Exploring the utility of AR for quality inspections in timber-frame house production – A case study from Småland, Sweden

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Abstract
About 80% of new homes in Sweden are being built using prefabricated elements. This rate of prefabrication is the highest in the world and the manufacturing of timber-frame homes has become a modern sector of the economy in Sweden. Information, and communication technology (ICT) has long played a key role in industrializing the wood-based building industry and novel ICT, like augmented reality, are believed to provide new opportunities. It is in this context that we explore how artificial reality solutions can be applied to improve the quality assurance process in a company producing prefabricated homes in Småland, Sweden. The research question asked in this study is: How can augmented reality be successfully applied to support quality assurance practice in the wood-based building industry? This question warrants investigation since improving quality assurance in house manufacturing not only improves products but also increases customer satisfaction. To investigate this question, we conduct a case study in a company where we set up a quasi-experiment with five quality assurance professionals using Microsoft's HoloLens displaying production data. To make sense of their experiences, we conducted a series of semi-structured de-briefing interviews. Moreover, for understanding how AR can be successfully deployed in quality assurance we apply the design science research method. Findings are that the success of using AR in quality assurance depends on the quality of information displayed on the system, the geolocation of the models, the quality of the software and hardware used, and the ruggedness of the devices. We claim to have provided a range of valuable practical and theoretical contributions transferable to other construction companies seeking to apply augmented reality in their quality assurance routines.

Keywords: Augmented reality, wood-based building, quality assurance

Introduction

Due to the often-harsh weather conditions in Sweden, off-site prefabrication has become the preferred method for timber frame home production. Nowadays, about 90% of new single-family homes are assembled using prefabricated structural timber elements (Kitek-Kuzman and Sandberg, 2017;). Moreover, 20% of the family homes are prefabricated to a high degree with solutions ranging from complete buildings being delivered to site, volumetric fitted-out units, volumetric units fitted-out on-site, to complete bathroom or kitchen pods being delivered as extensions for existing buildings (Steinhardt et al. 2020). Consequently, Sweden's wood construction industry has become highly automated and a global leader in pre-fabrication (Schauerte, 2010). Despite its advances in automation, the Swedish wood-based building construction industry continues to rely heavily on manual labor when compared to other industries like car manufacturing (Vestin et al. 2019, Manley and Widen 2019). This contributes to quality challenges leading to rework and variations causing substantial cost and time escalations (Josephson et al. 2002). At the same time, just like their counterparts elsewhere, Swedish construction clients have ever rising expectations when it comes to the quality of their homes (Frödell et al, 2008).

Achieving higher quality in house manufacturing requires attention to detail, monitoring and rigorous quality assurance. One idea for further improving the quality of timber-frame manufacturing is to increase the use of modern information systems in quality assurance. Ever since the dawn of computer aided design and building information modelling, information systems have been viewed to be influential for advancing quality in construction (Azhar 2011, Mathieu 1987). Nowadays, quality assurance and inspections in timber frame housing production are done through visual inspections using paper-based workshop drawings and component specifications. The inspection work is tedious and error prone and could be substantially improved through leveraging modern information systems (Schauerte, 2009). Especially augmented reality (AR) technology appears to be well suited for improving quality assurance in construction (Garcia-Pereira et al. 2020). In fact, AR may have the potential to improve both effectivity and quality in construction (Alizadehslehi et al. 2020).

The emerging research on AR in construction appears to focus foremost on workplace safety and there is a shortage of practical case studies exploring its application in the industrial context of construction production (Alizadehslehi et al. 2020, Li et al. 2018). However, a range of early case studies applying augmented reality to prototyping, training, production, operations, maintenance, and inspection work undertaken by manufacturing companies show promising results for quality improvements (e.g. Boing, Airbus, Lockheed Martin, Volkswagen, BMW, Volvo, Mitsubishi, Porsche, Bosch, ThyssenKrupp, and Newport News Shipbuilding) (Kohn and Harborth 2018).

In the past, there have been some attempts by Swedish contractors to transfer knowledge from manufacturing to construction (Bröchner 1997). For instance, in the nineties, when total quality management emerged, Swedish contractors attempted with varying degrees of success to transfer knowledge from the car manufacturer Volvo to construction (ibid.). The work in this paper can be viewed as a continuation of earlier work seeking to improve quality assurance work in wood-based construction inspired by successes in manufacturing. Moreover, by conducting an early case study of the industrial application of AR in construction, the paper provides insight for professionals and researchers. Based on the promising results from applying AR in quality inspections in other sectors of the economy and the persisting quality challenges in the wood-based building industry, this article sets out to explore: *How can augmented reality (AR) be successfully applied to support quality assurance practice in the wood-based building industry?*

This paper answers the research question by reporting on a case study conducted at a medium sized housing manufacturer located in the Småland region of Sweden. The case company produces turn-key, mass-customized family homes based on prefabricated timber elements. The work process placed at the center of this study is the final inspection of wall elements before packaging and shipping to the construction site. The paper follows the design science research method similar to what has been suggested by Hevner (2007). To understand where and how AR could be applied to resolve quality problems, we conducted interviews with three of the company's senior production engineers. Thereafter, the artefact was prepared namely by uploading digital "workshop" models via TrimbleConnect to a head-mounted HoloLens device. This was followed by a "quasi" experiment where five workers used the device for their day-to-day inspection work in the manufacturing plant.

Once the experiment concluded we conducted de-briefing interviews with the workers for developing an understanding of their perceptions of the utility of AR for supporting their work.

The remainder of the paper is arranged in accordance with the publication schema for design science research (DSR) studies (Gregor and Hevner 2013). Section two introduces the DSR research methodology applied. Section three introduces the application domain and provides a brief overview of the quality related challenges experienced in the wood-based building industry based on a literature review and the interviews with the senior engineers. Section four provides a description of the technological artefact. Section five presents an evaluation of the new system by the five production workers who applied the system in their work. The last two sections present the discussion and the conclusion of the article.

Method: Design Science Research

In this article we use a design science research (DSR) methodology for developing a new solution to a known problem which represents a research and knowledge contribution opportunity (Gregor and Hevner 2013). DSR is an important research paradigm in the field of information systems (ibid.). According to Simon, design science is research on the science and practice of design and developed elements driven by the desire to improve an environment (Simon 1996). Nowadays, it is widely accepted that system development in information systems can be viewed as a research method (Nunamaker el al. 1990). In our article we develop a process for AR in the context of quality inspections in the wood-based building industry. DSR is a well-suited methodology for inquiries with the goal of finding better or new solutions to existing problems (Hevner and Chatterjee 2010; Gregor and Hevner 2013). DSR is a method taking, as far as it is practical possible, the research process in use (Peffers et al. 2006). In this article we follow the "three cycle view of design science research" as suggested by Hevner (2007). A graphical depiction of this view is shown in figure 1.

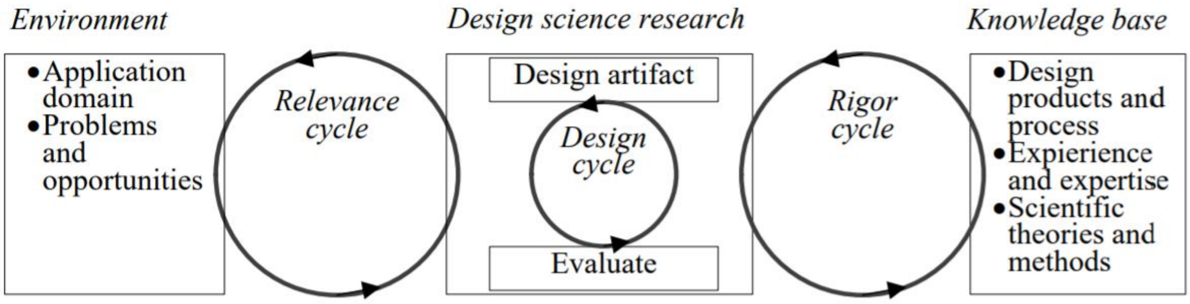

Fig.1 Design Science Research Cycles [p. 88, Hevner 2007]

The relevance cycle provides the requirements for the research in form of opportunities and problems that need to be addressed. An application domain consists of the people and technical systems that interact to work towards a goal. The application domain of the system presented in this article is the quality inspection of timber frame elements in a factory setting which is what has been introduced in section three of the article. For understanding the application domain, we conducted three semi-structured interviews with a production technician, the Health, safety, environment and quality manager, and a structural engineer (see table 1). Moreover, the opportunity provided by the new system is improving quality inspection whereby reducing faults emerged from this. The rigor cycle ensures that the DSR work is rigorously done. It provides a reflection on the relative advantage of the new system over existing solutions in the application domain. Moreover, it reflects the experiences and expertise that define the state-of-the art in the application domain of the research. How our work contributes to the knowledge base is debated in the discussion and conclusion parts of this article. The design cycle is at the heart of the study, it iterates between the design of an artefact and the evaluation against the requirements. In our research the requirement of the new system was to improve the quality of the product. Since our work is early stage, we provide an initial evaluation of the system by interviewing four workers and one superintended who evaluated as to whether this system has the potential of improving their jobs (see table 1). In this article the design of the system is introduced in the fourth section and a brief evaluation of the system is presented in the fifth section.

Table 1. Overview of the interviewees in the relevance and evaluation cycles

Professional role	Age	Experience	Duration (min)	Interview type	Date
Interviews: relevance cycle					
Production technician	32	-na-	49:21	Semi-structured interview (Microsoft teams)	210224
HSE and quality manager	32	-na-	78:51	Semi-structured interview (Microsoft teams)	210316
Innovation engineer 1	29	2,5 years	28:55	Semi-structured group-interview (Microsoft teams)	210330
Innovation engineer 2	27	2,5 years			
Evaluation: design cycle					
Evaluator 1 worker	27	10 years	7:05	Structured interview (face to face)	210428
Evaluator 2 worker	40	6 years	7:06	Structured interview (face to face)	210428
Evaluator 3 worker	51	6 years	9:54	Structured interview (face to face)	210428
Evaluator 4 worker	30	6 years	8:11	Structured interview (face to face)	210428
Evaluator 5 superintendent	53	17 years	7:07	Structured interview (face to face)	210428

Application domain: timber-frame house production

The application domain of the augmented reality solution presented in this paper is quality inspection in the industrial production of turn-key timber frame homes in Småland, Sweden. The case company is a branch of the largest housing developer in Scandinavia having overall 2600 employees. We selected the case study as example for cutting edge practice in the industry as the factory has witnessed considerable modernizations in recent years. The company focusses on a serial production of timber frame homes applying standardization, modulization, and a building system in their production (Nord 2008, Popovic 2020). Over 95 000 homes have been produced in this factory since its founding in 1927. In recent years, larger Swedish home manufacturers, like the one subject to our study, have begun working based on the lean production paradigm, invested in modern machinery, and modernized their processes including quality assurance routines (Manley and Widen 2019). To understand the application domain of AR in timber frame house production we interviewed three subject matter experts and an overview of the interviews can be found in table 1, an impression from the factory's storage facility can be found in figure 2. How the company subject to our case study has modernized its production is indicated by the following quote by the company's production technician:

> *The frame station is fairly automated, but you still have to stand by the machine and help. Then the plaster portal is fully automated where it nails everything. Similarly, when the element enters the panel stations, they are fully automated. [...] In the frame station, for example, insulation is cut and falls down so that the fitter can put it in place in the frame (production technician).*

Despite significant automation of the production line, and an availability of digital models of elements during the design stage the production technician explains how 2D paper-based workshop drawings continue to be used for quality inspections:

> *The production manager produces the drawings because we still use ordinary drawings. We can use digital drawings, but we currently do not have access to such equipment in production. The production manager instead keeps track of production via the business system and prints all the drawings that then follow from the first station (production technician).*

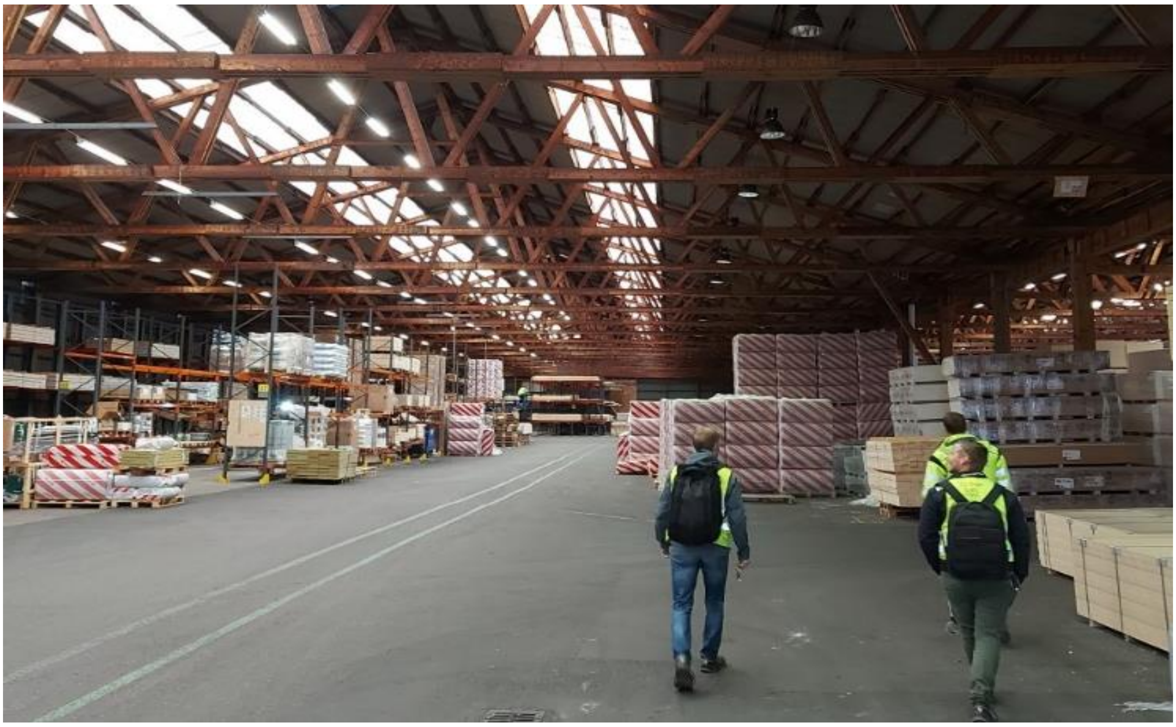

Fig.2 Case company: storage facility

How not using digital drawings in quality control is viewed as a problem and an area in need for improvement is indicated by the following quote of the production technician:

> *With paper drawings it is difficult to get proper visualizations of what the product and components look like since it is in 2D. It is very easy for something to look like something else, or for there to be to many dimension lines that make it difficult to understand the drawing itself. […] Moreover, the drawings that we get from the designers are black and white, so there will not be a huge difference between the actual material and what is shown in the drawing. When there are also many things happening in the same place, it is difficult to absorb the information (production technician).*

While the companies HSE and quality manager argued that there were very few customer complaints about product quality, he claimed that quality inconsistencies and related re-work caused considerable costs throughout the production process. According to the companies HSE and quality manager, small mistakes resulting from a loss in attention and focus are difficult to rule out:

> *My experience tells me that if you look at the mistakes we make, then I do not exaggerate if I say at least 95 % of them are, so-called careless mistakes, so this is something, if only you had a 100 percent focus that would never have happened. (HSE and quality manager)*

The innovation manager stressed that many of the required changes and related rework in production originate in mistakes made during the design stage. These types of errors are difficult to eradicate by applying AR in production since the design mistakes would appear in the digital models displayed. However, this manager having prior experience from working in a different industry, argued that embracing technical solutions in quality assurance could help mitigate for some of the quality problems.

> *Then you can say that technologically, the wooden house industry is pretty much behind. I myself have worked in the metal industry before where there are more technical solutions to minimize errors. You have more simulations of things, etc. (innovation manager).*

Based on the interviews with the experts it became possible to identify that there is a real potential for improving quality inspection in timber frame house production. This is in line with the long-standing interest of applying AR to the context of construction production. However, until recently hardware and software were not deemed "advanced enough to be applied in real [architecture, engineering, and construction] AEC project sites" (Shin 2007). Looking for practical applications of AR for quality assurance in industry, it became apparent that most cases would stem from manufacturing. Namely inspection work undertaken by manufacturing companies like Boing, Airbus, Lockheed Martin, Volkswagen, BMW, Volvo, Mitsubishi, Porsche, Bosch, ThyssenKrupp, and Newport News Shipbuilding (Kohn and Harborth 2018).

The devices used to support inspections in manufacturing test cases ranged from Head-mounted displays (Google glass, Oculus Rift and HoloLens) to tablets and mobile phones (Kohn and Harborth 2018). While most of the test cases were reported without quantifications of improvements, Lockheed Martin found that applying AR increased their engineers' accuracy in quality inspections to 96% and increased their work speed by 30% when overseeing production operations (ibid). Moreover, Airbus reported that applying Google glass in production operations cut error rates in half (ibid.). At the same time, Bosh reports that using tablets and smart glasses in inspections and maintenance increased the speed of technicians by 10-15% (ibid.). Airbus reports a time reduction of 80% in inspection and maintenance work by applying AR in inspections and error prevention (ibid.). Last, Newport News Shipbuilding reports to have reduced the time for final inspections and error prevention from 36 hours per vessel to just 90 minutes (ibid.).

Artifact: AR in quality inspection

Augmented reality (AR) can be defined through its three main characteristics namely that it combines the real and the virtual, that it is interactive and happens in real time and, that it takes place in three dimensions (Azuma 1997). As the technology emerged over the years, it has been suggested that a complete AR information system typically consists of (1) Visualization technology (e.g. Head mounted devices; hand held devices; projectors); (2) User interfaces allowing for feedback and input from users; (3) a processing unit for transferring data, calculating feedbacks and visual renderings; (4) a tracking system orienting the data relative to the physical world; (5) a sensor system gathering information about the environment; and lastly (6) an external database (Egger and Masood 2020). The visualization technology used in this case study is a head mounted display called Microsoft HoloLens2. HoloLens2 has an integrated tracking system, a sensor system and a user interface. The content uploaded to the HoloLens was prepared using a stationary PC running the software Trimble Connect for HoloLens. The software is purpose built for displaying construction design models in the field using a HoloLens 2 or XR10.

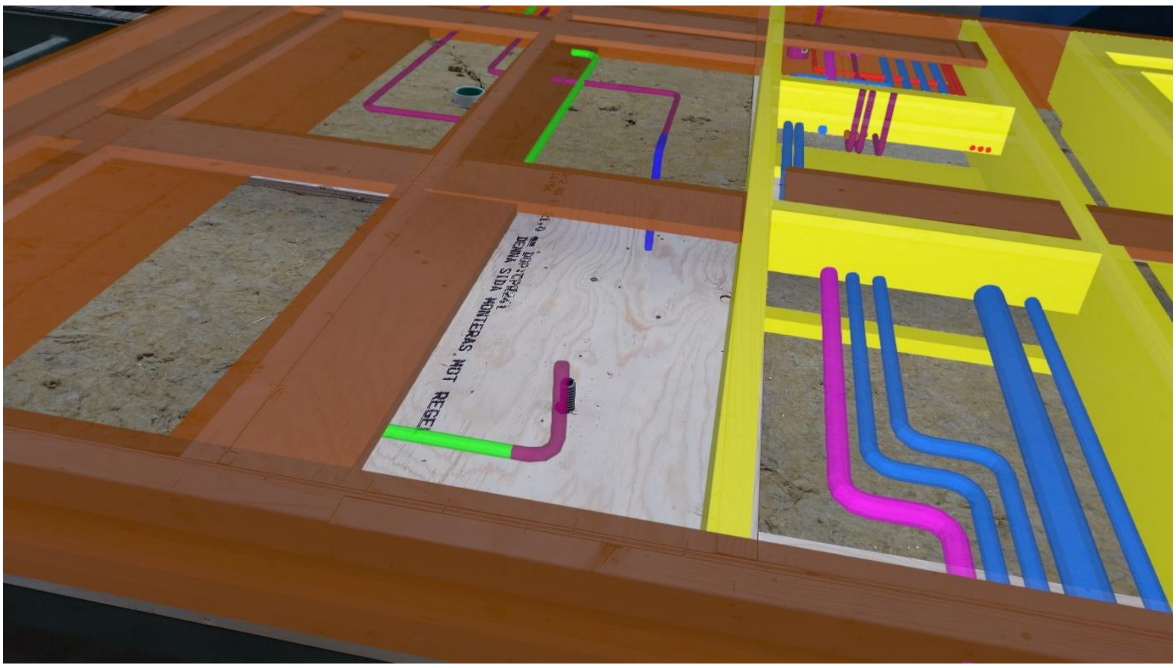

Fig.3 Overlay of the digital model and the physical timber frame element using AR

Fig.4 Quality inspection of a timber frame element using HoloLens2

Trimble Connect is in essence a collaboration platform designed for sharing digital 3D models in architecture, engineering, and construction project teams. Figure 3 shows a digital model of a timber frame element. This model was originally prepared by the factories engineering design team using HSBCad, a specialist software for timber frame production, then uploaded to the Trimble connect platform for HoloLens. The model was manually geo-located at the inspection site in the factory since the elements would not always be in the same place when being inspected. Figure 4 shows one of the workers inspecting the quality of a wall element using AR for the quality assurance process as part of the evaluation part of this study.

Evaluation

The evaluation of the artifact presented above was done based on a “quasi” experiment where five factory workers, hereafter evaluator 1-5, used the digital model displayed on the HoloLens2 to conduct a quality assessment of a timber-frame wall element. Each of the workers conducted one quality control seeking to find mismatches between the digital model and the physical reality. Figures 3 and 4 show how the model was presented in the head mounted display and a worker conducted a quality assessment. Each of the workers had about 5 minutes to conduct the assessment. The digital model was “manually” geolocated and overlayed with the physical element ahead of each quality control taking about 2-3 minutes. After each experiment, the workers were asked several questions to capture their perceptions of the new technology and whether they found it useful and easy to use in quality inspections. In the following paragraphs both the perceived strengths and weaknesses of the new quality inspection method are presented. Table 2 provides an overview over the strengths and weaknesses of AR use in quality inspection in the context of timber-frame construction as identified in the evaluation.

All the evaluators found that the HoloLens supported their understanding of the technical details of the elements. The tool was perceived to improve their understanding of details such as pipes, cables, and other components to be installed in the elements: “It was easy to understand the piping itself and everything like that, so anyone could understand. It would be useful to find major defects […] It was easier and clearer to see the color scale (on the tubes), so you can distinguish where it went right and where it went wrong, if it were to be wrong. It's easier to see it that way than on a black and white drawing." (evaluator 1) "It was good, you really saw the whole thing and I thought it was cool. It flowed in very nicely, some parts became […more visible…]. It was a cross-section, and I had no difficulty distinguishing between them." (evaluator 2)

The following quotes illustrate how the evaluators found mistakes that might otherwise have gone unnoticed: "It was a hose that stuck up and it differed a few centimeters in the middle of the workbench. Then there were two pipes floating in the doorway […] if you see the hose that stuck up […] it was wrong." (evaluator 2) […] It was a bit wrong, there was some electrical cable that was not exactly where it was displayed in the glasses." (evaluator 4) Some went so far to argue that a continued use of AR in quality inspections might substantially bring down installation errors. "I actually think that there would probably be zero errors if everyone used this and […if everyone were…] properly trained there would actually be no errors. Experiencing this now, is the element is a bit wrong like moving a cable and a bit of that, so I think we would probably have zero errors, I do actually think that." (evaluator 3)

Others felt that using the technology might make their work a bit more interesting by reducing the reliance on paper drawings. "I think, you look so much at the drawings all day so you can check the quality […], then you can get a little blind. I can imagine that if you put on glasses and make a check in the end, when the wall is finished, then [...] it will be better, I think. You get a little blind by just looking at the same drawings all the time." (evaluator 4) One of the evaluators cautioned that while he thought the technology would be helpful for improving quality in production, it might not help reducing design errors. "[Errors] should decrease then. Provided that the drawings are correct, otherwise that [AR model] will be wrong as well." (evaluator 5) Another evaluator argued that using AR throughout the production line would help somewhat increasing trust in the inspection work done at other workstations, too: "I cannot see [the prior inspection and quality work] now, in retrospect, but using more AR would allow for me to trust it. " (evaluator 4) When discussing the ease of use of the HoloLens2 there was consensus that it worked just fine for the evaluators and that there were no major concerns. The evaluators pointed out how the head mounted display was comfortable to wear and how they did not get "seasick" from wearing it*:* The glasses sat well on my head. It did not flicker as I feared it might, so that you would not get seasick. (evaluator 2) and "It was okay, comfortable to wear, nothing hurts when you wear it. (evaluator 5)

However, the evaluators pointed out some weaknesses of the AR device used in this experiment. That one needed to move and tilt one's head in a particular angle to be able to see certain aspects of the digital model was found challenging by some: "If you looked a bit up the digital model disappeared so you had to view in a downwards angle towards the workbench to see the pipes, which is probably a bit bad. It disappeared when you looked up a little, then some piping disappeared and then you did not see the whole thing anymore, but then you had to angle down the gaze again, it can be a little hard." (evaluator 1) This sentiment was shared by evaluator 4: "[…] it disappeared a bit, the pipes and cables were on the wall, so you had to check without the glasses a bit, and then a bit with […] to see the wall and then I checked again and so that it is true." (evaluator 4) Moreover, while wearing the head mounted display, the workers had limited vision reducing their awareness of the wider work environment which in turns can result in safety challenges: "[…] there is a lot of focus on the workbench, you do not think about what was happening around you so it might take your focus away a little too much." (evaluator 1). This concern is echoed by evaluator 2: "[…] you had a bad field of vision, a little narrow. I would like to have it so you do not have to be so precise with your eyes. But overall, it was very positive." (evaluator 2)

There were some additional concerns regarding both the price of the technology and a possible resistance to change by the workers in the factory: "I simply believe that it is we humans who need to change, and that it is our habits that need to change." (evaluator 1) Evaluator 2 voices a concern about the price: The price of the technology (laughs). No, but I do not really know, but it's about overcoming the fear of technology. It is so backward-looking in general, I think. I'm positive about all this stuff so I only see benefits from it. Or just benefits, but many benefits." (evaluator 2)

Table 2. Overview of the main evaluation results

Strengths	Weaknesses
• Easier to understand the pipe installations. • Color-scheme of pipes effective • MH2 is comfortable to wear • Easy to spot the differences between the 3D model and reality • Easy to spot deviations and mistakes • Quick geolocation • Makes quality inspections more interesting • MH2 is easy to use	• Limited field of vision in the glasses • Reduces attention to the wider work environment • Requires getting used to and learning • Geolocation not very precise • An exact model can never correspond to the imperfection of reality • The data loaded up to the MH2 needs to be correct

Discussion

AR has been used in military, medicine, and industry for many years and experiences from those sectors show that the technology needs to meet some basic requirements for optimal utility in day-to-day operations (Quandt et al. 2018). Maybe unsurprisingly, many of the evaluation results of the construction case study resemble those experienced in other sectors. For instance, it has been argued in literature that the devices need to be "rugged" enough to be used in day-to-day work meaning they need to have a minimal set up time, they need to be easy to clean, and require minimal maintenance (Caricato et al. 2014; Ong and Nee 2004).

While the HoloLens2 device that has been used in this case study was standard it was perceived as well suited for the work. However, judging based on observations in the workplace environment, there is quite some dust and risk for mechanical impacts possibly damaging the glasses. Thus, in these type of production facilities one would be well advised to set up lockers with charging stations keeping the equipment save while not being in use. Although the standard HoloLens2 meets basic impact protection requirements, using an additional protective shield attached to the front of the glasses could better prevent scratching due to saw dust or similar. Such shields are for instance being used in medicine namely the VSI Protection Shield (face protection film). Moreover, depending on the safety regulations in the factory, it could be worthwhile using special AR Hard heads for HoloLens like those being sold by Trimble.

Regarding the set-up time, the manual geolocation set up as applied in this case study was too slow and imprecise, it took on average 3 minutes per element. A learning of our case study is that several of the evaluators found the geolocation process not good enough. This leads us to recommend using QR codes for geolocation which could be prepared in advance and glued to one of the elements corners. This would allow for a quicker and more precise process of geolocation. During operation, the presentation needs to be accurate, and the alignment of real and virtual objects needs to be precise and QR codes could help improving this (Ong and Nee 2004).

Moreover, it has been argued that both ergonomics and prevention of motion sickness is important for the workplace use of AR (Tümler et al 2008). The evaluators reported that the head mounted displays used in this case study were comfortable to wear and no user experienced motion sickness indicating that the devices were well suited for industry use.

Overall, all evaluators found the AR supported inspection to be useful for their work. More precisely they found the new way of working to be a useful complementary activity to their existing practice of using paper-based shop drawings. Especially the AR visualization of cables and pipes was viewed as useful for improving the quality of timber-frame elements. Moreover, several of the evaluators argued that using this technology company wide would help further ruling out production errors and maybe altogether eliminating them. This finding is in line with what has been found in earlier case studies in manufacturing (Kohn and Harborth 2018). This leads us to conclude that applying AR in quality inspections in the context of timber-frame production could benefit the overall quality of houses. We are however limited in our ability to generalize the findings of our study in that we rely on only one evaluation of the technology in timber-frame production. While our qualitative research design, with its nine interviewees, presented a detailed account of AR use in timber-frame manufacturing, we did not prioritize statistical relevance at this stage. Nonetheless, the rich account of AR use provided in this paper enables readers to judge if the findings can be transferred to a different setting. Thus, while we argue to have provided an initial understanding of the phenomenon, further research testing the technology at a larger scale, over longer periods of time, and in a multitude of settings in timber frame construction is needed before concluding if quality can substantially be improved by using AR. However, our initial findings are promising.

Conclusion

The research question asked in this paper was "How can augmented reality (AR) be successfully applied to support quality assurance practice in the wood-based building industry?". The answer is threefold. First, the hardware would need to be protected from possible physical impacts of a factory environment which could be done by using lockers, protection shields or AR hardhats. Second, the geolocation of the virtual models in the real environment would need to be supported by placing QR codes on the timber frame elements. Last, users would need to be trained and acceptance for the technology would need to be created. Creating acceptance of the technology appears possible since the evaluators in this case study found the new AR based method intuitive and superior to their old way of working. To conclude, AR is a promising new technology which could help eradicating production errors in timber-frame house construction. However, more research is needed to further substantiate this claim.

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