A Method to Produce & Visualize Interactive Work Instructions for Modular Products within Onsite Construction

Raafat Hussamadin[a], Jani Mukkavaara[a], Gustav Jansson, Ph.D.[a]

[a] Department of Civil, Environmental and Natural Resources Engineering, Luleå University of Technology, Sweden
E-mail: Raafat.Hussamadin@ltu.se, Jani.Mukkavaara@ltu.se, Gustav.Jansson@ltu.se

Abstract –

Well detailed, informative and accurate work instructions are a necessity to mitigate delays in construction. Today, this is done through a combination of shop drawings, documents, sheets, work pre-planning meetings and onsite verbal work instructions to transfer knowledge and information between all actors. Due to the subjectivity of these methods, many incorrect assumptions and man-made errors originated from miscommunication and misinterpretation can occur. Such issues are tough to identify prior to their occurrence on construction sites, leading to construction delays. Virtual Reality (VR) technology can simulate and visualize assembly processes using Standard Operating Procedure (SOP). The visualization aims to ensure a quality communication with skilled workers and to aid their interpretation of SOPs by reducing assumptions. As a result of a more effective education, it can support the collaboration between actors. Utilization of SOPs for visualization of Work Instructions (WI) and assembly processes are important, because many process WIs on construction sites are repetitive. Modularity can increase the efficiency by supporting instancing and variation creation of construction tasks and products. Interactivity can support the continuously changing status and demands of construction sites.

A method has been iteratively developed to support visualization of modular and interactive SOPs within the context of industrialized house-building (IHB), to increase the quality and consistency of communication at construction sites. Concurrently to development of the method, a prototype using VR technology was developed. Interactive functionalities along with VR technology make it possible to adjust SOP and WI modules to suit the demands and conditions of the construction site, including real-time. As a result, the developed method is responsive and adjustable to conditions such as weather, man-made errors, assembly re-sequencing and re-scheduling. Combining product design, SOPs, WIs and assembly process in early stages of construction has shown to help identify potential issues and aid in planning for cautious measurements. Results show that by using the developed method, skilled workers were able to identify occurring miscommunications, and misinterpretations between them, site managers and foremen as well as ensuring their understanding.

Keywords –

Virtual Reality; Standard Operation Procedure; Work Instruction; Process Visualization; Interactive; Modular

1 Introduction

Usage and distribution of information within offsite manufacturing by having Standard Operating Procedures (SOP) and Work Instructions (WI) have improved the manufacturing workflow in industrialized house-building (IHB). This has however not been well translated to onsite construction, which has been lacking in development efficiency and has become a bottleneck. A well detailed SOP and WI, that are thoroughly and correctly communicated is a necessity to mitigate onsite construction delays.

The difference between the usage of SOP and WI in offsite manufacturing compared to onsite construction has been significant. Standardization reduces the complexity of information flows and its coordination [1]. With adoption of assembly line manufacturing and increased standardization, IHB has optimized offsite manufacturing tasks, resource flow, and repetitive assembly processes for the skilled workers. IHB has invested time and resources to create high quality SOPs and WIs that are thoroughly communicated to the associated skilled workers. This has however not been translated to a construction site in which the flow-oriented workflow meets the project-oriented workflow. Skilled workers on construction sites perform a variety of tasks and often have a limited holistic view of the project. This is due to only performing their allocated tasks and becoming indifferent to assembly sequence, schedule, construction quality and other tasks, leading to the hampering of progress and an increase in waste [2]. Current document-based WIs are time consuming, error prone, and inconsistent, leading to miscommunications and misinterpretations, which causes delays [3]. With one of the reasons being that many of the skilled workers are contractors, requiring reintroduction to SOPs and WIs of the said project and company, reducing the long-term sustainability benefits that can be acquired from a SOP and WI.

WIs are communicated through a combination of shop drawings, text documents, sheets, and meetings. This means that the recipient of the information, engineers and skilled workers, must interpret the information and create a visual image of the construction, its assembly sequence and its tasks. Due to the risk of misinterpretation, and in turn assembly errors, WIs are communicated to skilled workers mainly through verbal communication [3], resulting in the verbal communication often being a time-consuming and inefficient communication method [4]. Verbal communication of WIs leads to skilled workers having many uncertainties and misinterpretations, including assembly sequence, task instructions, and resource usage [5]. Uncertainty prevents them from recognizing potential problems, communicating potential improvements and simultaneously reduces their motivation [2,5].

The purpose of this study is to iteratively develop a method for the creation of modular interactive visualization of SOPs and WIs within the context of IHB. With the aim of increasing the quality of communication at construction sites, a prototype based on game engine technology was developed and evaluated to reduce man-made errors in construction sites.

2 Research Approach

The study has been conducted with a design science (DS) approach by Hevner [6], to develop the knowledge and understanding of the problems within the field by iteratively building a prototype. Data collection methods were semi-structured interviews, observations, meetings and supplemented by a literature review. The primary activities in DS research are the designing, building and evaluation of prototypes [7]. Prototypes can comprise processes, models, methods, and software. This paper uses DS to describe the development of a software prototype for modular and interactive visualization SOP and WI, and to propose a method based on this process.

To support the development of the method and its evaluation, a study was conducted in multiple IHB construction projects. These projects were selected for the study due to them having new assembly processes for onsite construction, meaning that SOPs and WIs for said assemblies were under development. In an iterative process, the method was designed and built for evaluation of construction sites works in collaboration with site managers and foremen. Using results from the evaluation of the prototype, the method was further developed for upcoming projects. Skilled workers were collaborated with within the later stages of the development, only when a certain maturity had been achieved.

Semi-structured interviews with process development engineers, site managers, foremen and skilled workers were used to identify the information flow within the company, the perception of the prototype, and for comparison of the prototype with text based WIs as well as mapping and development of assembly sequence, SOPs and WIs.

3 Theory

3.1 Standard Operating Procedure & Work Instruction

Standard Operating Procedure (SOP) is a means of documentation that describes the best-known practices within a specific company, often in the form of text-based documents. A company can use SOPs to achieve a reduction in scheduling waste, quality issues and environmental impacts, while simultaneously increasing the safety and consistency of assembly processes [2,8]. SOPs also benefits the company by encouraging the documentation of information resulting in knowledge staying within the company [2,8].

A SOP can include working methods, precautions, task durations, preparatory tasks, step-by-step instructions, resources, etc. [9]. The step-by-step instructions contain a specific start point and a description of each sequenced instruction, where a group of instructions is a WI. A SOP must be user-friendly, easy to understand and must be easily revisable [2].

Work instruction (WI) is an approach to manage the dissemination of information and knowledge within companies [10] and the best practices of work [11]. During its life-cycle, a WI goes through three phases, creation, use and maintenance phase [12]. The creation phase consists of product information, such as 3D models and shop drawings, and resource information such as tools, machinery, skilled workers, and process information that contain step-by-step instruction of the assembly process and construction rulesets [11,12]. Under the use phase, a WI is performed by skilled workers to support the sequenced assembly tasks with guided step-by-step instruction [12].

Process modularity improves the adaptability of a product, its requirements and standardization by simplifying the re-sequencing and addition of new modules to the assembly sequence [13]. It further improves the possibility of parallel assembly, hence reducing lead times [14]. Modular processes are built on three principles [15]:

- Standardization: Breakdown of a standard process into main sub-processes and instance sub-processes that can be derived and customized from the main sub-processes.
- Re-sequencing: Reordering of sub-processes.
- Postponement: Postponing instance sub-processes to increase flexibility.

3.2 Visualization & Interactivity of Modular SOP

Visualization is an effective method for introducing SOP to construction sites, where it can improve the understanding of construction aims, standards, quality, safety instructions, assembly sequence, schedule, and potentially give an improved holistic view of the construction project [2,16]. With the aim to reduce man-made errors, due to miscommunication and misinterpretation and prior expertize [2], an animated SOP and WI can enhance the holistic view of a project. In comparison to documents and static-pictures, animations are more effective, particularly when combined with realistic graphics and task instructions [17,18]. The improved holistic view and better understanding of construction tasks conducted by other skilled workers can encourage communication, and improve motivation, which can lead to further development of SOP and WI [2,5]. Text based SOP documents are more cognitively demanding, followed by pictures [10], whilst animation could reduce cognitive demand [17]. Visualization might also reduce language gaps, as they simplify communication of important information [8].

WIs require a combination of paper documentations, such as shop drawings and text-based instructions, risking misinterpretations due to subjectivity. Therefore, WIs are instead often delivered via verbal communication to skilled workers by foremen [11]. In a study comparing instructional texts, diagrams and animations for assembly tasks, visualization of WI through animations showed an increase of step-by-step instructions understanding, leading to less man-made errors, increases in efficiency and accuracy of process assembly for the novice users [17].

Best practice changes, design changes and personal changes require revisions and re-education of WI documentations to reflect the changes. These modifications to WI are performed in the maintenance phase [12]. Therefore, effective communication, where information is filtered according to the need of every actor, can improve lead times [17].

4 Development of the method

Real-time visualization of assembly processes with game engine technology can visualize SOPs and WIs. Game engine technology, through Unity, see Figure 1, was used due to its possibility for real-time rendering of realistic environments and models in combination with scripting to create interactivity and modularity as well as for its capability of developing and distributing the prototype to a variety of IT-platforms.

4.1 Development of SOP & WI

Due to the assembly process being a new roof solution within the studied company, no registered SOPs or WIs existed beforehand. Their development started with usage of a detailed 3D-model (with 6565 components) and shop drawings of the roof. In collaboration with process development engineers, site managers and foremen, the assembly process was iteratively mapped, modified and optimized. The mapping led to the possibility of identifying main and repetitive SOPs, WIs, instructions and some foreseeable issues that could occur, mainly due to their limited tolerance values, weather or logistics.

A total of 8 pre-defined main SOP modules were mapped and developed for the roof assembly sequence. These SOPs clarify the WIs required to be performed together with the information needed for a successful onsite construction. Therefore, emphasis on their development, content of information and visualization has been a major focal point. This was conducted through quality control procedures, where the prototype was evaluated by professionals with several roles using different IT-platforms. Every main SOP contains information about its title, a description and a list of sequenced WIs. The main SOPs were utilized to create a total of 25 SOP instances for the roof sequence assembly.

Similar to the described SOP above, a total of 26 pre-defined main WI modules, with 237 instances, were developed for the roof assembly sequence. Every main WI contains information about its title, a description and a sequenced list of step-by-step instructions.

A total of 6102 components have received instructions and animation information. A component (e.g. a single roof truss) contains a 3D model representing its geometrical, positional and rotational data as well as an instruction template. For reusability of information, component information is modularized using instructional templates, with a total of 18 main templates developed for the roof assembly sequence. A template consists of data about instruction, including descriptions, materials, tools, machinery and precautional notes. Each listed instruction has its template parameters gathered, sequenced and sorted in lists available to associated WI. Additionally, the instruction template describes how and when an animation should occur. This is described using four parameters: task duration, sequence type, adaptive position and adaptive rotation.

Adaptive position and rotation are three-dimensional vector values that indicate how far from the original position and rotation the animation should start.

Sequence type parameter modifies the relation of an instruction with other instructions under the same WI, as in, it makes it possible for the developer to decide when the sequences are animated, from sequence to sequence. The developer can give the user the choice to decide when to start a specific animation by setting its sequence type value in instruction to wait for user input, OnClick, (indicated by a mouse icon, Figure 2). In some cases, it might be preferable to start the next sequenced animation immediately when the previous animation is done instead of requiring user input. The developer can for such cases set the sequence type value in an instruction to wait and be played when the previous animation is done, AfterPrevious, (indicated by a clock icon, Figure 2). For cases where multiple animations should be played simultaneously, such as repetitive screwing of multiple screws, the developer can set the sequence type value in instruction to play the animation when the previous sequence animation starts playing, WithPrevious, (indicated by an arrow icon, Figure 2).

Alternative Sequences (AS) are pre-prepared solutions or modifications to foreseeable changes or issues that can be required to conduct a SOP correctly. From meetings and observations, AS has been identified as a possible interactive functionality where it opens the possibility to develop SOPs and visualize alternative construction solutions that existed but were not included.

AS is integrated with the modularity and interactivity of the method to allow the selection between multiple assembly sequence alternatives. AS modifies the WI sequence within a specific SOP, indicated by the circle icon as seen in Figure 2. Due to AS modifying data within SOPs in real-time, having and caching lists of precaution notices, task durations and resources, which according to theories mentioned before exist in SOP is no longer possible. The information has instead been moved to the individual instructions. With that, SOP now has access to this data through its list of WI, meaning that it dynamically collects data from instructions in accordance with the animation. These dynamically generated lists can later be presented to the user. As it is built on using modular WIs, it is possible for the user to swap modules of WI with other modules.

Sequence details are parameters available within SOPs. The parameter can modify the sequence type and task duration values for all instructions of the SOP. Sequence details were developed to utilize the instances and modularization of SOP by making it possible to use a single SOP in multiple different levels of detail, instead of being required to recreate the SOP or a variety that needs to be modified manually. As an example, in Figure 2, the SOP "Roof Cassette Montage" is using a sequence detail value of Low Detail, while "Roof Cassette & Gable Montage" is using Normal Detail. Both of the SOPs contain instances of the same main WI "Roof Cassette Assembly", we can however see that their instructions have different sequence types due to their sequence detail.

Sequence details follow rulesets defined by the developer to determine how the sequence type and task duration modifications occur. A ruleset can be based on fixed values but also instructions sequence order, such as first or last sequence. By default, a higher sequence detail value results in fewer simultaneous but more total animations. This corresponds to a more detailed instruction with more steps. Example of a sequence detail ruleset:

- Very High Detail: All Sequence Types to OnClick
- High Detail: WithPrevious to AfterPrevious
- Normal Detail: Preassigned values
- Low Detail: OnClick to AfterPrevious & AfterPrevious to WithPrevious
- Very Low Detail: All Sequence Types to WithPrevious

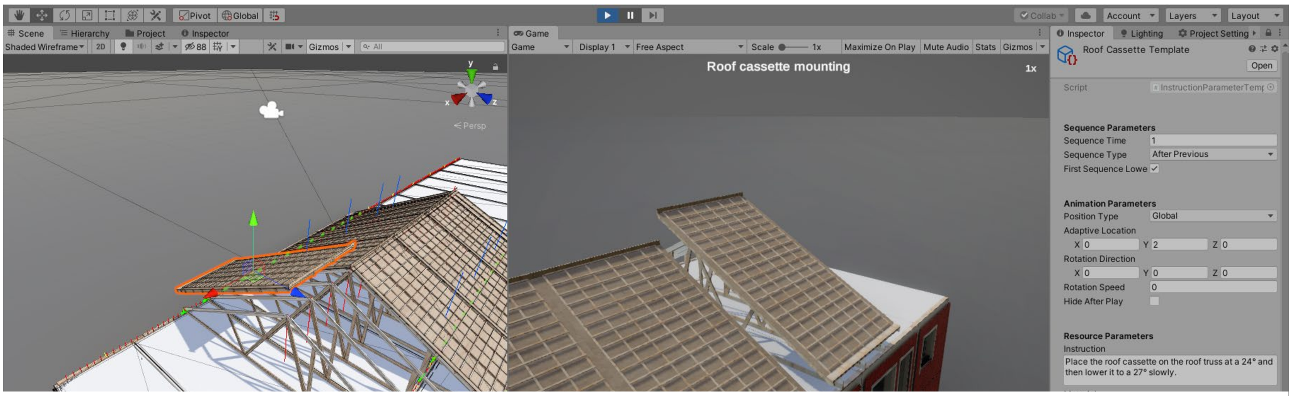

Figure 1. Prototype in Unity. Selected roof cassette (left, Scene tab) is using a Roof Cassette template (right, Inspector tab). Template information is utilized to visualize it (middle, Game tab).

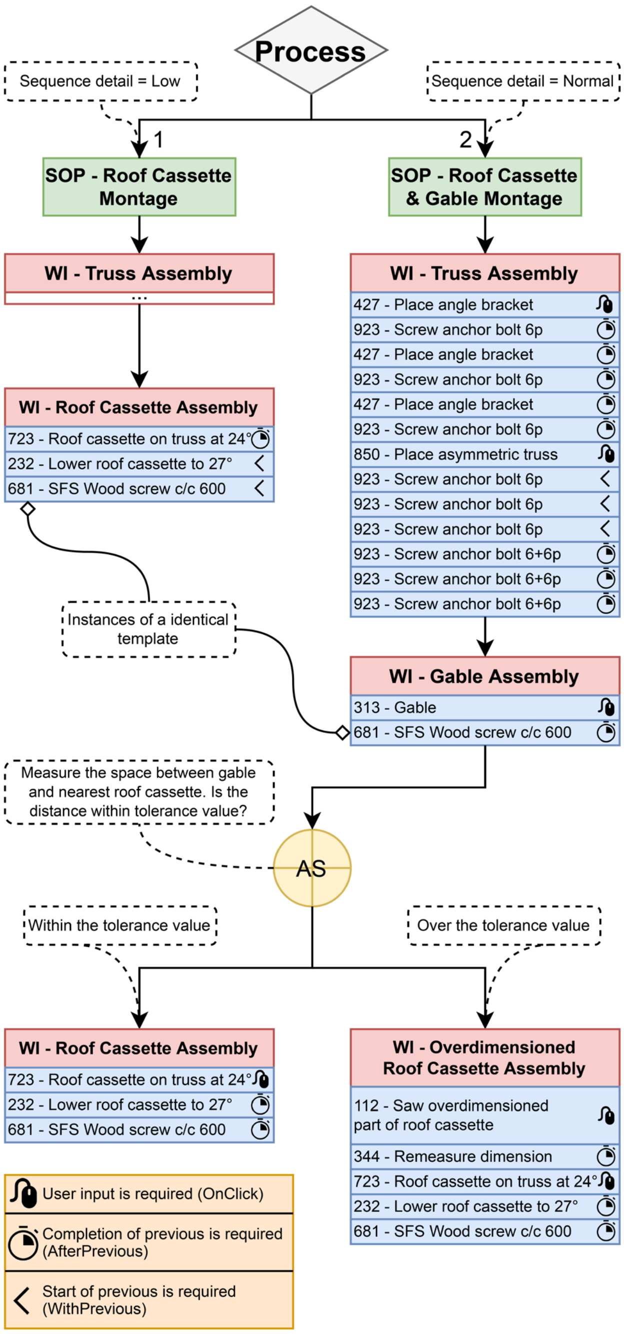

Figure 2. Data model for the developed conceptual model, identifying relations for SOP instances, WI instances, AS and instructional templates. Sequence type and sequence detail effect on instruction templates is also visualized in the diagram.

The use of modularity has been an essential factor for the development of SOPs, WIs and instruction templates. It has aided in the reduction of data redundancy by supporting reuse, updating and maintenance with the prototype. The main SOPs, WIs and instructional templates are developed from scratch. Variants and copies of SOPs as well as WIs are instanced, giving the potential to modify and update the main SOPs and WIs to automatically push the changes to all instances. Examples of main and instanced SOPs include the SOP "Roof Cassette Montage", which is a main SOP, and the SOP "Roof Cassette & Gable Montage", which is a variant from it (where a WI and an AS module are added to it), see Figure 2.

As for instructional templates, the components are using templates to pull data. The SOPs, WIs and template-based instructions are interchangeable, organizable and are decoupled from other SOPs, WIs and templates respectively. Modularization of instruction templates is developed to avoid the need of component instancing and data pushing. For example, 3 components in 2 main WIs are using an identical template "681 – SFS Wood screw c/c 600", as seen in Figure 2. This is desirable because components, in addition to containing identical data, also contain multiple unique data, such as geometrical, positional and rotational data.

4.2 Interactive prototype development

The developed method workflow is divided into 5 phases. First, the initiation phase, see green in Figure 4, where additional data is generated and cached for core functionalities of the prototype. It starts with initializing all components, SOPs, WIs, and instructions. Each SOP that has its sequence detail value changed from normal, gets its instruction sequence type values modified (OnClick, AfterPrevious, WithPrevious). That occurs according to the sequence detail as well as pre-defined rulesets by the developer. To identify animation paths for each component, their original position and rotation data (originalPosition & originalRotation) are cached. Afterwards, through addition with the adaptive values (adaptivePosition & adaptiveRotation), the start position and rotation (startPosition & startRotation) are calculated. Direction of the local axis is considered into the calculation, when the local option is selected. For each instruction not played simultaneously (Sequence Type != WithPrevious), it has its next sequence instruction checked, if any exist, to find out if that instruction needs to be simultaneously played (Sequence Type = WithPrevious). The instruction is added to a list of instructions planned to be animated simultaneously with the original instruction (simultaneousInstructions list), the method loops continuously until either finding no more sequenced instruction or finding a non-simultaneous instruction. The method, lastly in the first phase, disables and hides all component instructions for them to be later enabled and displayed when animated.

The second phase, see orange in Figure 4, focuses on searching for the next sequenced instruction within SOP-WI. A procedure to search for the next sequence starts.

This procedure can be called for multiple reasons, including when the user tries to view the next sequenced instruction. The SOPs, WIs and instructions are sequentially organized. Therefore, using current instructions sequence index + 1 in comparison with the total number of instructions within the WI, it is identified if there are more instructions available to be selected. However, if there are no more instructions available, using current WI sequence index + 1 in comparison with the total number of WI within the SOP identifies if there are more WIs available to be selected. The method selects found WI and selects the first available instruction. Otherwise, if none is found, using the current SOP sequence index + 1 in comparison with the total number of SOPs within the Process identifies if there are more SOPs available to be selected. If the method finds a new SOP, it gets selected together with the first sequenced WI/AS, with also a selection of the first instruction in case of it being a WI. The user is prompted to select one of the available AS options, if the first sequence was instead an AS, Figure 3. When none of the above processes can find a new instruction, the method identifies that no more instructions are available.

For the third phase, see blue in Figure 4, to start, the second phase must find a new instruction. The method utilizes the components' instruction data to animate them accordingly. The method ensures to loop through and animate all components if the instruction has simultaneously planned instructions to be animated (simultaneousInstructions list), else it only animates the selected instructions. The selected instruction is moved to its start position and rotation (startPosition & startRotation) and is made visible to the user. Through linear interpolation, it is possible (with a timer counting the duration of instruction animation as an interpolant) to calculate and animate a moving and rotation pattern for the component. This is a continuous process, until the component reaches its original position and rotation (originalPosition & originalRotation). Using the method in the second phase, the next sequenced instruction is searched. If found, and found instruction is planned to be animated immediately afterwards (Sequence Type = AfterPrevious), the next sequenced instructions animation is started.

Figure 4. AS, user selects a WI from list to modify current SOP. Including step-by-step instructions.

The fourth phase, see yellow in Figure 4, is simultaneously run with the third phase. This phase moves the camera to target the animated components. Using an orbit camera, it is possible, by moving the camera target, to rotate around and view the current instruction. An orbit camera also opens the possibility to zoom in/out (distance parameter). To customize and pre-define the camera viewpoint, two new parameters were added in the prototype to each component of all instructions, rotation (x & y) and distance. Through linear

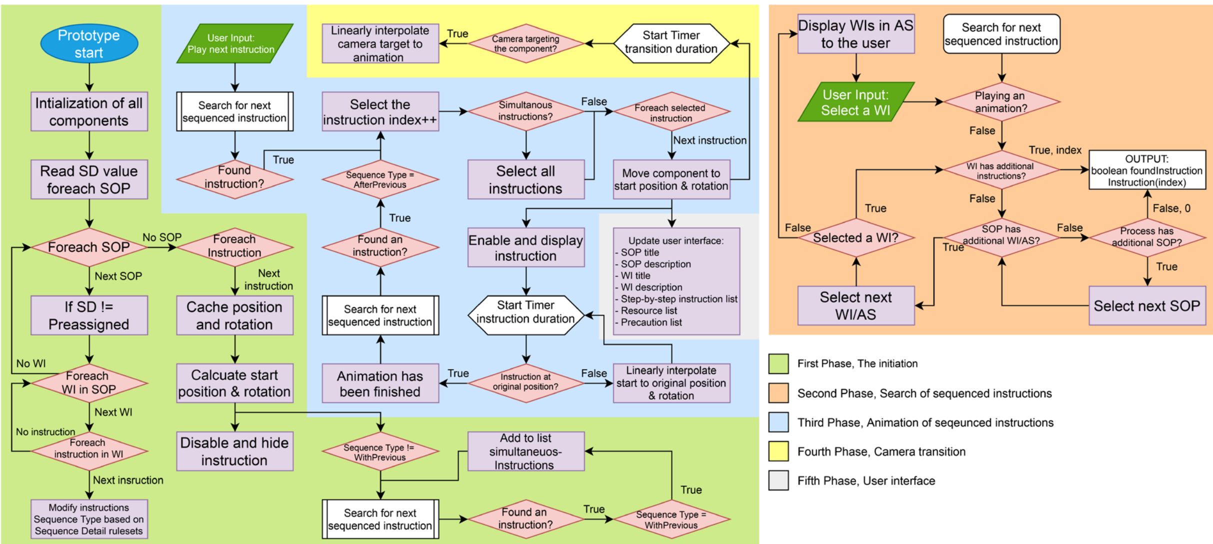

Figure 3. Flowchart of the prototype using the iteratively developed method.

interpolation, in combination with a transition duration timer as the interpolant, the camera glides to its target from its current position to its target position. In addition, linear interpolation occurs even for rotation and distance, ensuring a smooth rotation and modification of the camera's distance to the component's values.

The fifth phase, see gray in Figure 4, runs simultaneously with the second phase. This phase ensures that the user interface is functioning and displaying updated information. The user interface, Figure 5, to not overload the user, only presents the basic information. With additional information being only available when requested by the user. With each newly started animation of a component, its instruction data with description, resources and precautions are added to a list and presented to the user when requested. When a new SOP or WI is selected, the SOP and WI titles as well as descriptions are updated and can be presented to the user. The list is cleared when the selected SOP changes. Combining it all together results in a prototype that can be exported and utilized by a variety of devices for usage in construction sites, see Figure 5.

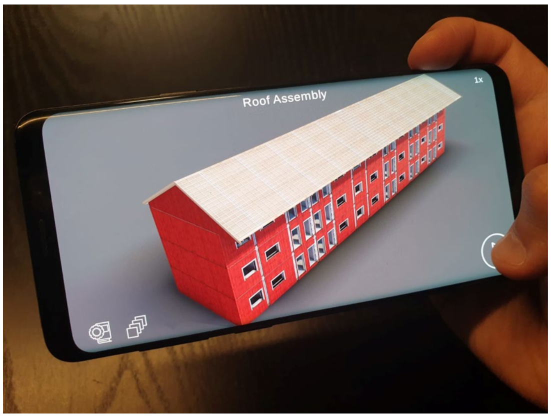

Figure 5. Prototype running on Android smartphone.

5 Discussion & Conclusion

According to the study, onsite construction at an IHB company has shown to utilize many repetitive processes as well as variants of these processes. Development of a method for the conception and usage of modular SOPs (main & instances), WIs (main & instances) and instructional templates has opened the possibility for reuse of information and experience within multiple construction projects, reducing data redundancy and in turn even decreasing lead times. Reusability of modular AS has encouraged the IHB company to increase their SOP quality by putting more resources into their development and identifying foreseeable issues.

Interactively defining modular SOPs, WIs and instructions has shown the potential to simplify and streamline the assembly sequence process with data within SOPs, etc. The structure of main and instances as well as templates ensured that modifications to mains and templates updated all instances accordingly, aside from unique values within said instances. The interactive modularity has aided the creation of unique variants for mains and templates that later can be utilized in the creation of instances and their connection to components, respectively.

Interactive visualization of modular SOPs, WIs and instructions with user inputs, accurate information and animations have been described by interviewees using the prototype as a usable and useful tool. This, combined with 3D models, potentially gives an improved holistic view of the construction project, assembly process sequence as well as step-by-step instructions that otherwise with many shop drawings and information sources was difficult to obtain. It has assisted the communication between site managers, foremen and skilled workers, resulting in earlier identification of misinterpretations and misassumptions that traditionally instead were identified during the assembly process by foremen. For inexperienced skilled workers and new processes, visualization of the assembly sequence is seen as a massive help in describing and educating how an assembly is correctly performed. Also, ensuring that site managers, foremen and skilled workers have a similar understanding of the construction's assembly processes. Reducing communication deficiencies that can occur due to actors having different backgrounds, experiences or standards is a key to reducing man-made errors. This is supported by theory, as 3D models and good quality instructions could be used for training of new assembly processes as well as for new skilled workers [3]. According to interviewees, inclusion of the developed prototype as a complimentary data source in construction site has shown to bring the typically occurring misinterpretations and misassumptions into the open. With many of them being due to usage of outdated and incorrect versions of the text-based instructions. Prior to usage of the prototype, interviewed skilled workers were certain that their processes were up to the standard set by the company. However, after inclusion of the prototype, they were able to identify multiple processes that are being conducted differently, noting that this is how they used to do it before.

Development of SOPs, WIs and instructions combined with detailed 3D models has been shown in the study to aid project engineers in the identification and mapping process of assembly sequences, their optimization possibilities, sequence errors as well as possible misinterpretations in early stages of the development. Leading to an improved holistic view for process sequence of the construction when the information is joined together and in turn minimizing possible process errors by improving planning for parameters such as object collisions, zones (reachable & unreachable), avoidance of uncomfortable and risky working conditions. Many of these optimizations and sequence errors are traditionally identified at later stages by foremen and skilled workers, which are often communicated to project engineers. The prototype is expected to increase the construction efficiency by:

- Reducing the required education time of inexperienced skilled workers.
- Reducing misunderstandings and misinterpretations of the standardized processes.
- Visualization of critical sequences, safety instructions, tools and materials.
- Simplifying the conduction of self-control.
- Assisting the daily follow-up of construction job planning.

As a complementary result of the study, improved feedback loops between skilled workers and engineers was observed at early stages using the developed prototype, for assisting in assembly sequence and construction processes.

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