Visualization Research Center of the University of Stuttgart (VISUS)

Bachelorarbeit

Augmented visualization guidance for wire placement in timber fabrication

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Abstract

Augmented reality has become a broad area over time, which opens up many opportunities, also for industry. Nevertheless, digital solutions have not yet been used for some industrial applications. We focus on the use case “wire placement in timber fabrication”. The task here is to place and fix a cable along a certain route on a timber panel. However, there are several important factors and risks to consider that could cause the task to fail. Usability and efficiency play an essential role in optimally supporting use cases like this. Furthermore, we hope to make the task of this special industrial use case easier for workers by using augmented reality. For such an optimization, the design of a suitable visualization as part of the augmented reality system is indispensable.

We constructed possible virtual representations for this use case and developed different suitable prototypes. Based on a user study, we compared the visualizations of these prototypes, evaluated their efficiency and user experience by measuring the workload, usability, task completion time, and determining error rates.

By analyzing the developed visualization prototypes, a certain prototype proved to be optimal. With this, the route of the cable is shown as a path on the timber plate and displayed in color. The efficiency differences between this prototype and the other prototypes, supported by augmented reality, are not severe. The use of the augmented reality system turned out to be an essential enrichment. Compared to an equivalent system that is not supported by augmented reality, the developed augmented reality systems showed clear advantages.

The suitability of this prototype has been checked and proven through a dry run. The task of the use case could be carried out successfully while the important factors and risks were also considered. The final fabrication has yet to be carried out.

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1 Introduction

Augmented Reality (AR) is a growing topic that offers diverse possibilities for end-users and researchers. Different fields like medical, construction, manufacturing, automobiles, education are utilising it for various purposes [CA15] [HH16] [BV19] [Lee12]. In addition to the use of AR in the entertainment industry, e.g. in the form of smartphone apps, engineers often use computers to expand their perception of reality to present scientific data in the industry. AR technology is being used more and more frequently in industrial manufacturing and production, for example, to be able to carry out manual tasks more efficiently or to enable them at all. This results in many advantages in terms of accuracy, speed, error rate, or Gamification when performing the task, compared to a system without using AR. In addition, depending on the task to be supported, the use of the AR system has a better learning curve, especially for less experienced users.

All of these positive aspects of using the AR system can only be fully exploited if the AR system is ideally set up. Since AR is being used more frequently, how information is presented now plays a far more important role. Depending on the specific use case, the repeated question of, how one should ideally visualize the information (in the AR system), turns out to be an important challenge.

This bachelor thesis is based on a construction project of the IntCDC University of Stuttgart, where the goal is to demonstrate novel digital fabrication and design methods. To achieve this goal, a group of students and tutors work on the fabrication and construction of a timber pavilion building. Prefabrication is the initial phase of the project, which is necessary to prepare all the building components for the construction. One important part of the prefabrication is the wiring use case, which deals with a fine motor task. This wiring task has to be carried out by the worker in the industrial fabrication environment. For this task one has to place conduits (and wires) on timber plates, avoiding certain obstacles (shear webs), without knowing the correct path or seeing the placed obstacles. Additional conditions and risks are attached to this specific task, which turn out to be important requirements for the success of the project.

As part of this research at the Visualization Institute of the University of Stuttgart (VISUS), concepts for the representation of certain information in this specific use case were developed. Using these concepts, we then developed multiple visualization prototypes, which use different visualizations, and compared them against each other. We are therefore trying to answer the research question of how information should be integrated and visualized in an AR system to guarantee a smooth procedure of the special use case task.

In the following chapter "Background and related work" (chapter 2), we will try to summarize important studies and past research in the field of AR and visualization. To present the current state of research, we will also include results, similar to the introduced use case above. To understand the use case and the construction project, we conducted a first interview with some stakeholders. The subsequent chapter "Project structure" (chapter 3) is a brief description of the construction project. To gather important requirements of this project, an expert interview has been carried out. Detailed results of the interview are collected in the section "General requirements and goals" (section 3.1) of the chapter “Project structure” (chapter 3). The specific wiring use case and other background information are also discussed further. This information is extremely important for understanding the following sections. In the following section, “Work process” (section 3.2), the entire research process is presented chronologically to retrace all the work steps. Other details of the software and hardware used are presented in “Implementation details” (section 3.3).

Chapter “Prototype concepts” (chapter 4) depicts a focus group and brainstorm sessions to develop first concepts of a prototype and gather different opinions on these concepts. Some of the developed prototypes are then introduced in the “Prototypes” chapter (chapter 5). The four sections “Wire-Path” (section 5.1), “Wire-Lines” (section 5.2), “Shear-Webs” (section 5.3), “Paper-Prototype” (section 5.4) represent four different prototypes. The chapter “Evaluation” (chapter 6), which deals with the evaluation of these four prototypes, consists of two sub-chapters. The prototypes presented are compared against each other and analyzed by conducting a user study in a study environment, which simulates the real fabrication environment. The structure and the results of the user study are explained in the section “User study” (section 6.1). By comparing the prototypes directly, we were able to answer the research question. To verify these findings and test the resulting prototype, we used this prototype in the actual task execution of the use case. This final review, in the form of a survey, is performed in the real fabrication environment. The procedure and the review results of the execution are discussed in the section “Final prototype” (section 6.2).

2 Background and related work

[SCLO21] describes state-of-the-art augmented reality applications. This article is a good introduction to augmented reality in the industry. The authors mention that augmented reality can be used in many different areas of life and show the gap between the possibilities of augmented reality applications and the later actual use of augmented reality applications in the industry. The authors claim that even if augmented reality technology has a lot of potentials, some hardware and software changes have to be made so that augmented reality can be used successfully and widely in the industry (e.g. for maintenance work, modifications, or training). The article indicates the limits and problems. It recommends reducing hardware costs for augmented reality, so that future research is possible. Apart from that, the authors state, that various technical deficiencies should be improved. This includes, for example, higher computing power, better ergonomics, and robustness against different lighting conditions. According to the authors, there is still room for improvement in terms of various realistic shadow and light behavior, realistic overlays, a more user-friendly user interface with gesture and finger tracking, and automatic setup.

[GGW+11] summarizes previous literature, whereby the authors developed four fixed design guidelines in their article based on past research. These guidelines are supposed to support the development of virtual reality and augmented reality systems, to train industry workers in maintenance and assembly tasks. The first design guideline states, that the training and learning efficiency increases if observational learning strategies are integrated into the virtual reality or augmented reality system. Observational learning strategies are techniques to allow the worker to observe the correct execution. The second guideline recommends, that one should combine physical and cognitive training, to further improve the acquisition of practical skills. This means that both physical activity and mental activity should be linked for training. In addition, the third guidelines states, that "guidance aids" should be chosen and implemented very carefully, as the selection seems to be very important. Finally, according to the last guideline, the performance of the user is supposed to be better, if additional information about the task is given, not only how to perform the task. The additional information can e.g. contain a lot more background information about the task.

[FKS16] compares instructions, displayed by different technologies, based on a Lego Duplo assembly task. This Lego assembly task took place at a work table on which various boxes and a Lego plate were available. The task had to be carried out by hand and consists of building a certain Lego construct step by step. To build the construct, a Lego part had to be taken out of a certain box and placed on the Lego plate at the respective location. This step is repeated with the help of the instructions until the construction is complete.

To provide the instructions for this task, four different instruction representations have been developed. Paper instructions, tablet instructions, augmented reality glasses instructions (HMD), and projector instructions were used for this task. The paper and tablet instructions are step-by-step instructions. The steps are shown in an instructions booklet or as a series of pictures on the tablet.

The instructions show an illustration of a certain brick and the Lego plate with the assembly position of the respective brick. The assembly position is highlighted by a red arrow, pointing towards it. Regarding the HMD instructions, the steps are projected directly in front of the participant using augmented reality glasses. The pictorial instructions are the same as the instructions, used for the paper and tablet system. These instructions were displayed by a full-screen application at the center of the field of view. When using the projector instruction, as in-situ instructions, the steps were visualized by a projector mounted above the head. The respective box and the position on the Lego plate were highlighted in green one after the other. The green light highlights the box, which the participant is supposed to pick from. The green light also highlights the assembly position on the Lego plate by projecting the contour of the brick at the position.

In a study, these four instructions were examined based on the measured TCT, error rate, and the NASA-TLX workload. From this, the authors could conclude, that the HMD instructions performed worst, followed by tablet instructions and paper instructions. According to [FKS16] in-situ instructions provided by the projector have turned out to be the best. It was positively noted that both hands could be used while using the HMD instructions. However, the instructions obscured the field of view. The authors state that tablet instructions were better than paper instructions because turning the pages was not a problem. With these two instructions, however, there is the option of putting the instructions down, so that the participant can use both hands as well. Concerning the projection instruction, it was also noted that the projection was too weak and the markings were barely visible. Regarding the HMD instruction, an important question is whether the instructions and visualizations are in the middle of the field of vision or not. This could be beneficial or cause problems depending on the context of the use case.

[FBB+17] developed a system for an assembly task and examined the use of it over a longer period in another article. The use of the system was therefore not only investigated as part of a study but observed over more than three days. A distinction was also made between experts and untrained workers.

For the task, augmented reality was used to help the participant to take the correct technical components out of boxes and assemble them in the right place, and to use the right tools.

Different colors, different lighting duration, and lighting patterns were also used for the system. A red marking highlights an error. A green marking represents a correct execution. A flashing light represents a certain special case.

The authors found that augmented reality visualizations are suitable and helpful for learning tasks. However, once one is getting used to the task, the technology can be hindering. In addition, the results show that the technology prevents the experienced worker from getting the task done quickly. It is therefore important to determine the level of experience, up to which augmented reality visualizations can be used as a technology, without disadvantages. According to the authors, there are no significant differences between implementation with augmented reality and implementation without augmented reality, regarding the workload. The authors state that, since the augmented reality system is better for learning the task than for routine tasks, untrained workers have been more satisfied than experts. However, the use of augmented reality has a positive effect on the error rate and the learning speed for untrained workers.

[HHB20] presented an industrial use case, in which an electrical cable is to be fastened manually by the worker between two specific points. These two points are different screws, which are installed on a timber surface. To deal with this task, a handheld (tablet) wiring tutor, which uses augmented reality, is being developed. Two prototypes based on this wiring guide tutoring system were developed to implement an assisted mode and a manual mode. The assisted mode uses an "Intelligent Tutoring System" (ITS), while the manual mode does not make use of it. In both modes, the tasks are shown and visualized the same way one after the other. The ITS additionally displays errors, correct actions, and if necessary further information. In manual mode, only the tasks are visualized one after the other. The graphical user interface is almost identical in both modes. The worker has the opportunity to switch between the working steps and to freeze the screen. At the top of the screen, textual instruction is displayed. For the visualization part, relevant points are highlighted by blue circles. Arrows are used to highlight specific locations, while green checks are used to confirm a correct step, and red crosses are used to notify an incorrect step. The cable path is visualized by a blue straight line, between the two respective points.

It was investigated which system shows better usability and which shows a lower workload. The assumption is that the usability is not significantly different because both systems contain the same user interface and the same interactions. In addition, the ITS system is expected to have a higher workload, as cognitive performance and processing are associated with the feedback. A user study was carried out, in which workload and usability were measured using questionnaires. In this study, the presented task was repeated three times. The first time, no augmented reality system was used. In the second run, the system was either used in manual mode or assisted mode. In the last run, no augmented reality system is used again.

The results show that both the usability and the workload were better in manual mode. Besides that, the usability showed a higher value and the workload values were lower than the values of the assisted mode. From this, the authors concluded that the assumption was on the one hand incorrect in terms of usability but on the other hand correct in terms of workload. Since, according to the authors, negative feedback subconsciously results in poorer usability, the conclusion is, that the manual mode is better because the feedback is not integrated here. The authors state that the reason for the lower workload in manual mode is the immersion since immersion leads to a higher workload.

[HWEB20] compared the usability, the workload, and the collected feedback from three different systems in their article. The first system is an augmented reality-based tablet tutor ("HAR"). The second system is an augmented reality-based HoloLens tutor ("HMD"). The third system is a tablet tutor ("HH"), which does not use augmented reality but contains simple instructions. HAR and HH are handheld systems, while HMD works with the HoloLens.

The research aims to integrate augmented reality into the untracked tablet network cabling tutoring system (HH). The research question is whether this integration changes usability or not and whether there are differences in usability when using HMD and HAR. A user study was conducted in which the task is to connect a network cable to two different ports on network hardware. All the ports are named explicitly. First of all, the instructions mention which two ports should be connected. The names of these two ports are displayed, but not where they are located. If the cable is connected correctly, the participant receives appropriate positive feedback and the participant can continue. If the cable is not connected correctly, the participant receives appropriate negative feedback and a message that the misplaced cable should be removed. It additionally shows where these two ports are located. The formulated hypothesis is that the augmented reality system has better usability than the system without augmented reality. The authors also assume that the HMD also has better usability than HAR. The visualizations used include icons with text to display the ports, rectangles, and arrows in different respective colors to display the location of the ports. However, the cable path is not visualized.

Based on the results it could be observed that the integration of augmented reality leads to lower usability. However, according to the authors, this may be because the design of the augmented reality system was inadequate or the task to be performed by the participant was too simple and unrealistic. In addition, the authors state that the reason could be that augmented reality was integrated into the tablet and the tablet leads to worse performance. Nevertheless, there are certain advantages of integration. According to the personal assessment of the participants, HMD is better than HAR, as the usability values do not differ significantly from one another. The authors state that the usability of HMD is not high, as the HoloLens device could have been very uncomfortable for certain users. In addition, the field of view is very limited by the device, according to [HWEB20]. When asked which system the participants found the best, 47% found the HMD, 33% the HH, and 13% the HAR the best. The participants thought the HAR was "cool and interactive". The feedback by the participants on the additional visual cues was also positive. The performance and workload of the HAR system were worse, according to the authors, because one had to look back and forth, making instructions more difficult to understand. The participants also found the HMD to be "cool", "interactive", and "easy". Participants also liked the visual cues using this system. However, according to the authors, the system has a limited field of view, limited practicality, and offers less convenience. [HWEB20] states that the HH is also simple and, in comparison, requires less physical effort. In addition, the results show that the usability of this system is lower. It also shows divided attention and a deteriorated performance. Nevertheless, the system is still very simple.

According to [JHLW21] most of the research targets the comparison of augmented reality and paper instructions or augmented reality and other devices. Instead, this article compares different types of visualization to support a machine set-up process. A machine set-up process is a process of assembling a machine from different technical components in a specific order. This process consists of many, differently complex, work steps, which can be dependent on one another.

With this process, two main types of visualization ("abstract" and "concrete") are examined. The abstract visualization shows the technical component roughly, by highlighting the edges and the outlines only, to display the shape or contour of the component. In the case of a concrete visualization, the technical component is fully highlighted. Both the outline and the entire surface of the components are highlighted. An additional video guide was also created with instructions on the machine set-up process. Based on the two types of representation and the video guide, four prototypes and one reference prototype were developed. The first prototype is based on the abstract representation including video instructions. The second prototype is also based on the abstract representation but dispenses with the video. The third prototype uses the concrete representation with a video guide. The fourth prototype also uses the concrete representation, but without a video guide. The reference prototype in this case is paper instructions and serves as a baseline.

A user study was carried out in which the participants were supposed to assemble certain components of a technical device. Several different components were used, while the participants had to assemble these components in a specific order using the prototypes. The hypothesis made is, that the four prototypes differ significantly from one another concerning the TCT, error rate, RSME, NASA-TLX value, UEQ, and SUS value. In addition, feedback from the participants regarding the system was collected.

Based on the feedback from the study, it was found that most participants find an augmented reality system useful and helpful for home and work situations or learning environments. The system seems to be easy, reliable, and also enjoyable. Some participants complained about the weight and poor comfort of the HoloLens device. Criticism was also expressed about the lack of feedback from the system in the event of correct or incorrect action. It was mentioned that there was too much focus on the technology and instruction rather than the parts themselves and their details. Some participants complained that the abstract representation is too imprecise and one cannot see what it is supposed to represent. Some participants mention that this is the reason why the participant could make more mistakes. Some participants expected additional arrows and circles to highlight important things. One participant wanted there to be a possibility to switch off the visualization after it became clear what to do because the visualization might disturb. Many participants found the videos to be very helpful and stated that it would be much more difficult, if not impossible, without these video guides.

Some interesting statements can also be made based on the measured data. Regarding the TCT, it can be observed that the abstract representation takes a little less time and is, therefore, better than the concrete representation. There are hardly any differences between the use of a prototype with the video and without the video. Regarding the workload, there are also no significant differences between the abstract and the concrete representation. However, it can be observed that using the video has positive effects. Concerning the error rate, the participants performed better with the concrete representation than the abstract representation. In addition, using the video might have some benefits again. In summary, it can be observed that, according to the authors, the concrete representation is more precise, while the abstract representation is more simple and more applicable. The authors state that the choice of presentation also depends heavily on the complexity of the task and the context of the use case or other factors. [JHLW21] mentions that a mixture of the abstract and the concrete representation would also be possible.

3 Project structure

3.1 General requirements and goals

The pavilion project is a building project of the IntCDC University of Stuttgart (Cluster of Excellence Integrative Computational Design and Construction for Architecture). About five to ten supervisors and more than 20 students work on this project. The project mainly comprises the manufacture and construction of a pavilion, which is mainly made of timber (figure 3.1). With this project, new digital fabrication and design methods are presented in the form of multi-story timber construction. This bachelor thesis is based on the pavilion project of the IntCDC.

Figure 3.1: Digital model of the entire fabricated timber pavilion.

The whole building project consists of multiple work phases and important tasks. An indispensable phase of the construction project is the prefabrication of the individual pavilion parts. Prefabrication includes the planning and implementation of preparatory fabrication steps before the final production and assembly of the pavilion. After the tailored constructs and building components have been delivered, these further preparatory fabrication steps are necessary.

The entire ceiling structure of the pavilion can be divided into the upper ceiling structure, the lower ceiling structure, and the additional elements (figure 3.2). The entire ceiling structure is triangular. Both the upper ceiling structure and the lower ceiling structure continue to consist of several different smaller ceiling panels. A total of four specific panels can be put together to form the top ceiling panel. For the lower ceiling tile, it is necessary to put four other specific plates (A, B, C, D) together (figure 3.3). This means that there are a total of eight ceiling panels for the entire ceiling structure. These eight ceiling plates are also called Slab elements (among experts). Two of these eight Slabs serve as the core and will be located in the center of the upper and lower ceiling structure. The other six Slab elements are elongated plates, which will be located around the core afterward and form a triangular shape. These panels have a maximum width of 2.4 meters and a maximum length of 7.8 meters. However, the shape and size of the entire upper ceiling and the lower ceiling are the same, so that they fit on one another. In terms of the use case explained below, we will mainly focus on the lower ceiling panel, which is depicted and divided in figure 3.3.

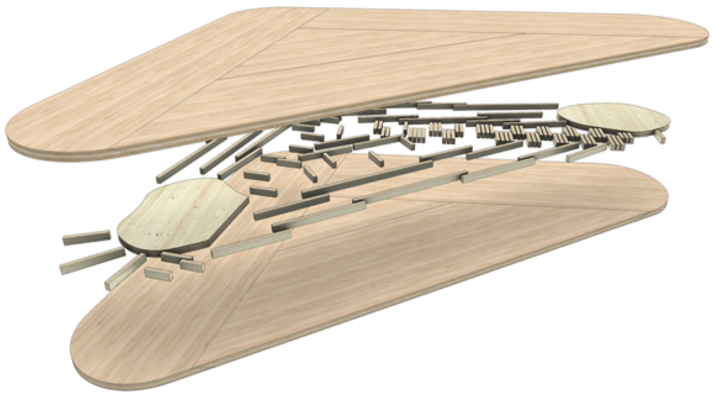

Figure 3.2: Digital model of the entire ceiling structure of the timber pavilion, including the upper ceiling structure, the lower ceiling structure, and the additional elements in between.

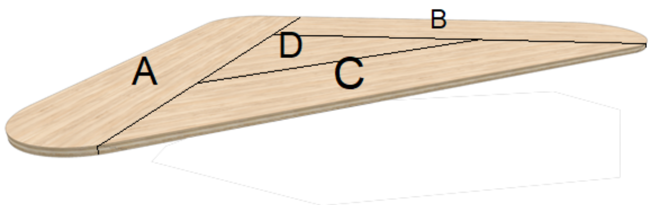

Figure 3.3: Digital model of the entire (lower) ceiling structure, divided into four smaller different timber panels (A, B, C, D).

The additional elements include components such as the so-called markers, placers, splotches, shear webs, junction boxes, conduits with various cables, and other elements which are not in the scope of this work. Markers, placers, and splotches only play an essential role in the architecture and other fabrication steps. Shear webs are rectangular components that are placed and attached to the lower ceiling panels by robots. The positions of the shear webs are defined, while these shear webs can fulfill various functions, including stabilization. Junction boxes are rectangular components and are used to bring cables and other (electrical) lines from different directions together and branch off in another direction. When prefabricating the entire ceiling structure, it is necessary to install different cables between the upper and lower ceiling panels. For example, network cables can be laid to enable internet connections. To make the cables less vulnerable to animal attacks or greater wear and tear, conduits are used and the cables are then passed through them (figure 3.4, left). The conduits are attached to the lower plates using specific spray adhesive and mechanical pipe clamps (figure 3.4, right).

The conduits and the cables only need to be attached to the outer plates (A, B, C). No cables are required on the center panel (D) as they are not intended there. As a result, the use case task has to be carried out on three different plates (A, B, C). Since the additional elements are placed differently on these three panels, the paths are also at different locations.

Figure 3.4: Conduit (left) and conduit clamps (right), used for the prefabrication task of the project.

In the timber context, the placement of the conduit and the cables must be carried out by humans, as the necessary technical robotic parts are not available. This use case also presents further possible issues and the order of the work sequence plays an important role. First, a suitable spray adhesive is applied to the bottom panels. This automatically creates a narrow time window and temporal pressure, as the adhesive dries out. The conduits are then placed in a respective position by hand and the conduit clamps are attached to the plate. As a result, the conduits are both glued in place and secured with conduit clamps. Only after these steps, the shear webs are placed on the plates by robots. For the worker when laying, this means that the shear webs are not yet attached to the panels. Therefore, it is not visible where the shear webs are located. The conduits with the containing cables must be laid fairly precisely, as the shear webs fixed afterward would otherwise collide with the cables. So, the main task of the use case is to lay the conduit and the cables among the shear webs. Drilling into the plates again to place the conduit clamps at a different location is also undesirable. It must also be taken into account that both conduits and cables have certain robustness or flexibility. The flexibility aspect means that the conduits and cables cannot easily be bent. Since both the conduits and the cables must be resistant to external influences, they are usually not too flexible. It is, therefore, to be expected that when laying the conduits, for example, 90-degree angles are not possible.

One example of the task of the use case is shown in figure 3.5 below. One of the timber panels is set in the working environment, while the worker has to perform the task.

This project has many challenges and also raises several questions. The key question is how these conduits, and thus the cables, can be laid appropriately and safely. The problems explained above must be respected at all times. In industry, a kind of manual or sketch drawing in paper form, which is also called “Electrical plan” has mostly been used up to now. In practice, electrical plans are not used exclusively. In some cases, these plans are supplemented by further plans. In addition, electrical plans sometimes contain more detailed information. This technology is a bit old-fashioned and less efficient by now, which is why we are trying to use AR. For this application, the Microsoft

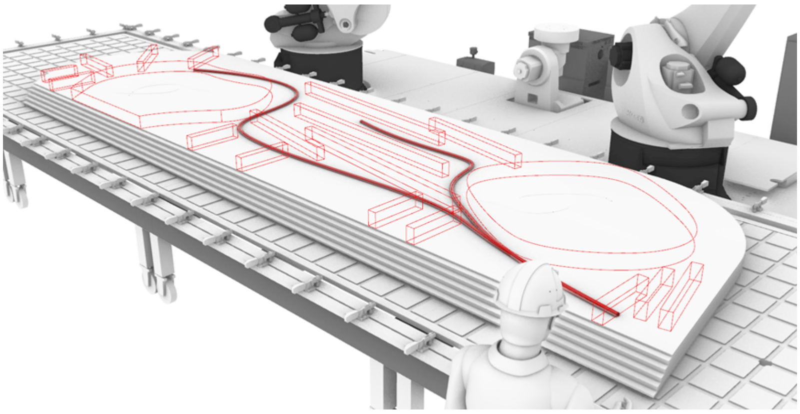

Figure 3.5: Digital representation of the use case task in the working environment, including the path of the conduit/cable (red spline), shear webs (red outlined cuboids), and splotches (two red outlined shapes) on top of one Slab panel.

HoloLens 2 will be used to develop an AR prototype. This prototype should support the worker with the task of fixing the conduits in the correct position on the lower plates. In this work, we investigate the best way to set up the visualizations for this specific task. The visualization to be developed must take all problems into account, to help the worker. Using this system, the worker should be able to complete the task of the use case quickly, accurately, and without major errors. If fatal errors occur during execution, it is hardly possible to repeat the task. At the time of the implementation of this task, the cut panels have already gone through several fabrication steps. In addition, re-ordering these panels is not possible, as the costs of a single element amount to several thousand euros.

3.2 Work process

An expert interview was performed and recorded to get a better understanding of the entire pavilion project. It is necessary to comprehend this project of the IntCDC to guarantee a successful implementation. Requirements, processes, and other important aspects were discussed in great detail to follow the concept of a user-centered design. In addition, the remaining ambiguities were clarified to guarantee a successful project. The participants, consisting of a supervisor and students, are already familiar with the project, the requirements, and the process. The interviewed participants are therefore experts and potential workers, who might use the prototype during the dry run and the final prefabrication. The results of the interview are composed and described extensively in the previous section “General requirements and goals” (section 3.1).

After familiarization with the software and hardware, these were set up appropriately so that versions are compatible with each other and the respective hardware is supported correctly. Details about the implementation, used applications, and versions can be found in the following section “Implementation details” (section 3.3).

Before the initial prototypes were developed, a focus group was carried out to work out the first concepts of the prototypes to be developed. Rough ideas and comments were recorded and documented in the “Prototype concepts” chapter (chapter 4). The suitable prototypes could then be developed from these concepts. These preliminary prototypes are introduced in the chapter “Prototypes” (chapter 5).

To compare these developed prototypes with one another, a user study was carried out. In the “User study” section (section 6.1), the entire user study, including preparation, process, and results, is presented precisely. The most efficient prototype resulting from this investigation was then mainly used for the construction project.

To use the developed system with the prototype for the pavilion project, however, further steps were necessary. The steps include familiarization with the former steps of the pavilion project and the integration of the prototype into the project. These had to be carried out at the “Large Scale Construction Robotics Laboratory” at Waiblingen, which serves as the production facility for the pavilion parts. Finally, the prototype was improved to run a trial run (dry run). After this successful dry run, the prototype had final adjustments and the actual task of the use case was carried out with the developed prototype. In this last phase, too, the prototype was evaluated in the form of surveys. Further information on this review can be found in the “Final prototype” section (section 6.2).

The figure below illustrates the entire work process by a flow chart (figure 3.6).

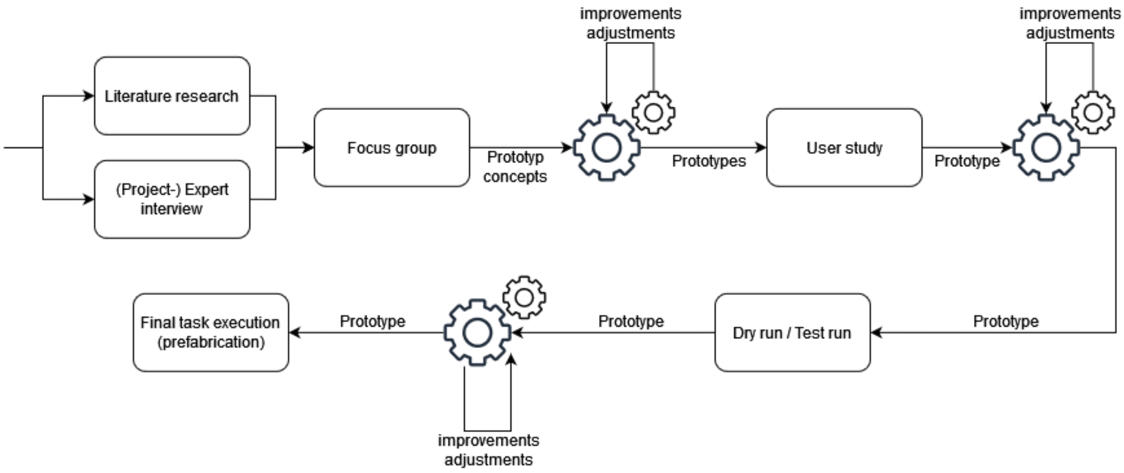

Figure 3.6: Graphical representation of the working process for the project research.

3.3 Implementation details

The development of the individual prototypes was implemented with the Unity Version 2019.4.8f1[1] of the Unity Engine and Microsoft Visual Studio 2019[2]. With these tools and C# as the main programming language, the prototypes (chapter 5) were developed, and thus the entire user study was

[1](https://unity3d.com/de/unity/whats-new/2019.4.8)

[2](https://visualstudio.microsoft.com/de/downloads/)

prepared. Other components of the prefabs, such as parts of the visualization, were developed with the given Unity standard assets. Further adjustments and auxiliary functions were also implemented with these tools.

The Vuforia Augmented Reality SDK (Vuforia Engine 9.8.8) offers a collection of functionalities that support AR[3]. We use Vuforia for the detection and tracking of the working environment for the prototypes. Different two-dimensional QR codes are printed on regular paper and used as ImageTarget markers for this. These are placed and fixed in the respective work environment of the user study (section 6.1) and the dry run (section 6.2) (and thus the real prefabrication).

In addition, some elements from the Mixed Reality Toolkit Unity (Microsoft MixedReality Toolkit Unity 2.7.2)[4] are used to create a simple user interface for the user study (section 6.1). For the evaluation of the prototype, the simple interface turns out to be essential support. The user interface is also used to utilize other features, which are explained in more detail in the "Prototypes" chapter (chapter 5).

The Microsoft HoloLens 2[5] as Mixed Reality Smartglasses was used both for the development of the prototypes (chapter 5) and for the evaluation afterward (chapter 6). The use of the hardware also brings with it some other specific system requirements, which are, however, neglected here. It is only worth noting that compatibility and support of the versions of the different components are essential.

[3](https://developer.vuforia.com/downloads/sdk?field_sdk_release_version_tid=57)
[4](https://github.com/Microsoft/MixedRealityToolkit-Unity/releases)
[5](https://www.microsoft.com/de-de/hololens)

4 Prototype concepts

To collect innovative ideas and suggestions for prototype concepts, a brainstorming session as a focus group has been conducted. This also offered the opportunity to get opinions about certain concepts. The prototype concepts can be used to develop the initial prototypes. The focus group also allows the prototypes to be adapted and compared at an early stage.

4.1 Preparation (apparatus)

Seven participants were invited to an online meeting for the focus group. The participants are students, graduates, or research assistants in the IT area between the ages of 18 and 30. The target group is represented appropriately by these participants. Five of the seven participants had little or no experience in using the HoloLens 2. Nobody was familiar with the actual practical task of the wiring use case.

A few questions for the participants were prepared in advance. In addition, rough sketches of the pavilion and the application were made to explain the problem of the use case and the purpose of the prototype.

4.2 Procedure

After a short round of introductions, the purpose and the procedure of the focus group were explained to the participants. The problem to be investigated was then presented based on the prepared sketches.

The participants were given three different tasks consecutively. The participants should put themselves in the role of the worker and first name what they could imagine using as a visualization for the task. All ideas were collected and documented separately. The collection and thus the current concepts were also shown to the participants during the discussions. Following this, the participants should point out some possible advantages and disadvantages of every concept. As the final task, the participants were asked to decide on one to two visualization concepts, which they would prefer to use.

The focus group was recorded so that the content can be documented and analyzed precisely.

4.3 Results

The participants suggested many different concepts which they consider useful for the application. It has been suggested, on the one hand, to highlight the cable route (figure 4.1, left) and, on the other hand, the shear webs as a visualization (figure 4.1, middle). A similar concept is an idea of highlighting the cable route by displaying two parallel paths directly next to the actual cable route (figure 4.1, right). As a result, these two paths delimit the cable route as markings.

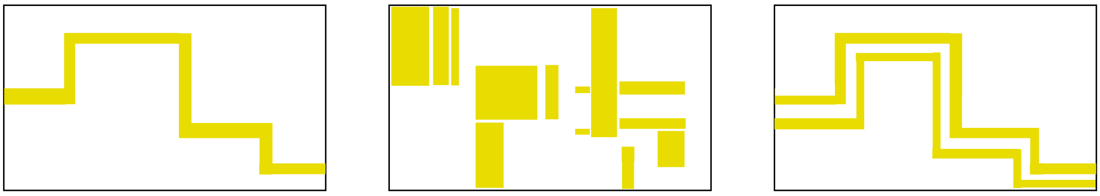

Figure 4.1: Simplified representation of the developed prototype concepts, including displaying cable route (left), shear webs (middle), and cable delimitations (right).

An alternative to displaying the cable route would be to color the area above the cable route in a certain color and the area below in a different color (figure 4.2, left). This emphasizes the cable route through the contrast of the colors. Another small addition to the first concept would be to map the cable route with textual information (e.g. exact length or angle of a cable section) (figure 4.2, right). This also resulted in the idea of only displaying this textual information (e.g. length, angle) and completely omitting the visualization.

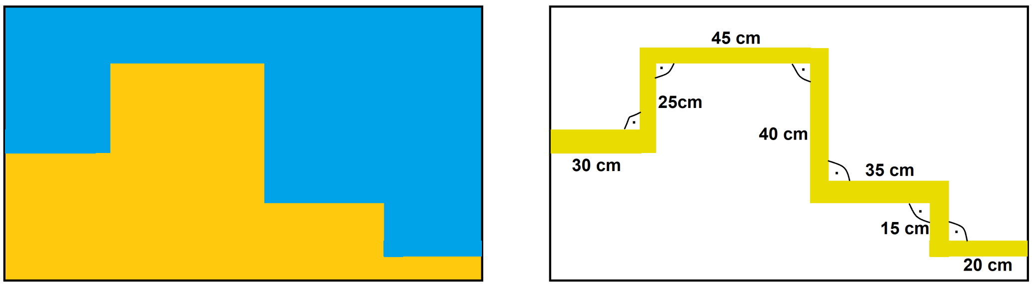

Figure 4.2: Simplified representation of the developed prototype concepts, including displaying the cable route by coloring the areas differently (left) and additional textual information (right).

Another concept is to show all corner points of the cable route (figure 4.3, left). This assumes that the cable route consists of contiguous straight lines and does not contain any Bézier curves, for example. The cable route is displayed minimally by only displaying the corner points. In addition, it would be possible to add a vertical arrow above every corner point, which is pointing to the respective corner point (figure 4.3, middle). The purpose of these arrows above the corner points is to emphasize the corner points so that they cannot be overlooked. It would also be conceivable to add a corresponding number above each displayed corner point (figure 4.3, right). This makes it clear which corner point follows after a certain corner point. This reduces the risk of taking a wrong path and connecting a point to a wrong point if, for example, corner points are overlooked.

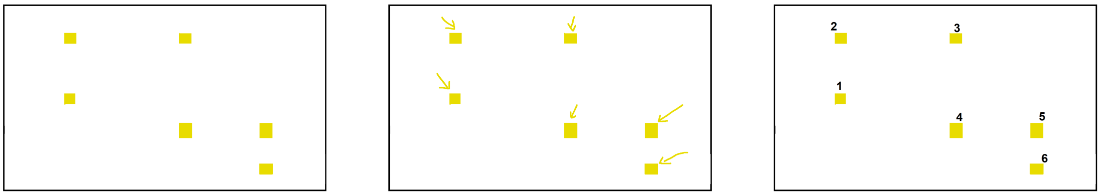

Figure 4.3: Simplified representation of the developed prototype concepts, including displaying corner points of the cable route (left), corner points with additional vertical arrows on top (middle), and corner points with corresponding numbers (right).

This type of numbering has also been proposed for the second concept. The shear webs of this concept could get a unique number (figure 4.4, left). However, if the visualization should be too confusing due to the number of shear webs, it would be a conceivable option to hide certain individual shear webs. A combination of the first concept and the second prototype has also been considered (figure 4.4, middle). Both the cable route and the shear webs are displayed in this case. There is also the option of adding different arrows to this combination alternative (figure 4.4, right). These arrows only serve to emphasize the course of the path.

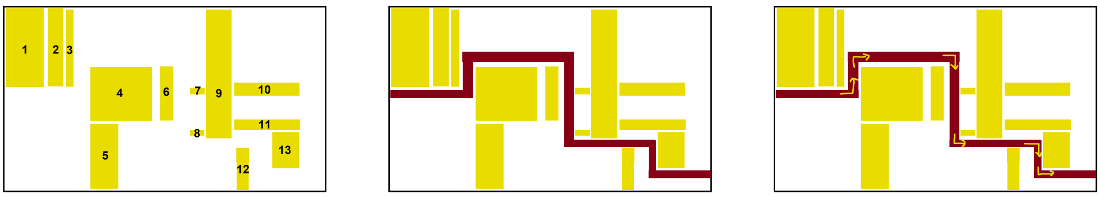

Figure 4.4: Simplified representation of the developed prototype concepts, including displaying numbered shear webs (left), shear webs with cable route (middle), and shear webs with cable route and additional arrows (right).

Apart from these visualization concepts for the fundamental visualization, some participants also expressed potential features. Some of these features are shown in the figure below (figure 4.5).

One method to emphasize the visualization and to make it more visually appealing is the (varying) use of color, width, and shape. Certain colors can be used to make the corresponding visualization more conspicuous or, for example, to highlight special parts. Using transparency on the respective visualization can also have a positive effect. The same principle applies equally to the width and shape, for example of cable routes. The cable route can be designed to be thicker or thinner or even have different shapes, e.g. a dotted shape. With the help of different colors, widths, and shapes there is also the option to use animations on different visualizations. Animations can also be used to show the visualization, e.g. the cable route, dynamically. In this case, the visualization will disappear at cable sections, which have been worked on and fixed already. Only upcoming sections which still need to be handled are visualized.

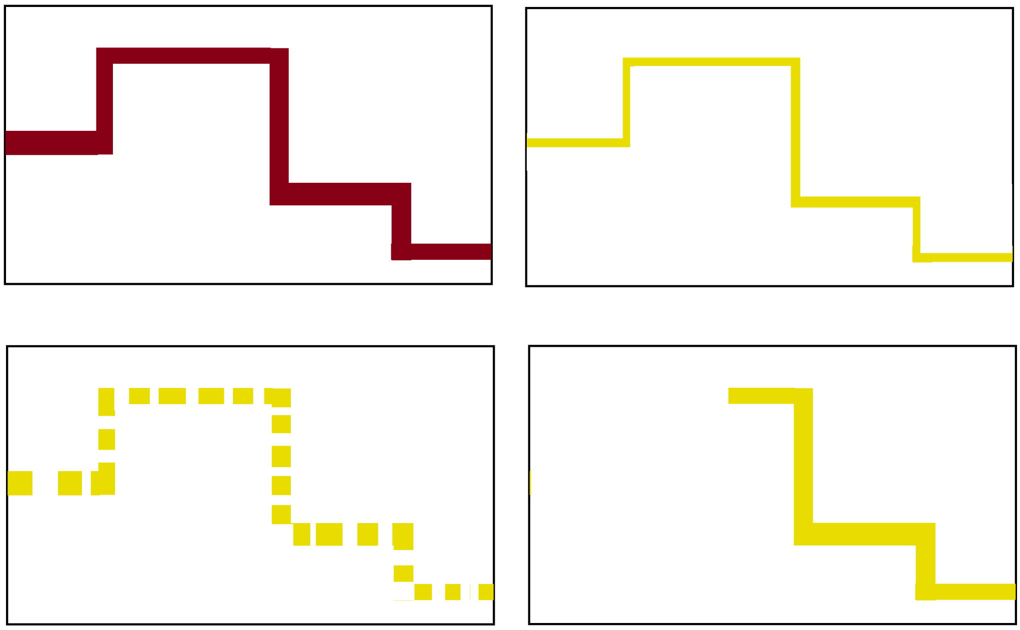

Figure 4.5: Simplified representation of using different color (top left), different width (top right), different shape (bottom left), and displaying a dynamic cable route (bottom right).

Another constructive aspect is the use of Magic Lenses. If the workers are operating on an area at a time, a circular area becomes active. This area can, for example, follow the hands of the worker or the line of sight of the worker. A specific visualization can now be shown in this area, while outside of this area all visualizations are hidden (figure 4.6, left). An alternative would be to use a specific visualization within the area, while a different visualization is used outside (figure 4.6, right). Based on the hand movements or the viewing directions, the area in which a certain visualization is displayed is shown dynamically.

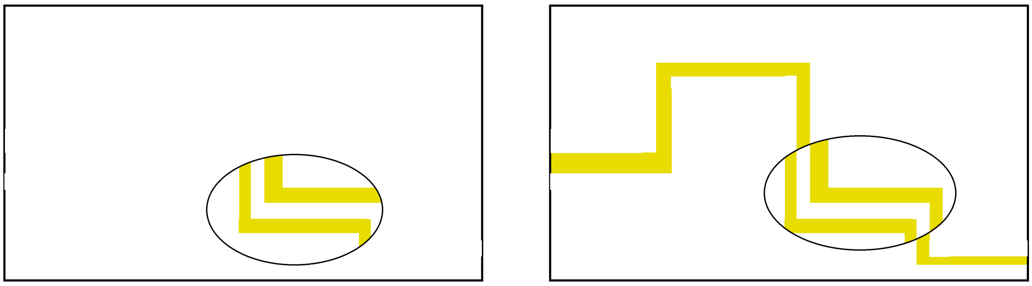

Figure 4.6: Simplified representation of magic lenses, hiding all visualizations outside the area (left), and displaying a different visualization outside the area (right).

Some participants also find it to be helpful to highlight areas in which there is a need for correction, e.g. if they were not worked on precisely enough. This correction step can either happen during the wiring task or only afterward. The visualization of this error correction feature was not discussed further.

For the user, it can also be helpful to add a dynamic display that shows the progress of the task so far. The visualization and placement of this progress status display were not discussed further.

In terms of adaptability, it would also make sense to enable the user to choose between different visualizations.

One possibility to change the placement of the visualization would be to either distribute it in the room or, for example, display it on a wall. The entire visualization can also be split up if needed, while one part continues to be on the worktop and another part is repositioned elsewhere.

Further suggestions are the general use of voice control in the AR system to simplify interactions and the use of other techniques for the display of information, such as a projector.

When asked which of the newly developed concepts is one's favorite, the opinions of the participants are divided considerably. Two participants prefer the first visualization concept of a cable route, together with the use of a magic lens. One participant prefers the second concept and thus to have only the shear webs visualized. Two participants prefer to use the third prototype and work with two parallel lines displayed and also a magic lens, whereby all holograms are hidden outside the lens. The remaining two participants favor a combination of the cable route and the shear webs.

4.4 Discussions

The first three concepts (figure 4.1) are simple structured because they consist of elementary structures and do not contain any additional features. As a result, these concepts appear simple and intuitive. That is why these concepts can easily be compared to one another.

The first concept (later: "Wire-Path" (section 5.1)) shows a visualization that already precisely specifies the path of the cable (figure 4.1, left). The workers only have to follow the instructions displayed. In this case, the worker does not need to make any extraordinary considerations. The worker makes little or no cognitive effort when using it, but the worker is forced to adhere to the instructions. The workers could therefore criticize the lack of freedom and the strict guideline. Another problem with this prototype is the overlap which might occur as soon as the cable is fixed at a section. The visualization is exactly where the cable has to be fixed. This can make either the visualization or the cable difficult to see.

The second concept (later: "Shear-Webs" (section 5.3)) represents a visualization that shows the elements, which are not allowed to touch the cable (figure 4.1, middle). In contrast to the first concept, this concept does not represent a fixed instruction or specification. Instead, the user is given the freedom to plan the appropriate path by himself, and thus the cognitive effort could be higher. The responsibility for the successful completion of the task is higher in this case and must be borne by the worker himself.

The third concept (later: “Wire-Lines” (section 5.2)) is also plain and represents a concept that can be placed between both of the prototypes above (figure 4.1, right). The path is already partially specified by the boundaries, but a small amount of cognitive effort is required to use the boundaries.

The concept in which the surface is colored in two different colors is an extension of the first prototype (figure 4.2, left). The cable route is highlighted by the contrast of the colors and thus the edge of the two colored areas, instead of the path itself. The visualization of this extension is still relatively simple but can be less intuitive compared to the previous concepts. The workers must also comply with an exact given specification. An additional serious aspect here is the problem that certain colors can be more difficult to perceive for people with visual impairments. Depending on the color, brightness, and contrast, this can affect a large part of the population. In addition, there is the aspect that the color of the displayed hologram can be severely impaired by the sunlight and the surrounding situation in the work environment. This could make the colors even less recognizable.

Another extension of this first prototype is the addition of textual information. By showing the length and angle, more precise information can be added (figure 4.2, right). These can also be useful for certain other use cases. For this use case, which is introduced in section 3.1, the exact information is of no interest to the worker. This addition can also lead to too much being displayed in the field of vision of the worker and ultimately reduce the efficiency and performance of the system. In our case, this concept has more adverse effects than beneficial effects.

Merely showing this textual information of the cable sections and doing without the visualization has already turned out to be negative in the past. Since we are using visualizations for this use case and want to benefit from it, this option is excluded.

The type of representation of the cable route through its corner points (figure 4.3, left) is minimalistic. This makes this concept seem simple and intuitive. It is also elementary and could therefore easily be compared with the first three prototype concepts. In this representation, the playful aspect (“Gamification”) stands out more than in the previous concepts. One can observe a mixture of strict specifications and freedom for the workers too. The major problem with this concept is that the implementation is prone to errors due to the sole representation of the corner points. If certain points are skipped when laying the cable because they were overlooked or the order is interpreted incorrectly, the cable can be placed wrong.

To solve the problem of points, which are easily overlooked, there is the option of highlighting these corner points with additional arrows (figure 4.3, middle). These arrows are vertical above the worktop and point to the respective corner point below. This counteracts the problem. This concept is therefore a satisfying addition. Depending on the color, size, and positioning of the arrows, the highlighting can work more or less well. This extended concept of the corner points concept is also minimal and thus simple and intuitive. The Gamification aspect is also retained in this concept. The problem that the cable is misplaced due to the wrong interpretation of the order is not yet resolved.

One way to address this problem is to add numbers to the corner points (figure 4.3, right). This number represents the order of the corner points in which they should be connected by the cable. This representation would solve this problem and would also be relatively minimal. Because numbers are used, these could be impaired by certain external light circumstances or by the eyesight of the user. For some people, this representation could also be less intuitive and a little confusing because of the numbers. In this representation, the Gamification aspect is increased even further compared to the concept of corner points without numbers.

The numbering of the shear webs (figure 4.4, left) could be helpful for identification and thus for other use cases or tasks. For this use case, which is introduced in section 3.1, it is not necessary to identify the shear webs, which is why the distinction between shear webs is irrelevant.

If there are too many elements in the field of vision of the worker, it makes sense to integrate this option to hide certain shear webs. The prerequisite for this is, that a concept is used with shear webs being displayed. This addition is only useful if there are many shear webs and the visualization is overloaded. The leading question for this idea is how to hide certain shear webs and show them again. This brings with it the danger that shear webs will be hidden and forgotten to be shown again. This problem would lead to major errors. This option can be helpful for certain use cases. In this use case, this additional interaction is unnecessary.

A convenient alternative is to use the combination of the first and the second prototype concept (figure 4.4, middle). This concept is an alternative to the individual previous visualizations. The fact that several visualizations are combined in this concept also might increase the overall workload. Additionally, the visualizations displayed might be too many and have rather negative effects. The performance is lower too because more holograms need to be rendered and tracked at the same time.

The extension of the combination concept with the additional arrows is a possibility to emphasize the path and its course more strongly from the shear webs (figure 4.4, right). The arrows are unnecessary for this use case because the information is redundant. The direction and the course are already sufficiently emphasized by the path in this combination concept. If the path does not stand out enough from the shear webs, the difference between the two visualizations could be increased by changing or removing some of the shear webs.

The use of color, width, and shape can be extremely useful to highlight certain areas and draw attention (figure 4.5). It can also be useful to improve the visibility of the visualization or even the error rate. The use of transparency can lead to better usability in the same way and eliminate the problem of overlay, which might occur when displaying the path. As an additional option, paying attention to the color, width, and shape (and transparency) is therefore beneficial, but it does not answer the main research aspect. However, this is an idea, which might be useful and therefore considered for the prototypes (chapter 5).

There is no need to use animations as this could cause more difficulties. The animations reduce the performance and higher computing power and more resources are required. In the use case explained above (section 3.1), the use of animations leads to typical “gold-plating”. The animations can strongly direct attention, but other concepts can direct the attention just as well and far more efficiently.

Using a dynamic path (figure 4.5, bottom right) can be useful and problematic at the same time. The worker has the opportunity to see the progress of the task directly. But as soon as the cable has been fixed at one point, the visualization is hidden at this point. Correcting an error at a point that has already been fixed is therefore not possible with this kind of concept. The worker can no longer correct this point once the cable is fixed because they can no longer see the visualization there. A final check of the entire cable is also not possible. To use this concept, it has to be further modified and refined. In addition, there is a problem with the recognition of the cable. It is difficult, if not even impossible, to track or recognize the cable with the HoloLens device, since the elements (cables, clamps) are narrow and small.

By using these Magic Lenses (figure 4.6), important or relevant sections can be highlighted well. Irrelevant sections can be hidden to maintain an overview. Both variations of this concept are a good additional feature to add a bit more interaction. For this concept to work, one has to adjust the size of the Magic Lens area appropriately. Otherwise, this area could be a little too small and therefore this concept can be cumbersome to use. Using the second variant, in which two different visualizations are used, it can be confusing for the worker. Nevertheless, this concept has the potential to make a useful feature.

The research question we are concerned with relates only to the previous phase (performing the task). The correction phase, which could take place afterward, is not examined as it is irrelevant to our research question.

With the possibility of choosing between different visualizations, users get a flexible choice depending on their personal preference. This is a good feature because the choice of the optimal visualization is up to the user. However, this concept is a general extension and, in this sense, does not solve the research question about the visualization itself. If a concept can also be found that is optimal, the selection option is also not urgently necessary.

Since we do not visualize a huge amount of data and the visualizations do not become large, the division of the visualization and distribution in the room is unnecessary. In addition, the space around the user is not always the same. This means that the work environment can be structured differently if necessary. The place of work may also change depending on where the Slab element is placed to work on it. The hardware also plays an important role in this concept. Unfortunately, the HoloLens 2 does not have a large field of vision, which means that the worker works with a slight tunnel vision. Elements outside this field of view can therefore not be perceived at all. Accordingly, if visualizations are split up and redistributed, many elements could be overlooked. Another side effect is that the workers have to move their heads more. This is necessary to recognize differently placed visualizations. This side effect is also suboptimal.

The use of voice control is both not efficient and unnecessary for our use case. The implementation of this idea would also lead to gold plating. Voice control would also create additional problems and offer fewer benefits. The problems here are primarily location-dependent. Because the above task is performed in a work environment where there may be relatively loud background noise, the likelihood of problems is not small.

It is of course always possible to use other techniques or hardware. For example, projectors have already been used and compared in previous studies. This is theoretically possible in our case, but we would like to use the HoloLens 2 specifically. The use of a different technology naturally also brings other problems with it. In the case of the projector, there might be problems with the structure and especially with the appropriate hardware. Since the panels are quite large, the projector would either have to be mounted high or have a wide-angled lens. These problems predominate with this technique. With the HoloLens, however, these problems do not exist. In addition, in the end, the same problem remains to which we devote ourselves. The question of visualization is also relevant for another technology.

The favorites gave a first impression of which concepts could emerge. Since the favorites were not named by the participants at the same time, but one after the other, some of the answers from certain participants could also have been influenced. The reason for the different opinions could be the lack of an actual (high-fidelity) prototype. It is, therefore, possible that the participants' ideas about the appearance and functionality of the developed concepts did not quite match. If participants had the opportunity to try out the concepts on their own, this could have led to a different result. However, all the participants favor the first three concepts, depicted in figure 4.1, including a combination of them and a magic lens.

Many of the suggested ideas are good concepts and helpful extensions for other or more general use cases. For this use case, presented in section 3.1, many concepts are irrelevant or inappropriate. In this context, we continue to examine the first three concepts (figure 4.1), as these are basic visualization concepts that can be compared with one another and represent the most solid concepts. These three concepts were also strongly favored by the participants. In retrospect, adjustments can be made in terms of color, width, shape, or transparency. Additional concepts such as magic lenses, error detection, and correction or progress status display can also be implemented afterward.

5 Prototypes

The following prototypes were developed based on the results of the focus group (chapter 4) and adjusted for the subsequent user study (section 6.1). These prototypes are described in the context of the user study. This means that the different prototypes, variants, and visualizations, which will be introduced, are adapted to the user study. This implies that, e.g., a regular table will be used for the user study as a worktop to simulate the Slab element.

To make the results of the user study more meaningful, two different variants of shear web placements and thus path placements were developed. The first variant is a little easier than the second variant because the shear webs are placed in a way that the path of the first variant has fewer bends. To compare the different prototype concepts with the user study, four different prototypes were developed for each variant. “Wire-Path” (section 5.1), “Wire-Lines” (section 5.2) and “Shear-Webs” (section 5.3) are AR prototypes. “Paper-Instructions” (section 5.4) serves as a reference prototype and is not based on AR. This results in a total of eight different conditions for the user study (“Wire-Path” with variant 1, “Wire-Path” with variant 2, “Wire-Lines” with variant 1, “Wire-Lines” with variant 2, “Shear-Webs” with variant 1, etc.).

In addition, a simple user interface (figure 5.1) was implemented for each one of the AR prototypes and thus for six of the eight conditions. The user interface consists of 2 buttons. The left button is the start button, labeled with “Start(x)” with “x” being the respective condition (1-6). The number of the condition as part of the label is for identification purposes only. The right button is the finish button, which is labeled with “I’m done”.

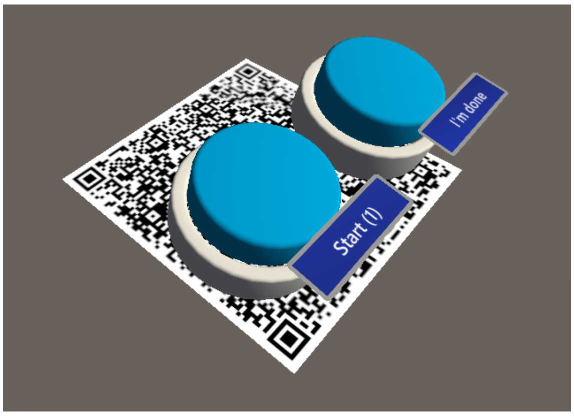

Figure 5.1: A simple user interface including buttons (start button and finish button) for activating and deactivating the visualizations of the AR prototypes.

Each prototype consists of one or two visualizations as detailed below. As soon as the start button is pushed, the respective visualizations are displayed. Whenever the finish button is pushed, these visualizations disappear. Using the buttons, we can simply activate and deactivate the visualizations of the prototype. Furthermore, the time in which the visualization is displayed (between pressing the start button and the finish button) is measured with these buttons.

Different QR codes are generated to create different Vuforia Image Target markers for each AR prototype. The six markers are scaled and placed appropriately to ensure the visualizations and the user interface will be at the correct position and have the correct size (figure 5.1). The markers serve as an entry point for the holograms.

5.1 Wire-Path

The prototype “Wire-Path” is one of the AR prototypes and based on the HoloLens 2. For this purpose, the generated Vuforia Image Target marker is attached in the bottom right corner of the prototype scene. Parallel to this, the marker can be printed and attached to the corresponding bottom right corner of the worktop. The worker can put on the AR glasses and look at the marker. As soon as the glasses recognize the marker, the user interface described above (chapter 5) is displayed above the marker.

As soon as the start button is pressed, a path visualization is displayed as a hologram on the worktop. The path visualization consists of a path and resembles a continuous line with a certain width and some right-angled bends. The path is highlighted in yellow. When the finish button is pressed, the visualization is hidden.

No shear webs are displayed on the worktop. The course of the path is, however, adapted to the shear webs so that the path is minimal and leads between the individual shear webs. The shear webs are not visible to the worker, but they are still in certain arbitrary positions.

Both variants of this prototype, including markers and buttons, are shown in the figure below (figure 5.2).

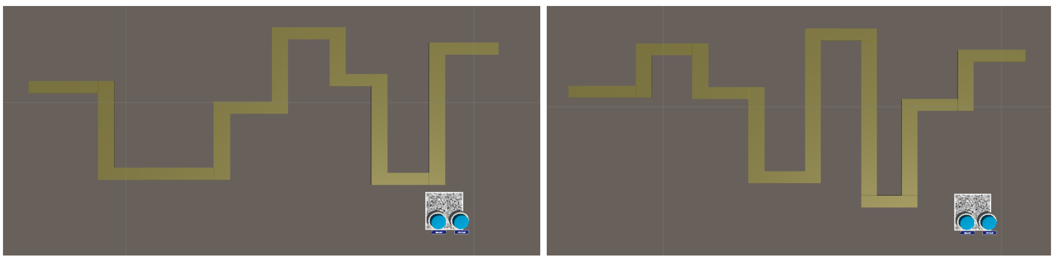

Figure 5.2: Prototype “Wire-Path” with variant one (left) and variant two (right) and the image target with the corresponding user interface in the bottom right corner.

5.2 Wire-Lines

The prototype “Wire-Lines” is one of the AR prototypes and based on the HoloLens 2. For this purpose, the generated Vuforia Image Target marker is attached in the bottom right corner of the prototype scene. Parallel to this, the marker can be printed and attached to the corresponding bottom right corner of the worktop. The worker can put on the AR glasses and look at the marker. As soon as the glasses recognize the marker, the user interface described above (chapter 5) is displayed above the marker.

As soon as the start button is pressed, a path delimitation visualization is displayed as a hologram on the worktop. The path delimitation visualization consists of two parallel path delimitations. Both path delimitations are boundaries of the wire path and resemble a steady line with a certain width and some right-angled bends. These boundaries are highlighted in red. When the finish button is pressed, the visualization is hidden.

No shear webs or paths are displayed on the worktop. The course of the boundaries is, however, adapted to the path and thus to the shear webs. The path is minimal and leads between the individual shear webs. The boundaries do not cross the path either but lie directly beside the path. This allows the path to be recognized by the delimitation above and below the path. The shear webs and path, although not visible to the worker, are still in specific locations.

Both variants of this prototype, including markers and buttons, are shown in the figure below (figure 5.3).

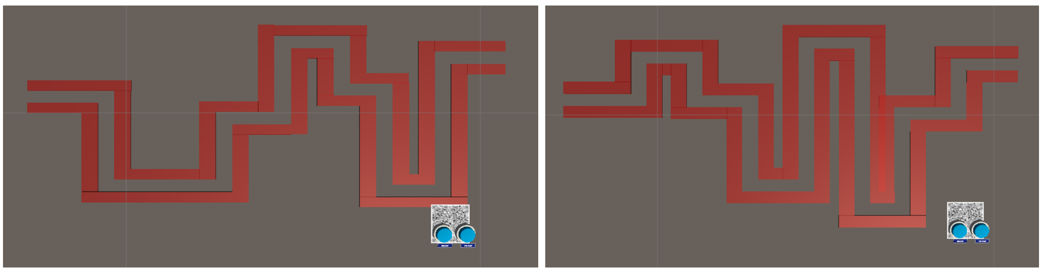

Figure 5.3: Prototype “Wire-Lines” with variant one (left) and variant two (right) and the image target with the corresponding user interface in the bottom right corner.

5.3 Shear-Webs

The prototype “Shear-Webs” is one of the AR prototypes and is based on the HoloLens 2. For this purpose, the generated Vuforia Image Target marker is attached in the bottom right corner of the prototype scene. Parallel to this, the marker can be printed and attached to the corresponding bottom right corner of the worktop. The worker can put on the AR glasses and look at the marker. As soon as the glasses recognize the marker, the user interface described above (chapter 5) is displayed above the marker.

As soon as the start button is pressed, a shear web visualization is displayed as a hologram on the worktop. The shear web visualization consists of several different shear webs, which may be placed and scaled arbitrarily. A shear web is represented as a rectangle of a certain size. The shear webs are highlighted in red. When the finish button is pressed, the visualization is hidden.

Both variants of this prototype, including markers and buttons, are shown in the figure below (figure 5.4).

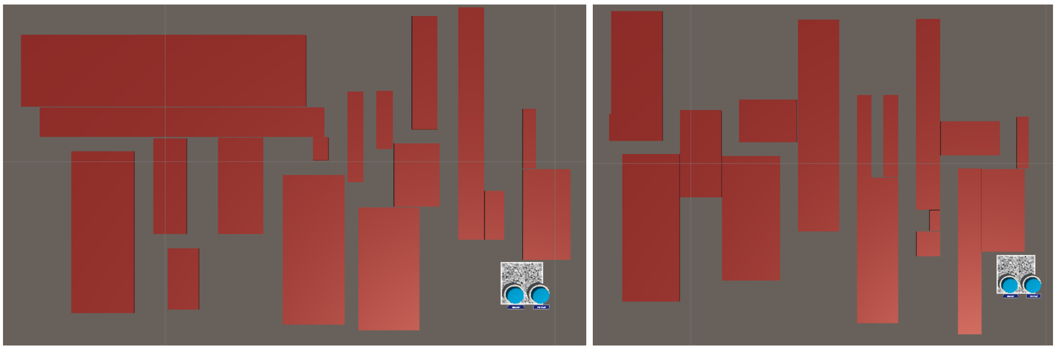

Figure 5.4: Prototype “Shear-Webs” with variant one (left) and variant two (right) and the image target with the corresponding user interface in the bottom right corner.

5.4 Paper-Instructions

The basic prototype “Paper-Instructions” serves as the reference prototype and is based on a typical paper prototype. A photo of the entire tabletop, which is used in the user study (section 6.1), is shown from above on a DIN A4 paper page. In the photo, one can see the tabletop shown as well as the additionally displayed path visualization and the shear web visualization. The path visualization consists of a path and resembles a continuous line with a certain width and some right-angled bends. The shear web visualization consists of several different shear webs. A shear web is represented as a rectangle of a certain size. The path is highlighted in yellow and the shear webs are highlighted in red.

The size and position of the shear webs on the tabletop can be chosen arbitrarily. The course of the path is adapted to the shear web visualization in such a way that the path does not cross any of the shear webs. The path leads through between the individual shear webs without touching them. The path is minimally constructed.

This basic prototype does not have an automatic stopwatch function as it is not supported by AR. To measure the time in which the visualization is shown, according to the AR prototypes (“Wire-Path”, “Wire-Lines”, “Shear-Webs”), one has to measure the time manually. As soon as this prototype is shown to the worker, the timer is started by hand. Whenever the worker is done with the task and does not apply any changes, the timer is stopped by hand.

This prototype serves as a reference for the user study because the instructions are the most similar to the state-of-the-art instructions (electrical plan), mentioned in section 3.1. To appropriately compare this prototype with the other prototypes for the user study (section 6.1), this prototype is kept simple and similar in design to the other AR prototypes.

Both variants of this prototype, including markers and buttons, are shown in the figure below (figure 5.5).

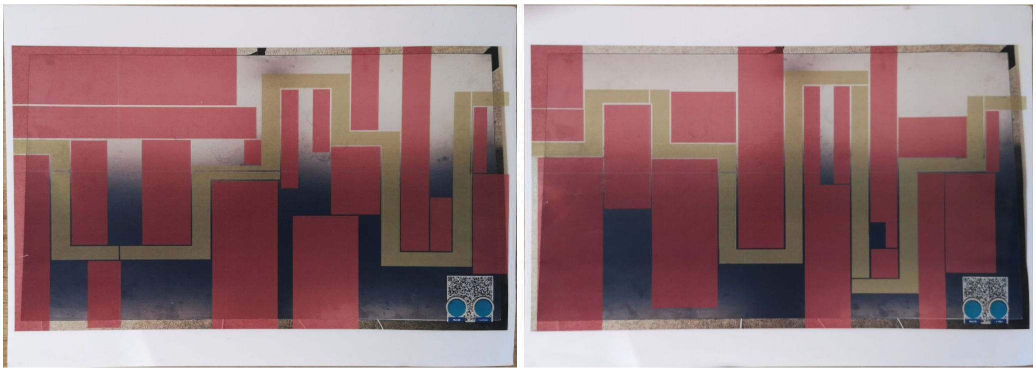

Figure 5.5: Prototype “Paper-Instructions” with variant one (left) and variant two (right).

6 Evaluation

Some evaluation methods were used as part of the bachelor thesis. To compare the different prototypes (chapter 5) with one another, a user study has been conducted. The user study is discussed in the sections below (section 6.1). The aim of the final review, in the form of a survey, (section 6.2) is to test the developed prototype, which results from the user study, in the real working environment. This contains the dry run (test run) of the prototype and the real prefabrication with this prototype.

6.1 User study

The user study aims to compare the prototypes illustrated above (chapter 5) from different perspectives. We chose the prototype visualization based on the study results and made some final adjustments for the final prototype used in the prefabrication of the pavilion (section 6.2).

6.1.1 Preparation (apparatus)

Twelve participants were invited for the user study in compliance with all Covid19 hygiene rules and regulations. The participants are students and graduates and research assistants in the IT area between the ages of 18 and 40. In addition, eight of the twelve participants had little or no practical experience in using the HoloLens 2. The task associated with the use case (placing and fixing the conduits and cables) was not familiar to any of the participants.

To compare the four prototypes (chapter 5) with one another, two different variants of the task were created as part of the user study. In these two variants, the positions of the shear webs and the paths differ. This leads to a total of eight conditions (four prototypes for each of the two variants). The prototypes and the variants are explained in the “Prototypes” chapter above (chapter 5).

Since it is impossible to recreate the actual working environment at the prefabrication laboratory for a user study, the actual working environment and the process were simulated. The simulated environment and task organized for the user study are adequately representing the laboratory and the actual task of the use case (figure 6.1). Two tables were made available as worktops and arranged orthogonally to each other (at right angles) so that participants could work at both tables. The main worktop was at the front, while the table on the side was only for filing and thus not important for the task itself. In the user study, the front worktop is a dark blue-colored table. An approximately three-meter-long white network cable (with a rough diameter of 4.5 mm and a circumference of 1.4 cm) and adhesive tape were provided on the sides of the two worktops. A digital camera is mounted on a stand, which was directly behind the front worktop. All of the prototypes were prepared, including the printed image targets, HoloLens device, and printed sheets of the prototype “Paper-Instructions” of both variants (section 5.4).

The modified task involved placing the network cable on the front worktop. Sufficient adhesive tape was always provided on the sides of the two worktops so that the cable can be attached to the table with tape.

To evaluate all eight conditions with less bias, a randomized order has been generated for every participant beforehand. This order determines the order of the eight conditions.

To collect quantitative data appropriately, a total of eight NASA-TLX questionnaires and eight SUS questionnaires were prepared in advance for each participant. The stopwatch function is activated for all of the AR prototypes ("Wire-Path" (section 5.1), "Wire-Lines" (section 5.2), "Shear-Webs" (section 5.3)). A manual stopwatch is prepared for the reference prototype ("Paper-Instructions" (section 5.4)) so that the task completion time (TCT) can also be measured.

In addition, a function was used to enable eye-tracking and to save eye-tracking information when using one of the AR prototypes. These could be analyzed afterward if necessary.

The camera setup was used, during the procedure, to take a photo of the cable attached to the tabletop after each of the eight runs (conditions). These photos represent the performance of the participants. To use these photos to measure the error rate, we take sufficient time to fix the cable on the tabletop in the correct place beforehand. Because we evaluate the prototypes of two different variants, the correct path has been laid two times. Two photos of the correct placements have been taken as reference photos. These two reference photos (of the two variants) can be compared to the other photos of the respective variant, representing the performance of the participants.

Our hypothesis for the user study is as follows:

H_1: The different visualizations will have a significant impact on TCT.

H_2: Users will prefer to use the visualizations that provide more information on the wire path than on the obstacles.

Figure 6.1: Simulated working environment for the user study, consisting of tabletop, cable, image target and digital camera.

6.1.2 Procedure

For the user study, the necessary technical devices were set up at the beginning and the corresponding applications were prepared on the computer. First, the purpose and the course of the user study were explained to the participants. After the instruction, the demographic data of the participants were collected. Then the participants got a short introduction to the operation of the technical devices, the functionality of the prototypes, and the task itself.

Each participant performed the simulated task of the use case in a total of eight runs. A previously determined prototype was used for each of the eight runs. The order of the conditions to be used was randomized for each participant. The study was carried out according to the within-subjects (or repeated-measures) study design.

As soon as the participant began performing the task, the timer started (either automatically by the user interface or manually by the researcher). As soon as the participant completed the task, the timer stopped. The participant was then asked to fill out the previously prepared questionnaires. At that time the digital camera behind the worktop was used to take a photo of the laid path on the table. Then the cable was removed from the table and reset, while the used tape was discarded. Finally, more tape was provided, if necessary. This procedure has been repeated eight times to allow the participant to complete the task with all prototypes and variants.

After all repetitions, the eye-tracking data, the TCT, and the photos were saved, the questionnaires were collected and the user study setting was reset for the next participant.

The entire procedure from the perspective of the participant can be seen in the figure below (figure 6.2).

6.1.3 Results and discussion

The box plot graphics in figure 6.3 show that there are hardly any differences between the prototypes of variant one and variant two. The NASA-TLX values of both variants show no significant deviations because the pattern of prototypes of the first variant is very similar to the pattern of the prototypes of the second variant. The difficulty differences between variant one and variant two, illustrated in chapter 5, are probably not great enough for a substantial difference between the results of the variants.

It can also be seen that both paper instructions for variant one and paper instructions for variant two have a higher workload than the rest of the prototypes. These prototypes (“Wire-Path”, “Wire-Lines”, “Shear-Webs”) have approximately the same workload for both variants. This is particularly noticeable regarding the performance in figure 6.3, bottom left. This observation occurs regarding the mental demand, performance, effort, and frustration (figure A.1). When asked about the physical demand and the temporal demand, this observation does not occur, as presented in figure 6.3, top right. In those cases, it can be observed that there are hardly any differences between the paper instructions prototypes and the other AR prototypes. This even occurs with both variants. This observation can be explained by the fact that the choice of the prototype does not influence the task itself. The prototype influences the mental performance and therefore other aspects e.g. usability and TCT. Since the manual task itself remains unchanged, regardless of the prototype, the physical and temporal demand does not change between the different prototypes either.

One reason why the workload, e.g. mental demand, for the “Paper-Instructions” prototype is that high would be that not enough information was provided on the manual. The participants could not see directly where the cable should be placed on the table. This meant that the participants had to determine the positions through the proportions of the tabletop and accordingly had to think more. The instructions on paper were also not attached, but rather placed on the table by the participants. That could have resulted in the instructions slipping back and forth. As a result, inaccuracies could have occurred, which could be the reason for the appearances in figure 6.6 and figure 6.7. Due to

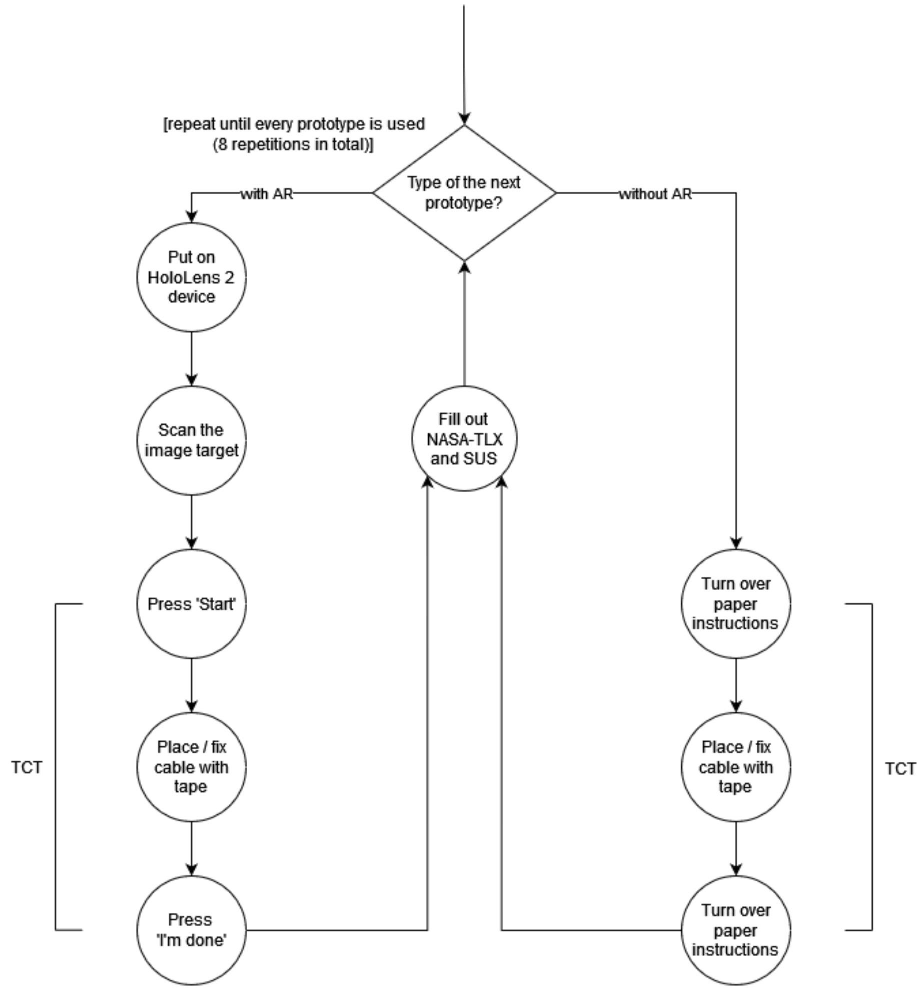

Figure 6.2: Graphical representation of the procedure of the user study (from the perspective of the participant).

these inaccuracies, some participants also had to make minor corrections, which could additionally increase the workload and especially the mental demand and frustration. However, the instructions can also slip in practice. Therefore, these influences are to be expected. Furthermore, in practice, electrical plans, which look similar to the “Paper-Instructions” prototype are not used exclusively. Practical electrical plans sometimes contain more detailed information. In some cases, these plans are supplemented by further plans and tools. In the context of the study, however, the prototypes would then no longer have been easy to compare with one another. In addition, the focus of the research would be more on the “Paper-Instructions”, which is not the purpose of the study.

Regarding the AR prototypes (“Wire-Path”, “Wire-Lines”, “Shear-Webs”), the workload values hardly differ from one another either. Nonetheless, for most NASA-TLX questions, the “Wire-Paths” prototype has a lower workload than “Wire-Lines”. “Wire-Lines” also has a lower workload than the “Shear-Webs” prototype. This can be seen in figure 6.3, bottom right. One can also see slight deviations in figure 6.3 and figure A.1. In some of the graphics, “Wire-Lines” has a lower workload than “Wire-Path” and “Wire-Path” has a lower workload than “Shear-Webs”. In rare cases, “Shear-Webs” has a lower workload than “Wire-Lines” and “Wire-Lines” has a lower workload than “Wire-Path”.

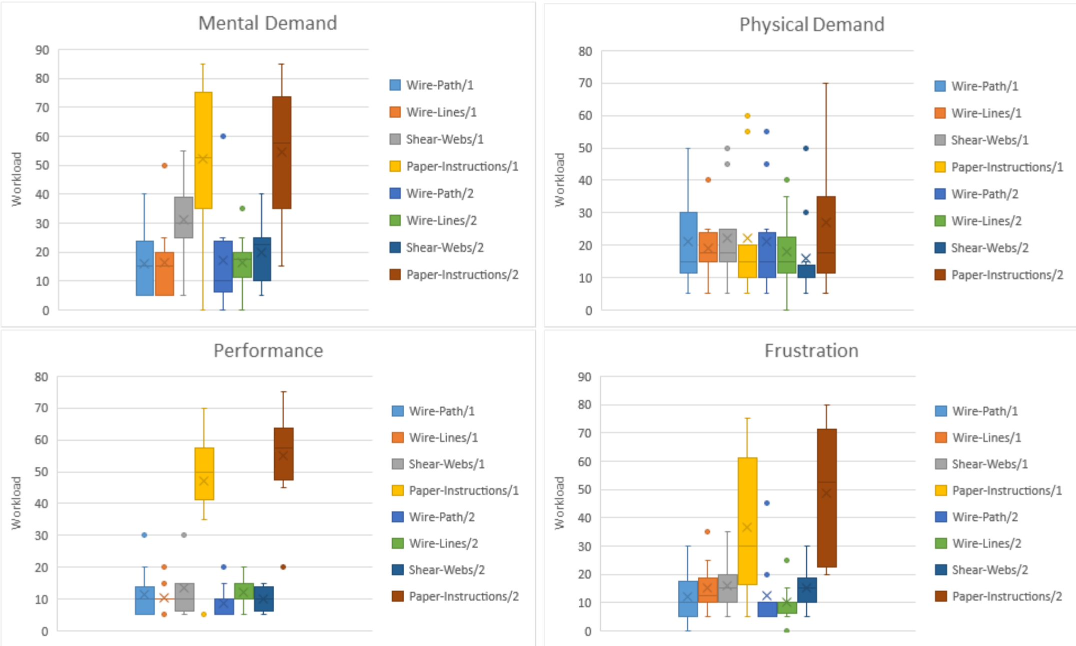

Figure 6.3: Graphical representation of the user study NASA-TLX results (× representing mean, — representing median, number after the slash (/1 or /2) representing the variant), including mental demand (top left), physical demand (top right), performance (bottom left) and frustration (bottom right) only.

The same observations that can be seen in the graphics of the NASA-TLX results can be observed again with the SUS results in figure 6.4. There are no substantial differences between the two variants since for some SUS questions, prototypes of the first variants show better usability than prototypes of the second variants. For some other SUS questions, prototypes of the second variants have better usability than prototypes of the first variant.

The SUS graphics also show that “Paper-Instructions” has worse usability than the AR prototypes. These prototypes (“Wire-Path”, “Wire-Lines”, “Shear-Webs”) have approximately the same usability values. Most of the figures show that “Wire-Paths” has better usability than “Wire-Lines” and “Wire-Lines” has a better usability value than “Shear-Webs”. Sometimes it is also the case that “Wire-Lines” has better usability than “Wire-Paths”, while “Wire-Paths” has better usability than “Shear-Webs”.

The task completion time (TCT) shows that the prototypes of the second variant have a higher TCT than the prototypes of the first variant. Figure 6.5 shows that using the “Paper-Instruction” prototypes of both variants also requires a higher TCT than the AR prototypes. Regarding the first variant of the AR prototypes, “Wire-Path” is more time-efficient than “Wire-Lines” and “Wire-Lines” is more time-efficient than “Shear-Webs”. In the second variation, however, using “Shear-Webs” takes less time than using “Wire-Path”, while “Wire-Path” takes less time than using “Wire-Lines”.

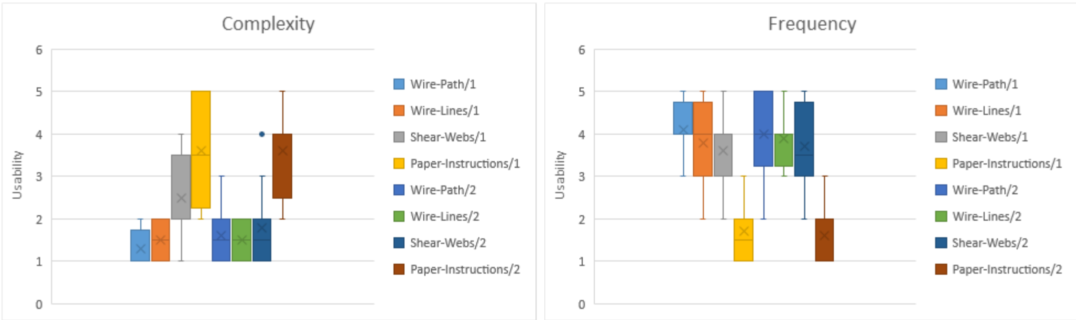

Figure 6.4: Graphical representation of the user study SUS results (× representing mean, — representing median, number after the slash (/1 or /2) representing the variant), including the aspects "I found the system unnecessarily complex" (left) and "I think that I would like to use this system frequently" (right) only.

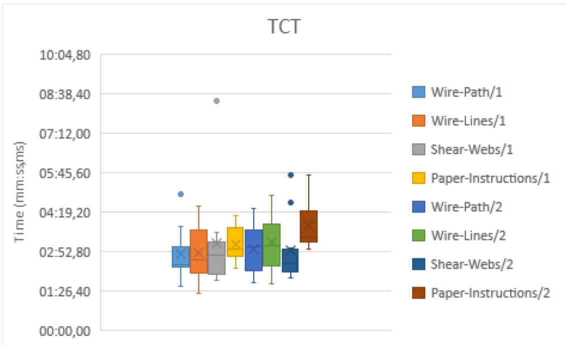

Figure 6.5: Graphical representation of the user study task completion time results (mm:ss,ms) (× representing mean, — representing median, number after the slash (/1 or /2) representing the variant).

The visualized cables in figure 6.6 and figure 6.7 show the deviations from the original path well. Furthermore, the results of using prototypes of variant 1 (figure 6.6) and the results of using prototypes of variant 2 (figure 6.7) show similar results. One can hardly see any differences in the pattern between the two variants. In any case, one can see that the cables were fixed much less precisely, when using the "Paper-Instructions", compared to using the other AR prototypes. One can also see that the use of the "Shear-Webs"prototype led to a less precise cable placement, compared to "Wire-Path" and "Wire-Lines". The visualizations of "Wire-Path" and "Wire-Lines" are very similar and it is difficult to determine the difference, using these visualizations. However, one could tend to say that "Wire-Paths" is a little better, regarding the error rate, than "Wire-Lines".

Furthermore, based on these figures (figure 6.6 and figure 6.7), one can see that the cable used has certain robustness and therefore is not too flexible. As a result, the corners are a little rounded instead of angular. Overall, this is not a major problem for the dry run and final prefabrication. Since in the actual task the cable is secured using clamps and additional adhesive spray, rather than adhesive tape only, the routing of the cables and conduits is more flexible than in this user study and corners can be shaped more angular. Nevertheless, no hard corners are required in the final prefabrication. For the real use case, rounds like those that occurred in the user study and can be detected in the figures are acceptable.

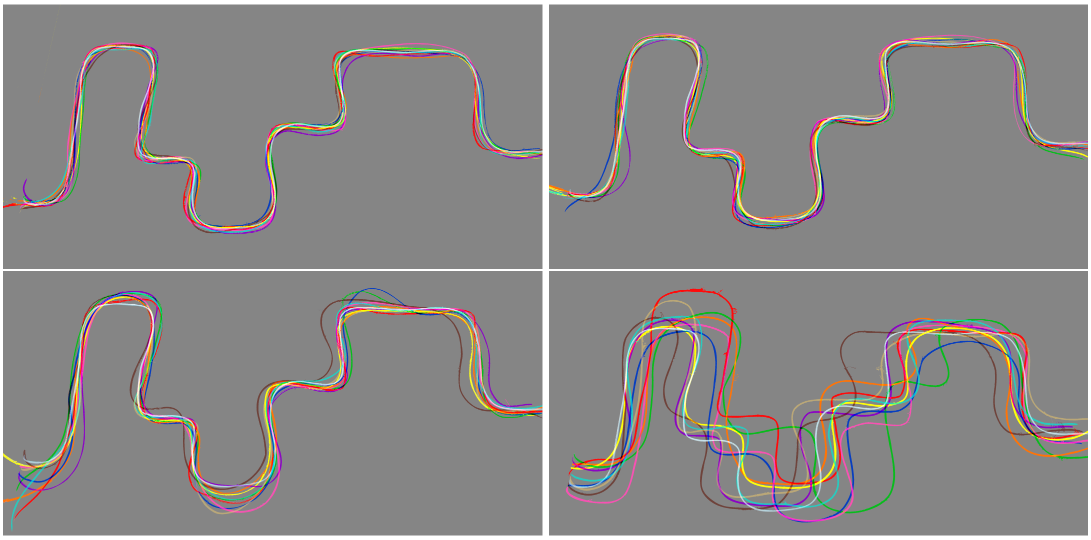

Figure 6.6: Layered visualization of the placed cables, using "Wire-Path" (top left), "Wire-Lines" (top right), "Shear-Webs" (bottom left) and "Paper-Instructions" (bottom right) as prototypes with variant one, whereby each color represents the cable path of a different participant while the white curve represents the correct cable path from the reference photo.

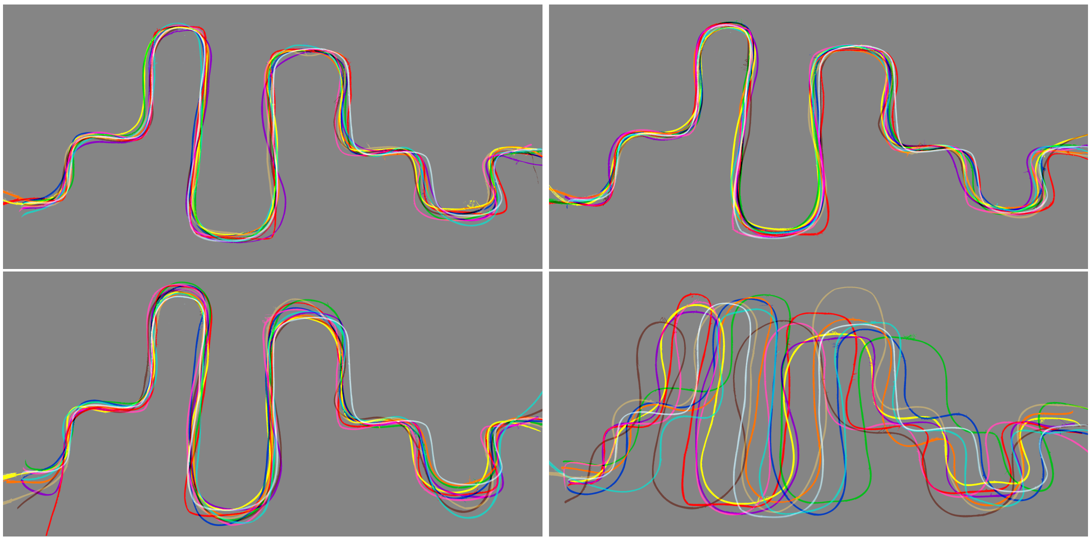

Figure 6.7: Layered visualization of the placed cables, using "Wire-Path" (top left), "Wire-Lines" (top right), "Shear-Webs" (bottom left) and "Paper-Instructions" (bottom right) as prototypes with variant two, whereby each color represents the cable path of a different participant while the white curve represents the correct cable path from the reference photo.

Since the differences between these two prototypes are not entirely clear, we use the "Image Similarity API"[1], an external tool to quantify the error rate. This tool takes two images as input, compares them, and computes a "Distance" value, which is supposed to represent the difference

[1](https://deepai.org/machine-learning-model/image-similarity)

between the two images. The greater the distance value, the more dissimilar are these images. The photos, taken by the camera, of the cable placements, are compared to the respective reference photo. The comparison results lead to figure 6.8. Based on the graphic, we can again determine, that there are hardly any differences between variant one and variant two. In general, there are relatively few differences in the values between all prototypes. However, it can be found that using “Wire-Paths” leads to less deviation than “Shear-Webs”, which has less deviation than using “Wire-Lines”, which again has less deviation than “Paper-Instructions”. Concerning variant two, however, one can notice, that “Shear-Webs” is the best prototype regarding the distance value. This value is less than the value of “Wire-Paths” and “Wire-Lines”. “Wire-Paths” and “Wire-Lines” are very similar, but still better than using “Paper-Instructions”.

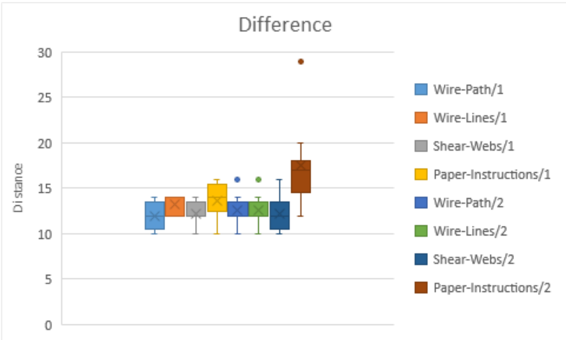

Figure 6.8: Graphical representation of the user study distance values to represent the difference and the error rate (× representing mean, — representing median, number after the slash (/1 or /2) representing the variant).

A one-way ANOVA was conducted to compare the effect of the respective prototype on the workload, usability, TCT and the distance value. The analysis of variance showed that the effect of the prototype on mental demand (F(3, 36) = 8,41, p = 0,00 for variant one, F(3, 36) = 11,46, p = 0,00 for variant two), performance (F(3, 36) = 24,38, p = 0,00 for variant one, F(3, 36) = 63,46, p = 0,00 for variant two), effort and frustration (F(3, 36) = 4,97, p = 0,01 for variant one, F(3, 36) = 15,31, p = 0,00 for variant two) was significant. The ANOVA results also showed that the effect of the prototype on all of the SUS questions, except the aspects “I think that I would need the support of a technical person to be able to use this system”, “I thought there was too much inconsistency in this system”, “I would imagine that most people would learn to use this system very quickly” (F(3, 36) = 4,09, p = 0,01 for variant one, F(3, 36) = 1,97, p = 0,14 for variant two) and “I needed to learn a lot of things before I could get going with this system” was significant. Mean values of the prototypes, regarding aspects like e.g. “I found the system unnecessarily complex” (F(3, 36) = 12,75, p = 0,00 for variant one, F(3, 36) = 12,24, p = 0,00 for variant two) and “I think that I would like to use this system frequently” (F(3, 36) = 15,73, p = 0,00 for variant one, F(3, 36) = 14,9, p = 0,00 for variant two) were found to be statistically-significant different. Furthermore, the analysis showed that the effect of the prototype on the physical demand (F(3, 36) = 0,08, p = 0,97 for variant one, F(3, 36) = 0,86, p = 0,47 for variant two), temporal demand, TCT (F(3, 36) = 0,27, p = 0,85 for variant one, F(3, 36) = 1,61, p = 0,2 for variant two) and the distance value (F(3, 36) = 2,16, p = 0,11 for variant one, F(3, 36) = 8,1, p = 0,00 for variant two) was not significant too. The critical F value for all conditions and variables is $2,87$. Based on the analysis we can conclude that many aspects show significant differences. Some aspects show differences that are not significant. Since more than half of all aspects of the study show significant results, likely, the study was not carried out with enough participants to conclude the totality of this sample.

The tables and figures in the appendix (chapter A) contain the exact values (section A.1) of this conducted user study and further graphics (section A.2) regarding workload, usability, TCT, distance, ANOVA, and additional confidence intervals.

To summarize the results of the user study, it can be concluded that there are no major differences between variant one and variant two. The AR prototypes have a significantly better workload, usability, TCT, and error rate than the reference prototype “Paper-Instructions”. Among the AR prototypes, we noticed that “Wire-Paths” has the best results on average, followed closely by “Wire-Lines”. Using the prototype “Shear-Webs” leads to a comparatively worse workload, usability, TCT, and error rate. Therefore, we cannot support entirely hypotheses H_1 and H_2 based on the ANOVA results. One reason for that could be that the scenario used in the study was rather simple, which did not allow us to perceive a large difference in the results. Nevertheless, we used the analysis performed here to decide on the visualizations used for the final prototype, described in the following section.

6.2 Final prototype

The final review is the last phase of the project. It consists of a dry run and the final prefabrication of the pavilion parts at the “Large Scale Construction Robotics Laboratory” at Waiblingen (figure 6.9). The laboratory serves as a production facility for the pavilion parts.

In contrast to the real fabrication, the dry run is carried out without the adhesive spray. If anything fails during the dry run, the system can be adjusted, before carrying out the final prefabrication. This procedure lowers the risk of ruining the pavilion parts. As soon as the dry run is completed successfully, the real prefabrication will follow after.

The dry run and the actual prefabrication are both performed by one or multiple workers, who are part of the project team and familiar with the task and its requirements. The workers will finally use the developed and adapted prototype for the dry run and the real prefabrication. During both of them, the prototype is evaluated in the form of an interview. This interview will be conducted for each worker, using the prototype.

This review aims to get expectations of the worker before using the system and direct feedback from the worker on the system after it has been used.

6.2.1 Preparation (apparatus)

First of all, it was necessary to familiarize oneself with the project and its current status at the laboratory. This includes identifying and measuring the various timber panels. In this case, it was mainly necessary to measure the three respective lower ceiling panels, because the conduits will only be fixed on these three panels. One of the timber panels in the working environment is depicted in the figure below (figure 6.9, left).

The optimal path of the conduit and cables has already been calculated and given. The data of the path and the data of the remaining elements (shear webs, junction boxes, placer, etc.) are stored in a JSON file. This data has been imported to a new Unity project, using a converting script as a parser. The data was visualized by different Unity objects (cube, sphere, splines, etc.) afterward. To be able to use the HoloLens 2 and AR in this project, a few obligatory libraries were added and settings were changed accordingly, including Vuforia image target markers. The Unity objects (elements, path) and the markers were placed and scaled accordingly in the Unity project. To have the visualizations displayed at the correct position on top of the panels, the markers were printed and fixed at a certain location on the panels (figure 6.9, right).

Figure 6.9: Lower ceiling timber panel (panel C) placed in the working environment at the laboratory (left) and lower ceiling timber panel (panel A) from the perspective of a worker, using the HoloLens and the AR system (with the different Unity objects and the fixed marker) (right).

The visualizations were also reduced. Instead of showing all data from the JSON file, only some of them were shown. This includes the complete path, the placers, the junction boxes, and a few distributed markers. The remaining elements (placers, markers) serve as control elements (figure 6.9, right). Since the junction boxes should also be installed at short notice and the system makes this possible, the junction boxes were also displayed in the system. The installation of the junction boxes is a small preparatory minor task and serves to ensure that the wiring use case explained above (section 3.1) can be carried out afterward. These are represented in the system by cuboids. The control elements are displayed so that the worker can check whether the visualizations are still in the correct position. The panels already have placers and markers installed on them. If the worker has moved too much and the visualizations have therefore shifted, the worker can tell by the shift between the displayed visualization of the control elements and the elements, already installed in the real world. Furthermore, the path and junction boxes have been colored light pink and made a little transparent for actual use. The width of the path has also been adjusted. These adjustments are made due to the different light conditions. Less daylight enters the laboratory and the lamps cast little light in a relatively large hall.

To make the HoloLens application as simple as possible, the button user interface, introduced in chapter 5, has been removed to save resources, increase efficiency and because it is not necessary for the actual usage. Three Vuforia markers have also been added (one for each relevant panel). This allows the worker to switch dynamically between the panels, while the visualizations of one panel are active at the same time. The remaining visualizations of the other panels are not displayed during this time. The worker does not need to control anything or do additional work besides interacting with the Vuforia image target. The user only has to scan the marker and, if necessary, check whether the visualizations are still in the right place.

6.2.2 Procedure

To begin with, the demographic data of the worker was collected before the workers put on the HoloLens device and started with the task. The worker was then asked to name a few expectations of the system. After that, the worker started with the task for the dry run.

The worker was asked a few questions about the system after the completion too. The worker was asked about the first impression, positive aspects, and negative aspects from their subjective point of view. It was asked to compare the usage to the expectations by asking what they did not expect beforehand but have noticed afterward. The worker was also asked how the system supported the task and how it did not. Finally, the worker was asked if there were any problems or abnormalities, open questions about the system, or even suggestions to improve the system. Furthermore, it was asked if they could imagine the system being used in another field in the industry or besides industry.

This procedure has been repeated for every worker who was using the system to complete the task explained in section 3.1.

6.2.3 Feedback and discussions

Due to time constraints, the final prefabrication could not yet be carried out. Nevertheless, the final prefabrication is expected to be carried out very soon. However, the dry run was carried out and completed successfully.

The workers who used the developed system were both male, 25 and 26, and students. Both have had limited to moderate experience with the manual task of the use case, presented in section 3.1. Both students had little or no experience with the HoloLens 2.

Regarding their expectation of the system before performing the task, the workers mentioned, that the system should show the junction boxes and the cable in a precise way and guide the worker to roughly the correct spots. The system should be easy to use and the familiarization with the new information should be quick. The worker should also see potential clashes in the digital model when using the system.

Regarding their impression of the system after performing the task, the workers mentioned, that they were surprised, that the visualization was still showing when they moved far away from the panel. The workers realized, that the holograms were even visible through walls. They also found positive, that they could change between the different panels very fast and easily only by scanning the respective marker. It was also astonishing, how quickly they familiarized themselves with the holograms and their position in the real world. The workers found the visual cues to be great since they did not require lengthy measuring of distances and finding intersections. They also think, that the system helped them to place things, which did not need zero tolerance but where measuring and determining the location would have taken a lot longer.

The workers also mentioned a few negative aspects. Most of the aspects were related to hardware limitations, e.g. the weight of the HoloLens device. It was affecting the task and the freedom of movement if the device is used for a long period. One could easily stumble on different things on the ground, wearing the device, because the device limits the field of view too. Another aspect is the tracking irregularities. Once the person moves too much, the holograms start to shake and are shifted eventually. In this case, the visualizations of the objects were approximately 5-10 mm shifted from the initial location of the visualizations. Once the worker recalibrated the system, by scanning the QR code again, this problem got solved and the visualizations were placed correctly again. Besides that, one worker mentioned, that he needed to be very careful with the device because the HoloLens device is very expensive. Apart from hardware difficulties, the workers complained about the fact, that some of the objects were overlapping other objects. Since all the objects also had the same color, the workers found it difficult to recognize and distinguish some relevant objects below other overlapping objects.

The system supported the workers during the task in different ways. The measuring of the positions of the junction boxes was not necessary when using the system. To make sure that the junction boxes are installed in the correct position, the positions were measured for safety before they were finally installed. But the system helped the workers to locate the positions of the junction boxes nevertheless. After that, the workers were able to drill holes and perform further prefabrication steps at that position.

The workers had some trouble using the HoloLens device. They found it to be difficult to start the application and needed a lot of time to get used to the control of the HoloLens system. When asked, if there are any pending issues, one worker asked if there is the possibility to hide certain objects or show all of the objects. He also asked if it was possible to change the transparency individually. The workers additionally suggested showing more information about the components, e.g. which junction boxes do cables lead through, the center of the junction boxes, or using different colors to distinguish specific objects.

When asked, in which areas this system, or a similar system, could be applied, the workers claimed, that the system could be used for other prefabrication steps or construction sites. The system could also be used by multiple installers for other complicated laying work in particular. These tasks should allow a bit of tolerance regarding the accurate positioning of components. This system would also be helpful for tasks, which require steps (e.g. measuring), which take considerably longer.

In conclusion, it can be summarized that the dry run worked well. The dry run was completed successfully using the developed system. The final prefabrication has not yet been implemented due to time constraints. Even so, the workers were relatively happy with the system. The system was very flexible and saved the workers a lot of time. The system is very convenient due to its simple structure. The workers were able to quickly familiarize themselves with the system and get used to the holograms. The system supported them significantly in their work, even if there were slight difficulties e.g. with controlling the device, as the workers had almost no experience of the HoloLens technology. There were also inevitable issues regarding the hardware, including the weight, shaking, and shifting holograms. The overlapping components, mentioned by the workers, were due to mistakes in the JSON file, which can be solved easily right away. For the project, however, the system was sufficient. A few suggestions from the workers could still be implemented in the future, e.g. integrating more interactions, allowing the worker to toggle certain objects, or customizing color and transparency.

7 Conclusion and Outlook

7.1 Conclusion

In this work, we have developed different approaches and concepts for visualization types to support the wire placement task in timber fabrication with AR, presented in chapter 4. From the individual concepts, prototypes were developed which are suitable for the actual prefabrication in the working environment. All important requirements of the project (section 3.1) were taken into account. Using interviews, a focus group, and a study, these concepts and prototypes were evaluated, in terms of different aspects, e.g. ease of use and efficiency. Since the use case is relatively specific, there are not many suitable research results for the visualization of timber fabrication in this or a similar context yet. Most related works examine AR from the technical side, compare AR with other technologies, or evaluate AR as a technological device itself. Further past research addresses AR visualizations in a completely different context and use case. Other related work, which deals with a similar use case, does not focus sufficiently on the visualization possibilities for our purposes. The developed prototypes (chapter 5) should serve as a solution proposal for the presented project. The concepts and prototypes presented in this work can be used for problems of a similar scenario in the future.

Among the prototypes supported by AR, the prototype "Wirepath" is preferred by workers. Based on the results of the NASA-TLX, SUS, TCT, and the error rate, we can conclude that the structure and the operation of this prototype are more efficient and intuitively understandable than the other prototypes presented. The differences between the AR system prototypes were not great. Nevertheless, we were able to determine that highlighting the path itself is the optimal solution for this specific use case.

The developed system was finally adapted and set up for final use. Based on the dry run, it was possible to verify that the system worked well for this use case in the work environment. There were a few technical issues due to hardware limitations, which always happen when dealing with prototypes. The final fabrication has not yet been carried out for time reasons.

7.2 Outlook

Since the final fabrication, mentioned in section 6.2, has not yet been carried out, the most important step is to complete this final fabrication phase. This makes it possible to conduct further interviews and collect further results to evaluate. Because the final fabrication differs from the dry run, the results might be more accurate and interesting.

Regarding the specific use case task, further visualization concepts can be designed and developed. These newly developed visualization concepts could be similar to the concepts in chapter 4.

In addition, the presented visualization concepts (chapter 4) can be improved. This can be implemented, for example, through some of the suggestions from the focus group. It would be conceivable to adjust the color and the shape in a more targeted manner. In addition, magic lenses could be used as these were also strongly favored. Extensions regarding the individual selection of different visualizations or the individual adjustment of the visualization (e.g., color, transparency, width) would also be conceivable. Furthermore, there is also the possibility of collecting further suggestions, which complement the already existing concepts.

Another useful addition is to consider error detection and correction tasks. These tasks can take place after the actual task of the use case or even at the same time. The error detection and correction can have a positive effect on the result of the wiring task. AR visualizations can also be used for displaying the detected error and the necessary correction. This addition would allow additional types of interaction between the system and a worker.

For the specific use case, presented in section 3.1, further adjustments are not necessary, as the results of the dry run were already satisfactory. Additional extensions could overload the displayed information and therefore have a negative effect.

However, the developed visualization concepts and prototypes or newly designed concepts can be examined for other (industrial) use case tasks. These other use cases could be more general than the specific use case in section 3.1. This investigation could allow the development of general principles and heuristics for the generalized (industrial) task.

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A Appendix

A.1 User study data

	WP. / 1	WL. / 1	SW. / 1	PI. / 1	WP. / 2	WL. / 2	SW./2	PI. / 2
Subject 1	25	25	55	75	25	20	30	70
Subject 2	25	20	35	85	5	25	25	85
Subject 3	20	5	50	50	10	10	25	30
Subject 4	5	15	40	55	5	20	40	60
Subject 5	5	5	15	75	25	15	25	55
Subject 6	15	20	25	30	20	20	10	50
Subject 7	40	50	35	80	60	35	20	85
Subject 8	5	5	5	0	0	0	5	15
Subject 9	5	5	25	50	10	5	10	75
Subject 10	15	15	25	20	10	15	10	20
Mean	16	16,5	31	52	17	16,5	20	54,5
Median	15	15	30	52,5	10	17,5	22,5	57,5
Mode	5	5	25	75	10	20	25	85
Standard deviation	11,14	13,24	14,46	26,76	16,46	9,5	10,49	24,34

Table A.1: NASA-TLX mental demand values of the user study (section 6.1), rounded to two decimal places (WP (Wire-Path), WL (Wire-Lines), SW (Shear-Webs), PI (Paper-Instructions), number after the slash (/1 or /2) representing the variant).

	WP. / 1	WL. / 1	SW. / 1	PI. / 1	WP. / 2	WL. / 2	SW./2	PI. / 2
Subject 1	35	25	25	55	25	25	15	35
Subject 2	15	20	15	20	15	15	10	35
Subject 3	5	10	5	10	10	10	10	10
Subject 4	10	20	20	15	10	15	10	10
Subject 5	45	25	50	20	55	35	50	55
Subject 6	15	15	25	10	20	15	10	15
Subject 7	50	40	45	60	45	40	30	70
Subject 8	5	15	5	5	5	0	5	5
Subject 9	15	5	15	10	10	10	10	20
Subject 10	15	15	15	15	15	15	10	15
Mean	21	19	22	22	21	18	16	27
Median	15	17,5	17,5	15	15	15	10	17,5
Mode	15	15	15	10	10	15	10	35
Standard deviation	15,46	9,17	14,35	18,33	15,62	11,45	13	20,4

Table A.2: NASA-TLX physical demand values of the user study (section 6.1), rounded to two decimal places (WP (Wire-Path), WL (Wire-Lines), SW (Shear-Webs), PI (Paper-Instructions), number after the slash (/1 or /2) representing the variant).

	WP. / 1	WL. / 1	SW. / 1	PI. / 1	WP. / 2	WL. / 2	SW./2	PI. / 2
Subject 1	20	40	20	30	20	20	55	25
Subject 2	5	5	15	15	10	5	20	40
Subject 3	25	25	20	10	25	10	20	40
Subject 4	30	60	55	40	50	50	55	45
Subject 5	40	40	65	70	55	30	30	55
Subject 6	5	10	15	10	10	15	10	10
Subject 7	55	45	20	50	50	45	35	65
Subject 8	5	5	5	5	5	0	10	15
Subject 9	25	20	25	25	25	20	25	60
Subject 10	10	15	20	25	20	5	10	20
Mean	22	26,5	26	28	27	20	27	37,5
Median	22,5	22,5	20	25	22,5	17,5	22,5	40
Mode	5	40	20	10	20	20	10	40
Standard deviation	15,84	17,9	17,86	19,39	17,35	16,12	16,16	18,34

Table A.3: NASA-TLX temporal demand values of the user study (section 6.1), rounded to two decimal places (WP (Wire-Path), WL (Wire-Lines), SW (Shear-Webs), PI (Paper-Instructions), number after the slash (/1 or /2) representing the variant).

	WP. / 1	WL. / 1	SW. / 1	PI. / 1	WP. / 2	WL. / 2	SW./2	PI. / 2
Subject 1	10	5	5	40	5	10	5	45
Subject 2	20	10	15	35	5	15	15	45
Subject 3	30	10	15	70	10	10	15	60
Subject 4	5	15	5	50	5	20	10	55
Subject 5	10	10	30	50	20	10	15	70
Subject 6	15	10	30	45	15	20	10	65
Subject 7	5	20	5	60	5	10	5	60
Subject 8	5	10	10	5	5	5	10	20
Subject 9	5	5	10	50	5	5	5	75
Subject 10	10	10	10	65	10	15	10	55
Mean	11,5	10,5	13,5	47	8,5	12	10	55
Median	10	10	10	50	5	10	10	57,5
Mode	5	10	5	50	5	10	10	45
Standard deviation	7,76	4,15	8,96	17,35	5,02	5,1	3,87	14,83

Table A.4: NASA-TLX performance values of the user study (section 6.1), rounded to two decimal places (WP (Wire-Path), WL (Wire-Lines), SW (Shear-Webs), PI (Paper-Instructions), number after the slash (/1 or /2) representing the variant).

	WP. / 1	WL. / 1	SW. / 1	PI. / 1	WP. / 2	WL. / 2	SW./2	PI. / 2
Subject 1	30	30	15	70	20	40	25	60
Subject 2	25	25	10	75	20	20	20	65
Subject 3	10	15	40	40	10	10	10	60
Subject 4	15	30	35	65	5	20	40	65
Subject 5	35	30	65	75	70	35	25	70
Subject 6	20	20	50	40	10	20	10	30
Subject 7	20	15	20	85	60	35	25	70
Subject 8	0	5	10	5	5	5	10	20
Subject 9	10	10	25	50	10	10	5	75
Subject 10	25	25	20	30	25	15	10	35
Mean	19	20,5	29	53,5	23,5	21	18	55
Median	20	22,5	22,5	57,5	15	20	15	62,5
Mode	25	30	10	75	10	20	10	60
Standard deviation	9,95	8,5	17,29	23,67	21,8	11,36	10,3	18,3

Table A.5: NASA-TLX effort values of the user study (section 6.1), rounded to two decimal places (WP (Wire-Path), WL (Wire-Lines), SW (Shear-Webs), PI (Paper-Instructions), number after the slash (/1 or /2) representing the variant).

	WP. / 1	WL. / 1	SW. / 1	PI. / 1	WP. / 2	WL. / 2	SW./2	PI. / 2
Subject 1	20	15	15	35	10	15	25	20
Subject 2	25	20	20	35	5	10	15	60
Subject 3	10	5	10	10	10	10	10	20
Subject 4	5	25	20	75	5	10	15	75
Subject 5	10	15	35	20	20	10	30	55
Subject 6	10	10	15	15	10	10	10	20
Subject 7	30	35	25	75	45	25	20	80
Subject 8	0	10	10	5	5	0	15	30
Subject 9	5	10	5	25	5	5	5	75
Subject 10	5	5	5	70	10	5	5	50
Mean	12	15	16	36,5	12,5	10	15	48,5
Median	10	12,5	15	30	10	10	15	52,5
Mode	10	10	15	35	10	10	15	20
Standard deviation	9,27	8,94	8,89	25,79	11,67	6,32	7,75	23,14

Table A.6: NASA-TLX frustration values of the user study (section 6.1), rounded to two decimal places (WP (Wire-Path), WL (Wire-Lines), SW (Shear-Webs), PI (Paper-Instructions), number after the slash (/1 or /2) representing the variant).

	WP. / 1	WL. / 1	SW. / 1	PI. / 1	WP. / 2	WL. / 2	SW./2	PI. / 2
Subject 1	4	3	5	2	5	4	3	2
Subject 2	4	4	3	1	5	4	4	1
Subject 3	3	2	3	1	3	3	3	1
Subject 4	5	3	2	1	5	3	2	1
Subject 5	4	5	4	2	2	5	3	1
Subject 6	3	4	3	3	4	3	5	3
Subject 7	4	4	4	2	3	4	5	2
Subject 8	4	3	4	3	4	4	3	3
Subject 9	5	5	4	1	4	5	4	1
Subject 10	5	5	4	1	5	4	5	1
Mean	4,1	3,8	3,6	1,7	4	3,9	3,7	1,6
Median	4	4	4	1,5	4	4	3,5	1
Mode	4	3	4	1	5	4	3	1
Standard deviation	0,7	0,98	0,8	0,78	1	0,7	1	0,8

Table A.7: SUS values of the aspect “I think that I would like to use this system frequently” of the user study (section 6.1), rounded to two decimal places (WP (Wire-Path), WL (Wire-Lines), SW (Shear-Webs), PI (Paper-Instructions), number after the slash (/1 or /2) representing the variant).

	WP. / 1	WL. / 1	SW. / 1	PI. / 1	WP. / 2	WL. / 2	SW./2	PI. / 2
Subject 1	1	1	1	2	1	1	1	4
Subject 2	1	2	2	5	1	2	2	5
Subject 3	1	1	2	4	2	1	1	5
Subject 4	1	2	4	5	1	2	4	4
Subject 5	2	1	2	3	3	1	1	4
Subject 6	1	2	2	2	1	2	1	2
Subject 7	2	2	2	3	2	2	1	2
Subject 8	2	2	2	2	2	2	2	2
Subject 9	1	1	4	5	2	1	3	4
Subject 10	1	1	4	5	1	1	2	4
Mean	1,3	1,5	2,5	3,6	1,6	1,5	1,8	3,6
Median	1	1,5	2	3,5	1,5	1,5	1,5	4
Mode	1	1	2	5	1	1	1	4
Standard deviation	0,46	0,5	1,02	1,28	0,66	0,5	0,98	1,11

Table A.8: SUS values of the aspect “I found the system unnecessarily complex” of the user study (section 6.1), rounded to two decimal places (WP (Wire-Path), WL (Wire-Lines), SW (Shear-Webs), PI (Paper-Instructions), number after the slash (/1 or /2) representing the variant).

	WP. / 1	WL. / 1	SW. / 1	PI. / 1	WP. / 2	WL. / 2	SW./2	PI. / 2
Subject 1	3	4	5	4	5	3	3	4
Subject 2	5	4	4	1	4	5	5	1
Subject 3	5	5	5	3	5	4	5	4
Subject 4	5	4	2	2	5	4	2	4
Subject 5	4	5	4	2	3	5	5	2
Subject 6	4	4	3	4	5	4	4	3
Subject 7	5	4	5	3	3	5	4	3
Subject 8	4	2	2	4	4	4	3	3
Subject 9	5	5	5	3	5	5	5	2
Subject 10	5	5	5	2	5	5	5	4
Mean	4,5	4,2	4	2,8	4,4	4,4	4,1	3
Median	5	4	4,5	3	5	4,5	4,5	3
Mode	5	4	5	4	5	5	5	4
Standard deviation	0,67	0,87	1,18	0,98	0,8	0,66	1,04	1

Table A.9: SUS values of the aspect “ I thought the system was easy to use” of the user study (section 6.1), rounded to two decimal places (WP (Wire-Path), WL (Wire-Lines), SW (Shear-Webs), PI (Paper-Instructions), number after the slash (/1 or /2) representing the variant).

	WP. / 1	WL. / 1	SW. / 1	PI. / 1	WP. / 2	WL. / 2	SW./2	PI. / 2
Subject 1	3	4	2	3	3	3	3	4
Subject 2	1	1	1	1	1	1	1	1
Subject 3	1	2	1	1	1	1	1	1
Subject 4	1	1	1	1	1	1	1	1
Subject 5	1	1	1	2	1	1	1	1
Subject 6	2	1	2	2	2	2	2	2
Subject 7	1	5	1	2	1	1	1	4
Subject 8	3	4	3	2	3	5	2	1
Subject 9	1	2	1	1	1	1	1	1
Subject 10	1	1	1	1	1	1	1	1,5
Mean	2,1	1,5	1,6	1,5	1,33	1,7	1,8	1
Median	1	1	1,5	1	1	1	1	1
Mode	1	1	1	1	1	1	1	0,81
Standard deviation	0,81	1,51	0,67	0,66	0,81	0,67	1,27	1,17

Table A.10: SUS values of the aspect “I think that I would need the support of a technical person to be able to use this system” of the user study (section 6.1), rounded to two decimal places (WP (Wire-Path), WL (Wire-Lines), SW (Shear-Webs), PI (Paper-Instructions), number after the slash (/1 or /2) representing the variant).

	WP. / 1	WL. / 1	SW. / 1	PI. / 1	WP. / 2	WL. / 2	SW./2	PI. / 2
Subject 1	4	4	4	1	4	4	2	2
Subject 2	5	5	4	1	5	5	4	2
Subject 3	4	4	4	1	3	4	4	2
Subject 4	4	4	4	3	4	4	3	3
Subject 5	4	5	4	1	2	5	4	2
Subject 6	4	4	3	3	4	4	4	3
Subject 7	4	4	4	2	5	4	4	3
Subject 8	4	4	4	4	4	4	3	4
Subject 9	3	3	3	3	3	3	3	3
Subject 10	3	3	3	3	3	3	3	3
Mean	3,9	4	3,7	2,2	3,7	4	3,4	2,7
Median	4	4	4	2,5	4	4	3,5	3
Mode	4	4	4	1	4	4	4	3
Standard deviation	0,54	0,63	0,46	1,08	0,9	0,63	0,66	0,64

Table A.11: SUS values of the aspect “I found the various functions in this system were well integrated” of the user study (section 6.1), rounded to two decimal places (WP (Wire-Path), WL (Wire-Lines), SW (Shear-Webs), PI (Paper-Instructions), number after the slash (/1 or /2) representing the variant).

	WP. / 1	WL. / 1	SW. / 1	PI. / 1	WP. / 2	WL. / 2	SW./2	PI. / 2
Subject 1	3	3	2	5	2	3	2	4
Subject 2	2	1	2	2	1	1	1	2
Subject 3	2	2	1	3	1	2	1	4
Subject 4	1	1	1	2	1	1	1	1
Subject 5	1	1	2	3	2	1	1	2
Subject 6	4	4	4	2	2	4	2	3
Subject 7	1	3	2	5	2	2	3	5
Subject 8	3	2	2	2	2	2	2	2
Subject 9	1	1	1	1	1	1	1	1
Subject 10	1	1	1	2	1	1	1	3
Mean	1,9	1,9	1,8	2,7	1,5	1,8	1,5	2,7
Median	1,5	1,5	2	2	1,5	1,5	1	2,5
Mode	1	1	2	2	2	1	1	2
Standard deviation	1,04	1,04	0,87	1,27	0,5	0,98	0,67	1,27

Table A.12: SUS values of the aspect “I thought there was too much inconsistency in this system” of the user study (section 6.1), rounded to two decimal places (WP (Wire-Path), WL (Wire-Lines), SW (Shear-Webs), PI (Paper-Instructions), number after the slash (/1 or /2) representing the variant).

	WP. / 1	WL. / 1	SW. / 1	PI. / 1	WP. / 2	WL. / 2	SW./2	PI. / 2
Subject 1	4	4	4	3	3	4	5	2
Subject 2	4	4	4	3	5	4	4	3
Subject 3	5	5	5	4	5	5	5	5
Subject 4	5	5	5	4	5	5	4	4
Subject 5	5	5	4	1	4	4	5	3
Subject 6	4	4	4	3	4	4	4	3
Subject 7	4	4	5	3	4	4	4	3
Subject 8	3	4	3	3	3	3	3	3
Subject 9	5	5	5	5	5	5	5	5
Subject 10	5	5	5	5	5	5	5	5
Mean	4,4	4,5	4,4	3,4	4,3	4,3	4,4	3,6
Median	4,5	4,5	4,5	3	4,5	4	4,5	3
Mode	5	4	5	3	5	4	5	3
Standard deviation	0,66	0,5	0,66	1,11	0,78	0,64	0,66	1,02

Table A.13: SUS values of the aspect “I would imagine that most people would learn to use this system very quickly” of the user study (section 6.1), rounded to two decimal places (WP (Wire-Path), WL (Wire-Lines), SW (Shear-Webs), PI (Paper-Instructions), number after the slash (/1 or /2) representing the variant).

	WP. / 1	WL. / 1	SW. / 1	PI. / 1	WP. / 2	WL. / 2	SW./2	PI. / 2
Subject 1	1	2	1	4	2	2	2	4
Subject 2	1	1	2	5	1	2	2	5
Subject 3	1	2	1	5	3	2	1	4
Subject 4	1	2	4	5	1	2	4	5
Subject 5	2	1	2	5	2	1	3	5
Subject 6	2	1	2	2	1	2	2	3
Subject 7	2	2	1	5	3	2	2	5
Subject 8	3	2	2	2	3	3	3	3
Subject 9	1	1	2	5	1	1	2	5
Subject 10	3	3	3	3	3	3	3	3
Mean	1,7	1,7	2	4,1	2	2	2,4	4,2
Median	1,5	2	2	5	2	2	2	4,5
Mode	1	2	2	5	1	2	2	5
Standard deviation	0,78	0,64	0,89	1,22	0,89	0,63	0,8	0,87

Table A.14: SUS values of the aspect “I found the system very cumbersome to use” of the user study (section 6.1), rounded to two decimal places (WP (Wire-Path), WL (Wire-Lines), SW (Shear-Webs), PI (Paper-Instructions), number after the slash (/1 or /2) representing the variant).

	WP. / 1	WL. / 1	SW. / 1	PI. / 1	WP. / 2	WL. / 2	SW./2	PI. / 2
Subject 1	4	4	4	2	5	4	5	3
Subject 2	5	5	5	2	5	5	5	2
Subject 3	4	4	5	2	4	4	4	2
Subject 4	5	4	4	1	5	5	3	1
Subject 5	5	5	4	3	3	5	5	2
Subject 6	4	4	3	4	4	4	4	3
Subject 7	4	4	5	3	4	4	4	2
Subject 8	4	3	4	4	4	4	2	2
Subject 9	5	5	4	2	5	5	5	2
Subject 10	5	5	5	2	5	5	5	1
Mean	4,5	4,3	4,3	2,5	4,4	4,5	4,2	2
Median	4,5	4	4	2	4,5	4,5	4,5	2
Mode	4	4	4	2	5	4	5	2
Standard deviation	0,5	0,64	0,64	0,92	0,66	0,5	0,98	0,63

Table A.15: SUS values of the aspect “I felt very confident using the system” of the user study (section 6.1), rounded to two decimal places (WP (Wire-Path), WL (Wire-Lines), SW (Shear-Webs), PI (Paper-Instructions), number after the slash (/1 or /2) representing the variant).

	WP. / 1	WL. / 1	SW. / 1	PI. / 1	WP. / 2	WL. / 2	SW./2	PI. / 2
Subject 1	1	1	2	2	2	1	1	2
Subject 2	1	1	1	1	1	1	1	1
Subject 3	2	1	1	1	1	1	1	1
Subject 4	1	1	1	1	1	1	1	1
Subject 5	1	1	1	1	1	1	2	2
Subject 6	1	1	1	1	1	1	1	2
Subject 7	2	1	2	2	2	1	1	1
Subject 8	3	2	3	2	3	2	3	2
Subject 9	1	1	1	1	1	1	1	1
Subject 10	1	1	1	1	1	1	1	1
Mean	1,4	1,1	1,4	1,3	1,4	1,1	1,3	1,4
Median	1	1	1	1	1	1	1	1
Mode	1	1	1	1	1	1	1	1
Standard deviation	0,66	0,3	0,66	0,46	0,66	0,3	0,64	0,49

Table A.16: SUS values of the aspect “I needed to learn a lot of things before I could get going with this system” of the user study (section 6.1), rounded to two decimal places (WP (Wire-Path), WL (Wire-Lines), SW (Shear-Webs), PI (Paper-Instructions), number after the slash (/1 or /2) representing the variant).

	WP. / 1	WL. / 1	SW. / 1	PI. / 1	WP. / 2	WL. / 2	SW./2	PI. / 2
S. 1	03:46,62	02:49,98	03:16,93	02:48,52	03:48,64	03:51,37	04:40,75	03:15,74
S. 2	02:17,97	01:56,53	01:53,97	02:38,96	02:30,07	03:29,95	01:54,78	04:56,46
S. 3	03:12,59	02:34,55	02:35,05	02:16,88	03:33,72	02:41,46	02:36,11	03:11,93
S. 4	02:32,33	02:16,27	01:58,92	02:59,99	01:48,99	02:04,02	01:56,75	02:58,97
S. 5	01:36,85	01:21,11	02:10,64	02:57,00	02:02,54	01:42,68	02:42,37	03:58,68
S. 6	04:57,01	04:30,78	08:21,19	03:57,92	03:41,74	04:44,56	05:38,90	05:38,84
S. 7	02:21,56	02:32,89	02:55,06	03:13,25	02:54,14	02:21,59	02:06,11	04:27,71
S. 8	02:24,98	04:31,33	03:33,34	03:55,34	04:26,87	03:52,06	03:01,51	03:29,35
S. 9	02:10,56	02:01,91	01:49,77	02:37,06	01:44,20	02:23,14	02:18,15	03:13,94
S. 10	02:20,48	03:55,24	03:01,03	04:10,45	03:11,71	04:56,46	02:16,07	03:16,33
Mean	02:46,10	02:51,06	03:09,59	03:09,54	02:58,26	03:12,73	02:55,15	03:50,79
Median	02:23,27	02:33,72	02:45,06	02:58,49	03:02,93	03:05,70	02:27,13	03:22,84
Mode	n.eind.	n.eind.	n.eind.	n.eind.	n.eind.	n.eind.	n.eind.	n.eind.
S. d.	00:55,00	01:02,78	01:49,43	00:36,90	00:52,84	01:04,35	01:11,34	00:50,83

Table A.17: TCT values (mm:ss,ms) of the user study (section 6.1) (WP (Wire-Path), WL (Wire-Lines), SW (Shear-Webs), PI (Paper-Instructions), number after the slash (/1 or /2) representing the variant).

	WP. / 1	WL. / 1	SW. / 1	PI. / 1	WP. / 2	WL. / 2	SW./2	PI. / 2
Subject 1	10	12	14	10	12	10	10	12
Subject 2	12	14	10	14	14	16	12	18
Subject 3	14	14	12	16	12	14	14	18
Subject 4	12	12	14	14	12	12	12	18
Subject 5	10	14	14	14	12	14	10	29
Subject 6	14	12	12	14	12	12	12	14
Subject 7	12	14	12	16	14	12	16	16
Subject 8	10	12	12	12	12	12	10	16
Subject 9	14	14	12	10	10	12	12	14
Subject 10	12	14	10	16	16	12	14	20
Mean	12	13,2	12,2	13,6	12,6	12,6	12,2	17,5
Median	12	14	12	14	12	12	12	17
Mode	12	14	12	14	12	12	12	18
Standard deviation	1,55	0,98	1,4	2,15	1,56	1,56	1,89	4,46

Table A.18: Distance values as difference between the cable, fixed by the participants, and the cable, fixed “correctly” as reference, of the user study (section 6.1) to represent the error rate, rounded to two decimal places (WP (Wire-Path), WL (Wire-Lines), SW (Shear-Webs), PI (Paper-Instructions), number after the slash (/1 or /2) representing the variant).

Aspect / Question	Limit	WP. / 1	WL. / 1	SW. / 1	PI. / 1
Mental demand	upper	22,90	24,71	39,96	68,58
	lower	9,1	8,29	22,04	35,42
Physical demand	upper	30,58	24,68	30,9	33,36
	lower	11,42	13,32	13,1	10,64
Temporal demand	upper	31,82	37,59	37,07	40,02
	lower	12,18	15,41	14,93	15,98
Performance	upper	16,31	13,07	19,05	57,75
	lower	6,69	7,93	7,95	36,25
Effort	upper	25,17	25,77	39,72	68,17
	lower	12,83	15,23	18,28	38,83
Frustration	upper	17,75	20,54	21,51	52,49
	lower	6,25	9,46	10,49	20,51
I think that I would like to use this system frequently	upper	4,53	4,41	4,1	2,18
	lower	3,67	3,19	3,1	1,22
I found the system unnecessarily complex	upper	1,58	1,81	3,14	4,39
	lower	1,02	1,19	1,86	2,81
I thought the system was easy to use	upper	4,92	4,74	4,73	3,41
	lower	4,08	3,66	3,27	2,19
I think that I would need the support of a technical person to be able to use this system	upper	2	3,04	1,92	2,01
	lower	1	1,16	1,08	1,19
I found the various functions in this system were well integrated	upper	4,23	4,39	3,98	2,87
	lower	3,57	3,61	3,42	1,53
I thought there was too much inconsistency in this system	upper	2,55	2,55	2,34	3,49
	lower	1,25	1,25	1,26	1,91
I would imagine that most people would learn to use this system very quickly	upper	4,81	4,81	4,81	4,09
	lower	3,99	4,19	3,99	2,71
I found the system very cumbersome to use	upper	2,18	2,1	2,55	4,86
	lower	1,22	1,3	1,45	3,34
I felt very confident using the system	upper	4,81	4,7	4,7	3,07
	lower	4,19	3,9	3,9	1,93
I needed to learn a lot of things before I could get going with this system	upper	1,81	1,29	1,81	1,58
	lower	0,99	0,91	0,99	1,02
TCT	upper	03:20,18	03:29,97	04:17,42	03:32,41
	lower	02:12,01	02:12,15	02:01,76	02:46,67
Distance	upper	12,96	13,81	13,07	14,94
	lower	11,04	12,59	11,33	12,26

Table A.19: Confidence intervals, including upper and lower limit ($\alpha = 5\%, n = 10$), of the different workload, usability, TCT (mm:ss,ms) and distance aspects and the different prototypes of variant one, rounded to two decimal places (WP (Wire-Path), WL (Wire-Lines), SW (Shear-Webs), PI (Paper-Instructions), number after the slash (/1 or /2) representing the variant).

Aspect / Question	Limit	WP. / 2	WL. / 2	SW./2	PI. / 2
Mental demand	upper	27,20	22,39	26,5	69,58
	lower	6,8	10,61	13,5	39,42
Physical demand	upper	30,68	25,09	24,06	39,64
	lower	11,32	10,91	7,94	14,36
Temporal demand	upper	37,75	29,99	37,01	48,87
	lower	16,25	10,01	16,99	26,13
Performance	upper	11,61	15,16	12,4	64,19
	lower	5,39	8,84	7,6	45,81
Effort	upper	37,01	28,04	24,38	66,34
	lower	9,99	13,96	11,62	43,66
Frustration	upper	19,73	13,92	19,8	62,84
	lower	5,27	6,08	10,2	34,16
I think that I would like to use this system frequently	upper	4,62	4,33	4,32	2,1
	lower	3,38	3,47	3,08	1,1
I found the system unnecessarily complex	upper	2,01	1,81	2,41	4,29
	lower	1,19	1,19	1,19	2,91
I thought the system was easy to use	upper	4,9	4,81	4,75	3,62
	lower	3,9	3,99	3,45	2,38
I think that I would need the support of a technical person to be able to use this system	upper	2	1,81	2,49	2,52
	lower	1	0,99	0,91	1,08
I found the various functions in this system were well integrated	upper	4,26	4,39	3,81	3,1
	lower	3,14	3,61	2,99	2,3
I thought there was too much inconsistency in this system	upper	1,81	2,41	1,92	3,49
	lower	1,19	1,19	1,08	1,91
I would imagine that most people would learn to use this system very quickly	upper	4,78	4,7	4,81	4,23
	lower	3,82	3,9	3,99	2,97
I found the system very cumbersome to use	upper	2,55	2,39	2,9	4,74
	lower	1,45	1,61	1,9	3,66
I felt very confident using the system	upper	4,81	4,81	4,81	2,39
	lower	3,99	4,19	3,59	1,61
I needed to learn a lot of things before I could get going with this system	upper	1,81	1,29	1,7	1,7
	lower	0,99	0,91	0,9	1,1
TCT	upper	03:31,01	03:52,61	03:39,36	04:22,30
	lower	02:25,51	02:32,84	02:10,94	03:19,29
Distance	upper	13,57	13,57	13,37	20,26
	lower	11,63	11,63	11,03	14,74

Table A.20: Confidence intervals, including upper and lower limit ($\alpha = 5\%, n = 10$), of the different workload, usability, TCT (mm:ss,ms) and distance aspects and the different prototypes of variant two, rounded to two decimal places (WP (Wire-Path), WL (Wire-Lines), SW (Shear-Webs), PI (Paper-Instructions), number after the slash (/1 or /2) representing the variant).

Aspect / Question	Variant	F(3, 36) ratio value	P value	Critical F value
Mental demand	1	8,41	0,00	2,87
	2	11,46	0,00	2,87
Physical demand	1	0,08	0,97	2,87
	2	0,86	0,47	2,87
Temporal demand	1	0,19	0,9	2,87
	2	1,62	0,2	2,87
Performance	1	24,38	0,00	2,87
	2	63,46	0,00	2,87
Effort	1	8,89	0,00	2,87
	2	10,23	0,00	2,87
Frustration	1	4,97	0,01	2,87
	2	15,31	0,00	2,87
I think that I would like to use this system frequently	1	15,73	0,00	2,87
	2	14,9	0,00	2,87
I found the system unnecessarily complex	1	12,75	0,00	2,87
	2	12,24	0,00	2,87
I thought the system was easy to use	1	5,61	0,00	2,87
	2	5,03	0,01	2,87
I think that I would need the support of a technical person to be able to use this system	1	0,78	0,52	2,87
	2	0,3	0,83	2,87
I found the various functions in this system were well integrated	1	12,41	0,00	2,87
	2	5,42	0,00	2,87
I thought there was too much inconsistency in this system	1	1,39	0,26	2,87
	2	3,55	0,02	2,87
I would imagine that most people would learn to use this system very quickly	1	4,09	0,01	2,87
	2	1,97	0,14	2,87
I found the system very cumbersome to use	1	14,6	0,00	2,87
	2	15,28	0,00	2,87
I felt very confident using the system	1	16,5	0,00	2,87
	2	24,86	0,00	2,87
I needed to learn a lot of things before I could get going with this system	1	0,61	0,61	2,87
	2	0,61	0,61	2,87
TCT	1	0,27	0,85	2,87
	2	1,61	0,2	2,87
Distance	1	2,16	0,11	2,87
	2	8,1	0,00	2,87

Table A.21: ANOVA test results to verify the significant difference of the mean values of the different prototypes (degrees of freedom between groups = 3, degrees of freedom within groups = 36) on the workload, usability, TCT and distance, rounded to two decimal places.

A.2 User study graphics

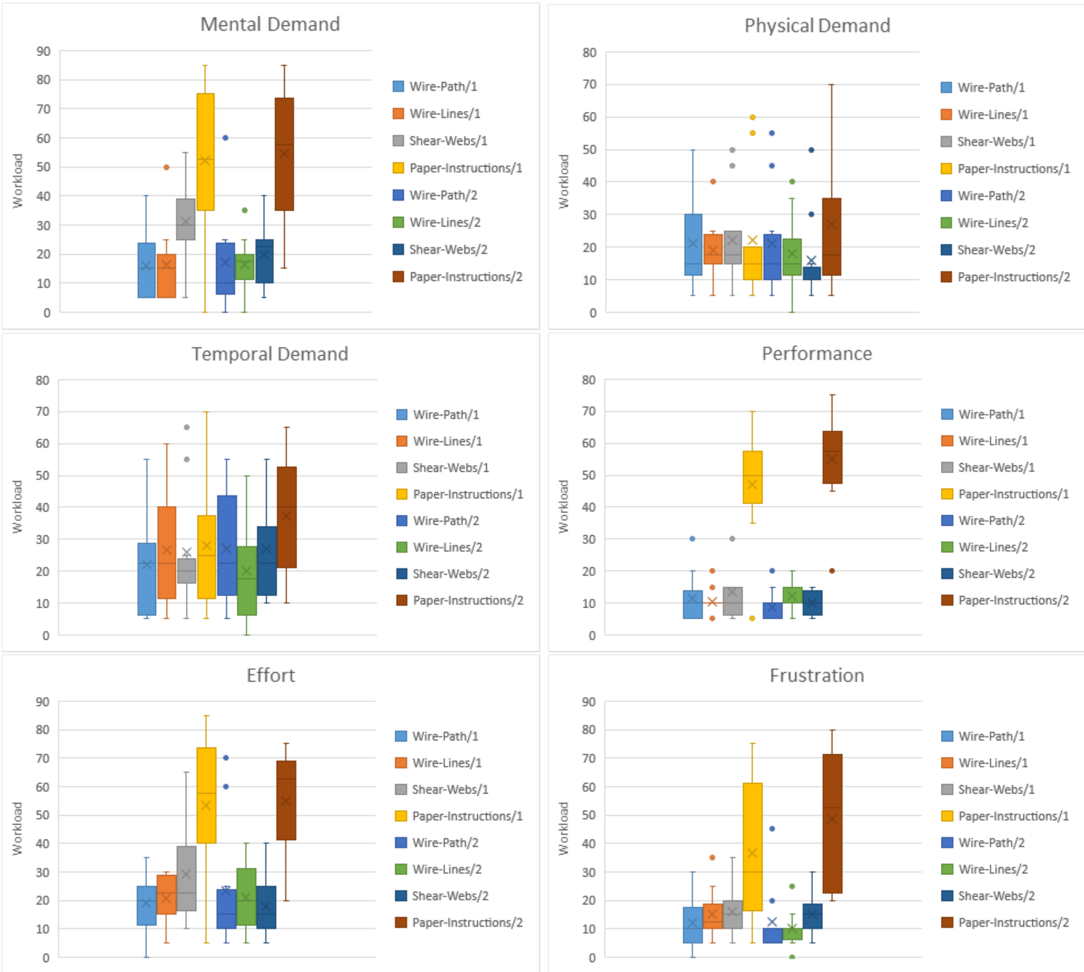

Figure A.1: Graphical representation of the user study (section 6.1) NASA-TLX results (× representing mean, — representing median, number after the slash (/1 or /2) representing the variant), including mental demand (top left), physical demand (top right), temporal demand (middle left), performance (middle right), effort (bottom left), frustration (bottom right).

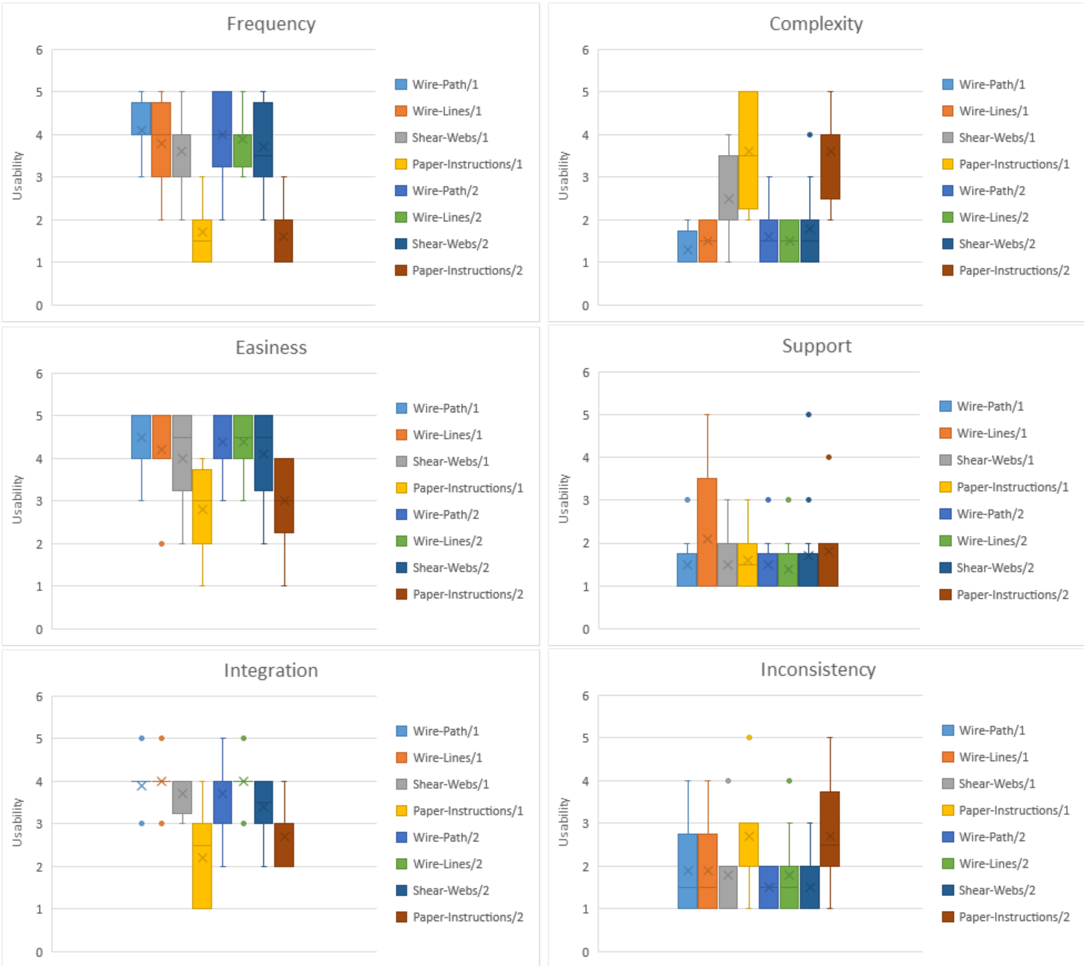

Figure A.2: Graphical representation of the user study (section 6.1) SUS results (× representing mean, — representing median, number after the slash (/1 or /2) representing the variant), including the aspects "I think that I would like to use this system frequently" (Frequency), "I found the system unnecessarily complex" (Complexity), "I thought the system was easy to use" (Easiness), "I think that I would need the support of a technical person to be able to use this system" (Support), "I found the various functions in this system were well integrated" (Integration), "I thought there was too much inconsistency in this system" (Inconsistency).

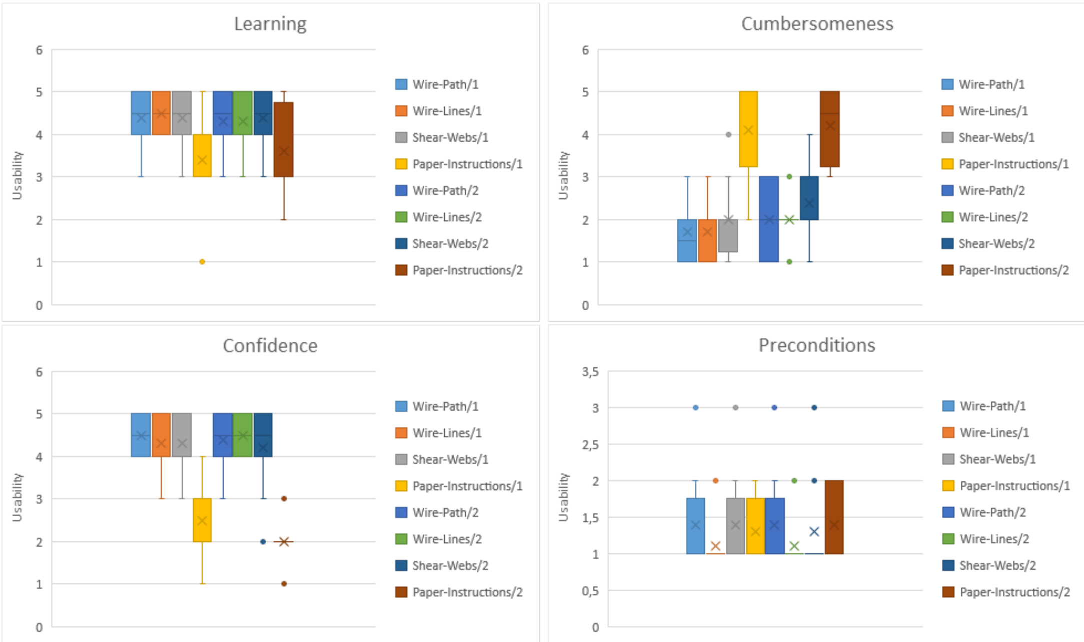

Figure A.3: Graphical representation of the user study (section 6.1) SUS results (× representing mean, — representing median, number after the slash (/1 or /2) representing the variant), including the aspects "I would imagine that most people would learn to use this system very quickly" (Learning), "I found the system very cumbersome to use" (Cumbersomeness), "I felt very confident using the system" (Confidence), "I needed to learn a lot of things before I could get going with this system" (Preconditions).

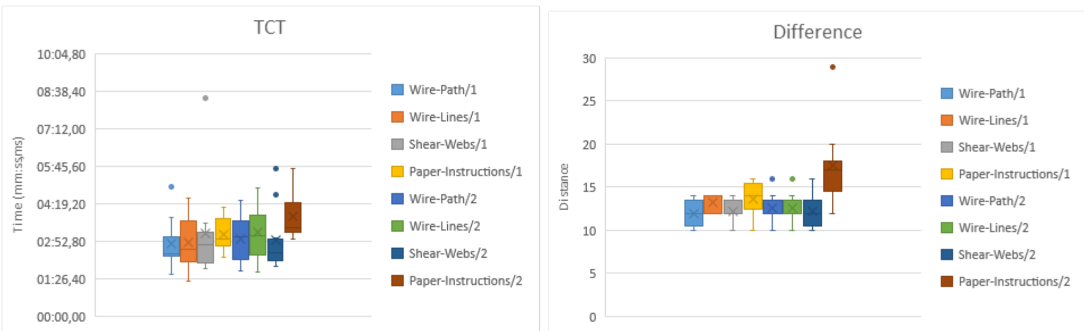

Figure A.4: Graphical representation of the user study (section 6.1) TCT results (left) (mm:ss,ms) and distance values to represent the difference and the error rate (right) (× representing mean, — representing median, number after the slash (/1 or /2) representing the variant).

Declaration

I hereby declare that the work presented in this thesis is entirely my own and that I did not use any other sources and references than the listed ones. I have marked all direct or indirect statements from other sources contained therein as quotations. Neither this work nor significant parts of it were part of another examination procedure. I have not published this work in whole or in part before. The electronic copy is consistent with all submitted copies.

Stuttgart, 22.11.2021

place, date, signature