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UTILIZING AUGMENTED REALITY FOR THE ASSEMBLY AND DISASSEMBLY OF PANELIZED CONSTRUCTION

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SUMMARY**:** *Prefabricated construction allows for efficient resource usage while creating higher-quality products that can be assembled on-site within a short time. While this translates to significant benefits for the overall construction, challenges arise from an increased demand for trained prefabrication assembly workers. As prefabrication calls for skills differing from traditional construction, the local labor force can be negatively affected to impede the successful uptake of prefabricated construction. Upskilling the local workforce to take on prefabrication assembly and potential disassembly can solve this problem. This is more relevant to remote construction projects as they stand to gain more from prefabricated construction. This study presents two workflows for creating Augmented Reality (AR) solutions. The AR solutions are aimed to help workers transition between traditional and prefabrication assembly in a panelized construction project. They are: (1) using QR codes to identify a panel's intended location and construction sequence and (2) using predefined markers to show required equipment and on-site assembly procedures. The solutions are delivered through smartphones, which are readily available and provide a cost-effective medium. Furthermore, developed workflows present an opportunity to implement Design for Disassembly (DfD) concepts in a project. The proposed workflows show the potential to substantially help communicate to the workers the instructions on both the panel assembly and disassembly activities and upskill the local workforce to support the transition to prefabrication assembly in construction projects.*

KEYWORDS**:** *Prefabrication, Game engine, Construction Training, Workforce Upskilling, Design for Disassembly, Augmented Reality, Mobile Application.*

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1. INTRODUCTION

Construction is one of the main contributors to global pollution and a major consumer of global resources (WBCSD, 2023; Global Alliance for Buildings and Construction, 2022). It falls on the AEC industry to take responsibility for maximizing resource usage while minimizing carbon emissions. Off-site manufacturing allows for higher-quality components to be prefabricated with minimal resource wastage. In prefabricated construction, the parts of the structure are fabricated off-site, transported, and assembled on-site. This allows the on-site construction to be completed quickly, minimizing any waste and emissions that can happen in traditional construction. However, the skills required for prefabricated construction are different from that of traditional construction, and in prefabrication, the traditional skilled jobs are converted to factory jobs and transferred to the manufacturing location. This can negatively affect the local labor market unless they obtain the necessary skills. Lack of the required skills has been cited as one of the main obstacles to prefabrication adoption, especially in developing countries (Rotimi et al., 2022). As prefabricated construction is an ideal solution for the problems encountered in remote construction, the need for upskilling the local workforce is dire for these communities. Remote construction refers to any construction that is carried out in a location that is harder to access due to its geographic location, unfavorable weather conditions, infrastructure facilities, and/or underdeveloped economy.

'Construction 4.0' is the transformative framework that may help the construction industry address the labor shortage and upskilling problems. Among different technologies, Extended Reality (XR) technologies such as Augmented Reality (AR) and Virtual Reality (VR) are set to advance Construction 4.0 (El Jazzar et al., 2021). Delgado et al. (2020) generalized XR use cases in the construction industry into six areas, i.e., (1) Stakeholder engagement, (2) Design support, (3) Design review, (4) Construction support, (5) Operations management and (6) Training. While there has been a great deal of interest from both industry and academia in XR implementation in different stages of construction, only a few studies have been carried out on utilizing XR to support construction workers on site. In addition, the possibility of XR implementation in the end-of-life (EOL) of a construction project has not been explored in greater detail.

EOL is a crucial phase of construction projects, especially of prefabricated projects that grant plenty of deconstruction opportunities to reduce construction waste and emissions. Design for Disassembly (DfD) refers to the process of designing buildings to enable future change and eventual dismantlement for the recovery of systems, components, and materials (Guy and Ciarimboli, 2008). We can make buildings circular by using DfD principles as the design framework and off-site construction as the fabrication mode (Yan et al., 2022). Despite the benefits of DfD for low-carbon construction prefabrication design, technologies to advance the realization of the DfD projects - assembly and disassembly processes - are not adequately investigated. Knowledge gaps remain in what and how specific/suitable technologies will address the overall integration (DfD from assembly to disassembly) for improved efficiency of any entire project supply chain.

Types of prefabricated constructions are characterized by the level of prefabrication involved in that specific method. The major types are modular, panelized, and hybrid construction (Salama et al, 2021). Transportation constraints make panelized, and hybrid construction appealing choices for remote construction. This study focuses on how AR technology can help workers transition between traditional and panelized construction. In this, we explore how AR can effectively deliver assembly/ disassembly instruction in a live construction setting. The scope of this study is limited to solution formulation and proof of concept. The experimental evidence of the developed solutions will be explored in future studies. The first part of this paper presents workflows to create AR solutions that can help workers during in assembly of a panelized project. In a typical panelized project, the workers are expected to perform two major duties. These are (1) locating and placing the panels in their correct position and (2) connecting the panels and securing them in their position. The created solutions need to be used in a live construction site. In this study, two such solutions are conceptualized and demonstrated. The second part of the paper explores how the created workflows can be adapted to be used during disassembly. The objective of this study is to provide work procedures that can be adopted by many, with ease and with minimal cost, that can help local laborers transition to panelized construction assembly and disassembly. We are using marker-based AR solutions to achieve this objective, as they can be deployed in live construction sites with minimal distraction in a cost-effective and easy-to-replicate manner.

The remainder of the paper is structured as follows: Section 2 provides a literature review focused on AR in construction assembly and disassembly while giving a background in DfD. Section 3 illustrates the workflows to create the two AR-based solutions, which are then demonstrated using an example of assembling a structural wall panel. The details of how the presented workflows can be adapted for DfD are also given in Section 3. Section 4 discusses the advantages and disadvantages of the proposed solutions, followed by the conclusions and future work in Section 5.

2. LITERATURE REVIEW

2.1 AR in Construction Assembly

In AR, the computer-generated information such as characters, animations, or general information is overlaid onto the real environment seen through the AR device, thus presenting an enhanced real-life experience. The main types of AR methods include (1) marker-based AR, (2) location-based AR, (3) projection-based AR, and (4) superimposition-based AR (Alizadehsalehi et al., 2020). The implementation of AR solutions has prevailed in construction practices in the last decade. Commercial AR applications have prioritized stakeholder engagement, collaboration during the design stage, and information retrieval during the construction stage. Out of the AR-use cases identified in the literature, use cases related to visualization and information retrieval are prized among industry professionals (Nassereddine et al., 2022). While there have been a lot of studies on AR for construction support, we'll focus on its use case for assembly in construction and any training relating to it. Nee et al. (2012), Wang et al. (2016), and recently, Wang et al. (2022) have collected previous literature on AR-based assembly operations. It can be noted that most of the literature deals with the manufacturing industry. Ho et al. (2022) noted that most of the literature on AR-based training can be grouped into a small number of groups, while assembly brings the prominent one among them. Wang et al. (2022) noted that most AR instructions (73%) are used in experimental-level assembly instead of industry-level. They also noted that 64% of AR instructions are presented as static. Research on assembly using AR can be grouped into three major categories, i.e., AR for assembly guidance, AR for assembly training, and AR for assembly process simulation and planning (Wang et al., 2016). Radkowski (2015) identified that AR can support the parts of "Identification, Handling, Alignment, Joining, Adjustment and Inspection" in a manual assembly process. Assembly sequence, the components that need to be assembled in that specific step, assembly location, and required tools are noted as the most important assembly instructions. He also highlighted that less significant parts of the assembly (e.g., parts supporting the process, such as nuts and bolts) do not require rich instructions.

In a study by Chalhoub et al. (2021) that represents the construction AR, three groups (construction professionals, construction students, and individuals with no construction experience) were given two tasks (prefabricated conduit assembly and electrical point layout) to be completed using AR. The authors reported that though the time taken for task completion was similar between all groups, the accuracy was significantly lower for individuals with no construction experience. Ahn et al. (2019) explored the possibility of using a projection-based AR method to visualize essential information during manual assembly in a panel manufacturing factory. The modified wall drawing was projected onto the panel under fabrication and aligned using markers on the panel itself. Fazel and Izadi (2018) presented an AR system using multiple markers to construct free-form modular surfaces. They placed the markers on the floor and the worker's HMD. A fixed camera tracked the markers to determine the camera's location within the HMD. Based on this and the loaded 3D model, vertical guides were augmented on the HMD. Hou et al. (2015) checked the effectiveness of AR-based animation for guiding workers in piping assembly. This experiment also used multiple markers to locate the pipe assembly. The augmented scene was displayed on a monitor/screen to be referred to by the assembler. They reported that AR reduced the assembly time by 50% and reduced the assembly errors by 50%. Kurdve (2018) argued that displaying animations of instructions on a large screen makes 'easy jobs' more efficient in the module-building industry. Tools were color-coded in these animations to provide an intuitive response. Bellalouna (2020) discussed the possibility of using dynamic sections and exploded views in AR to better understand the internal parts of machinery.

Utilizing AR to improve the efficiency and precision of the assembly process of prefabrication construction has been identified as one of four future research directions concerning AR in prefabrication construction (Wang et al., 2020). However, the specific methods and processes of utilizing AR to guide construction assembly processes have not been fully investigated. The implementation of AR at the construction stage is poor, and its potential is still not fully realized (Delgado et al., 2020). Especially the AR implementation in a live construction setting is not explored in detail. Table 1 details some of the observed characteristics in scenarios where AR is used for assembly. Factors such as 'maturity of technology, lack of skilled personnel, cost of implementation, distraction while using AR, excess cognitive load, and decreased vision of user' are often cited as obstacles to the adoption of AR in the construction phase (Nassereddine et al., 2022; Kolaei et al., 2022). This research intends to fill the knowledge gap by providing two workflows to create AR solutions to guide assembly in panelized projects, that can overcome the identified challenges. These solutions will help in the upskilling of the local labor force in remote communities.

TABLE 1: Characteristics of using AR for assembly in different scenarios based on literature review.

	Manufacturing Industry	Construction Industry (Post-Structural Works)	Construction Industry (During-Structural Works)
Location of AR solution deployment	Static	Less Dynamic	Highly Dynamic
Type of assembly work	Mostly Routine	Dynamic	Mostly Routine
Level of distraction in the deployed environment	Low	Medium	High
Risk associated with that distraction	Low	Medium	High
Cost of AR solution development and deployment	Medium (Display Screens) to High (HMD & Projection based AR)	Medium (Display Screens) to High (HMD)	*
Ease of Use	High	Medium	*

* Specific methods for the construction assembly of structural systems, at a live construction site, are not identified in the literature

2.2 Design for Disassembly and Deconstruction

Several governments and their institutions have committed to limiting global warming by 1.5°C, which means that emissions need to be reduced by 45% by 2030 and need to reach net zero by 2050 (United Nations, 2022). The carbon emissions relating to the built environment throughout its life cycle can be divided into two: embodied carbon and operational carbon. Operational carbon refers to the amount of emission created during the use of the building, and embodied carbon refers to the carbon emitted while producing a building's materials, their transport and installation, as well as their eventual disposal. As buildings become more energy efficient and start using renewable energy, the operational carbon will be diminished, highlighting the embodied carbon in the building (London Energy Transformation Initiative, 2020). DfD allows us to reduce embodied carbon by ensuring that the building components will have more than one life. Though the importance of DfD is well realized, the practical application of the concept has not been fully explored yet. Many studies have stated that the lack of evaluation criteria that allows for weighing the environmental benefits of DfD is the biggest barrier to DfD implementation (Ostapska et al., 2021). In addition, lack of technical knowledge, supporting tools, and time constraints (which favor demolition rather than deconstruction) can also be stated as barriers for DfD (Kanters, 2018). Several studies have focused on solving the identified issues and provided recommendations for building design, material & connections, design process, and more. A few scholars suggested that the information about the used material, as-built drawings, and proposed deconstruction method need to be stored for future reference (Kanters, 2018). In addition, the used components need to be easily identifiable as well. A deconstruction plan needs to be developed in the design stage to pass on this information to facilitate future disassembly. Guy and Ciarimboli (2008) stated that a successful deconstruction plan needs to have the following items: (1) a Statement of DfD strategy, (2) a List of building elements, (3) Disassembly instructions, and (4) Distribution of DfD plan. To assist the DfD project implementation, we will focus on the recommendations that are relevant to this study.

The deconstruction process is a labor-intensive task and only requires a reasonable amount of skills. However, training the workers in disassembly and providing the needed tools can increase efficiency and reduce the overall deconstruction duration (Chini and Bruening, 2013). It should be noted that deconstruction workers must undergo 'hazardous materials training' in addition to the disassembly training. This is not included in the scope of this study. As choices made during the design stage play a huge role in the implementation of DfD, Akinade et al. (2017) noted that improved education for architects and design engineers is also required. Jaclyn (2021) summarized the advantages and disadvantages of currently existing construction systems in terms of disassembly. DfD implementation of panelized construction has not been studied much, especially regarding timber panels (Yan et al., 2022). Ostapska et al. (2021) noted that most of the existing and planned DfD structures use frame (62% of 117) or a combination of frame and modular (15%) as the primary structural system, while only 14% use purely modular systems. However, these buildings mostly used wood or EWP (engineered wood product) (52%), followed by steel or iron (38%). Under the 'Buildings as Material Banks' project, several reversible buildings/ components were investigated (Goens et al., 2018). In this, the Circular Retrofit Lab (CRL) compared different wall systems for their performance and ability to be disassembled. NEXII conducted a deconstruction case study involving constructing and disassembling a small, panelized building (Light House Sustainability Society, 2022). Yan et al. (2022) investigated the possibility of adopting reversible timber connections for light timber framed panelized construction. The studies demonstrated the various opportunities for prefabricated projects to apply DfD concepts to ease the deconstruction when projects reach the EOL stage.

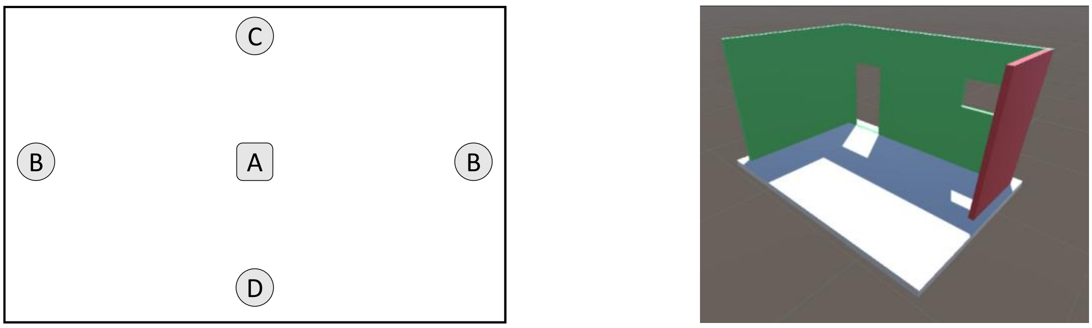
In the manufacturing industry, delivering disassembly instructions for maintenance or eventual dismantlement has been identified as a potential use case for AR. In a study by Frizziero et al. (2022), the optimal disassembly sequence of a float condensate drain is first determined, modeled, and showcased in AR. Akinade et al. (2017) identified 'Visualization of the deconstruction process' as an important expected feature of a BIM-based DfD tool. However, the use of AR in the EOL of construction is still an unexplored research avenue. To address this knowledge gap, we can adapt the workflows developed for assembly to disassembly. In this study, we will explore how the adapted workflows can benefit not only the workers during disassembly but also the designers in the design phase.

3. METHODOLOGY

The AR solutions were designed to have the following features to counter these obstacles identified in the literature: they should be able to be deployed using current consumer-level technology, the cost of implementation and level of training required to use them should be lower, and they should cause the least amount of distraction, requiring the least amount of cognitive processing. Considering all the above, it was decided to develop marker-based AR solutions to be deployed through smartphones. The workflows use game engines to make the development of these solutions easier and quicker.

As stated above, in a panelized project, most workers are expected to locate the panels at the correct location and connect them properly. Two solutions are created to help workers in these tasks: (1) Solution 01- using a QR code placed in the middle of a panel as an AR marker to display the intended location and sequence of placement of that specific panel, (2) Solution 02 – placing predetermined markers at locations where a panel connects with others, to display information of those connections using AR technology. The developed solutions are demonstrated in the panelized project using Structural Insulated Panels (SIP) as an example. However, the workflows can also easily be adapted for other types of panelization. SIPs consist of an insulating core sandwiched between two structural facings. Structurally these are similar to steel 'I' (transformed) sections and have high strength and high-performance characteristics. SIPs are predominantly used for residential and light commercial constructions ("Prefabricated Structural Panels," 2021).

Fig. 1 (a) shows the representation of the front view of a typical wall panel as the example SIP used for this study.



(a) (b)

FIG. 1: (a) representation of markings in a typical wall panel (front view) and (b) 3D model showing a specific panel in red.

The textbox showing ‘A’ indicates the location of the QR code placement. This will be unique to each panel. The same QR code can be used to store information on the supply chain if necessary. Since our application would only see the QR code as a marker, the secondary function would not be impaired. The rest of the textboxes ‘B’, ‘C’, and ‘D’ indicate the possible locations of the markers assigned to a specific connection type. For example, the textbox ‘D’ can act as the marker for a wall-foundation beam connection. Similarly, marker ‘C’ can be assigned to a wall-floor or wall-roof connection, whereas ‘B’ can indicate a wall-wall connection. These markers are not unique to the panel but the connection type. Since we are dealing with standardized connection types in panelized construction, these markers can be used for projects with a similar panel type.

3.1 Workflow for Solution 01 (QR Recognition)

The purpose of Solution 01 is to communicate the intended physical location and placement order of a specific panel to the worker. The worker needs to understand this information with minimal effort. It was decided that we can relay that information effectively by displaying a three-dimensional (3D) model showing the construction progress up to that specific panel on top of the marker. Fig. 1 (b) shows an example 3D model. The panel relating to that QR code is shown in red, and the other panels are shown in green to minimize the visual effort to identify the panel correctly. Fig. 2 shows the BPMN (Business Process Modelling and Notation) diagram for the workflow to develop Solution 01.

The proposed workflow involves three stages. In the first stage, a linearized installation sequence is created based on the project progress plan. Installation steps, along with respective panel IDs, are extracted from the project progress plan. Then the panel IDs are arranged in a step-by-step list, reflecting the installation sequence. In the second stage, separate 3D models are created for each step in the list from the first stage. Initially, the 3D model of the complete structure is extracted. Then all panels are identified by their panel IDs and separately saved within the model. Then all panels are hidden using visibility controls in the 3D program. Following that, the first panel is made visible in the viewport, and the color of the model is changed to red. Then the visible objects are exported as a ‘.fbx’ file named with the corresponding panel ID. From the second step, the color of the panels up to the previous step is changed to green, indicating they have already been installed. Then the panel corresponding to that specific step is made visible, and its color is changed to red. As done earlier, the visible objects are exported and saved in a database. For this study, the 3D modeling software ‘Blender’ (Foundation, 2022) was used to create these models and animation.

In the third stage, the database created in the second stage is used to create an AR application that will display a 3D model corresponding to a panel when detecting the QR marker of that panel (Fig. 3(b)). The Unity engine (Unity Technologies, 2023) was used to create this application. Initially, QR codes are created for each panel ID or extracted from the supply chain data. Then the QR codes are uploaded to the ‘Vuforia engine’ (Vuforia EDP, 2022) to create a marker database. For easier tracking, the markers are identified by their corresponding panel IDs. Then this database is imported into the Unity engine. 3D models are also imported to the same Unity project and assigned to the corresponding QR markers (Fig. 3(a)). Finally, the desired platform is set, and the application is exported to the smartphone.

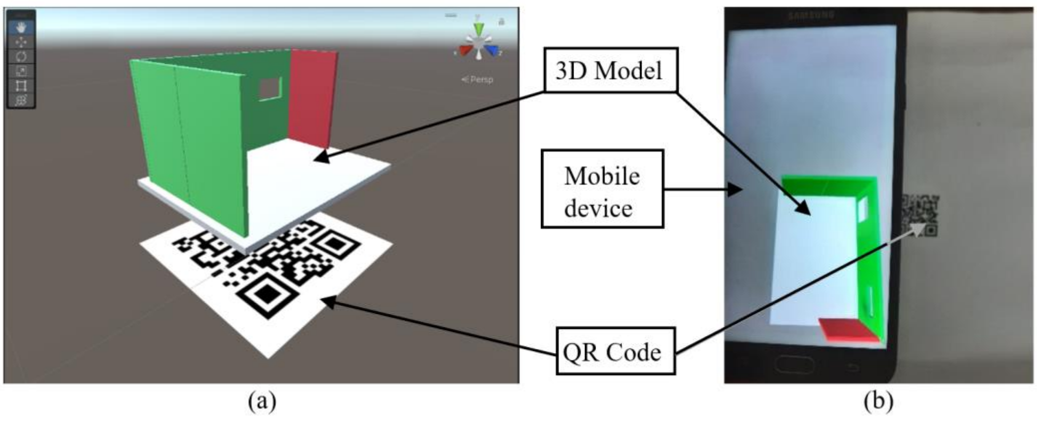


FIG. 3: (a) Assigning the 3D model to the QR code in Unity, (b) 3D model displayed in the AR mobile application while scanning the QR Code on the panel.

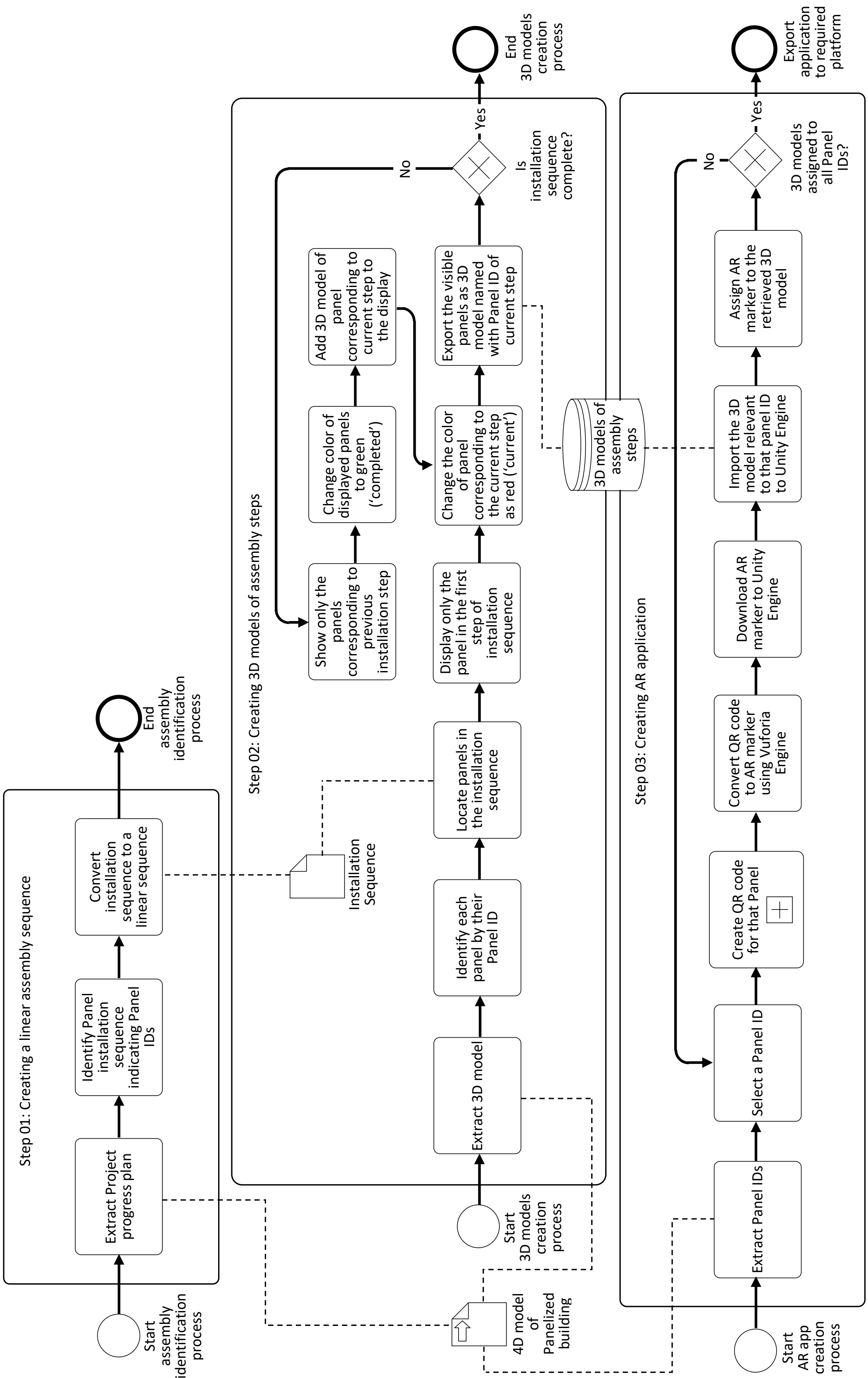


FIG. 2: BPMN Diagram of Workflow for Solution 01.

3.2 Workflow for Solution 02 (Connection Assembly)

The second solution aims to help the worker identify different types of connections and to provide a quick reminder on how to assemble the connection. The solution is conceptualized as complementary to the assembly training that workers would receive. Since this solution would be utilized during site work, the required level of input from the workers should be minimal. Thus, it was decided to display a video of how a connection is assembled when detecting that specific connection marker. In this research, a wall-wall connection from 'Structural Insulated Panels (SIPs)- Basic Connection Details' by SIPA (Structural Insulated Panel Association) (2022) was modeled. Fig. 4 shows the surface spline-type connection taken for modeling. The BPMN diagram for the second solution is given in Fig. 5.

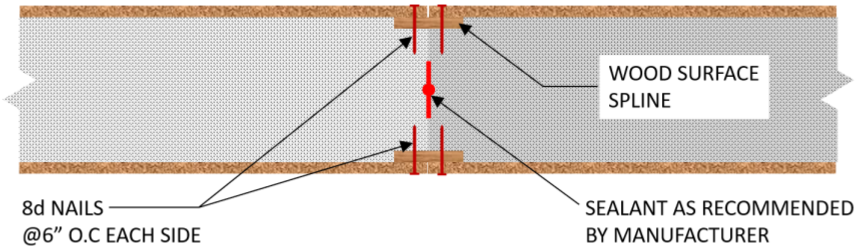


FIG. 4: Wall-Wall (Surface Spline) Connection (adapted from SIPA [2022])

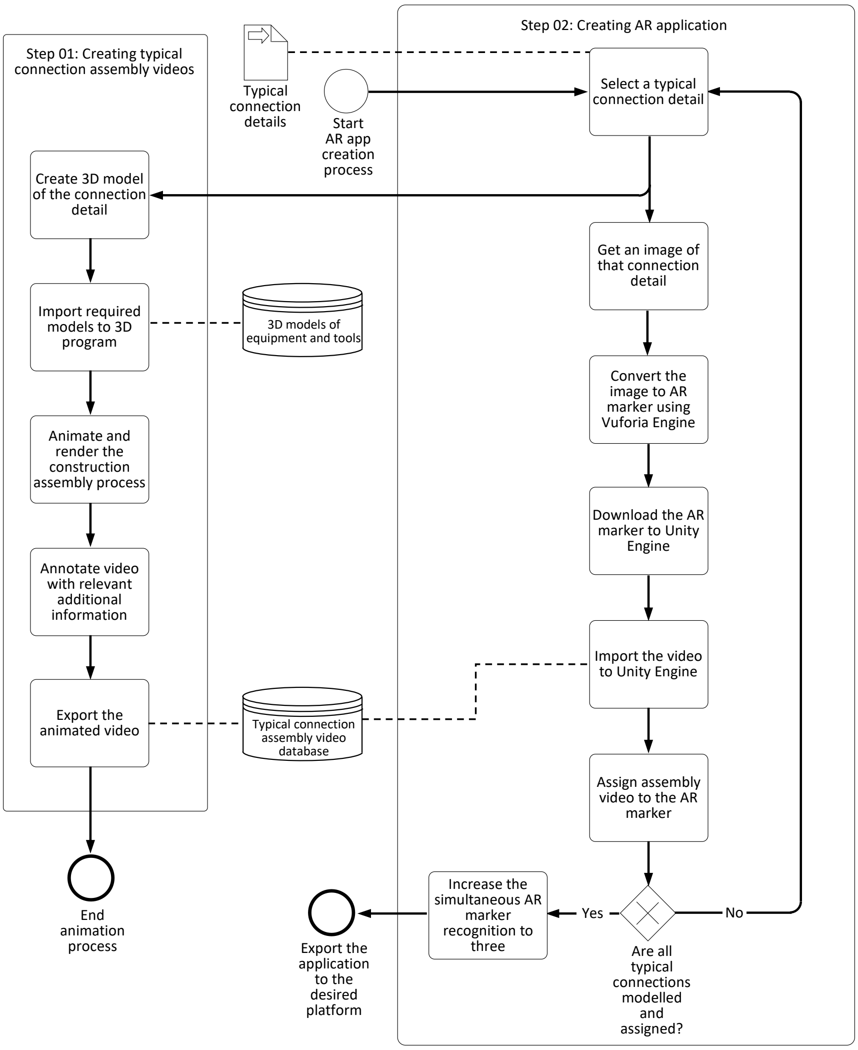


FIG. 5: BPMN Diagram of Workflow for Solution 02

The workflow for Solution 02 has two stages. In the first stage, we create a video showcasing each step in the connection assembly sequence for each connection type. Initially, we select a connection detail from the typical connection detail manual. These can be different for different manufacturers. Then the 3D model of all assembly parts of that connection needs to be modeled. The 3D models of the required tools and equipment are also imported into the software to animate the assembly stages. Then the assembly stages are animated in a clear and understandable manner, and the video is rendered. The rendered video is annotated with further information like nail sizes & spacing, sealant name, and dimensions of additional timber boards in a video editing software (such as Adobe Premier Pro). The final video is named as the corresponding connection type for easier tracking.

The second stage (creating an AR application) is similar to the third stage of Solution 01. Instead of QR codes, diagrams of the actual connections are used as AR markers. The diagrams should have enough visual features for the AR application to recognize them easily. The maximum simultaneous marker recognition is increased above one to account for locations where multiple connections are located within a small area. Fig. 6 shows snapshots from the animated video created for the selected connection. The complete video is available on CID's YouTube page (2022).

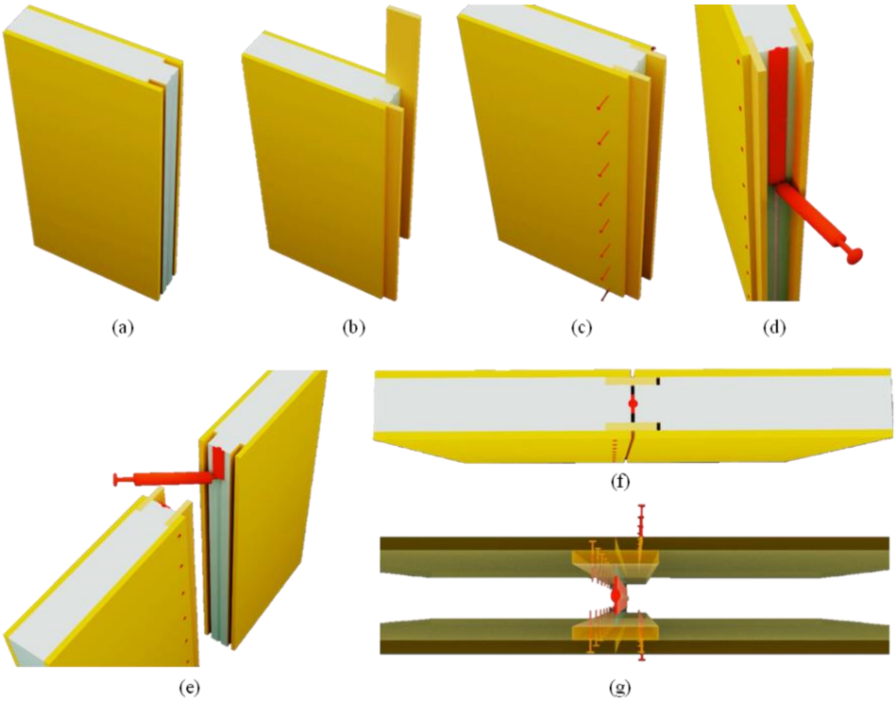


FIG. 6: Snapshots from assembly video, (a) installed SIP, (b) assembling spline, (c) nailing spline in place, (d) & (e) applying the sealant to SIPs, (f) joining the SIPs, (g) nailing the connection secure (in X-ray vision)

3.3 Adapting the Workflows for DfD and Deconstruction

Similar to assembly, (1) panel disassembly sequence and (2) connection disassembly procedure are essential during a disassembly process. This information will be part of the deconstruction plan. The workflow of Solution 01 can be modified to showcase the panel disassembly sequence, while the workflow of Solution 02 can be modified to display the connection disassembly procedure. First, we'll focus on connection disassembly. Similar to connection assembly, a detailed list of disassembly steps needs to be obtained. While this would be the inverse of assembly steps for fully reversive connections, some additional or different steps might be required for most connections in real practice. For example, to separate the panels in the NEXII deconstruction study, in addition to disconnecting bolts, the sealant had to be broken by a reciprocating saw (Light House Sustainability Society, 2022). Additional tools and equipment required for these steps also need to be identified before starting the workflow. Following this 3D model of the connection disassembly can be modeled and animated following the existing workflow. Additional details relating to safety can also be annotated in the video to remind workers of their safety training, including 'hazardous material training' if required. The videos can then be assigned to the same connection diagrams in the game engine, and a different smartphone application can be exported.

The workflow for creating an AR solution showing a panel disassembly sequence is similar to the one for the assembly sequence assuming that dry connections were applied to ease the difficulty of deconstruction. The only difference is that the list of panel IDs in the order of assembly is replaced by a list of panel IDs in the order of disassembly. The color coding of the panels in the 3D models can be reversed for easier comprehension (green - current panel being disassembled and red - panels that need to follow this). According to the established workflow, the 3D models are assigned to the same QR code, and a different smartphone application is exported. It should be noted that only the input for workflow changes between assembly and disassembly while workflow remains the same.

4. DISCUSSION

The state-of-the-art research has focused on implementing AR for assembly works on the factory floor in the manufacturing industry. However, the same concept and technologies have not been available for the construction assembly and disassembly on site. Previous research deals with pipe assembly, electrical circuit assembly, and building walls. These can be helpful for the assembly workers in jobs succeeding the completion of structural works like MEP assembly or bricklaying. Other AR implementations at construction sites vary between information retrieval, QA/QC implementation, and construction management using 4D BIM models. While other studies have discussed the advantages of AR in construction, the implementation of AR in a live construction setting is not explored in detail and no studies were found for panelized construction. This research brings additional insights into the application of AR in the live construction site for assembly purposes during structural works and disassembly in the EOL stage.

As noted in Table 1, the main difference between AR for the assembly process in the manufacturing industry and construction is the environment in which it is used. In the manufacturing industry, the application designer has greater control over the environment. When operating the HMD, the user's vision is restricted to what is visible through the glasses. For example, the diagonal field of view available in HoloLens 2 is 52 degrees (Microsoft, 2022). This would not be a concern in the manufacturing industry as the workers are generally expected to concentrate only on the assembly in front of them. However, this becomes a major concern in an environment like a construction site. The workers not only need to concentrate on their work but also need to be aware of their surroundings due to safety concerns. Deploying the created marker-based AR solutions through smartphones can solve this problem. One of the aims was to convey information to the workers with minimal distractions while causing the least amount of cognitive load. To activate the marker-based AR, the worker just needs to launch the smartphone application (this needs to be done only once). Following that, the application itself will detect the markers and display the relevant information. The workflows emphasize using brighter colors that can transfer information through visual cues. However, there is an inherent risk in using smartphones on live construction sites. Even though the current commercial solutions depend on smartphones or tablets to deliver their services at the construction site, the risk associated with using smartphones at the site to identify panels and connections needs to be studied before implementation.

As most workers are already familiar with smartphones, we can reduce the extra training required to operate the AR equipment by utilizing smartphones as a delivery medium. The marker-based AR requires lower computational power compared to other forms of AR. It means that even cheaper or older smartphones can be used to deploy the developed applications. Fig. 3(b) shows the application running in Samsung Galaxy J7 Prime (released in November 2016). This can allow firms to purchase refurbished smartphones for these projects, lowering the cost of entry.

Creating visual instructions helps improve the workers' understanding of assembly or disassembly during their site work. However, outputs from these workflows can also help the designers during the design stage. A proper DfD implementation calls for the deconstruction plan to be drawn up during the design stage itself. Thus, the disassembly video from the second workflow can visually inform the designers of the ease of disassembly. This can lead to further optimizing or changing those connections. One of the recommendations for DfD is enabling parallel disassembly, which will allow the removal of some components or materials without disturbing other components. The 3D models from the first workflow can help the designers investigate these possibilities. They can also help to optimize the deconstruction plan to minimize the disassembly time, which can, in turn, modify how the building is assembled in the first place. Most importantly, these applications not only store information on how the building was assembled but also distribute that information, which is an important aspect of DfD. As discussed before, while the importance of DfD and the importance of reducing carbon emissions are well understood, simpler methods for its implementation are lacking. We believe that providing these easy-to-use solutions can encourage more practitioners to get involved in DfD. The consultants also can benefit from this type of application, as they can easily verify the location of a panel during construction assembly.

It should be noted that we use the same markers to display different information using different applications. The QR code used to display the panel assembly sequence in Solution 01 is reused to display the disassembly sequence. As stated before, the same QR can also be used to store supply chain information. However, there is a concern about whether these QR stickers or connection diagrams will withstand the building use over time to be used during disassembly. Placing proactive covers on them before applying finishes or etching them permanently on the panels during manufacturing might solve this problem. While the workflows are designed for the assembly and disassembly of panelized wall construction, their application is not limited to structural works. The same workflow can be adapted for MEP assembly and associated maintenance and disassembly. Moreover, these workflows can be modified for other types of prefabricated construction. The workflows are designed to be implemented with minimal cost, effort, and technical knowledge. This is done so to encourage easier adoption for remote communities. This will, in turn, facilitate the integration of the local labor force in panelized construction.

5. CONCLUSIONS AND FUTURE WORK

The skills required for traditional construction differ from those required for prefabricated construction. Thus, the workforce must be provided with adequate skillsets and tools to embrace new construction methods. To address the challenges, this paper develops workflows and suggestions to create AR solutions that can assist workers in two different stages of construction, including the assembly and disassembly of panelized construction elements. The proposed solutions are simple, use basic AR technology (marker-based AR requires comparatively lower computational power), and use visual features to convey information more efficiently. This paper initially focuses on detailing the arguments of solution formulation and implementation procedure for two solutions. In the first solution, the worker can easily observe the intended location and placement order of panels and then communicate to the crane operator to lift and place it in the correct location. The second solution provides the assembly workers with a quick reminder on how to assemble the connections. As they gain more experience, their reliance on this specific application will be reduced. If different manufacturers standardize the connection details, this solution will become very effective since workers can improve their understanding of complex variations of the connection details. The second part of the paper focuses on adopting the developed workflows to create AR solutions that can be used during the disassembly of a project. This involves providing information on how to disassemble specific connections and in which sequence the panels need to be removed. It is also discussed how this information can help the designers to optimize the assembly and, in turn, disassembly of a project. A proper DfD implementation and associated deconstruction plan are suggested to be companion with AR-based assembly instructions, which will substantially improve design-to-construction integration in panelized construction projects.

Future research will be conducted to include the development of a VR application aimed at familiarizing workers with connection assembly. The effectiveness of these solutions in a laboratory setting will be analyzed to test and improve the application, in accordance with the guidelines provided by UBC Behavioral Research Ethics Board. The risk assessment for implementing these solutions in real settings will also be explored, and then the effectiveness of the modified solutions will be assessed on a construction site. Further research on using other available technologies in upskilling laborers should also be given high importance.

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