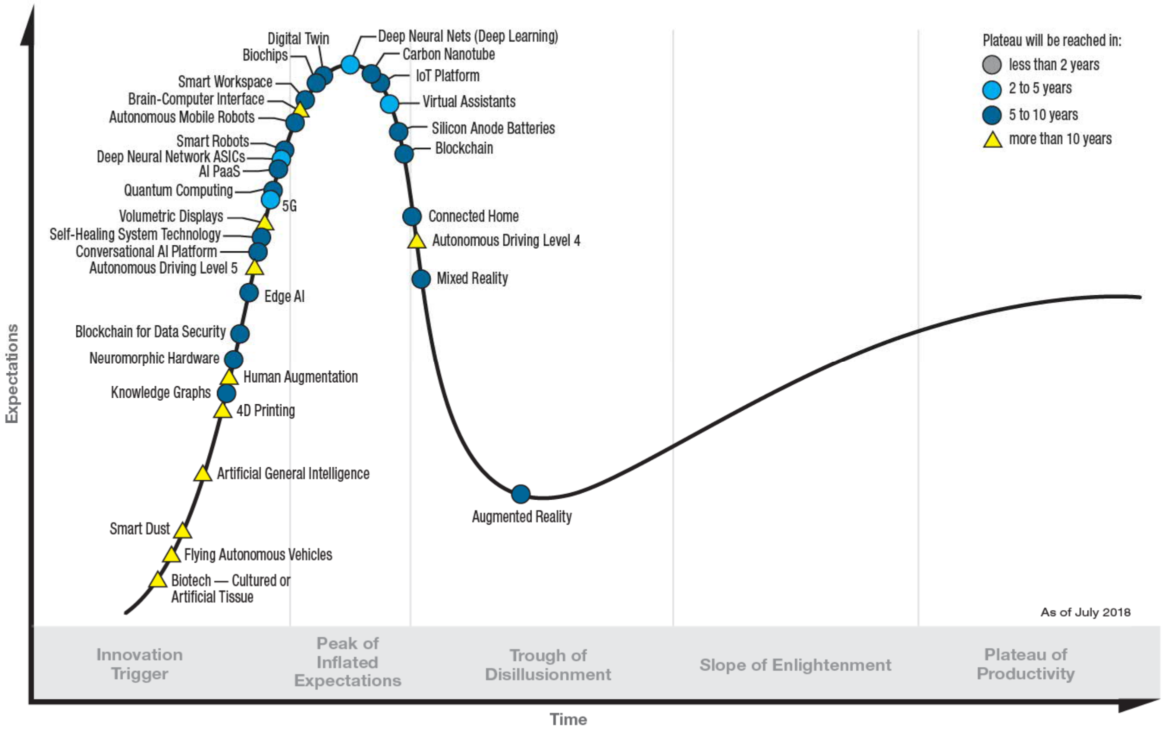


Figure 4. Hype cycle for emerging technologies 2018 (Gartner, 2018).

The first head-mounted display utilizing spatial tracking was introduced by Ivan Sutherland in 1968 (cited in Kangdon, 2012). Itself the term Augmented Reality was coined by Boeing researcher Thomas Caudell in 1990 (Kangdon, 2012). Manufacturing assistance was one of the early applications of AR. In 1992, Caudell and Mizell introduced the first prototype of manufacturing assistance AR system and a vision of how the technology could change manufacturing. The particular use case was instructing the manufacture of wire harnesses for Boeing's airplanes. The prototype was successful, and Boeing is still using AR, although much improved version, to instruct wire harnessing. (Radkowski, 2015; Caudell & Mizell, 1992). In addition to manufacturing, AR has been introduced to various other areas, such as medicine, design, interior design, education, and construction (Salonen et al., 2009; Wang et al., 2016).

As stated earlier, AR systems superimpose virtual 3D objects or information into the user's direct or indirect view of the real physical world in real time. Virtual objects can be text, 3D objects or even animations. (Radkowski et al., 2015). On the left in the Figure 5 is a screen capture from the camera feed with a special marker in the scene and on the right is the processed image with a digital object overlaid into the scene.

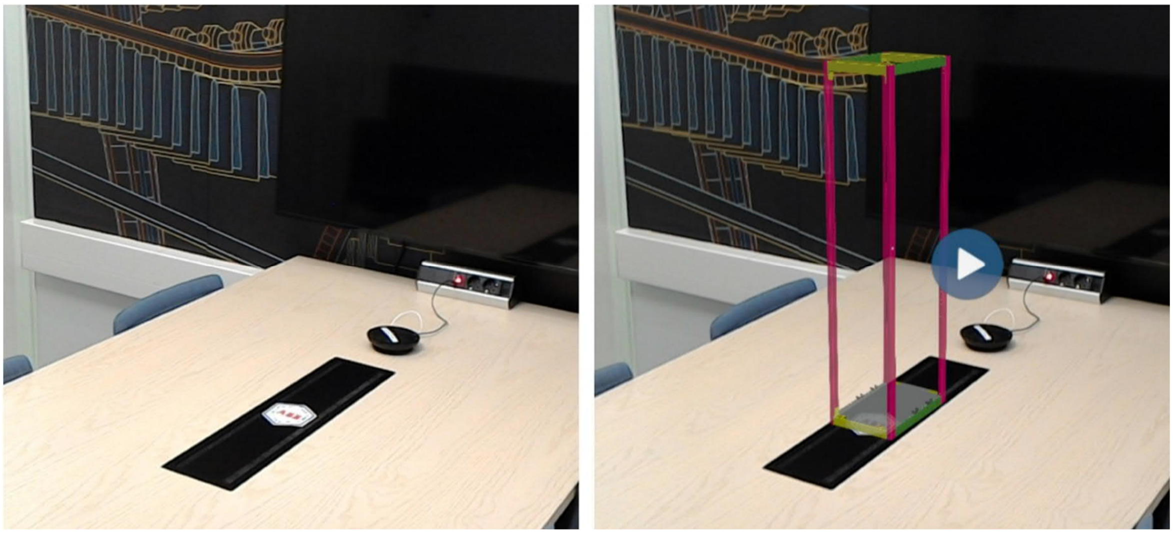


Figure 5. On the left: A marker on a table. On the right: An object overlaid in the scene relative to the marker.

AR utilizes computer vision to track and recognize its environment. In practice, AR uses typically a video camera to capture the physical world. The system analyzes the video feed and detects special markers, images or interest points using various image processing methods for interpretation. Most of the tracking techniques can be divided into two classes: feature-based and model-based. Feature-based methods rely on the known relation between the 2D image features and their 3D world frame. Model-based methods make use of for example a CAD-model of the tracked object to detect its features. After the connection between 2D image and 3D world frame is established, the camera position can be calculated and then a real-world coordinate system is reconstructed. Once the coordinate system is known, the desired content can be overlaid into the view. (Carmigniani & Fuhrt, 2011, p. 6).

To create the illusion that the virtual objects really coexist in the real environment, the two worlds must be carefully aligned, which as a process is called registration. Without accurate registration many applications of AR are useless. (Azuma, 1997). For example, if an operator is instructed to drill a hole in a steel plate, but the feature guiding the placement of the hole is in wrong place, the drilled hole will be misplaced as well.

Keeping the registration errors under control is difficult, since there are so many sources of error. Error sources can be divided into two types: static and dynamic. Static error occurs even when the position of the camera and real-world objects are totally still, whereas dynamic error occurs when the pose of the camera or location of tracked objects are changed. (Azuma, 1997). For example, if the camera is tilted, the location of the overlaid virtual objects must not change in relation to the real environment. Main source of dynamic error is system delay. Each component of the AR system takes some time to process. When dynamic error occurs, the augmented objects stay stationary, relative to the display, not to the environment as they should. Real time image processing requires high processing power to generate flawless image with high enough refresh rates. (Azuma, 1997). However, technological development has eased the issue, and for example Waegel and Brooks (2013) were able to demonstrate a stable and drift-free registration through implementing a low-latency inertial measurement and more efficient 3D reconstruction algorithm.

2.4.1 Systems

An AR system consist of four core components: A display, input devices, tracking devices, and a computer. The input devices enable the user to interact with the augmented experience and control it. Input methods depend on the other devices of the system. For example, a touch screen can be used as an input device, or the system can detect gestures which the user makes with their hands. Tracking devices are usually video cameras, but other sensors can be used as well, for instance other optical sensors, GPS receivers, or accelerometers. In addition, AR system requires a powerful CPU and enough RAM to enable efficient processing. (Carmigniani & Fuhrt, 2011, pp. 9 & 12).

Rest of this section will focus on discussing the displays, since they are the most relevant component regarding the present study. The displays, their benefits and disadvantages are presented through possible applications in a manufacturing environment. The available benefits of AR instruction system depend heavily on the way the information is displayed. There are four types of displays which are used in AR: a conventional monitor, head mounted displays (HMD), handheld displays, and spatial displays (Carmigniani & Fuhrt, 2011, p. 9; Salonen et al., 2009).

A monitor-based AR setup could be realized in a similar way as Loch et al. (2016) demonstrated in their study: there is a camera in a fixed position directed over a workstation, and the monitor is fixed on the workstation. Figure 6 shows the configuration of the workstation, although the camera is behind the man on the left. Camera records the workstation and the ongoing assembly work. Video is processed in real time and the next assembly step is displayed on the monitor animated and overlaid on the assembly. The instructions are controlled with foot pedals or using a touch screen. Like Loch et al. propose, in this kind of setup it could be useful if the system could automatically detect when a certain step is done and proceed to the next step. This way the operators could focus on the job and they would not need to shift their focus unless necessary to verify the step information from the instructions. According to Wang et al. (2016), this has been implemented in some studies, and since an AR system observes the assembly operation, it is possible to recognize errors and completion of the assembly steps and report the assembly status in real-time.

The monitor has an evident drawback when used with large assemblies: the monitor is in a fixed position, probably on a table somewhere nearby the assembly. This means that the operator must pause his work to read the instructions on the monitor. In addition, in this case there is not much sense using AR, since one fixed camera cannot cover large assemblies, or at least the instructions become unreadable, or then the operator must change the location of the camera constantly. (Haag et al., 2011).

It should be noted, that whether the instructions are based on AR, diagrams or animations, the fixed location of the display is disadvantageous with large assemblies. Thorvald (2011, p. 119) suggests that with a stationary information source, the information is gathered but forgotten before the execution of a task takes place. This phenomenon is called stimulus-response gap. Due to the spatial distance between the work area and the information source, the information is attended more seldom compared to an information source which is always within reach. In his study, Thorvald (2011, p. 95) showed that by improving the accessibility of the information by using a mobile information source, the assembly error rate was reduced significantly.

Figure 6. Workstation equipped with monitor-based AR system (Loch et al., 2016).

The second display option is a handheld screen of a smartphone or tablet. In this case the AR system uses the integrated camera and/or possibly other sensors of the device for tracking. The video feed can be processed locally in the device or the device can be used as a client and the processing is executed over the air on a server. The display of the device works as a “window” to the augmented reality. Assembly steps can be displayed in the same manner as on monitor, so either as animated or stationary 3D parts. With a mobile device the operator can view the assembly from different directions, and the application could be used with larger assemblies as well. The drawback with mobile handheld devices is that the operator has only one hand available for assembling, in case the operator looks the instructions at the same time. If both hands are needed, the operator must put down the device to execute the assembly step. Additionally, dropping the device might break it, which would cause a significant pause from the work. (Carmigniani & Fuhrt, 2011, p. 10; Salonen et al., 2009; Funk et al., 2016).

Third and the most immersive display class is head mounted displays (HMD). In this case the operator wears a HMD while working. An example of a HMD can be seen in Figure 8 on page 20. There are two types of HMDs: video see-through and optical see-through. Additionally, a HMD might have either monocular or binocular display optic. Video see-through HMD is more demanding choice regarding the system, since it has two cameras and the feed of the both must be processed. The system must provide both the real environment and the virtual objects on the displays. Optical see-through HMD utilizes for example semi-transparent mirror, which enables the operator to view the real environment as without the device, and the virtual content is optically overlaid and reflected into the user’s eyes. Either way, the operator sees the overlaid image in his direct view of the real environment. (Carmigniani & Fuhrt, 2011, pp. 9-10). The major benefit of the HMD is that the operator has both hands free, and he does not need to break his focus to look at the instructions, since they are brought seamlessly into his direct view. The proceeding in the instructions can be controlled with voice commands, hand gestures (Salonen et al., 2007), manual input or even by tracking eye movement (Nilsson et al., 2009).

However, HMDs have disadvantages as well. Considering the instructions, the overlaid instructions might occlude the real part and interfere with the assembly task (Tang et al., 2003). There might be problems with wearing these displays for extended periods of time. For example, HMDs have been reported to cause headache, eye fatigue and discomfort (Kampmeier et al., 2007). Another issue with HMD is tunneling of attention (Tang et al., 2003). The operators might lose their sense of surroundings while focusing on assembling and instructions, which might be a health or a safety risk in a factory environment. Information security must be considered carefully as well, since wearing a HMD means every operator is wearing a device with a camera and an internet connection. However, wearing the video cameras should not be a problem considering privacy of the other operators on an industrial environment since the video signal is not recorded (Quint et al., 2017).

The fourth display option which is used in AR is to use a dedicated projector. This method is called Spatial Augmented Reality (SAR). SAR system uses a camera to track objects and possibly user movement. The virtual information is projected directly onto physical objects or surfaces. (Carmigniani & Fuhrt, 2011, p. 11). Projector needs to be in a fixed position, although there is a wearable prototype of an augmented reality interface equipped with cameras and a projector developed by Mistry and Maes (2009). For example, Funk et al. (2015) built an assistive system for a workstation, which consisted of a work area on a table and eight boxes for parts on the back of the table, similar to the workstation in Figure 6. The system consisted of a top-mounted depth camera for detecting hand movement and a top-mounted projector. The system highlights the box containing the part for the next assembly step. The assembly step is instructed by displaying the contour of the part at the correct position.

2.4.2 Results and analysis of comparative studies of AR instructions

Most of the research in the area of supporting manufacturing with AR has focused on producing proof-of-concepts using HMDs. The efficiency of AR instructions compared to other methods has been researched as well. (Kohn & Harborth, 2018). The ability of AR, especially with HMDs, to represent dynamic actions in 3D and even overlap the virtual objects spatially over the real assembly should minimize the perceived cognitive load and hence result more accurate and faster performance (Baldassi et al., 2016). The study of Sääski et al. (2008) support this idea and they state that presentation of the objects overlaid to the assembly in the correct orientation and the animation showing how the object should be put to the right place is the characteristic and most valuable feature of AR instructions.

Table 1 summarizes the findings and classifies the methods of the comparative studies found in the literature, and next, the findings of the studies are analyzed. The table classifies the types of carrier and content of the main and the baseline methods and the classification is done using the terms presented earlier in the present study. To recap, the key term pairs of content types are: final state diagrams – step-by-step diagrams, structural diagrams – action diagrams, and static instructions – dynamic (animated) instructions.

Table 1. Comparative AR studies.

Author(s) and year	Display type	Content type	Baseline type(s)	Baseline content type	Assembly task	Results regarding error rate and assembly time
Tang et al., 2003	See-through HMD	Overlaid static 3D AR, step-by-step, action cues	Paper, monitor, virtual display on HMD (CAI on HMD)	Step-by-step, static action diagrams	LEGO Duplo assembly	Time of completion -25 % compared to paper, no significant difference compared to Monitor and CAI on HMD. Errors: on average -82 % compared to other methods
Sääski et al., 2008	Monocular 2D HMD	Overlaid dynamic step-by-step 3D AR, not in the direct view of the real environment	Paper	Two assembly drawings illustrating finshed product and a subassembly, bill of materials, textual work instruction	Auxiliary power unit of a tractor	Assembly duration -15 %, errors -58 %
Baldassi et al., 2016	HMD	Two types of dynamic step-by-step 3D-instructions, showed in a locked position in the field of view	Paper	Step-by-step structural diagrams	LEGO assembly	Static 3D had the slowest and the Dynamic 3D the fastest time to completion, no total assembly time available
Loch et al., 2016	Monitor	Overlaid, dynamic 3D AR, step-by-step	Video	Photorealistic video depicting whole operation	Two different LEGO assemblies, one for each method	Assembly duration -18 %, errors -90 %
Funk et al. 2016	Projector	Projector highlights boxes containing parts and correct assembly location	Paper, tablet, and see-through HMD	Step-by-step structural diagrams, new part indicated.	LEGO Duplo assembly	Average errors: Projector 0,37, Tablet 0,69, Paper 1,31, HMD 2,44. Assembly time was divided into four types: locating, picking, positioning, and assembling the part. HMD performed worst in all, projector was fastest in locating and assembling, paper was fastest in picking and positioning.
Radkowski et al., 2015	Monitor	Abstract AR (AAR) shows text, 2D diagram of the step, and spatially registered cues. Concrete AR (CAR) shows 2D text, and either static or animated overlaid 3D parts depending on the difficulty of a task	Paper	Step-by-step structural diagrams, new part depicted.	Axial piston motor	Paper and CAR instructions yielded similar results regarding both errors, and assembly time, whereas the performance of AAR was significantly poorer for both.
Blattgerste et al., 2017	See-through HMD, Smartphone	Overlaid static 3D AR, step-by-step, part displayed in its final position	See-through HMD, paper	Step-by-step structural diagrams, new part indicated.	LEGO Duplo assembly	Both baseline mehods yielded significantly less assembly errors than both AR methods.

The overlaid AR instructions provide the most interesting results. Regardless of the display type, the overlaid and animated AR instructions reduced total assembly errors and especially cumulative errors, meaning placement errors which occur if an earlier part is assembled in wrong position. While the AR system overlays virtual components on top of the earlier assembled physical parts, the operator quickly notices if the parts are in wrong place. (Sääski et al., 2008; Loch et al., 2016; Tang et al., 2003). The only exception is the study of Radkowski et al. (2015) in which no difference between the number of total errors was found. The reason for this might be that they used both animated and static steps in the AR instruction depending on the assumed difficulty of the step. This proposal is supported by the findings of Blattgerste et al. (2017), who used static overlaid AR instructions, but the parts were displayed in the final position. This yielded significantly more errors than the baseline methods.

Additionally, the presented findings suggest that the overlaid AR instructions might result in shorter assembly durations. However, the content and the realization of the baseline instructions used in the studies varies. For example, Loch et al. (2016) used a photorealistic video as the baseline, and it was not specified, if the subjects were able to pause the video or if they had to watch it in one go and memorize the whole procedure. Sääski et al. (2008) used final state diagrams combined with descriptive text as the baseline, which was understandable, since this depicted the current state of the instructions in industry. However, according to the research presented in earlier sections, neither of these methods are the most efficient method suited for the selected carrier, and this affects the comparability of the results to other methods.

Most of the studies use LEGO assemblies as the case task. Radkowski et al. (2015) argue that these assemblies and their level of difficulty do not represent real world cases, since the assembly of LEGO sets do not need information on installation or fastening of the parts as it is intuitive. Wiedenmaier et al. (2003) showed that AR instructions do not provide advantage if the assembly task is too easy. Hence, the applicability of the results of the LEGO assembly studies in an industrial environment might be questionable.

2.4.3 Industrial use cases in assembly

Although the use of AR in industrial applications is not yet widespread, there are some reports of industrial use cases. In their systematic literature review study, Kohn & Harborth (2018) were able to find 15 industrial use cases of which four concerned production operations. Three of these were from the aerospace industry, and one was from the automotive industry.

Next, two recent industrial assembly support use cases are briefly presented. However, it should be noted that the starting points before the adoption of a new system in these cases are not presented in the source materials, so it is hard to critically evaluate the outcomes. Additionally, the impact of other actions taken is difficult to distinguish.

The first example is from an agricultural equipment and service provider AGCO. They use 2D ‘Assisted Reality’ instructions displayed on a HMD, Glass (AGCO, 2018). Glass inserts a display into the operator’s upper right corner of the field of view and the device can be installed onto the operator’s eyeglasses or safety goggles, like seen in Figure 7 (X Development, 2018). By switching to Glass, which provides access to parts lists and assembly instructions, AGCO has been able to reduce the production time for low-volume, high-complexity assemblies by 25 percent. The needed time to train a new employee has reduced by 50 percent. (AGCO, 2018).

Figure 7. Operator wearing Glass (X Development, 2018).

The second use case is from BAE Systems which has started using AR instructions with Microsoft's HoloLens HMD in the assembly of a complex battery pack. They report that assembly duration decreased by 50 percent, and the cost of the creation of the instructions decreased by 90 percent. Training new people is 30 to 40 percent more efficient with the AR instructions. As seen in Figure 8, the instructions are displayed behind the assembly object and there are text instructions next to the virtual model of the assembly.

Place P3 Cell with factory marking down in cell frame. Align the bottom and sides of the cell with the cell frame shown by red lines.

Figure 8. An operator wearing HoloLens. There is a 3D instruction overlaid on the front of the workplace wall. Next to it on the right is a textual description of the task. (PTC, 2018).

2.5 *Product configuration and assembly instructions*

This section discusses the concept of product configuration and then presents briefly the product life cycle management. Only issues relevant to the topic of the present study are covered. It would be superfluous to describe all functions and aspects of PLM and product configuration here.

2.5.1 Product and document configuration

In the introduction it was discussed that product customization increases the complexity of the products and their assembly. Basically, product customization means that the product features and the product structure are altered according to the customers' wishes. At the same time, interactive instructions impose a strong requirement for the content of the instructions: it must be correct and accurate for the specific object under assembly. With conventional assembly instructions, it is possible to present alternative steps which instruct to assemble parts that come only with some specific condition of parameters. However, checking if these conditions apply takes valuable time and increases the risk of misinterpretation. With the interactive instructions it is not possible to present alternative procedures at the same time, since the assemblies are instructed step-by-step based on the 3D model of the specific assembly object. Hence, each unique object should have unique assembly instructions. When we combine this requirement with the nowadays common solution to offer customizable products, problems arise.

Product configuration is the process in which a customized product unit is generated by choosing product features from different predefined options. A product model, or general product structure, contains all the available options and defines their legal combinations, *variants*. In the context of configurable products, the word *product* can refer either to the product family (which contains all variants defined by the product model), to a variant, or to an individual unit, so the meaning is not always clear. Product configuration enables companies to increase both customer value, through answering better the customer needs, and cost efficiency, by leaving out what the customer does not need. The configuration process is usually divided into two phases, namely, sales and production configuration. Sales configuration handles the product features and their relations, while the production configuration manipulates the product and document structure to correspond to the combination of features defined in sales configuration. The configuration process is illustrated in Figure 9. In general, the result of the configuration process is a specification for the following subprocess generated from the source information, for example manufacturing documentation. (Martio, 2015, pp. 9, 13-15, 23, 35, 112; Sääksvuori & Immonen, 2008, pp. 22, 61-63).

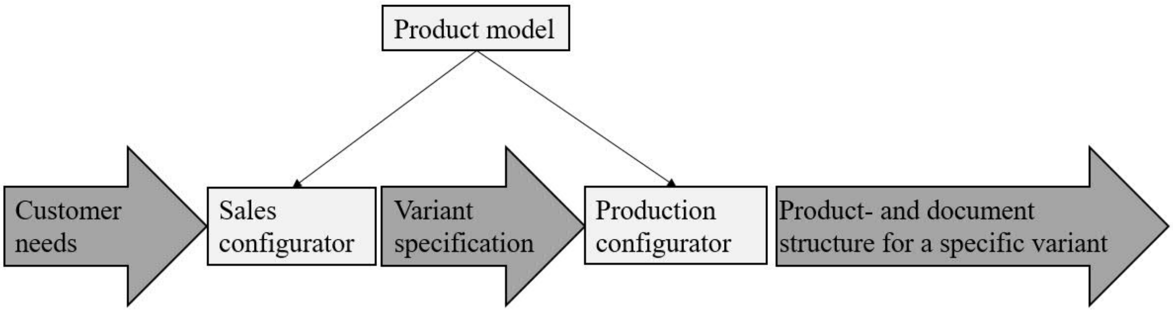


Figure 9. Product configuration process.

A car is a familiar example of a configurable product. Let us imagine a car that has four configurable features: chassis, transmission, engine type, and engine's power output. Each feature has three options, as illustrated in the Figure 10. If all combinations were allowed, this would give us $3 * 3 * 3 * 3 = 3^4 = 81$ different variants. If we make a set of rules which forbids combining automatic and manual transmission with electric motor and the transmission option "none" with gasoline or diesel engines, the number of possible variants is now restricted down to 45. However, it is easy to see that the number of variants grows rapidly with the number of different configurable features, rising easily to thousands or hundreds of thousands (Sääksvuori & Immonen, 2008, p. 63).

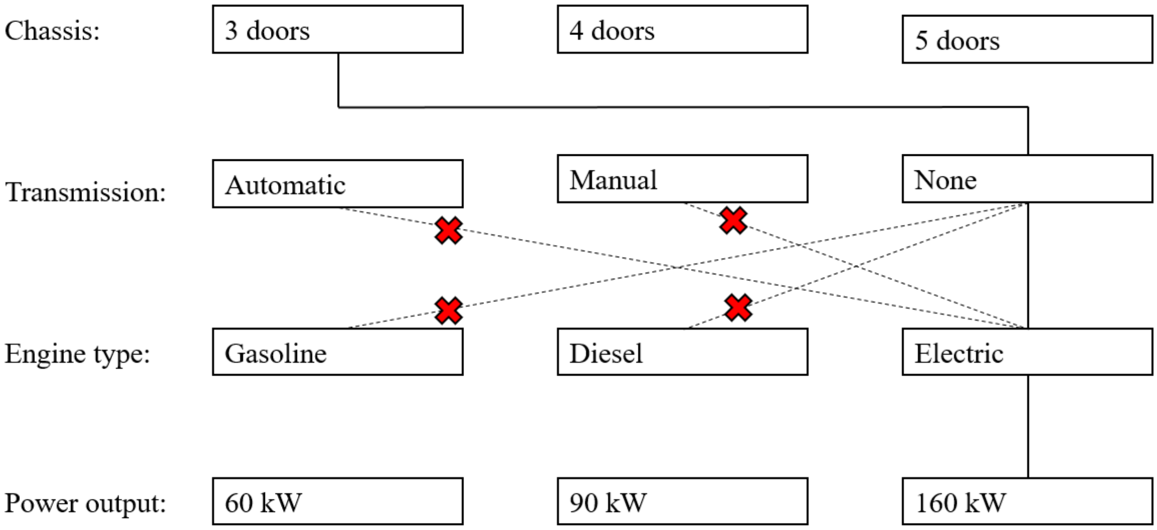


Figure 10. Configuration example of a car (adapted from Sääksvuori & Immonen, 2008, p. 63).

There are at least two problems which emerge with large number of variants combined with variant specific assembly instructions. First problem is how to create all the instructions. If the assembly instructions are easy to create, for example by copying and modifying the instructions created for other variants, it might be reasonable to create those uniquely for a very low number of variants. In this case we could use a configurator to pick automatically a ready-made document which matches the features of a variant. But if the number of variants reaches to thousands, it is not possible to create instructions manually anymore. (Martio, 2015, pp. 20, 36).

The second problem has the same origin. Namely, when there is a need to change the instructions due to changes in the product, the task becomes easily impossible with variant specific unique instructions. Again, with only a few variants, it might be reasonable to maintain unique instructions. Making the same change to multiple instructions wastes time and there is a risk that some instructions remain unchanged.

A solution to both problems is to configure the content of the instructions, similar to configuring the product structure. Same approach can be used to other documents as well. The trade-off is that implementing and maintaining a configuration system has a cost, too. Document configuration is similar to generating the variant specific product structure. In practice, the configuration can be done on two levels. The first level is to compose the document from predefined elements to a document template, and the second level includes additionally manipulation of the structure of the document, or of the contents of the elements. The configurator requires a general document structure, which defines the available elements and how they are matched with the variant specification, which comes from the sales configurator. The actual composing of the document is done by external tools, which can modify the file type in question according to the configurator output (Martio, 2015, pp. 36-38). When the instructions are compiled from elements, the creation and change implementation becomes relatively simple. Instead of changing all instructions, we can now just change the element which contains the parts requiring change. In reality, the configuration of the instructions is not this straightforward. Often, different product options have overlapping effects on the product structure, resulting in that same information must be presented in multiple elements.

2.5.2 Product lifecycle management

The configurators need a large variety of product data, so they must somehow communicate with the systems managing that data. In addition, the elements of the configurable instructions must be stored, organized, and managed. A common approach to manage and integrate product data, is to use a special system called product data management (PDM). PDM was originally developed to maintain and keep track of design files generated by CAD systems. Nowadays, it is more common to use the term PLM, product lifecycle management, which emphasizes the management of product data generated in the different company departments through the whole lifecycle of the product. As PLM is wider, holistic approach, PDM can be seen as a subset of PLM. Although PDM and PLM are in principle processes, both abbreviations refer to corresponding information systems which manage product lifecycle and product related data. (Martio, 2008, pp. 9 & 267; Sääksvuori & Immonen, 2008, p. 2-3). In their book, Sääksvuori and Immonen (2008, p.3) define product lifecycle management (PLM) as follows:

> *"Product lifecycle management (PLM) is a systematic, controlled concept for managing and developing products and product related information. PLM offers management and control of the product (product development, productizing and product marketing) process and the order-delivery process, the control of product related information throughout the product life cycle, from the initial idea to the scrap yard."*

Figure 11 illustrates PLM, its area of effect and the stakeholders. Creation and maintaining of information relating to the company's products and activities are in the core of PLM. The corresponding key functions are the management of items, product structures, documents, and the management and implementation of changes of the product data. There can be a wide variety of tools which are used to create and edit information, for example CAD systems, ERP, sales tools and so on. PLM integrates different systems and enables efficient transfer of information. PLM ensures fast and easy finding, refining, distribution and reutilization of the product data. Possibly the most important benefit of a functional PLM system is the improvement in communication between different company functions. (Sääksvuori & Immonen, 2008, pp. 3, 44 & 93)

The product and document configurators can be integrated into the PLM, as well. Moving from an external configurator to an integrated system will make the system architecture much simpler. All product structures are then maintained in the same system, which reduces the need to maintain overlapping data in multiple systems and makes the utilization of existing data easier. Additionally, in this case the generated variant product structures are complete, which is not always the case with external configurators. (Martio, 2008, p.267).

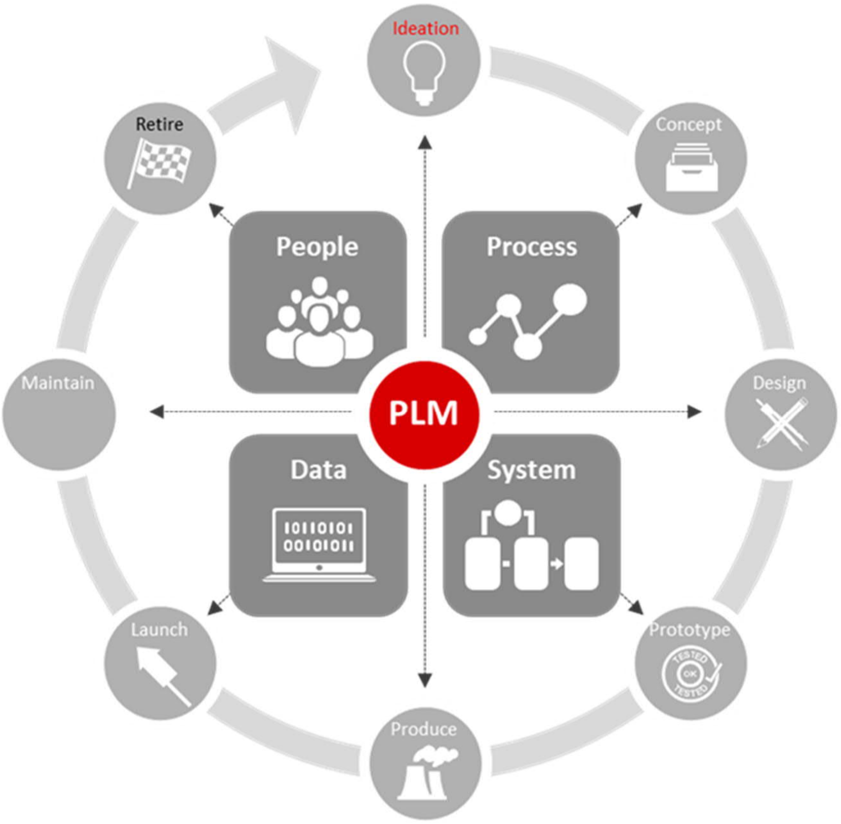


Figure 11. PLM concerns data created and used by different stakeholders at all phases of the product lifecycle. (Kauhanen,M. personal communication, 2019).

2.6 Analysis of the literature review

The contents of the preceding chapter are now analyzed through reflecting on the research questions 1-4 which were addressed in the chapter.

The purpose of the assembly instructions is to provide information on the parts and tools, but more importantly, they support the mental process through which the task is realized. This involves building an internal representation of the assembly object based on the external representation and updating it while the assembly task proceeds. Each assembly step must be first mapped on the internal model and then visualized on the real assembly before it can be executed.

The more explicit the instructions are, the easier it is to execute the mental process, and the smaller is the risk of misinterpretations. For example, textual instructions are descriptive, and need a lot of processing, thus ineffective. Diagrams are a depictive representation of the assembly and therefore more efficient. The efficiency of the instructions can be enhanced further by dividing the assembly in steps. However, the number of the steps in which the assembly is divided should be considered carefully, otherwise the single diagrams might contain too much information or the instructions become too long. In the light of the presented studies, the most efficient instructions based on paper format are reached by using action diagrams to depict the assembly tasks.

Taking the efficiency of the instructions further requires utilizing technology. However, it is important to note that new technology alone does not ensure better quality instructions. For example, Funk et al. (2016), Tang et al. (2003), as well as Blattgerste et al. (2017) compared as part of their studies the effectiveness of paper instructions with instructions displayed in the operator's field of view using a HMD. The content was in both methods exactly same. As a result, no significant benefit of using HMD was observed.

However, harnessing the features which modern displaying methods enable should yield more efficient instructions. Animations enable the perception of dynamic information, whereas AR can additionally provide the information in 3D and overlay it on the real assembly. Presented practical user studies suggest that animations do have an advantage over traditional instructions. In similar studies conducted with AR, the results were mixed. Nonetheless, studies demonstrate that overlaid and animated AR instructions reduce assembly errors significantly, and there might be a benefit regarding the assembly duration.

Despite that there are comparative studies, a definitive answer on which instruction method is the most efficient cannot be concluded. Research suggests that the complexity of the assembly task affects the benefit which can be gained using interactive instructions. In addition, for fair comparison the baseline of the studies should be similar. Therefore, the current comparability of studies on AR instructions and animations is low. Either the baseline of the studies was matching poorly (e.g. Sääski et al., 2008) or the complexity of the studies could not be matched (e.g. Tang et al., 2003) or both (e.g. Loch et al., 2016). This is a significant gap in the literature. To find a conclusion, a study comparing the most efficient combinations of the carriers and content should be carried out. Additionally, to confirm the effect of complexity, the study should include multiple tasks with different levels of difficulty.

Regarding the research question four, it was identified that interactive instructions require unique instructions for each product variant. When this requirement is combined with configurable products, it becomes evident that the instructions need to be configurable as well. However, if this is implemented with a standalone configurator, the resulting system is complex. Integrating the configurator in a PLM system simplifies the system architecture, since there is a decreased need to maintain same data in multiple systems.

3 Current state analysis

This chapter establishes an understanding of the current state of different documents that instruct assembly operations in the case company. The main focus is on the content of the documents, and how do the operators use the instructions. Additionally, the creation processes for the main documents are presented. Research methods are presented in Section 3.1 and the case company products and their production in Section 3.2. Then, Section 3.3 presents different assembly document types, their contents, and corresponding creation processes.

3.1 Research methods

The information needed to form an understanding of the current state was gathered using multiple qualitative methods: conducting semi-structured interviews, analyzing internal documents, and performing participant observation. Quantitative methods are used to measure by numerical data how widespread or strong a certain phenomenon is, while qualitative methods are more exploratory and flexible in nature (Denscombe, 2010, pp. 104-110), which were the features needed in this analysis. Utilizing multi-method approach, also known as triangulation, helps to form a broader view of the object of observation and enhances the rigor of the research (Hirsjärvi & Hurme, 2011, p. 38; Robson, 2002, p. 174, 371).

Observation enables direct data gathering of the actions of the object of study, whether it is an individual, a team or an organization. Participant observation requires that the observer is part or seeks to become part of the observed group or organization and takes an active role as part of the group. (Robson, 2002, p. 309-314). The author has been working as a trainee in the case company product development in the mechanical engineering team which offered a natural way to conduct participant observation. Especially doing the actual work before the present study has provided valuable experience in preparing assembly drawings and knowledge on other instructions used in the production. In the role of a trainee, it was easy to ask quick corrective questions from colleagues during the study. However, the knowledge gained through participant observation was not sufficient, so other methods were used to confirm and correct the existing knowledge and fill the information gaps.

Interviews are a useful method when the aim is to form an overview of a situation. In this case, semi-structured interviews were used. In a semi-structured interview, the main topics of the interview are decided beforehand, but the exact sequence, wording and number of the questions are flexible and can be adjusted in the interviewing situation. This approach gives more control to the interviewees and they can bring up other information that they consider relevant to the topic of the interview. (Hirsijärvi & Hurme, 2011, p. 46; Robson, 2002, p. 278).

In the present study, an extensive interview was carried out by interviewing a chosen informant, an experienced production quality engineer to form an overview of the current state and cover the information gaps of the existing knowledge. The participant was chosen by first investigating who would know best the current processes. The framework of the interview is presented in the Appendix 1.

In addition, to get in contact with the actual practitioners, smaller semi-structured interviews were carried out by discussing with the operators at the factory. This method was inspired by Gemba walk, a common tool in Lean philosophy. To form an understanding of an actual work or process, it must be seen in the actual location carried out by the real practitioners (Liker, 2004, pp. 223-225). The aim was to learn and get an overview how the operators use the instructions and drawings. However, these interviews were much closer to informal discussion or unstructured interviews than the one explained above, and only the general theme was decided beforehand. Discussions were carried out both in the case company's own plant and in a factory of a contract manufacturer to see if there are differences in the use of the instructions.

The third research method used was document analysis. For example, the actual currently used assembly instructions and drawings were examined. The aim was to inspect what information is presented and how. In addition, other documents, e.g. process charts were analyzed. The documents can be an important source of information, supporting findings from other sources and providing additional research data (Bowen, 2009).

3.2 Description of the products and production

The case company designs and manufactures frequency converters. There are three distinct product categories that are assembled in the local plant in corresponding dedicated assembly lines. The categories are:

- Drive modules
- Cabinet-built Single Drives
- Multidrives

Drive modules are standard products, and they are used as system components both internally and externally. Multidrives (MD) are always engineered-to-order (ETO) and thus they are the most varying products. Most of the Single Drives (SD) are configured-to-order (CTO), but a significant minority of the SD products involve order-specific engineering as well. Both MD and SD products consist of a cabinet-built unit or of multiple units. In case there are multiple units, they are combined and together they form a line-up, as illustrated in Figure 12. If a line-up is very long, it is divided into transport lengths (TL). Each TL is assembled separately but they are connected temporarily in the final tests before shipping.

The assembly of the drive modules is repetitive, and the products vary only little. In addition, the operation differs significantly from the assembly of SD and MD products. Therefore, drive modules were left out of the scope of the present study.

As discussed in Section 2.5.1, the CTO products are configured according to the customer wishes using predefined options, whereas the ETO products involve additional engineering and design to satisfy special needs. The level of required order-specific engineering varies. In practice, the ETO products are based on standard CTO units. In the case of MD products, there is such a large amount of choice that even if a product consists only of CTO units, the generated product must be inspected manually to ensure its validity and that all required parts are included in the bill of material (BOM). Nevertheless, customer applications require often non-standard units. Some of the special units occur often and can therefore be realized effortlessly using knowledge and designs from earlier cases. However, some of the applications require totally new designs.

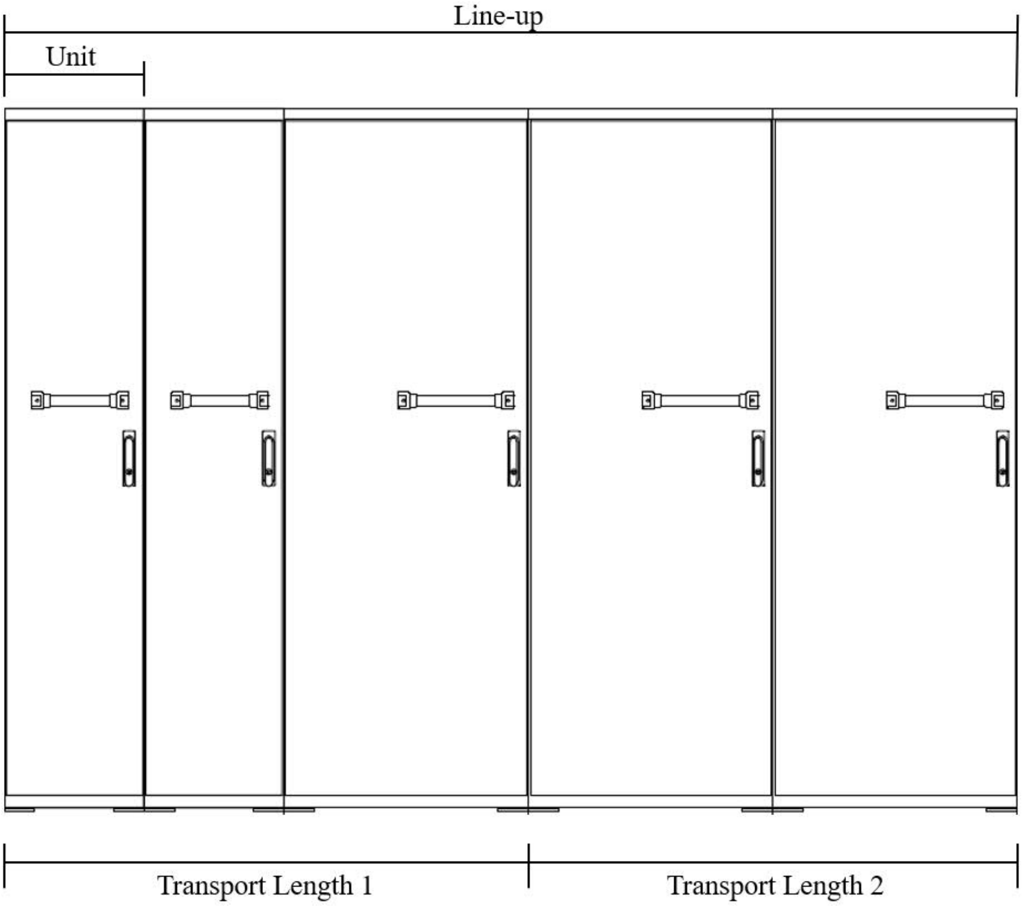


Figure 12. The key terms of the case company products illustrated. Line-up consists of units, and the line-up can be divided into transport lengths which are handled individually in the assembly.

The often occurring special ETO units are problematic regarding the assembly documents. Since the units are based on earlier designs, also the formerly created assembly documents are reused. However, since these products do not belong to the standard offering, the documents are not maintained.

The main assembly process of the MD and SD products is divided into three phases: frame assembly, final assembly, and finishing. At the MD assembly line at the local factory, there are two dedicated assembly areas consisting of multiple assembly cells. There is an area for the frame assembly and another one is for both final assembly and finishing. In the SD assembly line, the assembly process is divided into smaller fractions and the TL is moved forward more often. According to process chart, the tasks in these phases are clearly separated but it was observed that in practice the assembly task allocation between the frame assembly and final assembly of MD products is flexible. Task allocation can be changed due to availability of components or high loads in either of the assembly line parts. At the SD assembly line, the task allocation is followed more strictly. In the SD production the assembly procedure is more standardized than what it is in MD due to higher throughput and lower variation of the products. In addition to the main assembly, there are dedicated subassembly areas for both SD and MD assembly lines, which assemble components for the main assembly lines.

3.3 Assembly documents

There are four types of main assembly documents used in the mechanical assembly of the case company's products: assembly drawings, assembly work instructions, manufacturing drawings, and dimension drawings. The assembly documents are summarized in Table 2. Assembly drawings and assembly work instructions are unit-specific, while dimension drawings and manufacturing drawings are prepared for line-ups. Their use and availability depend on the product category. For MD products, there are only assembly drawings and manufacturing drawings available, since these products are too varying to make the creation of detailed assembly work instructions reasonable. For SD products, there are assembly drawings and dimension drawings. Dimension drawings are similar to the manufacturing drawings but contain less information. For SD units, there are also the assembly work instructions available. In addition to the presented instructions and drawings, there are other documents containing general assembly information. For instance, there are instructions for the use of adhesive labels, and for common tightening torques for bolt-nut connections.

Table 2. Main assembly documents.

	Multidrives	**Single Drives**
Unit	Assembly drawing	Assembly drawing Assembly work instruction
Line-up	Manufacturing drawing	Dimension drawing

In the company office, there are three different departments preparing and maintaining the assembly documents: research & development (R&D), order-specific engineering (OSE), and product engineering (PE). In addition, there is a dedicated team in the SD production which prepares the assembly work instructions. R&D handles the development and design of the new products, their product structures and assembly drawings. OSE handles the ETO customer projects, their technical execution and design of the special applications. OSE prepares manufacturing drawings for the ETO products and assembly drawings for the special application units. PE maintains and improves existing products and their assembly documentation.

Maintaining all documents so that the information is uniform is difficult. Information presented in the different documents is overlapping and sometimes contradictory, especially for MD products. In addition to the assembly documents, there is another source of information, namely the BOMs. BOMs are not usually used by the assembly operators, since logistics operators pick and deliver the required parts for each assembly phase. However, if the BOM information differs from that of assembly drawings, manufacturing drawings and assembly instructions, operators become confused. A small part of the mechanical engineering team of the OSE department, mechanical inspection team, prepares both the manufacturing drawings and BOMs. However, the information can be contradicting even between these two due to human error. Assembly drawings are not altered in the mechanical inspection, and therefore some of the items in the BOM might not be presented in the assembly drawing. For SD products, the BOMs are generated automatically with a configurator, and therefore the mismatches of information are more due to the time-consuming process for updating the assembly work instructions.

3.3.1 Assembly drawings

Assembly drawings are unit-specific wireframe drawings. The drawings illustrate the assembly of components using mainly structural diagrams. Exploded views are used only if the parts would not be visible otherwise. Figure 13 presents an example of a sheet of an assembly drawing. As seen in the Figure 13, the components to be assembled are tagged with a note presenting the material code of the part. If the same part is presented multiple times, the material number and the total quantity of the parts is usually denoted on one part. Additionally, instructive text, for example tightening torques for screws, can be presented. If a part is assembled only in the case of a certain option, this is denoted conditionally with the word 'IF' combined with the option code.

The parts are not necessarily presented in the order of their assembly but instead as part of functional groups. Usually, different part groups are presented on their own sheets. These functional groups are for instance bus bars, mechanical supports, and piping. Assembling all the parts of a given functional group may prevent the assembly of the parts belonging to other groups. Vice versa, some parts cannot be assembled before certain parts from other functional groups are installed. For example, Figure 13 presents all the mechanical parts of a unit. However, this specific unit includes also cooling pipes, which must be assembled before certain mechanical parts, but they are not shown in the same assembly drawing sheet. Consequently, the key issue of the assembly drawings is that to figure out the assembly order, the operator must examine multiple sheets at the same time, which is very demanding, especially when an operator assembles a certain unit for the first time or after a long time. The problem is highlighted if there are many small parts assembled tightly close to each other.

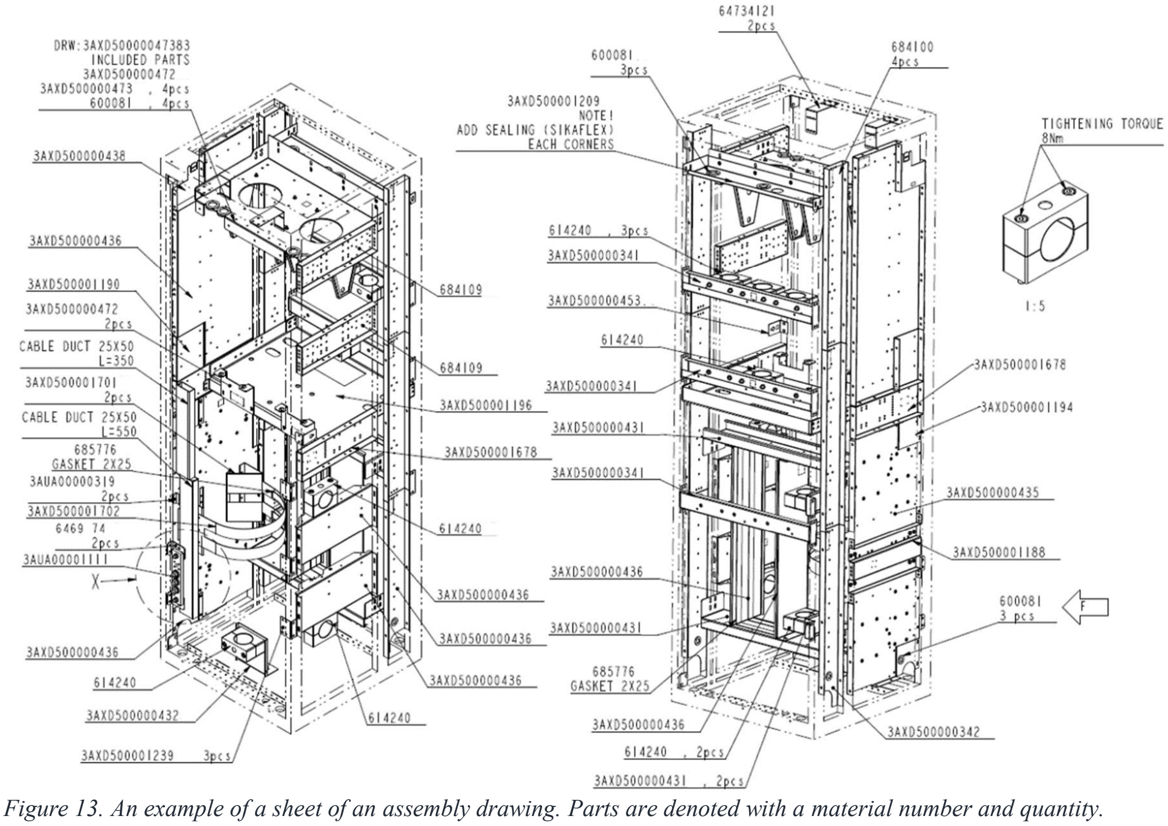


Figure 13. An example of a sheet of an assembly drawing. Parts are denoted with a material number and quantity.

Other frequent problem is that correct placement of side beams and supports are not clearly presented, or it is hard to interpret from assembly drawings. These parts are assembled first into the cabinet frame and misplacement of supports can result cumulative errors and time-consuming rework. Sometimes the operators need to check the correct position from the 3D model of the product. Some operators reported that when the drawings utilize exploded views and there is another view of the unit close to the correct one, there is a risk that a part is perceived to belong to the wrong view.

The assembly drawings are created using the 3D models of the units using a 3D CAD software. For each sheet of the drawing, an own simplified representation must be made, and additionally specific exploded views must be created as well. There are no strict guidelines for creating the drawings, instead there are only some common practices. For example, the instructions present first the parts belonging to the unit frame and bottom and in the last sheets of the drawing the assembly of doors and covers are presented. What is presented in between, depends on the unit and on the engineer creating the instructions.

R&D creates the assembly drawings when the first prototypes are scheduled, and the drawings are refined incrementally when the design process proceeds, and more prototypes and pilots are built. PE becomes responsible for maintaining the drawings after the product is officially launched and the responsibility is transferred. The exception for this are the special application units for which OSE prepares assembly drawings.

The drawings are stored in a document management system (DMS) in PDF format. DMS limits the size of the stored files to around 60 megabytes. The result is that the number of the sheets in assembly drawings become limited as well.

The drawings can be viewed with a computer. In MD assembly line, there are some laptops in the final assembly area which are used for this purpose. In SD assembly line, each assembly cell has its own laptop. The operators open the drawings from ERP (enterprise resource planning) client application which automatically opens the latest version of the needed drawing. The drawings are also available on paper. Production planners print the assembly drawings of each unit of a TL into a folder, and each TL has its own folder. Printing and filing the drawings takes time from other tasks and thus the job is considered frustrating. In addition, the dedicated printer and the paper material add overhead operation costs, although probably only marginally.

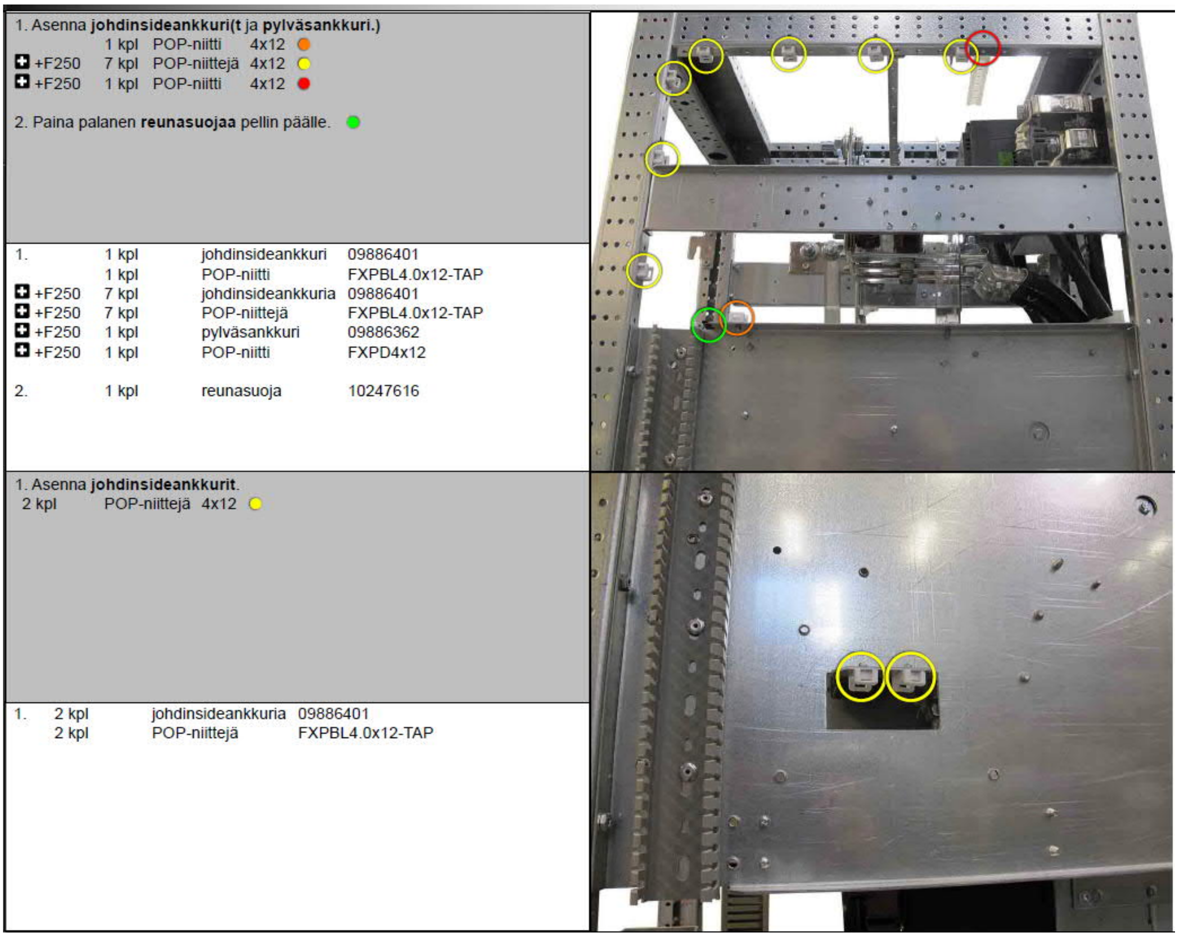
Important changes to the units and their assembly drawings are communicated to the operators in the daily management meetings in the mornings. The smaller changes the operators need to point out from the drawings by themselves. However, these changes are noted in assembly drawings by an arrow and a revision letter.

3.3.2 Assembly work instructions

Assembly work instructions, which are available for SD units, describe the assembly procedure for a certain unit in detail, step-by-step. The instructions are meant to be detailed enough that even an unexperienced operator can carry out the assembly using the instructions. Assembly work instructions make use of descriptive text and photos of real assembly steps of the units to communicate the assembly information. Figure 14 presents a sheet from an assembly work instruction. As seen in the Figure 14, there are text instructions for the task in the grey box. The tasks are divided into numbered steps. The parts to be assembled are denoted with bolded text in the step description. The fasteners used in the described step are denoted below the step description and marked with a color-coded circle.

In the white box below the grey box, are the corresponding parts needed in each step described in more detail using text description and material number.

Similar to assembly drawings, assembly work instructions are stored in the DMS, but they are available only in the electronic PDF format. The assembly work instructions include some interactive features. Namely, the instructions are constructed so that the operator can select in certain points of the assembly procedure between different options. These options have a significant effect on the product structure and hence result differing assembly procedures. The option text is a hyperlink, which opens the instruction page from which the assembly continues. However, parts for options, which have only small effect to the product structure, are presented conditionally regardless of the choices the operator makes. For instance, in the Figure 14 there are parts that are denoted with "+F250", which means that they are assembled only if the option F250 is selected for the specific unit. The presented means enable having practically variant-specific instructions in one document.



1. Asenna **johdinsideankkuri(t** ja **pylväsankkuri.)**

	1 kpl	POP-niitti	4x12	🟠
⊞ +F250	7 kpl	POP-niittejä	4x12	🟡
⊞ +F250	1 kpl	POP-niitti	4x12	🔴

2. Paina palanen **reunasuojaa** pellin päälle. 🟢

1.		1 kpl	johdinsideankkuri	09886401
		1 kpl	POP-niitti	FXPBL4.0x12-TAP
	⊞ +F250	7 kpl	johdinsideankkuria	09886401
	⊞ +F250	7 kpl	POP-niittejä	FXPBL4.0x12-TAP
	⊞ +F250	1 kpl	pylväsankkuri	09886362
	⊞ +F250	1 kpl	POP-niitti	FXPD4x12
2.		1 kpl	reunasuoja	10247616

1. Asenna **johdinsideankkurit**.

2 kpl	POP-niittejä	4x12	🟡

1.	2 kpl	johdinsideankkuria	09886401
	2 kpl	POP-niittejä	FXPBL4.0x12-TAP

Figure 14. Example of a sheet of assembly work instruction. Grey boxes explain the assembly steps, and white boxes define the needed parts. On the right are images of the actual assembly object.

The assembly work instruction for a new unit is created when it enters pilot and ramp-up phase. Creation of the instructions takes a significant amount of time, since every step must be photographed and documented. Additionally, creating the instructions requires that multiple units are assembled so that units with different option combinations can be documented. Consequently, multiple products are assembled so that time is spent on learning the assembly procedure while only assembly drawings are available. The actual document is created using software dedicated to handling PDF files and specific document templates.

When there are changes implemented in the units or their subassemblies, the instructions must be updated as well. For some changes it is enough to denote the changed parts, but others require taking new photos and making major changes to the instructions. The aim is to implement changes in the instructions in the same schedule as the particular change is implemented.

The disadvantage of the assembly work instructions is that they are laborious to create and maintain. Use of multiple information sources is problematic. The instructions are slow to use if the operator uses mainly the assembly drawings. If the assembly drawings do not contain the information or are difficult to interpret, the information must be checked from the assembly instructions. Checking information from the instructions is slow because the operator has to browse the instructions to find the needed information and opening the instruction file takes time. If the work instructions were the only document type in use, the operators would not need to use time for browsing, since they would already be on the right page. Then again, operators can memorize most of the information, so keeping the instructions on the right page would be waste of time until some information is needed.

3.3.3 Manufacturing drawings and dimension drawings

Manufacturing drawings and dimension drawings differ significantly from the other presented assembly documents, since they depict the whole line-up instead of a single unit. Dimension drawings or manufacturing drawings are printed to the project folder, but they are not delivered in electronic format to the factory.

The main purpose of the dimension drawings is to communicate and confirm product details with an end-customer. In addition, dimension drawings are used in the SD assembly to present the whole assembled product. Dimension drawings are generated automatically using a dedicated document generator. The generator takes the product type code as an input and produces the drawing according to generation rules. Dimension drawings, like their name suggests, presents the customer-critical dimensions of the product and the appearance of the product.

Manufacturing drawings are prepared only for MD products. Mechanical inspection team prepares the manufacturing drawings by adding information and modifying the automatically generated dimension drawings on a 2D CAD software. For example, the manufacturing drawing includes the material codes and visual representation for the line-up busbars, doors, lifting plates, and lifting beams, which can be seen in the Figure 15. In addition, the material codes and dimensions for the holing of the doors are presented.

The manufacturing drawing is the only document visualizing the whole line-up and works as an overview of the whole assembly operation. Manufacturing drawing contains also information that affects the assembly of single units and describes in which order the units are placed in the line-up. For example, busbars are presented only in manufacturing drawing, and their placement affects the holing of the dividing walls between the units. At the contract manufacturers plant, the manufacturing drawing had more important role than at the case company's own factory. Namely, it was observed that the frame assembly at the contract manufacturer is carried out using often solely the manufacturing drawing.

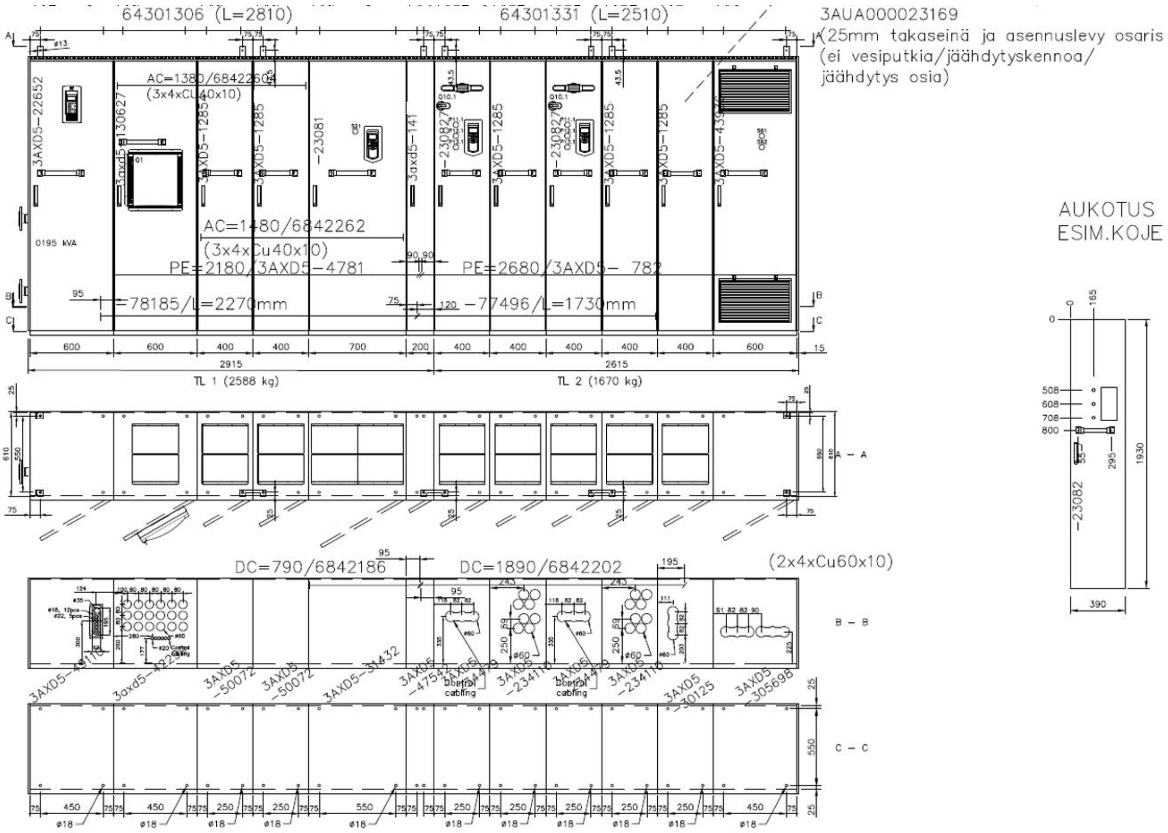


Figure 15. Manufacturing drawing. All texts with the larger text type are added to a dimension drawing when the manufacturing drawing is prepared.

4 Design and evaluation of the interactive instructions

Two instruction approaches were developed based on the literature review and current state analysis. According to the research presented in the literature review, displaying the assembly information step-by-step makes the instructions efficient. Animations enhance the efficiency further, and as discussed in Section 2.4.2, overlaying the animation of the assembly step on the real assembly object should make perceiving information even more easier. However, literature could not provide a definitive answer on the most effective instruction method, so two approaches, 3D instructions and AR instructions, were first developed and then evaluated in a user study. Section 4.1 describes the instructions and their development. Then, Section 4.2 presents the user study and its results.

4.1 Design and development of the instructions

The design of the instructions required continuous refining and iteration throughout the study. Vision of the design formed slowly as the literature review proceeded. Eventually the vision was refined and realized when the content for the instructions was developed. Next, the concept, contents, and authoring processes of the both 3D instructions and AR instructions are described. In addition, the software used for authoring the contents are shortly presented.

4.1.1 3D instructions

3D instructions present the assembly procedure as an animated sequence of the assembly steps. The animation pauses after each step. Each part is animated so that it first appears and then glides in the correct final position. Then, a tag denoting the part material number appears. If there are multiple same parts, the quantity of the parts is denoted after the material number. In addition, vertical distance from the bottom of the frame is denoted for the parts which are assembled directly to the unit frame. Other parts are assumed to be placed relative to the earlier assembled parts. Figure 16 presents a screenshot of the 3D instructions in which the item tags and measures are shown. Orientation of the assembly object is changed dynamically so that all parts and mating surfaces are visible in each step. Fasteners were left out of the instructions, since they were missing from the original CAD model.

The 3D instructions were created using Creo Illustrate. Creo Illustrate is a software for creating technical 2D and 3D illustrations and animated instructions for various purposes utilizing existing CAD models. Illustrate can associate the instructions with the original CAD files, which enables linking the created illustrations to the 3D model. Hence, design changes are updated automatically to the instructions. (PTC, 2019A).

Next, the creation workflow of the 3D instructions is briefly presented. A more detailed description of the workflow is presented in Appendix 2. First, the CAD model of the assembly object was imported to the program. Next, the product structure of the model was manipulated to match the specific variant going to be assembled. Then, the actual assembly sequence was created by recording the trajectories for each part. Complex trajectories can be created as well. Lastly, the annotations were added to the sequence steps. A custom annotation tool was created and used which enabled to automatically display the material code of a part and the amount of the parts. Custom annotations can be used to show other parameter values as well.

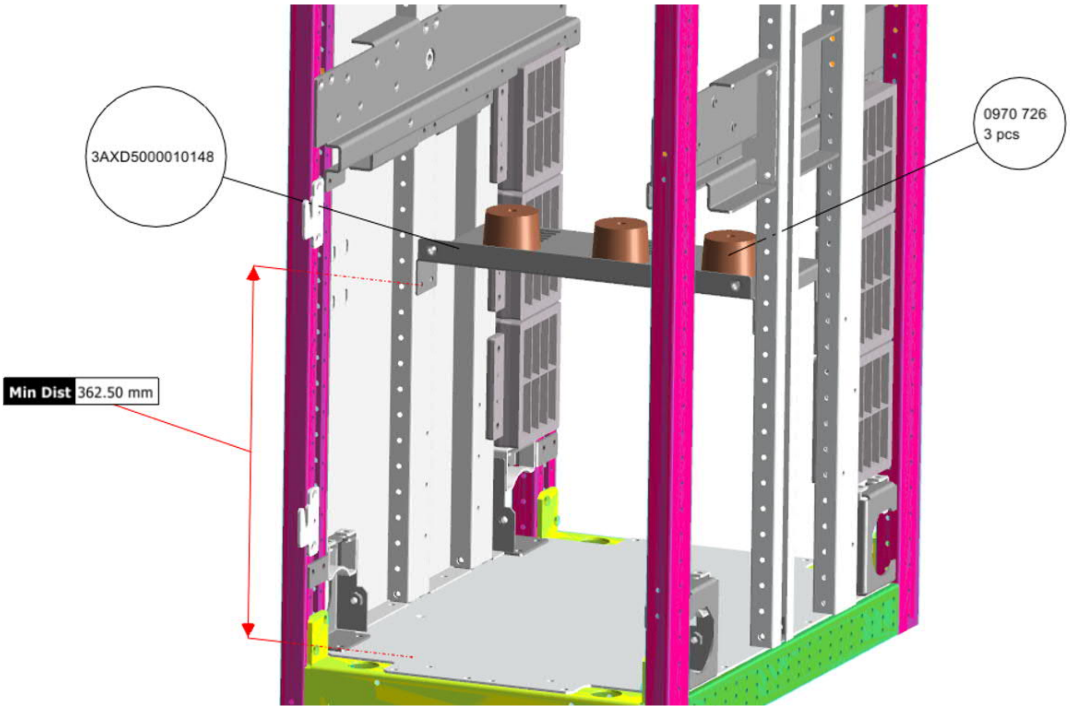


Figure 16. Screenshot of a step from the 3D instruction. Parts are denoted with material number.

During the development of the content, a quick iteration was made by presenting the instructions for the operators at the shop floor before the actual user study. Based on feedback, small changes were made to the annotations and to the assembly sequence.

4.1.2 AR Instructions

AR instructions present similar step-wise animations as the 3D instructions. However, in this case the animation is spatially overlaid on the physical assembly object, as seen in Figure 17. Another difference is that the parts, which are already assembled, disappear after proceeding to the next assembly step to prevent the virtual objects occluding the view of the real assembly. For practical reasons, the item annotations had to be left out of the instructions.

The AR instructions were created using a software dedicated for authoring AR content, Vuforia Studio. Vuforia Studio can use the product structures and sequences created in Creo Illustrate. Vuforia Studio publishes the “experiences” created in the software to a specific experience server from which the viewing software retrieves the content over the internet. (PTC, 2019B).

In the authoring process, the first step was to import the CAD model into the program. The model was first modified in the Creo Illustrate in a similar way as in the case of 3D instructions. Then the model and a specific marker were placed in the design area and positioned relative to each other. The item annotations were left out, since Vuforia Studio does not import them along the CAD model. Creating the annotations inside the Vuforia Studio would have been too laborious a task.

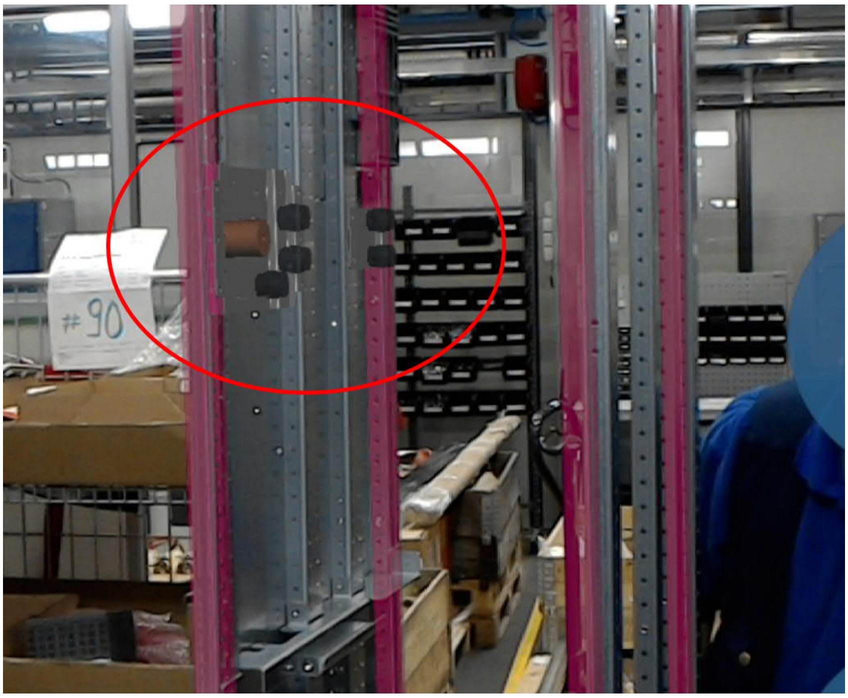


Figure 17. A capture of the view through the HMD. Virtual objects representing the parts to be assembled are shown inside the red circle.

An iteration according to feedback was made during the AR authoring process as well. The instructions were tested at the shop floor, and as a result, the placement of the marker was changed to improve registration, and the opacity of the virtual model was decreased.

4.2 User study

Since the aim was to investigate the operators' opinions of the instructions, qualitative methods suited well for the purpose. However, there was also a need to measure the subjective difference between the efficiency of interactive instructions and the ordinary assembly drawings. Hence, a mixed method approach combining qualitative and quantitative methods was selected. In addition, use of quantitative methods can support and clarify the qualitative results (Robson, 2002, p. 371). According to Dünser et al. (2008), questionnaires utilizing both subjective measurements and qualitative analysis, and in addition informal evaluation, are common methods used to evaluate AR systems, and therefore they were selected as research methods in the present study as well.

4.2.1 Test setup and hypotheses

Tests were carried out in a frame assembly cell of the Multidrives assembly line. MD products were selected to be used as test objects since they are more varying than SD products, and the literature suggest that the higher the complexity of the products, the greater is the benefit from interactive instructions. The 3D instruction was tested in the mechanical assembly phase of a rather new unit. Since the AR instruction was more experimental and uncertain by its characteristics, it was decided to be tested in mechanical assembly of a prototype unit to avoid causing problems in the actual production. Since the number of samples in both cases is only one, the hypotheses were kept simple.

- Hypothesis 1: 3D instructions are easier and faster to use than the current assembly instructions.

- Hypothesis 2: AR instructions are easier and faster to use than the current assembly instructions.

3D instructions were viewed on a performance laptop equipped with a 15,6’’ LCD screen. Laptop was used for practical reasons, although there is a risk for the stimulus-response gap, as Thorvald (2011) suggests. The laptop was placed few meters away from the assembly object. The assembly object and the placement of the laptop is presented in Figure 18.

The software used to view the 3D instructions was Creo View Lite. With Creo View, the operator was able to go back or forth in the instructions and skip the animation using the playback controls. Additionally, the operator could manipulate the orientation of the 3D model and zoom in to check for example the placement of the parts in detail.

Figure 18. Picture of the mechanical assembly cell. The laptop with the 3D instructions is on the left. Test objects are the two units in the middle of the line-up.

The AR instructions were tested using a holographic HMD, more precisely Microsoft’s HoloLens, seen in Figure 19. HoloLens presents the image so that the in-depth position of the virtual object can be perceived. The instructions were viewed using Vuforia View software. The registration was based on a specific marker, and the marker was placed on the middle of the left pillar of the unit frame. Similar to the 3D instructions, the operator was able to control the playback of the animation by directing their gaze to the virtual buttons next to the unit and making a pinching gesture with fingers.

Figure 19. An operator installing support plate into the assembly object while wearing a HMD.

4.2.2 User study structure

Test subjects were two experienced operators from the MD assembly line. They were selected indirectly, as they had been assigned to carry out the assembly of the selected test objects without knowing about the upcoming user study. Also, the author in the role of experimenter did not know who were assigned to build the selected test objects.

The user study was discussed with each subject a day before the actual study to have their acceptance for participation. The upcoming study and its objectives were explained as well. Depending on the test object, it was explained that the instructions would be viewed using a laptop or a HMD. They were also told that the instructions would present the assembly procedure in a step-by-step manner.

The experimenter observed the participants during the tests but did not participate in the assembly operations. The purpose was to gather direct evidence of the actions of the operators during the tests and to ensure operators use the interactive instructions. Additionally, the presence of the observer enabled support in case of technical problems.

After the experiment, the participants were asked to complete a questionnaire. The questionnaire consisted of two parts. The first part focused on examining the perceived efficiency of the instructions compared to the assembly drawings which the operators use usually. Secondary focus of the first part was on general feedback of the instructions. The questions were targeting the key issues identified in the current state analysis and key features of the interactive instructions. The first part consisted of five open questions and three questions which were graded on eleven-point Likert scale. The questions are presented in Appendix 4. The second part of the questionnaire was aimed to assess the operators' acceptance of the tested instructions. In this part, a questionnaire developed specifically for this purpose by Syberfeldt et al. (2015) was used. The questions of the second part are presented in Appendix 5.

4.2.3 Results

In general, both tested interactive instruction methods got a positive reception. However, the results of both the questionnaire and observation suggest that 3D instructions performed better than AR instructions.

Compared to the assembly drawings, the 3D instructions were considered to enhance the assembly performance significantly. The main reasons were that the presentation of the tasks was clear and depictive, and the tasks were presented step-by-step. The animation played a vital role in supporting identification of the parts to be assembled.

AR instructions supported identification of the parts as well and were deemed to perform better than assembly drawings despite that the material codes were not displayed. The strength of the AR instructions was the placing of the parts into the assembly. Since the placement could be done without measuring distances, the assembly operation was considered more efficient than with the regular assembly drawings. However, the placement was not trouble-free due to alignment errors of the virtual and real units, as can be seen in the Figure 20. In addition, the virtual objects occluded the real parts and the hands of the operator, which caused that the operator had to lift the HMD off his eyes to see where to put the screws. In addition, occlusion caused a few times alignment errors.

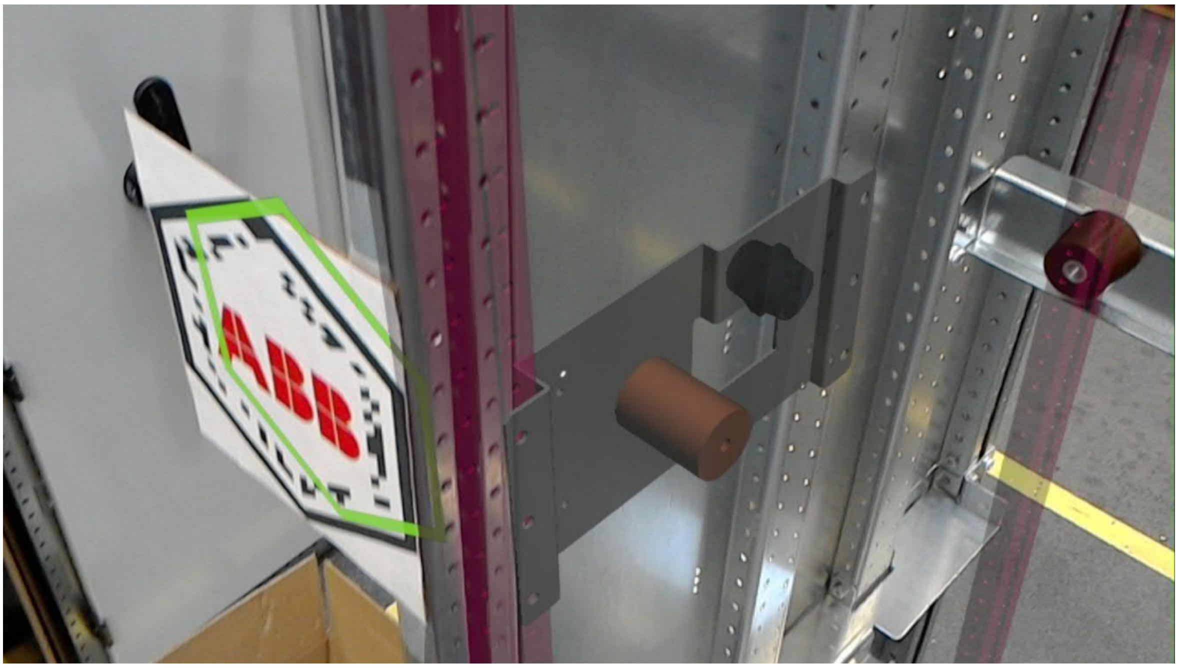


Figure 20. Bad alignment of the virtual and the physical model. The green hexagon should be aligned with the grey hexagon of the marker.

To summarize, both methods were reported to perform better than the regular assembly drawings according to each comparative question. Hence, the results support both hypotheses. In addition, the results are in line with the findings of Tang et al. (2003), Sääski et al. (2008), Watson et al. (2010), and Lušić et al. (2016).

According to the results of the second part of questionnaire, presented in the Figure 21, 3D instructions resulted very high operator acceptance whereas AR instructions did not perform as well. Especially, the question five, which measured if the system is considered physically demanding, yielded differing results. Based on the qualitative questions and observation, the acceptance of the AR instructions was lowered by the registration errors, narrow field of view, and cumbersome use of the HMD. In addition, the HMD felt heavy and sweaty.

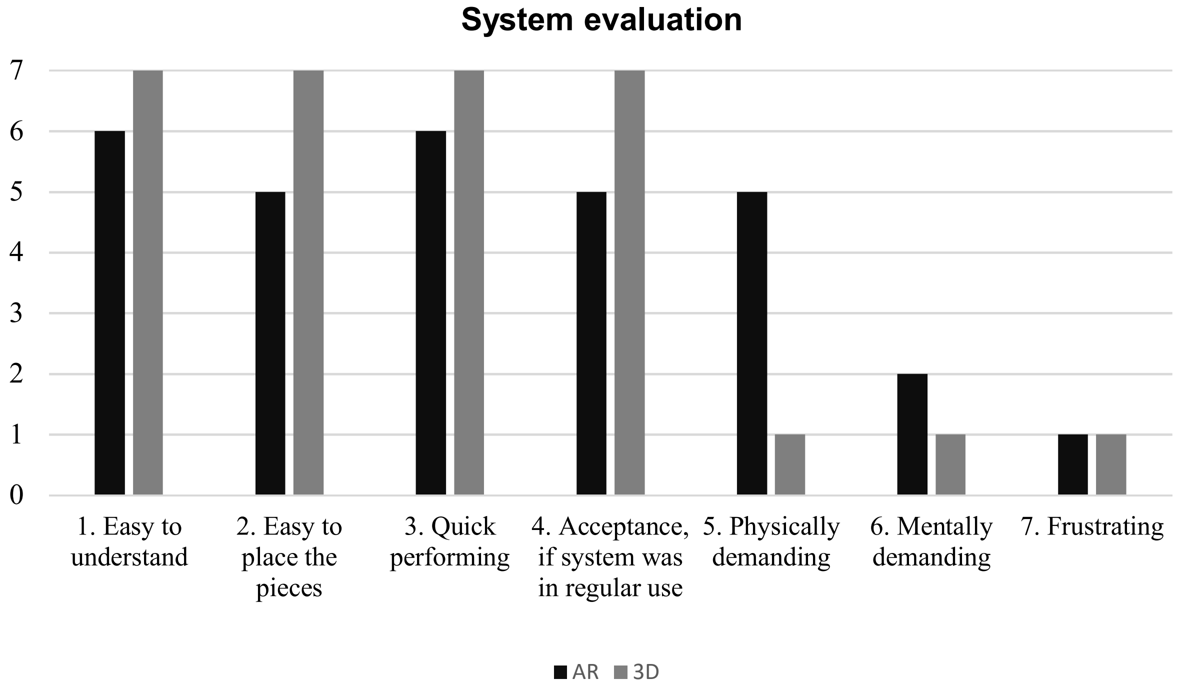


Figure 21. Results of the second part of the questionnaire. Each question was graded on seven-point Likert scale. (1= totally disagree, 7=totally agree)

5 Discussion

The main objective of the present study was to investigate whether interactive assembly instructions could substitute the currently used assembly drawings and assembly work instructions in the case company. To enable the evaluation, the interactive assembly instructions had to be first designed and the content developed on the basis of the results from literature review and current state analysis.

Section 5.1 discusses the findings of the literature review, current state analysis and the user study utilizing a SWOT analysis. The aim of the analysis is to form an overview of the key benefits and concerns and evaluate the 3D instructions and AR instructions with respect to the main objective of the present study. The analysis can be used as a support for drawing conclusions and making decisions.

Section 5.2 assesses the validity and reliability of the research. Then, Section 5.3 discusses significance of the study. In Section 5.4, the present study is concluded, and lastly, Section 5.5 presents the recommendations for the case company. In Section 5.6, the identified gaps in the current body of research are presented and suggestions for further research is given.

5.1 SWOT Analysis

SWOT analysis is a qualitative tool developed for examining the relationship of an organization and its environment. Nevertheless, SWOT analysis is nowadays applied usefully on other objects, e.g. products, policies, and whole sectors. SWOT stands for strengths, weaknesses, opportunities, and threats. Strengths and weaknesses are internal features of the analyzed object, whereas opportunities and threats derive from external trends. (Rizzo & Kim, 2005; Lindroos & Lohivesi, 2010). In the present study, SWOT analysis provides a constructed approach for conducting qualitative analysis of the properties of the proposed instruction systems and facilitates discussion from multiple aspects. The identified strengths, weaknesses, opportunities, and threats for the 3D instructions and AR instructions are presented in the Table 3 and Table 4, respectively. AR instructions are based on the 3D instructions and therefore they share many characteristics. Therefore, the identified properties of both instructions are discussed jointly in the following four sections.

Table 3. Summary of SWOT analysis for 3D instructions.

Strengths	**Weaknesses**
• Step-by-step • Dynamic • Model-based • Variant specific • Easy to use and understand • Easy to implement, regarding hardware and software • Hardware is well tested • Shorter assembly duration • PLM integration	• Variant specific • New software • Fixed location
Opportunities	**Threats**
• Standardization of the work • Global transfer of information • Enhanced training • Less skilled workforce can be used • Enables AR • Facilitates assessing the feasibility of assembly	• Unwillingness to adopt change • Too low cost-benefit • Functioning of the configuration

Table 4. Summary of SWOT analysis for AR instructions.

Strengths	**Weaknesses**
• Step-by-step • Dynamic • Model-based • Variant specific • Seamless integration of the instructions and reality • Mobile, instructions always visible • Reduced errors, especially cumulative • Easier placement of parts • Shorter assembly duration	• Variant specific • New software • Wearing for extended periods • Tunneling of attention • Immature technology • Endurance of the devices • Annotations cannot be imported • Requires training • Occlusion • Registration errors
Opportunities	**Threats**
• Standardization of work • Global transfer of information • Enhanced training • Less skilled workforce can be used • Automation of content publishing • Development of hardware • Development of software • Use of IIoT data, Real time process control • Positive effect on the brand image • Quality assurance	• Unwillingness to adopt change • Too low cost-benefit • Information security • Changes required to network infrastructure • Unperfect system • Assembly tasks not enough varying

5.1.1 Strengths

Both the 3D instructions and AR instructions are very depictive. The core strength of the interactive assembly instructions is the ability to communicate dynamic assembly information step-by-step while presenting the installation trajectories, thus making the perception of the information easier. Step-by-step instructions remove the need to figure out the assembly order either by recalling it from the memory or by making decisions and interpreting the assembly drawings each time a unit is built. Hence, assembly errors, rework and ultimately the assembly duration are reduced. Use of the instructions is very straight-forward, and because the instructions are variant-specific, only relevant information is presented.

The instructions are created based on the virtual 3D model of the assembly object, which enables authoring the first versions of the instructions already in an early phase of product development. This makes the step-by-step instructions available for even the first prototypes, well before the creation of assembly work instructions could be initiated. Furthermore, the instructions can be associated with the original 3D models through integrating the authoring software in to the PLM system, which enables automated updating of the instructions.

An additional strength of the AR instructions is that they present the virtual parts and their animation overlaid on the real assembly, enabling built-in error detection, hence reducing cumulative errors significantly. The operator will detect quickly, if the installed part is misaligned with the virtual part. Since the AR instructions are realized using a HMD, the AR instructions are available whenever the operator wears the device. The hands are left free to carry out assembly, and the transition between executing the assembly and looking instructions is seamless.

For 3D instructions, if used with a laptop, the hardware is well-known, and there is a standard way to integrate them and take in use in the case company. 3D instructions would require only little training of the operators. Therefore, 3D instructions would be rather easy to implement regarding the needed equipment. Furthermore, 3D instructions have additional interactive features, namely the model can be freely rotated and viewed in close-up, and the user can examine single parts for additional details.

5.1.2 Weaknesses

Variant-specific instructions are a strength but can be considered additionally as a weakness. When unique assembly instructions are combined with varying products, the instructions must be configurable to enable efficient authoring and maintaining of the instructions. The authoring of the instructions becomes more complicated compared to creating a single instruction, since the instructions are compiled from elements. Other possibility would be to prepare the instructions for each unique unit just before they enter production, and not maintain the instructions at all. However, by intuition, this does not seem very efficient. Each line-up has multiple units and preparing instructions for each unit every time a product is released to production would probably yield too much work and might risk the efficient operation of the factory.

The second shared weakness is the new software, which is required for authoring the instructions. Although the software can be integrated into current systems, the successful implementation needs a significant amount of work. Additionally, the engineers authoring the instructions must be trained to use the software and to create instructions efficiently.

The only weakness identified specifically for 3D instructions is the low mobility of the instructions. If the displaying of the instructions is realized with a laptop, there is a risk that the lower availability leads to lower attending of the instructions and to forgetting the information due to the stimulus-response gap (Thorvald, 2011). However, this problem could possibly be tackled by using a tablet to view the instructions. The tablet could have a holder that could be temporarily installed in the line-up frame leaving the hands of the operator free. However, a tablet is more fragile and there is a risk that the tablet breaks down which would force the operator to stop working. Additionally, the usability of the instructions on the tablet must be tested to define which, tablet or laptop, is more suitable. This might be also a question of individual preference; some operators might prefer using a tablet, while others would might to like to use a laptop.

For AR instructions, multiple weaknesses were identified. Firstly, the content used in the tests occluded the real assembly interfering with the assembly execution. To tackle this, the virtual parts could be displayed first in full, but then changed to a wireframe representation.

Another significant problem identified in the development of the AR content was that item annotations could not be imported to the AR instructions, thus reducing the ability to identify parts. Instead, if one wishes to add labeling for parts, these should be added separately in Vuforia Studio. As a result, this requires repeating the manual work to add item annotations.

The registration of the virtual content is in a key position affecting the usefulness of the AR instructions. If the registration is poor like in the user study of the present study, the reliability of the instructions is impaired. For example, when installing supports to the unit frame, which has holes for installation with a spacing of 25 millimeters as seen in Figure 20 on page 41, the operator could not be exactly sure where to place the parts. The problem could be avoided by using more accurate tracking targets, for example model targeting or multiple markers. The software licenses in the case company did not allow using other tracking methods than a single marker, thus limiting further tests in the present study.

The hardware required for AR instructions is still considerably immature, and there is only little experience of using them in an industrial environment. For example, the field of view of the HoloLens used in the user study was very limited. In addition, the endurance of the devices is questionable. The HoloLens is quite bulky, and for example colliding the device against the unit frame might cause the device to break. During the tests, it was noted that the battery life of the device is only about three hours, which would not be sufficient to cover a whole work shift of 8 hours. However, HoloLens is not the only available device, and other HMDs might be suitable as well. The use of the HMDs differs significantly from the use of ordinary computers due to different input methods; therefore, the use of the HMDs require that operators are trained to use them.

Lastly, there are the side effects of wearing a HMD. Tunneling of attention causes the operator to focus on the content of the instructions and attending the surrounding physical environment might decrease. This might cause a safety risk, especially in an industrial environment. Furthermore, few studies have reported eye fatigue and headaches. In the user study, the operator was concerned about the ergonomics of wearing the device due to the weight of the device and strain on the neck.

5.1.3 Opportunities

A significant outcome and opportunity of adopting step-by-step instructions is work standardization. Work standardization means that the process to reach a certain outcome is depicted so that it can be carried out the same way each time. Work standardization results in controllable, well defined processes, and it enables their continuous improvement. Through continuous improvement of the assembly process, it is possible to integrate tacit assembly knowledge, meaning personal knowledge gained through experience, of the operators into organizational knowledge. (Liker, 2004, pp. 140-148; Fast-Berglund et al., 2014). This could for example mean capturing the best assembly practices into the assembly instructions. Currently in the case company, the efficient assembly is based on the experience of the operators and every operator has their own way of working, especially on the MD assembly line.

The creation of the animations for the interactive instructions facilitates assessing the feasibility of the assembly of new units. When the instructions are created, the engineers have to practically assemble the unit in a virtual space to create the content for the instructions. Collisions of the parts and difficulties in putting the parts in correct places are therefore revealed early in the product development. However, engineers do not usually have extended experience on the hands-on assembly work, and they might not be able to figure out the optimal assembly order. Therefore, involving operators or team leaders from the factory floor in the content creation or in review sessions could further enhance assessing the feasibility and enable creating feasible assembly phasing for even the first prototypes. Additionally, the earlier the assembly problems are spotted and the earlier the changes are made, the easier the changes are and the less will the changes cost (Falck et al., 2010).

Interactive instructions provide opportunities in training of operators. Perceiving of assembly information does not require interpreting of the instructions, hence less skilled workforce can be hired to carry out assembly. This is important, since there is a growing need for skilled labor in manufacturing, but there is not enough qualified workforce available (Abraham & Annunziata, 2017). Traditionally, new employees have been trained by assigning an experienced operator to work with them as a mentor. The mentoring is needed, because much of the assembly knowledge is tacit (Fast-Berglund et al., 2014). Interactive instructions reduce the amount of tacit knowledge through work standardization and therefore enhance the learning of the practices.

For similar reasons, the interactive instructions can be used to distribute assembly information globally, making production ramp-up easier. If a factory is located near the product development, the engineers can support the assembly operators in difficult situations, but in remote factory locations this is not possible. In case of new products, the operators must rely on the assembly drawings.

An important opportunity of the 3D instructions is that they enable the AR instructions. AR can be seen as the next step forward from 3D instructions. AR instructions are based on the same assembly sequences created for 3D instructions, and by slight modification they are utilized in AR instructions. Therefore, by implementing first 3D instructions also the AR instructions are a step closer.

Furthermore, the publishing process of the AR instructions could be automated. During the content development phase of the present study, a semi-automatic third-party software used for publishing AR content based on the 3D instructions was tested. The third party providing support for the semi-automated tool suggested that publishing of AR instructions could be further automated, and it can be linked to PLM-transactions. For example, the publishing could be triggered by approving a new revision of instructions, or it could be triggered manually. However, currently a barrier for automating the AR content publishing is that the item annotations created for 3D instructions do not work in the AR instructions. It is also uncertain if the modification of the assembly sequences can be automated. For example, to avoid occlusion, the earlier assembled parts must be hidden.

AR is an emerging technology, so the hardware and software, which are used to view and create the instructions, is being developed rapidly. Although the performance of the HoloLens used in the user study was not very convincing, the situation might change in few years. For example, Microsoft announced a new, more powerful and more comfortable model of HoloLens in February 2019 (Kaplan & Lacoma, 2019).

The HMDs used for viewing the AR instructions might enable other possibilities as well. For example, the sensors of a HMD could be used in quality assurance and automatic detection of the completed steps, thus enabling automatic proceeding of the instructions. The data on the completed steps could be used to monitor assembly operations in real time. Another possibility is to visualize external data from connected services to enhance assembly operations. For example, smart tools could report tightening torque measurements of critical screw joints and this could be presented for the operator and saved into a database.

5.1.4 Threats

In addition to opportunities, the standardization of the work might pose a threat. Work standardization has been criticized that it makes the work monotonous and decreases work motivation. However, this seems to depend on how far the standardization goes and what is the approach to standardization. If the standardization comes top-down, for example from the product development to the factory operators, the results are probably very negative. But if the standardization is built bottom-up, involving the operators in the improvement and encouraging them to make improvement proposals, the operators are much more likely to co-operate. In addition, if standardization is implemented poorly, the flexibility of the assembly procedure is reduced, and the ability to adapt to missing parts or other problems may decrease. However, if done correctly, flexibility can be maintained (Liker, 2004, pp. 140-148).

Cost-benefit analysis of the interactive instructions is ultimately what justifies their implementation. If the authoring, configuring and maintaining of the instructions and investments related to the implementation are found to cause more costs than how much costs can be saved through decreased quality costs and increased productivity, then the implementation of the instructions is not reasonable. The threat is highlighted in the case of AR instructions, and depends what is the actual benefit of AR instructions. It should be considered that do AR instructions provide enough advantage over 3D instructions to justify implementing AR instructions instead, or on top of, 3D instructions. Related concern is that are the products varying enough to bring out the benefits of AR instructions.

If the benefits do turn out to justify the adoption of the interactive instructions, the next shared threat, as often with change projects, is the employees' willingness to adopt the change. Since the acceptability of 3D instructions according to the user study seems to be higher than for AR instructions, the unwillingness to adopt change is more likely to affect AR instructions. However, implementing interactive instructions require changes to many processes, including product development, and OSE but most prominently to the operations at the shop floor. Firstly, the risk is that operators and the organization refuse to adopt the change and secondly, there is also the risk that competitors will adopt the change and gain competitive edge.

The realization of the configuration of the instructions is a vital part of the functioning of the instructions system for complex products. If the configuration is implemented poorly, the quality of the instructions is affected. The realization must be studied well beforehand to ensure correct functioning. Flawlessly working system is easier to accept, although it will not be easy task to build a perfect system (Syberfeldt et al., 2015).

Lastly, regarding AR instructions, the HMDs will need a reliable internet connection to enable flawless use of the instructions since the instructions are downloaded from servers on-demand. This might mean that the factory network infrastructure needs to be updated. A related concern is information security, since every operator would wear a device with an internet connection and video cameras.

5.2 Research reliability and validity

The validity of a research concerns if the results are really representing the real values of the study objects Reliability refers to the consistency of the measures across not only the measures in a single study but also across other studies repeating the study with the same methods. The consistency of the selected research methods defines the accuracy of the gathered data. The concepts of reliability and validity were originally developed for quantitative studies and it has been much debated if the concept of reliability can be applied to qualitative study designs. In qualitative research, repeating the exact same setups to investigate similar situation is difficult. (Robson, 2002, p. 93; Denscombe, 2010, p. 152-154).

In observing and interviewing, the observer or interviewer is concerned as a key part of the research method, thus the researcher should take effort to minimize the subjectivity of the findings. In addition, the sole presence of the researcher in observation and in interviews can influence the actions of the objects of observation and the answers provided by interviewees. For example, the participants might try to operate differently as how they would if they were not observed. Likewise, in interviews, participants may give false information or leave something untold. (Robson, 2002, pp. 322 – 324).

In questionnaires, the choice of questions affects also the validity of the results (Denscombe, 2010, p. 155). Questionnaires are subjective, and the participants might give biased answers about their attitudes (Robson, 2002, p. 233). To ensure that the questions were targeting the right issues, the advisor of the present study validated the first part of questionnaire. The baseline used in the comparative part of the questionnaire was based on the operators' subjective experience of the assembly drawings, which might have affected the validity of the results of the user study questionnaire.

Document analysis tackles with the trustworthiness of the examined documents. They might be outdated, or present how the things work idealistically, not how they work in reality (Dumas et al., 2013, p. 161). This was also the case in the present study, as document analysis resulted contradicting results for the production processes. The process charts presented the assembly process but then in observation it was noted that the reality is somewhat different. However, for other parts of the study, the analyzed documents seemed to be in line with other results.

In the current state analysis, the validity and reliability were ensured by triangulating the data by using semi-structured interviews, participant observation and document analysis. Although individual research methods might not be reliable, the results can be considered as valid and reliable for the current state analysis, since the data gathered from multiple sources by multiple methods was consistent.

In the user study, the data was triangulated by using mixed-method questionnaire, and participant observation, enabling better validity of the results. However, the reliability of the findings of the user study is limited, since only one study for each instruction method was conducted. The reliability of the results could have been further enhanced by conducting more tests and using objective measures but as there was no baseline data available, objective measurements could not have fitted in the scope of the present study. Likewise, carrying out industrial tests was very demanding regarding the arrangements with production, and therefore further studies would not have fitted into the schedule of the research.

5.3 Significance of the study

Although the results of the present study serve mainly the case company, the results can also be applied and used to support decision making in other companies looking to update means of assembly instructions.

The literature review considered widely the current knowledge on assembly instructions and effects of existing instruction methods. The throughout review of the role of the assembly instructions and the efficiency of different instruction methods, which together formed a coherent whole, can be considered as a significant contribution of the study.

The second notable contribution of the study is the industrial tests conducted for the interactive assembly instructions, which were designed and developed based on the literature review and current state analysis. User study revealed barriers for adopting AR technology in the assembly of large industrial objects.

The SWOT analysis gathered the results from the literature review, the current state analysis and from the user study together to identify and discuss the key benefits and concerns of adopting interactive assembly instructions. At the same time the analysis formed an overview of the current and future possibilities and obstacles regarding implementation of such systems.

5.4 Conclusions

In the current state analysis of the case company, it was identified that the key issue of the assembly drawings is the difficult interpretation of the assembly order. Efficient assembly is based on the experience of the assembly workers. For assembly work instructions, the problem is the laborious authoring and maintaining of the instructions. In addition, the work instructions utilize descriptive text, which the literature review revealed as inefficient. Manufacturing drawings and dimension drawings present overlapping information and the use of multiple information sources confuses operators. The current state of the assembly documents in the case company is quite contradicting. The low variety SD products have detailed work instructions, whereas more varying ETO units have only assembly drawings.

The literature review and the user study suggested, that interactive instructions enhance perception of assembly information and therefore perform better than the currently used assembly drawings and assembly work instructions. The core strengths of the interactive assembly instructions, the model-based and animated step-by-step instructions, address directly the problems of the assembly drawings and assembly work instructions enabling efficient communication of the assembly procedure and creation of the instructions well before the first prototype of a new unit. Since they are variant-specific, only relevant information is presented. Hence, it can be concluded that the interactive instructions have the required potential to substitute assembly drawings and assembly work instructions. However, manufacturing drawings or dimension drawings are still needed to present an overview of the assembly as a whole.

Augmented Reality based instructions provide an interesting approach to supporting the assembly work. However, as there is currently no reliable proof of real advantage of using AR instructions over other simpler methods, and as the user study showed, the technology is still immature, a quick shift to AR instructions cannot be recommended at the moment. Nevertheless, AR seems very promising and the technology is evolving fast. Therefore, the situation might change rapidly in few years, so following the development of AR and conducting small scale studies could be wise.

The 3D instructions got more positive feedback and results from the user study as the AR instructions. Also, the literature review showed more consistent results for similar instruction methods. Therefore, 3D instructions prove to be more desirable solution at the moment. In addition, 3D instructions can be seen as a step towards AR instructions, so by implementing 3D instructions first, the step to AR instructions becomes significantly smaller. However, there are still major obstacles to overcome in order to implement either of the interactive assembly drawings.

5.5 Recommendations

During the course of the study, additional questions arose which have to be addressed before decisions on the instruction system can be made and the development can be started. Firstly, the feasibility of configuration of the instructions must be examined. With complex products, configuration is vital to ensure efficient authoring and maintaining of the instructions. Secondly, as stressed in the Threats section of the SWOT analysis, a cost-benefit analysis considering the costs related to authoring, maintaining, and configuring the instructions and the required investments must be compared with the gained benefits. Third issue to find out is the most feasible method of using the 3D instructions. As discussed in the SWOT analysis, laptop would be in a fixed location which might be undesirable, whereas a tablet might increase the mobility of the instructions but might be more difficult to use and handle. To study these issues, a pilot study could be initiated.

However, some cases were identified in which 3D instructions could be utilized already. This would gain experience of the use of the instructions and provide valuable input for further studies. The identified cases are discussed next.

In the case company, there is a dedicated team supporting system integrator customers, who buy components for larger systems. These customers need accurate instructions to be able to install the components correctly. The team provides already diagram-based step-by-step instructions, but they have considered to provide animations depicting the installation procedures. However, the authoring of the animations is more or less complicated and creating 3D instructions instead could provide easier and more efficient way to deliver the information. The additional benefit of the 3D instructions is that the model can be freely rotated and examined in close-up.

Another possible target of applicating 3D instructions are the special, unique units designed by the OSE team. Since they are unique, the operators are building the units always for the first time. The OSE team prepares assembly drawings for the units anyway, and by creating 3D instructions instead, the feasibility of the designs regarding assembly could be assessed, and the instructions would ensure trouble-free assembly procedure.

5.6 Further research

As stated in the analysis of the literature review, most of the comparative studies presented were found lacking regarding the comparability of the different studies. In addition, the existing research of animations in assembly instructions have not reached statistical significance, although they have suggested an advantage for animations. Same can be stated on the results for assembly durations for AR instructions in the studies comparing them to other methods. The complexity of the assembly tasks was found to fluctuate from study to study.

Therefore, more research is needed to first confirm the suggestions that overlaid, animated AR instructions further enhance the perception of assembly information, and secondly to find out if there is real benefit of using AR instructions over animated instructions. This would be important to form justification for AR instructions over other instruction methods. In addition, future research should investigate the effects of different levels of complexity of the assembly tasks on the efficiency of the instructions. A framework suggesting how different assembly tasks and assembly instructions should be combined could be developed.

6 Summary

Industrial products are increasingly varying, and the assembly of customized or unique products is slow, expensive, and prone to errors. Conventional static assembly drawings and instructions are suboptimal in supporting complex and dynamic assembly operations. In the case company, the assembly drawings are prepared the same way as in the age of earlier product families, when the products varied less, and the operators were able to memorize the assembly procedure. However, today even the experienced operators need assembly drawings to support their work. The main objective of the study was to investigate if interactive assembly instructions could be used to substitute the current documents instructing assembly in the case company.

Literature review studied the existing knowledge on manual assembly, assembly instructions and their efficiency, and the use of animations and augmented reality (AR) in assembly instructions to form a coherent overview and understanding of the underlying issues. In addition, the literature review examined product configuration and problems related to combining configurable products with interactive instructions.

According to the literature review, assembly instructions facilitate a mental process. In general, any information is processed so that internal, or mental, representations are built based on external representations. In assembly, this means building an internal representation of the assembly object. Each assembly task must be visualized first internally before it can be carried out on the physical object. The more explicit and depictive the information is, the more efficient is the mental process, and the less there is room for misinterpretation. Displaying the assembly information in depictive format and step-by-step will make the instructions efficient. Animations enhance the efficiency further and overlaying the animation of the assembly step on the real assembly object using AR should enhance the perceiving of the information even more. However, literature review did not provide proof if the AR has a significant advantage over animations.

In the current state analysis, interviews, participant observation, and document analysis were applied. The aim was to gather information and to examine the state of the assembly documents used to instruct manual assembly in the case company. Current state analysis revealed that the key problem of the assembly drawings is the difficult interpretation of assembly order. Assembly work instructions utilize descriptive text and images of real units, and therefore they are laborious to create and maintain. In case of new products, the work instructions can be created only after a unit has already entered piloting and ramp-up phase, which means that the first units are assembled relying only on assembly drawings. Additionally, for the complex product category consisting of highly customized products, the assembly work instructions are not created at all.

Based on the analysis of theory and practice presented by literature review and current state analysis, two concrete interactive assembly instruction approaches, 3D instructions and AR instructions, and their contents were designed and developed. The instructions were based directly on the 3D model of the assembly object. 3D instructions consisted of assembly steps in which the assembly of the parts were animated. In addition, the 3D model presented in the instructions could be freely rotated and examined in detail. AR instructions utilized the same assembly sequence as the 3D instructions. AR instructions were viewed using a head-mounted display, which presented the assembly step animations spatially overlaid on the physical assembly.

The developed instructions were evaluated in a user study. Two cabinet-built units were selected as test objects, and the participants assembled the units using either 3D instructions or AR instructions. The tests were observed by the author, and the participants answered to a post-study questionnaire targeting subjective efficiency and user acceptance. Both AR instructions and 3D instructions received positive feedback and were evaluated more efficient as the current assembly drawings.

The core strengths of the interactive assembly drawings address directly the problems of the current assembly instruction documents of the case company. The step-by-step instructions depict the assembly order in detail, and since the instructions are model-based, they can be created well before first prototypes. Hence, it was concluded that interactive assembly instructions could be used instead of the current assembly drawings and work instructions. In addition, adopting the interactive assembly instructions would standardize the assembly work and enable continuous improvement. However, the complexity of the products require that the instructions are configured in order to make the authoring and maintaining efficient.

The case company should further study the feasibility of the 3D instructions. There are also two specific teams, who could take 3D instructions into use already. These teams are anyway preparing assembly drawings for unique assemblies, so the configuration of the instructions is not an issue in these cases.

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Appendices

Appendix 1. Framework for the semi-structured interview

1. Who are responsible and what they do?
    - In Multidrives?
    - In Cabinet Drives?

2. In which format are the current instructions and drawings and where are they stored?

3. Which products have the assembly instruction, and which have only the assembly drawing?

4. What is the starting point for the instruction, when a new product is launched?

5. Who is responsible for maintaining the drawings and instructions?

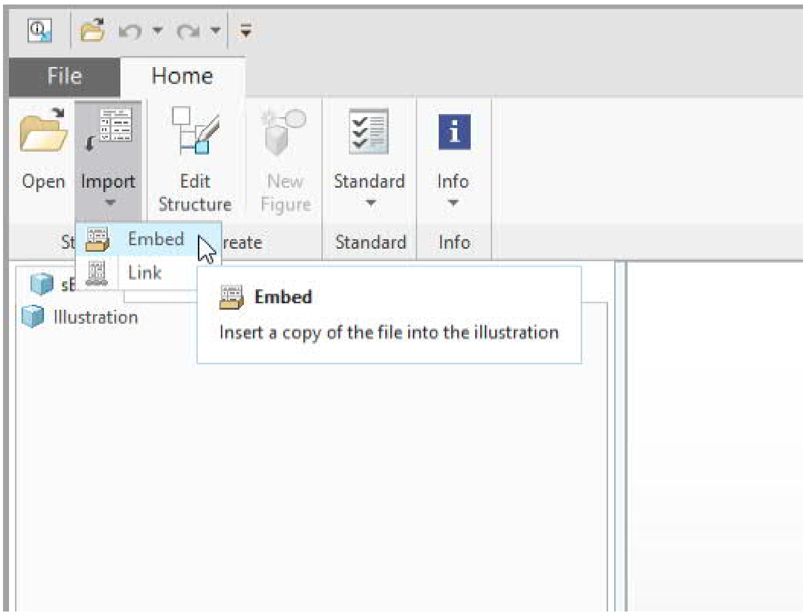
6. What is the schedule for implementing changes to instructions?

7. How are the changes communicated to the operators? Are all changes communicated?

8. How are the new revisions of the assembly drawings implemented?

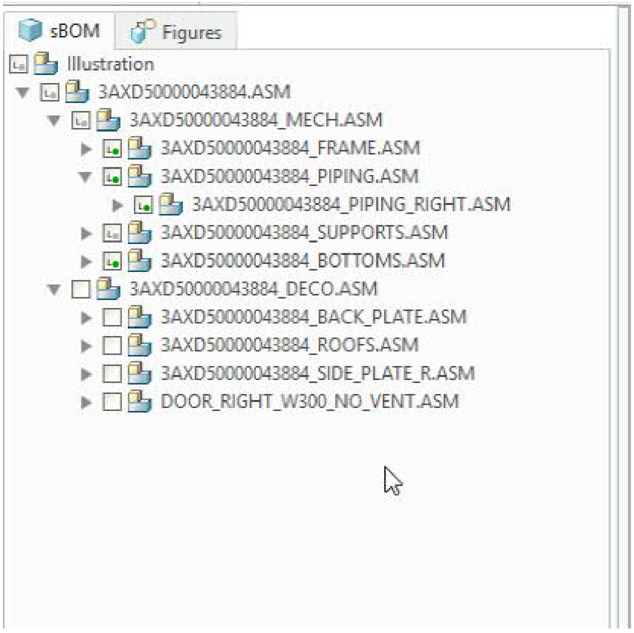
Appendix 2. Creo Illustrate workflow

This appendix describes the workflow for creating 3D instructions with Creo Illustrate.



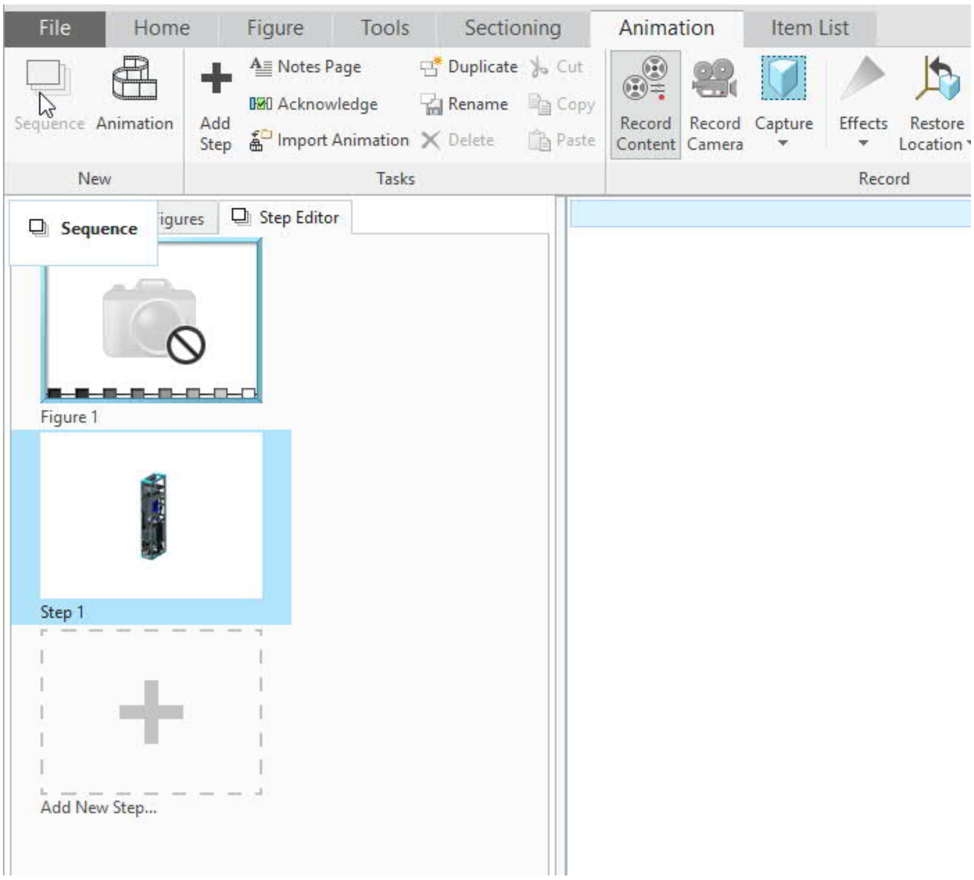
Embed
Insert a copy of the file into the illustration

First import the 3D model of the desired assembly object. The program prompts to create a new Figure.

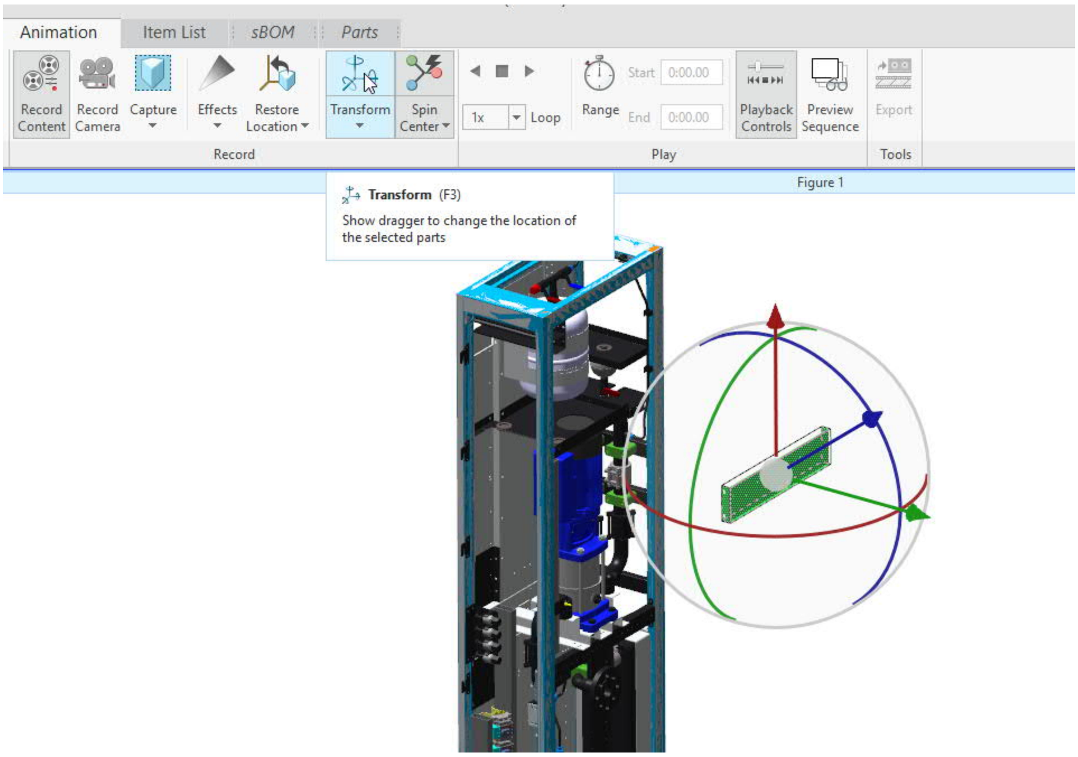


- Illustration
  - 3AXD50000043884.ASM
    - 3AXD50000043884_MECH.ASM
      - 3AXD50000043884_FRAME.ASM
      - 3AXD50000043884_PIPING.ASM
        - 3AXD50000043884_PIPING_RIGHT.ASM
      - 3AXD50000043884_SUPPORTS.ASM
      - 3AXD50000043884_BOTTOMS.ASM
    - 3AXD50000043884_DECO.ASM
      - 3AXD50000043884_BACK_PLATE.ASM
      - 3AXD50000043884_ROOFS.ASM
      - 3AXD50000043884_SIDE_PLATE_R.ASM
      - DOOR_RIGHT_W300_NO_VENT.ASM

Manipulate the sBOM tree to match the desired outcome of the assembly operation.

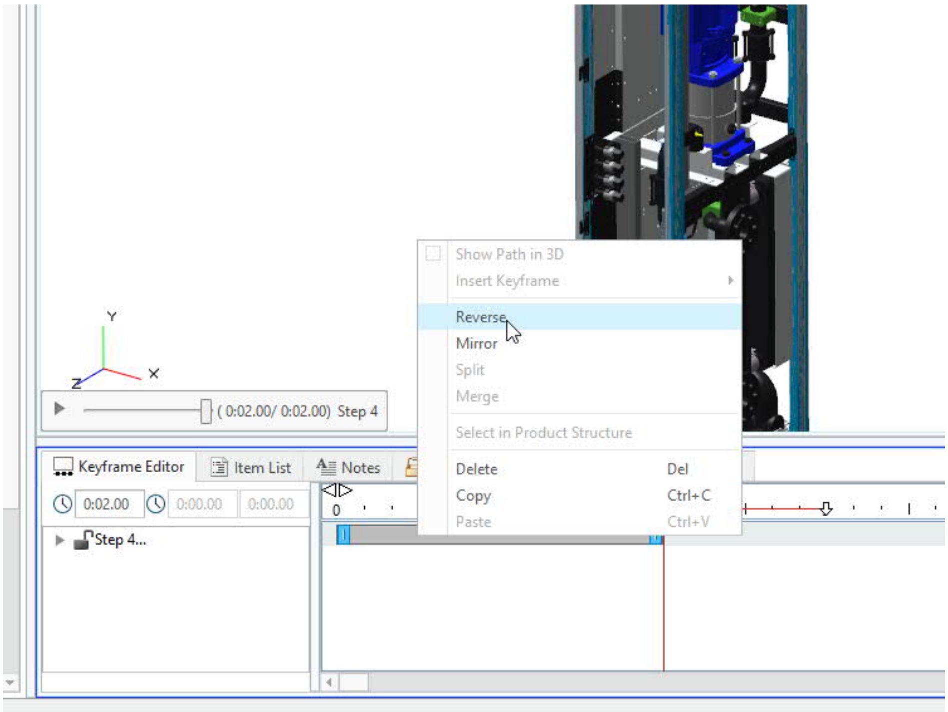


Create a new sequence for the Figure from under the Animation tab.

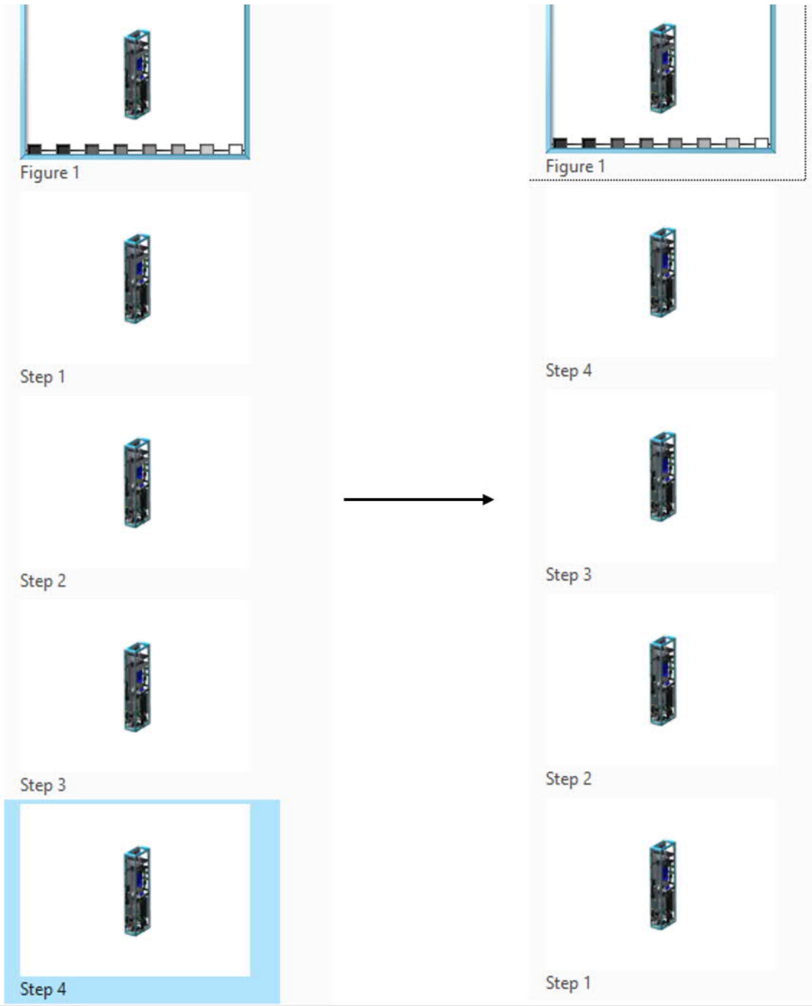


Transform (F3)
Show dragger to change the location of the selected parts

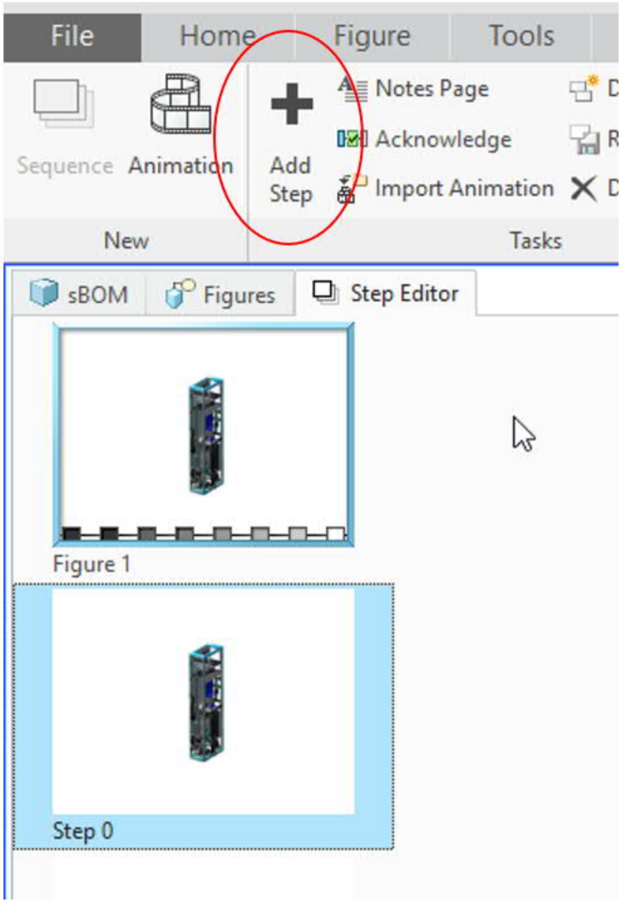
Manipulate the parts in a reversed assembly order. Pull the parts out of the assembly, and then select the “Fade Out” effect from the “Effects” menu.



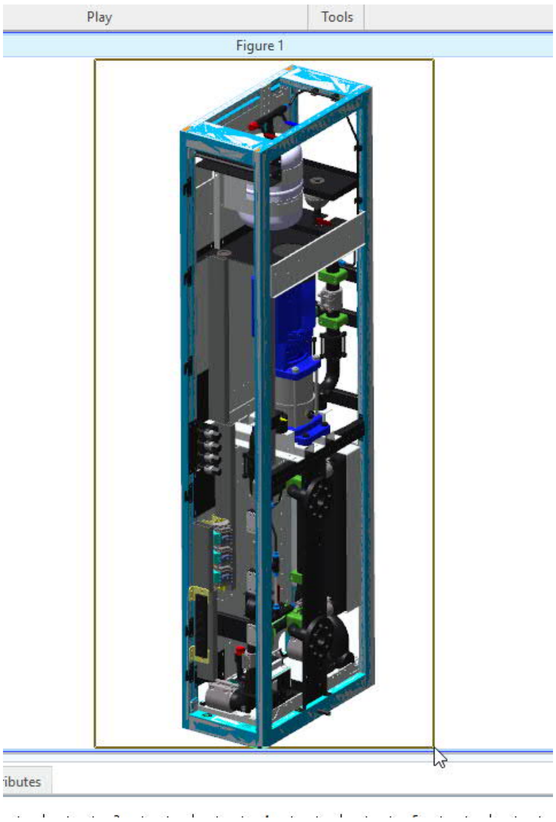
When the object is disassembled, reverse all animations under the sequence steps.



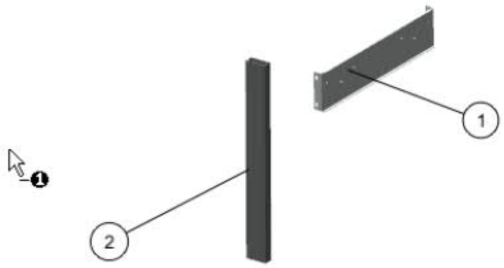
Then, reverse the order of all sequence steps.



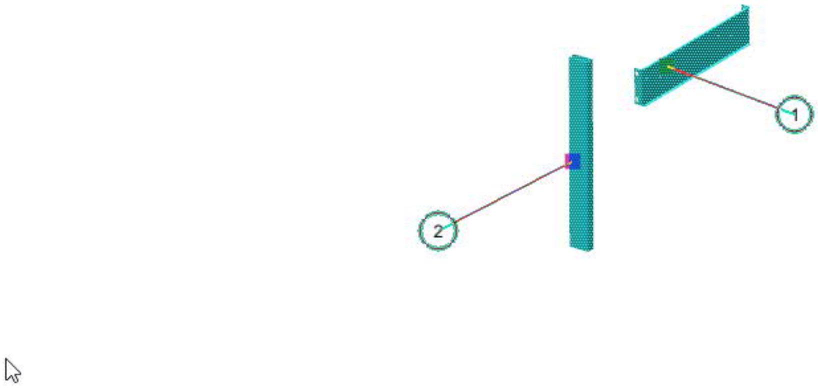
Add new step to the beginning of the sequence.

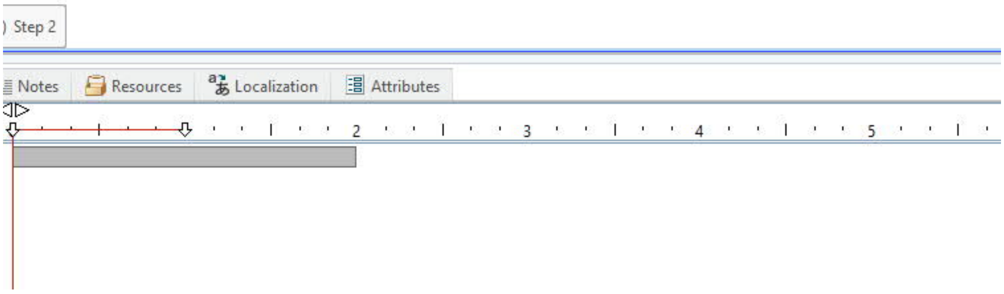


Select all parts of the figure, and select Fade Out from the Effects.



Add annotations. Custom annotation can be used to display any parameters created in Creo Parametric.

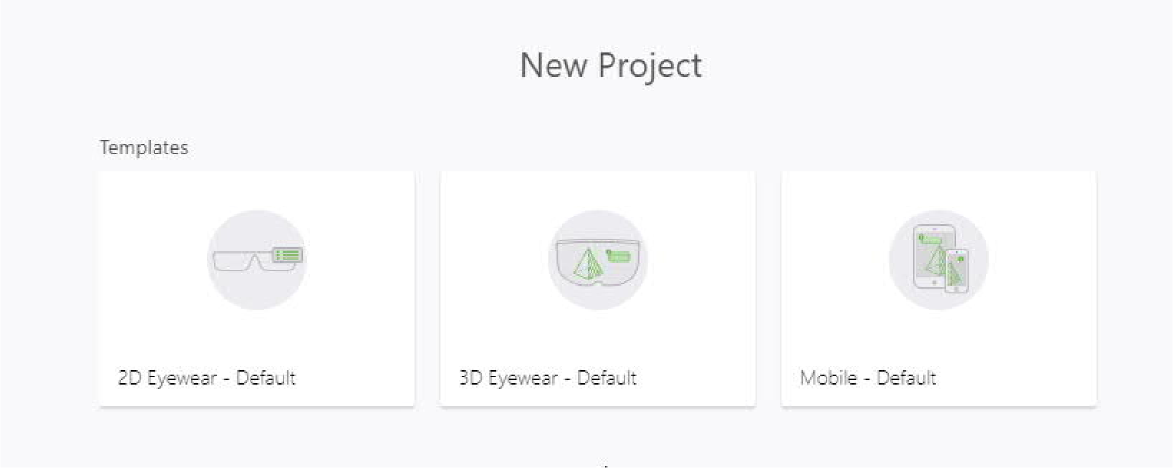




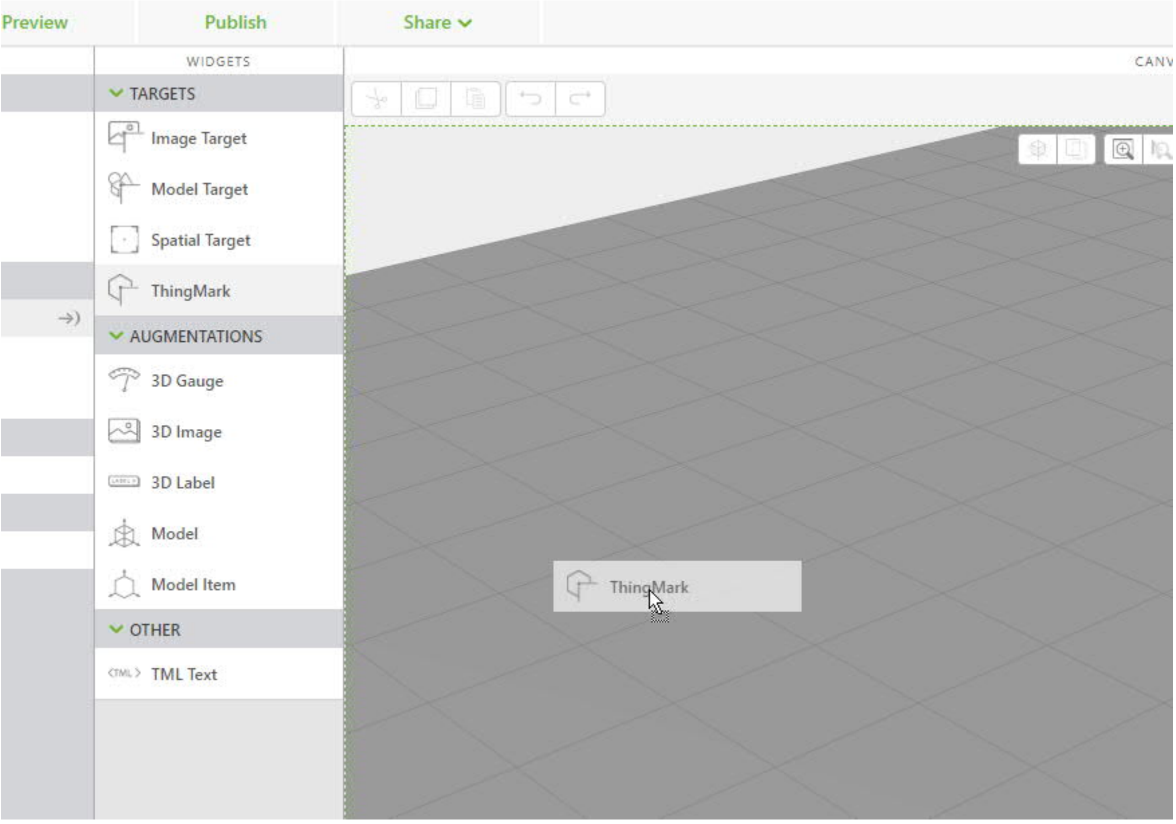
Annotations must be faded out at the beginning of each following step. Otherwise the annotations will be left visible throughout the rest of the sequence. Move the time selector to the beginning of the animation, select the annotations and select Fade Out from the Effects.

Appendix 3. Vuforia Studio workflow

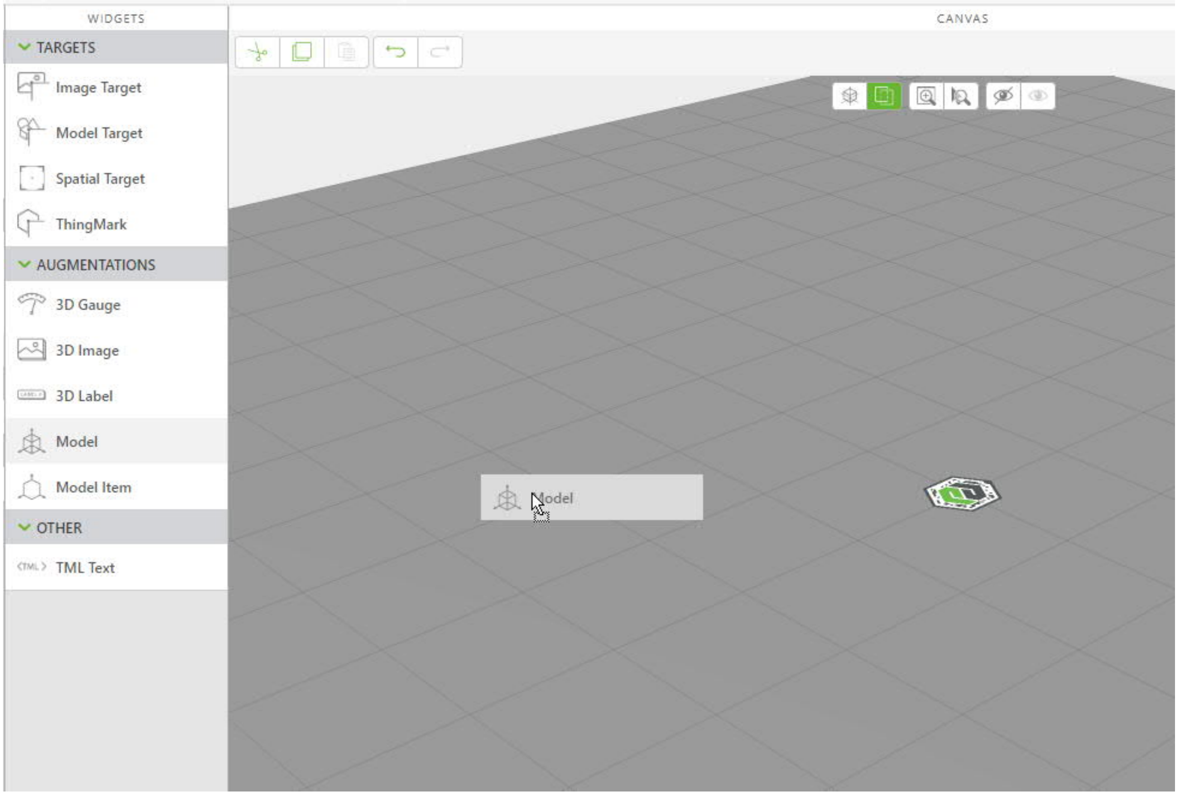
This appendix describes the workflow for authoring AR instructions for HoloLens based on the animation created in Creo Illustrate.



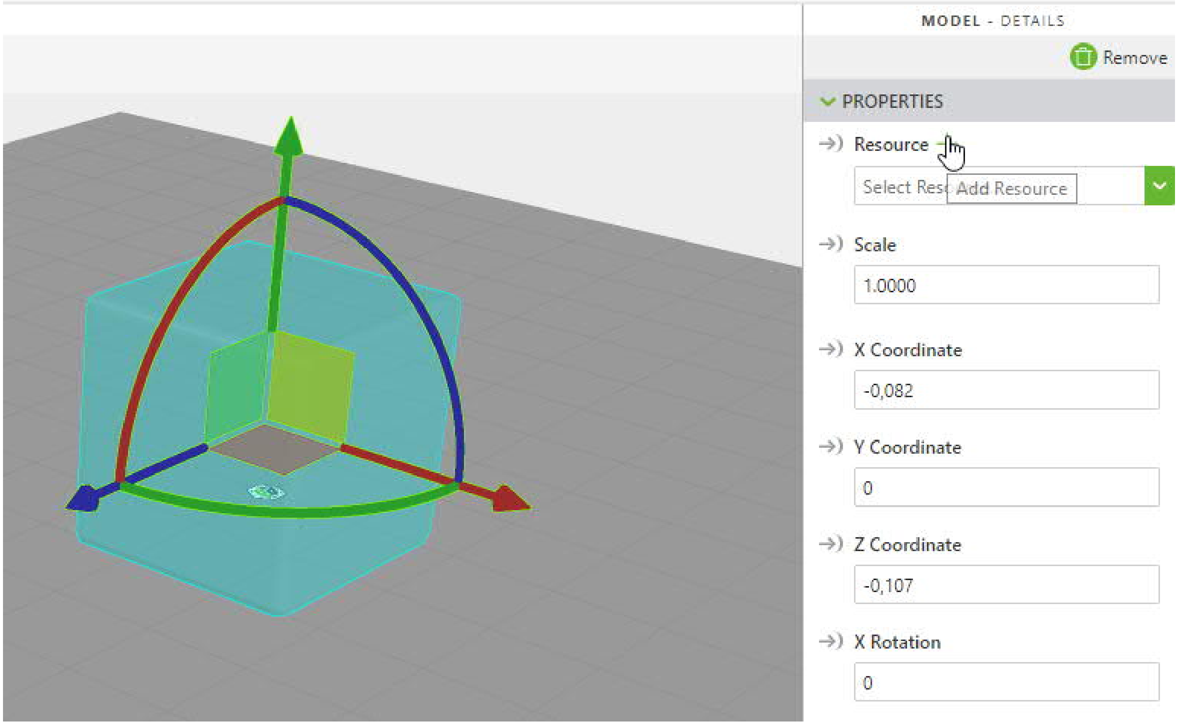
First a new project for 3D Eyewear



Drag and drop a ThingMark to the design area.



Similarly, drag and drop a model widget to the design area.



Scale
1.0000

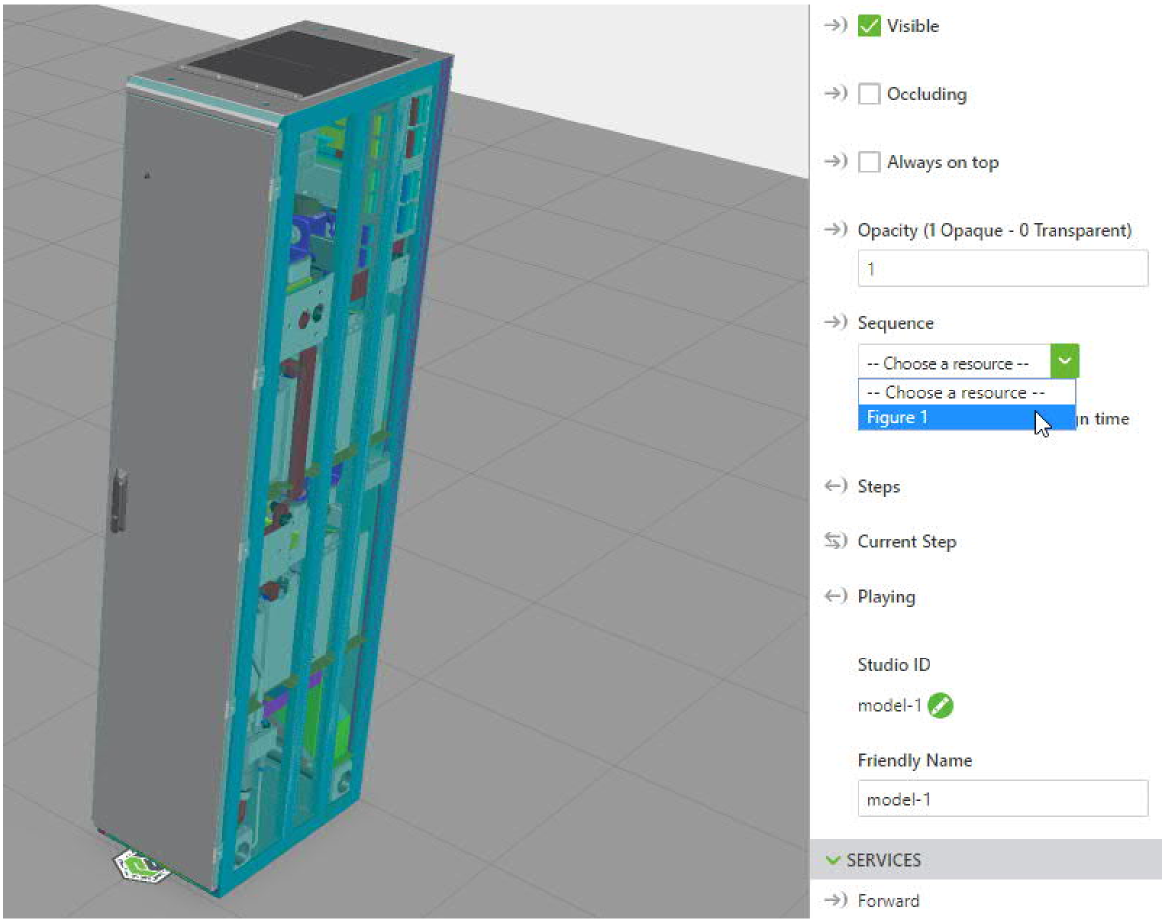
X Coordinate
-0,082

Y Coordinate
0

Z Coordinate
-0,107

X Rotation
0

Click the cube which appeared and click Add Resource under the Properties. Upload the desired 3D model exported from Creo Illustrate.



☑ Visible

☐ Occluding

☐ Always on top

Opacity (1 Opaque - 0 Transparent)

1

Sequence

-- Choose a resource --

-- Choose a resource --

Figure 1

Steps

Current Step

Playing

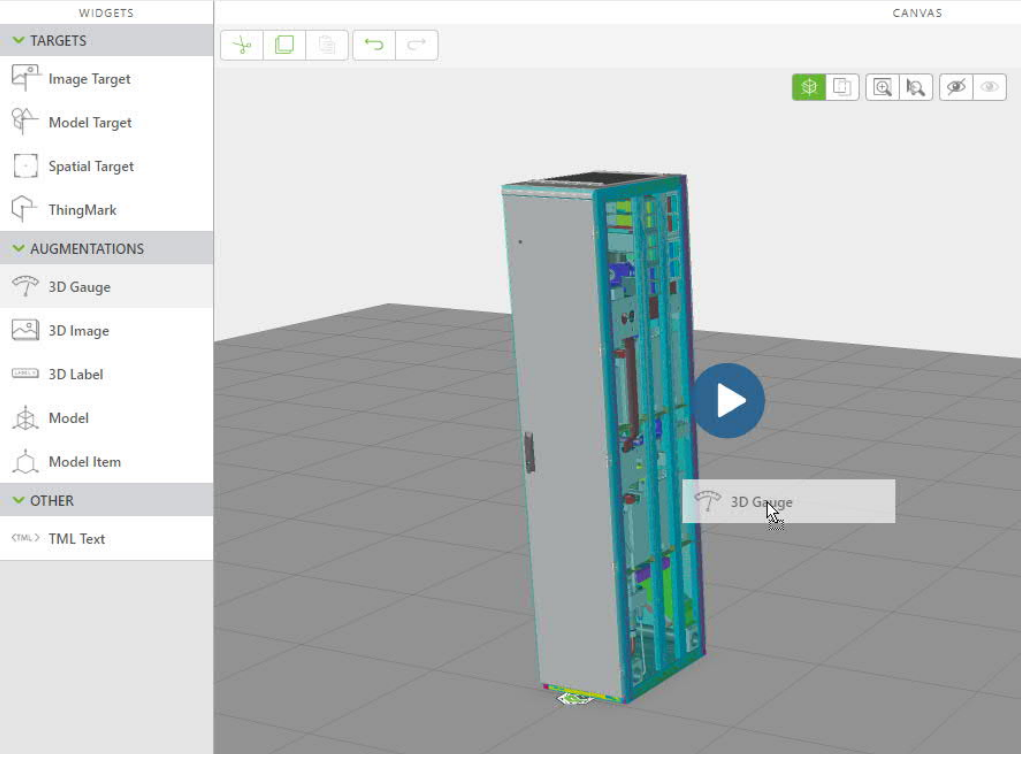
Studio ID

model-1

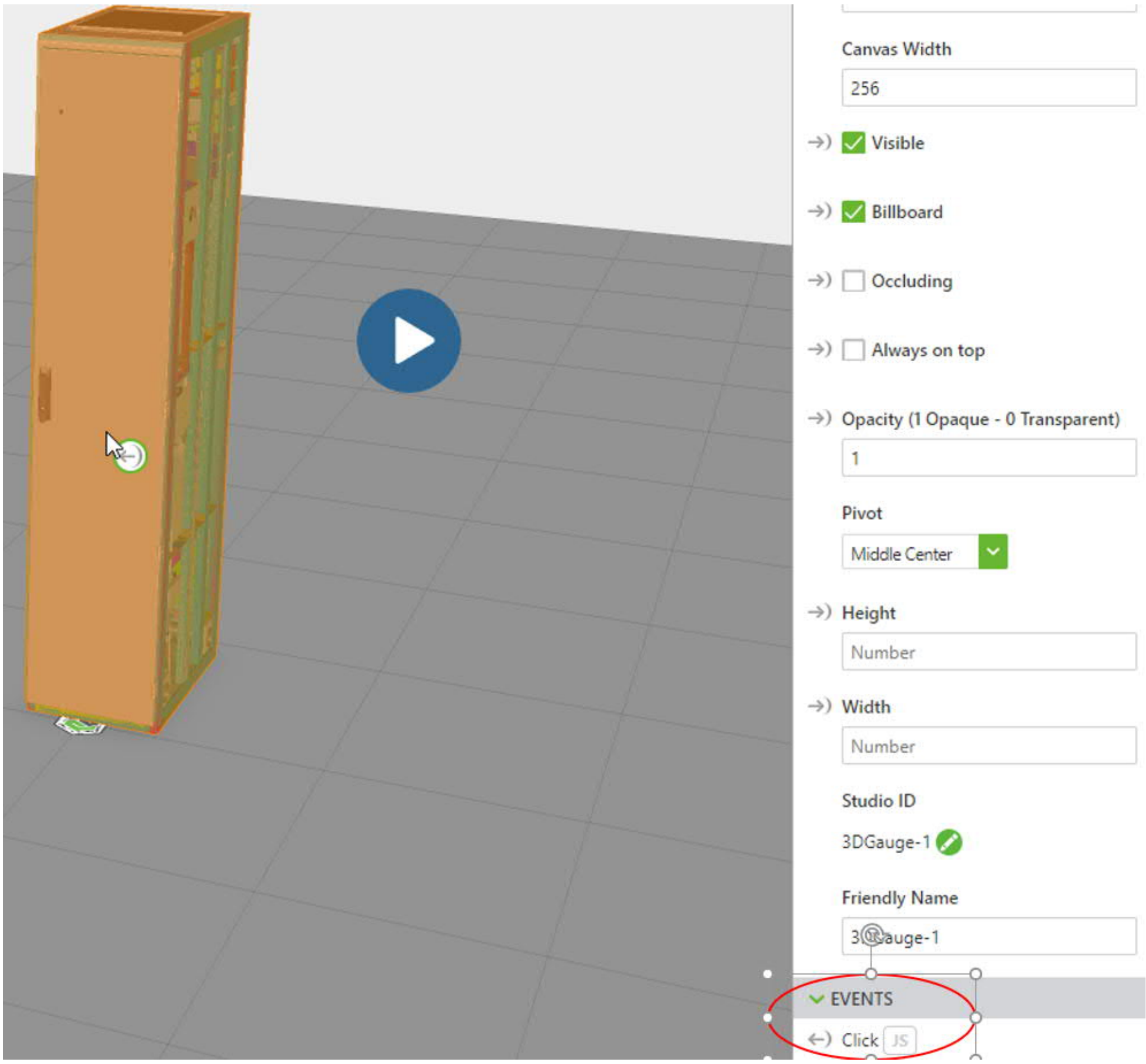
Friendly Name

model-1

Place the model relative to the ThingMark and choose the correct animation sequence in the Properties.



Drag and drop 3D gauges to use as the controls for the animation. The gauge icon can be changed from the Properties.



Canvas Width
256

☑ Visible

☑ Billboard

☐ Occluding

☐ Always on top

Opacity (1 Opaque - 0 Transparent)
1

Pivot
Middle Center

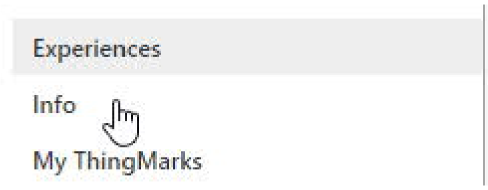
Height
Number

Width
Number

Studio ID
3DGauge-1

Friendly Name
3DGauge-1

Associate the click event of the 3D labels with the corresponding actions by dragging and dropping the event from the bottom of the Properties on the model in design area.



Finally, input the needed information in Experiences and Info menus and publish the experience.

Appendix 4. First part of the user study questionnaire

1. *How did the identification of the parts and material codes succeed in comparison to assembly drawings?*
2. *On scale from 0 to 10, how would you grade the identification of the parts when compared to assembly drawings?*
3. *How did the placement of the parts succeed in comparison to assembly drawings?*
4. *On scale from 0 to 10, how would you grade the identification of the parts when compared to assembly drawings?*
5. *Did looking the instructions take more or less time when compared to assembly drawings? Evaluate time usage on scale from 0 to 10.*
6. *What did you think about the phasing of the instructions?*
7. *What did you think about the animations of the instructions?*
8. *Do you have any other comments about the use of the instructions?*

In the quantitative questions, the answers graded using Likert scale from 0 to 10, where 0 = significantly more/more difficult and 10 = significantly easier/less.

Appendix 5. Second part of the user study questionnaire

Questionnaire developed by Syberfeldt et al. (2015):

1. *I found the AR system easy to understand.*
2. *I found it easy to use the AR system to place the pieces.*
3. *I felt that I performed quickly with the AR system.*
4. *If I had to use an AR system like this on a regular basis, this is a technique I would appreciate having available.*
5. *I found the AR system physically demanding.*
6. *I found the AR system mentally demanding.*
7. *I found the AR system frustrating.*

In the case of 3D instructions, the abbreviation "AR" was substituted with "3D instructions". The operators were asked to grade each of the questions on a seven-point Likert scale from 1 to 7, where 1 = totally disagree and 7 = totally agree.