VR in Construction – Multi-User and Multi-Purpose

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VR IN CONSTRUCTION – MULTI-USER AND MULTI-PURPOSE

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ABSTRACT: *The integration of immersive virtual reality (VR) and Building Information Modeling (BIM) has many applications within the Architecture, Engineering, and Construction (AEC) industries, and it is mainly VR's ability to convey scale and details that is put forward when comparing it to non-immersive visualizations. More recently, immersive VR has been extended to support multi-user sessions where several participants can experience the same model at the same time. However, there is currently a lack of real-world studies exploring multi-user VR in a construction-oriented context. In this paper we present and discuss our findings from evaluating a VR-system with multi-user capabilities at multiple occasions on several real-world construction projects. In all cases the VR visualization has been directly realized from the design teams IFC-models and the multi-user sessions has been performed both co-located as well as fully remote. Our results show that multi-user VR improves communication, understanding, and collaboration, and by letting staff with knowledge and experience from construction production review the project in VR, many design errors and constructability issues can be identified and resolved before reaching the actual production stage. Moreover, the use of VR is helpful regarding sequencing and planning, and to identify alternative design solutions. In addition to the evaluations and analysis, we present technical details of the developed VR-system.*

KEYWORDS: *BIM, VIRTUAL REALITY, VR.*

1. INTRODUCTION

The integration of immersive virtual reality (VR) and Building Information Modeling (BIM) has many applications within the Architecture, Engineering, and Construction (AEC) industries. Prime examples include design review sessions (Roupé et al., 2016), production planning (Muhammad et al., 2019), and construction safety (Hafsia et al. 2018), and it's mainly VR's ability to convey scale and details that is put forward when comparing it to non-immersive desktop visualizations (Wolfartsberger, 2019; Han & Leite, 2021). More recently, immersive VR has been extended to support multi-user sessions, where several participants can experience the same model at the same time (Du et al., 2018). For design review sessions and model inspection this has been shown to enhance communication and improve collaboration among participants (Heinonen et al., 2022). However, most studies concerning multi-user VR build on controlled experiments (Shi et al., 2018; Birt & Vasilevski, 2021), synthetic cases (Du et al., 2018), or software evaluation workshops (Huang & Odeley, 2018), and there is currently a lack of studies regarding actual use of the technology in real-world projects. A few exceptions include elevator machine room planning (Truong et al., 2021), collaborative 4D-planning (Tallgren et al., 2021), end-user design review (Sateei et al., 2022), and MEP design review (Zaker & Coloma, 2018). Still, we argue that there is limited research and a gap in knowledge concerning benefits and use-cases of multi-user VR in a *construction-oriented context*, such as for design and constructability review, sequencing, and job planning.

Furthermore, going beyond real-world use cases, there are still open questions and unsolved issues regarding both single and multi-user VR, including:

- Importance or non-importance of realistic avatars for efficient multi-user meetings (Hepperle et al., 2022; Prabhakaran et al., 2022; Pakanen et al., 2022)
- Issues with easy overview and orientation in immersive VR (Liu et al., 2020)
- Lack of user-friendly tools for measurement and dimensioning (Johansson & Roupé, 2019)
- Data loss and interoperability issues between BIM and VR software (Truong et al., 2021; Potseluyko et al., 2022)
- Challenges to handle massive federated BIMs in real-time (Chen et al., 2021; Graham et al. 2019):

In this paper we address the current research gap by presenting our findings from evaluating single- and multi-user immersive VR at multiple occasions on eight real-world projects. Our primary contribution is the identification of real-world benefits and practical uses cases of the VR technology in a construction-oriented context. In addition, we focus on and address a number of general VR challenges, including efficient real-time rendering of massive BIMs, support for overview and easy orientation, BIM-data management and interoperability, representation of avatars, as well as construction-specific functionality requirements, such as dimensioning and filtering.

2. RESEARCH APPROACH

In order to explore the benefits, use cases, and potential of immersive VR in a construction-oriented context, a customized VR system was evaluated in eight (8) real-world projects. The study follows a qualitative approach with empirical data collected by means of a questionnaire together with observations, video recordings, and further discussions with the participants. The following subsections explain the *technology*, *case projects*, and *data collection* in more detail.

2.1 VR system

As the technical platform in this study we have used and further developed BIMXplorer (Johansson, 2016; BIMXplorer, 2022). BIMXplorer is a high-performance VR-viewer that supports the IFC file format (IFC2x3, IFC4) and creation of federated building models (i.e. typically using a single IFC-file per discipline). IFC-files are imported directly and no other preparation or optimization is needed before entering the project in immersive VR. The user interface mainly consists of a tools palette with several different tools as seen in Fig 1. The following is some example of tools that exist, see Fig 1.; Measurement and dimensioning with snapping (also c/c), filtering and color-coding, 3D-markups, object information (BIM-properties) and 3D-labels, section planes, miniature model, multi-user functionality (e.g. gather, goto), and BCF snapshots.

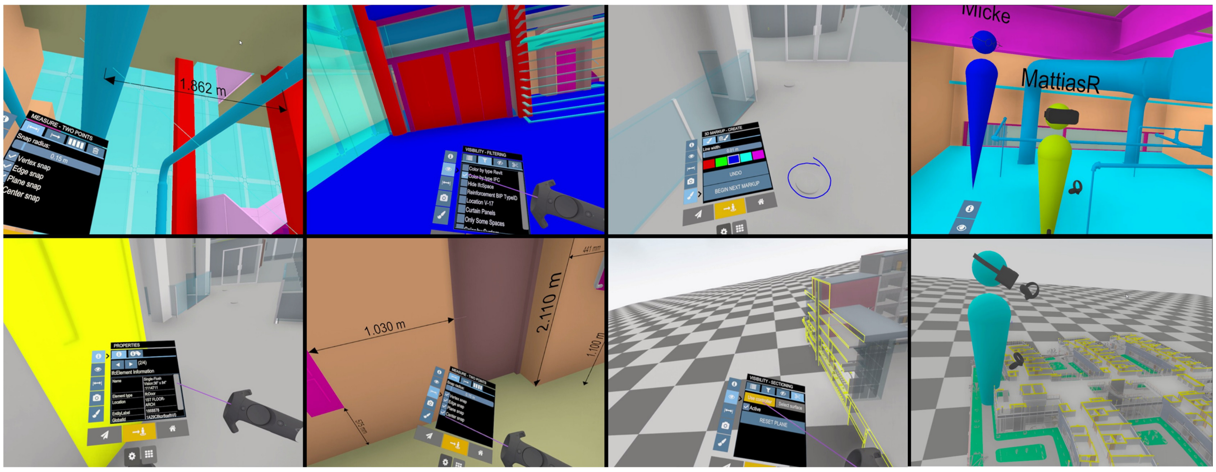

Fig. 1: VR-Screenshots from BIMXplorer of the different tools that exist.

2.1.1 Implementation and technical details

BIMXplorer is developed in C++ and uses OpenGL as rendering API. For Oculus HMDs (e.g. Quest and Rift) the Oculus API is used, all other HMDs (e.g. HTC Vive) are connected through OpenVR. A full description of all the technical details in this system is out of scope for this paper, but a few essential components can be outlined.

IFC-support: IFC-files are imported using the xBIM framework (Lockley et al., 2017). xBIM extracts all elements, relations, properties, and quantities, and the actual geometry as indexed triangular meshes. The import speed of xBIM is typically around 75-85% compared to Solibri depending on discipline. For instance, importing only the architectural model (524 MB IFC-file) in project A (see Fig. 3) takes ~120 seconds.

Frame rate and performance: High performance even for massive models is provided by occlusion culling and geometry instancing. The occlusion culling algorithm and implementation is based on the work of (Boudier & Kubisch, 2015) and takes advantage of modern OpenGL features like indirect draw calls and Shader Storage Buffer Object (SSBO). With occlusion culling only potentially visible objects are processed by the GPU.

VR UI: The in-VR tools palette is implemented with Dear IMGUI, but instead of rendering the UI to the screen, it is rendered to a texture every frame. This texture is then applied on a simple quad rendered above the controller.

Multi-user: The multi-user implementation is based on the Photon Realtime SDK. This is a prototype implementation using no other server infrastructure. All clients load the same model, and then call "JoinOrCreateRoom" (Photon API) with an agreed upon meeting ID. Every modification to the shared environment, such as section planes, 3D-markups, or hiding/showing objects is transferred to all clients with the use of Photon events. These events use the "SendReliable" and "Cached Event" functionality in Photon to make sure that even if a client is connecting much later than the other, that client will still receive all the modification events that have already happened when joining. Position and orientation of all the clients, on the other hand, is using "SendUnreliable" because it is regularly updated anyway. Voice chat is handled through Discord.

Filtering and color-coding: It is possible to control visibility and color of objects based on their IFC-properties in a similar way that can be done in Solibri. By defining a set of rules, such as "Color by discipline" or "Color by classification code", etc., the BIM can then be color coded according to request from the user. The user in VR can then from a list of predefined color coding rulesets filter and color-code the model directly in the VR interface.

Edge and vertex snapping: During IFC-import, the geometry is processed in order to find all the free edges per surface and then cache that information. Each object is initially seen as a "triangle soup" and surfaces are formed by comparing vertices and normals among triangles. Sometimes, surface information is already available for the geometry, and the process then becomes considerably faster as only free edges need to be found. As an example, when using Threading Building Blocks (TBB) with a parallel loop implementation this only takes around 2 seconds for all the geometry in the architectural model in project A, see Fig 3. During measuring, when the user points at a surface, all the (pre-calculated) free edges for that surface can be obtained from the cache and then see if any edge or vertex is inside the snap radius.

Center snapping: Many of the ducts, piping, and rebars in an IFC file are often represented as extrusions which naturally gives access to the centerline of the geometry. However, depending on the authoring software (e.g. Tekla, Revit, or Archicad) these types of object might also be represented with explicit geometry, such as a triangular mesh. Due to this a more general algorithm to find an object's centerline was developed – one that works directly on triangular meshes and finds the centerline by shooting a small number of rays inside the circular geometry. As illustrated in Fig 2, the algorithm finds the starting point and direction of ray #1 (red) by reversing the intersection normal N (at the position where the user is pointing). The endpoint of ray#1 is then found as the intersection with the circular geometry. From the midpoint of ray #1, a new ray is created (green) by expanding in the direction perpendicular to ray #1. Because the geometry is typically faceted (and not a perfect circle), this process is continued for a fixed number of rays in order to find an approximate center, which is then used as the snapping centerline C. However, in practice, this method also first does a Jordan curve test (Haines, 1994) on the reversed as well as non-reversed normal-ray (N) in order to find out if the user is pointing at the geometry from the outside or from the inside. Because of this, it is equally possible to take exact measurements also from holes (e.g. distance from a wall edge to the center of an opening hole that should be drilled on-site).

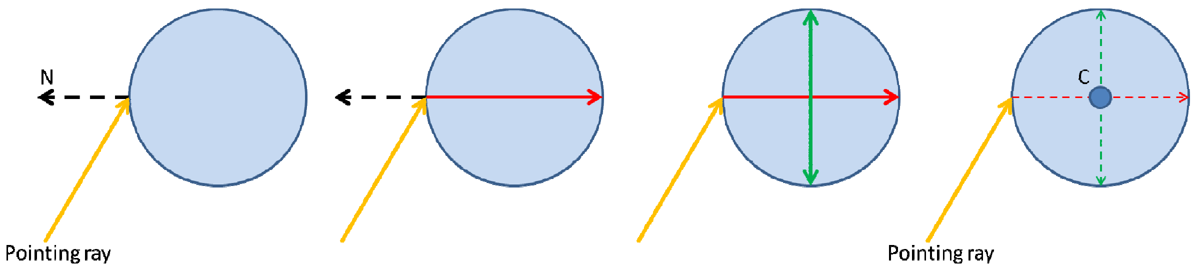

Fig 2. Illustration of the how the center snapping algorithm works. This is used for centerline measurement between ducts, piping, and rebars in VR.

2.2 Case projects and BIMs

The developed VR system has been evaluated at eight different projects, representing a diverse set of buildings and one bridge (Fig 3). These projects where all ongoing, but in different stages (e.g. foundation completed, MEP work has just started, etc.). All of them were considered "BIM-projects" with all of the design and design collaboration done in various BIM systems (e.g. Tekla, Revit, Solibri) and with IFC as the collaboration format. One of the projects is a "Total BIM" project where the BIM is the legally binding construction document and no traditional 2D drawings are used (Disney et al., 2022). The other projects, however, still hold a combination of (digital) 2D drawings and BIM as the construction documents. All projects feature some degree of parallel work between design and construction, however, main focus in the study has been from the perspective of construction and not the architectural design or the client or building end-users perspective. In Table 1, model statistics for the different BIMs is presented.

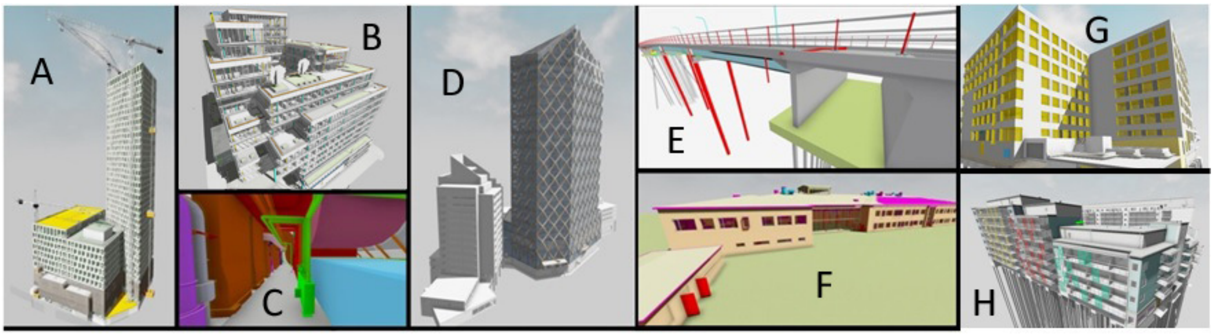

Fig. 3. The eight real-world case projects which was used in this study.

Table 1: Case projects and model statistics.

Project	A	B	C	D	E	F	G	H
Type	Office	Office/ hotel	Facility	Office/ hotel	Bridge	School	Office	Residential building
# of objects	798,059	761,120	227,248	551,654	21,821	158,849	120,585	208,685
# of triangles	111,339,263	85,643,233	28,873,553	48,375,635	2,172,125	3,493,359	10,267,139	29,621,584
Multi-user	X	-	-	X	X	-	X	X

2.3 Data collection

In the majority of cases, we (i.e. the authors) have physically visited the site office in each project to evaluate the VR technology. In some cases, a dedicated "VR room" has already been present at the office, and in other cases we have brought and set up one or more portable VR sets consisting of gaming laptops with NVIDIA GTX 1080 GPU and different HMDs. During the study, HTC Vive (Pro), Oculus Rift S, Oculus Quest 1/2, and HP Reverb G1/G2 have been used. Due to the COVID-19 pandemic, however, three of the evaluation occasions had to take place fully remote and then a supervisor or a BIM/VDC manager at the respective project has set up the VR system.

The primary focus during the evaluations has been slightly different from project to project. In some cases, it has been a more general review of the project as a whole, while in other cases there has been a clear focus on a specific part, for instance a specific floor or a certain installation space. However, important to note is that all of the respondents have been actively involved in each respective project. Projects A, D, F, and H have been visited several times. Still, all of the functionality in the VR system has not been available in all of the evaluation session. For instance, multi-user and BCF-functionality was only available in projects A, D, E, G, and H. However, multiple VR sets have been available during all evaluations sessions.

To gather empirical data a questionnaire was prepared containing both open and closed questions regarding the respondents' role, knowledge and use of BIM and VR, information they require to perform their work, and how they experienced different aspects of the VR system and its functionality. In addition, data has been collected by means of observations, recordings, as well as open questions and discussions with the participants.

3. RESULTS AND DISCUSSION

In total 62 persons evaluated the VR technology, many of them at multiple occasions. As already stated they all had a formal role in any of the projects (e.g. supervisor, MEP fitter, carpenter, etc.) and can therefore be considered actual stakeholders. About half of them, 34 persons, also completed the questionnaire. In the following subsections we present and discuss the results that were captured together via the questionnaire, observations, recordings, open questions, and discussions with the test participants.

3.1 Navigation, overview, and dimensioning

Overview and orientation of AEC projects in VR is often highlighted as an issue in the literature. The purpose of the mini-model is mainly to allow participant to get an overview of the project and ability to “jump into” a specific location in the building. The concept is not new and has almost become a de-facto standard in recent years (Huang & Odeley, 2018; Satei et al., 2022). Still, for very tall buildings it can be difficult to pinpoint a specific floor from the Mini-model perspective, which was expressed at the first evaluation at Project A. Especially construction workers express that a lot of the discussions and planning is in relation to the different floors (e.g. *“next week the ventilation subcontractor will start at the seventh floor.”*). To handle this situation all the floors (i.e. IfcBuildingStorey) are directly extracted from the IFC-files, and exposed as a drop down list in the tools palette. Selecting a specific floor will then section the building 1.2 m above the floor with the purpose being that it would be easy to jump into a specific location (e.g. Room) at a specific floor. For the taller buildings this was seen as a huge improvement compared to guessing or visually counting floors. However, a bit surprisingly, this also turned out to be a powerful ”2D drawing mode”, allowing participants to discuss and review larger areas, such as the main MEP ”corridors”, in a similar way that is typically done on a blueprint. Fig. 4 illustrates such an example from Project B, which was performed fully remote.

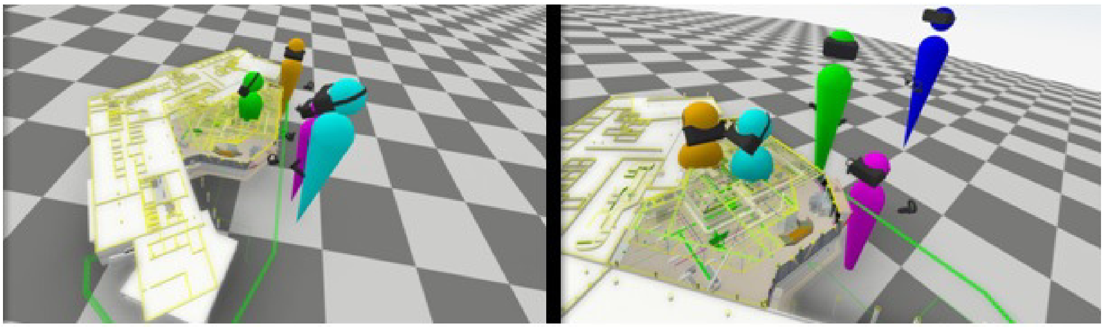

Fig. 4. The mini-model used for navigation and overview. (From remote multi-user meeting in Project D)

Another aspect seen as an issue in previous research is the ability to easily take accurate measurements from the BIM in VR (Johansson & Roupé, 2019). In fact, even in the context of non-VR BIM-viewers this is still considered one of the main obstacles for going fully “drawingless” on the construction site (Disney et al., 2022). Most of the time, it is sufficient to use the perpendicular measurement (which shoots a dimension ray perpendicular to the selected surface), which is a quick way to get the height to the ceiling or width of a corridor. However, once slightly more complicated dimensions are needed, such as shortest distance between two edges, snapping becomes very important in order for it to be user-friendly. For the MEP-workers, the center snapping was actually seen as something completely novel, even in a non-VR context. Many of them were familiar with Solibri or BIMCollab Zoom, which does have edge, vertex, and plane snapping, but not the ability to use center snap. However, as they typically start by placing the hangers, they need the distance from a wall or reference plane to the center of the pipe or duct, something that they now could easily extract, as seen in Fig 5.

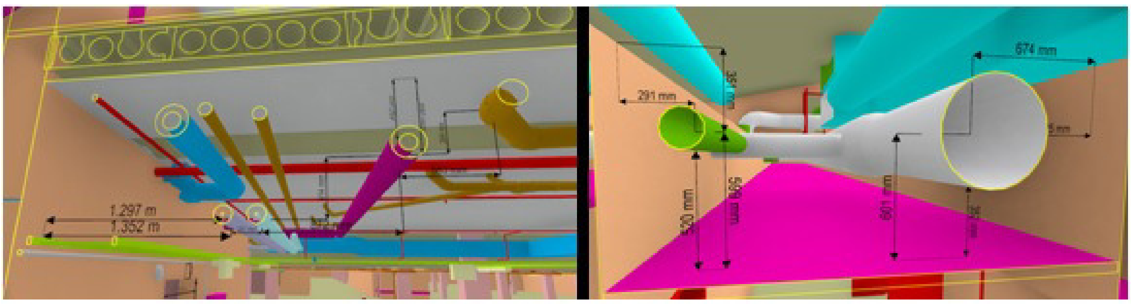

Fig. 5. Measurement and dimensioning created and done directly in VR. (From: Project B)

3.2 Information and understanding

Previous studies have highlighted how directly and intuitively people seem to perceive various situations in a VR environment (e.g. Zaker and Coloma, 2018; Wolfartsberger, 2019). This is strongly confirmed by our data. Above all, it is that the fact that the model is viewed on a 1:1 scale which is highlighted and several comments are linked to how size, spaces, and details, are given a completely different understanding and feeling compared to when the model is (re)viewed on a regular screen. Furthermore, it becomes clear from the observations that review in VR is similar to how you look or inspect something in the real world. In several cases, the VR controllers were used to represent different tools to see if there was enough space in the model to perform a certain set of work steps. On several occasions, users also asked for the ability to replace the controller models with that of tools, such as a screw driver or wrench, which should be considered in future studies. In general, size-related issues, such as height of railings or dimensions of openings, are primarily discovered by viewing the model in a 1:1 scale and that the users instinctively relate to their own, egocentric perspective (e.g.: *"that feels like it's a little low"* or *“that feels a bit tight”*) before using the measurement tool. To better illustrate the respondents' thoughts, we give some representative examples of what they answered to the question *“What information do you find (in VR) and want to use?"*. Also here it becomes clear that it is mainly the visual and geometric representation that conveys a large part of the information they seek and find. In fact, almost 70% of the answers to this question relate to the visual or geometric representation of the model.

"A lot about planning work steps"
"Mainly geometries and clashes between models. It's like Solibri on steroids."
"Complex solutions that becomes clearer in a larger 3D model. Better understanding of how everything is connected."
"Overall, a VR model creates a better understanding than a normal, traditional BIM models"
"Dimensions, object information, details and sections"
"Mainly using VR to see what space is available to be able to plan and build in the right order"
"Clashes between installations, issues around accessibility"
"The same object information as in BIM"

3.3 Multi-user

The multi-user functionality was evaluated on five (5) occasions, where three (3) of them was performed fully remote. Interestingly, out of all the questions in the questionnaire, the one about added value provided by multi-user functionality was rated highest and most consistent.

In one of the cases, it concerned a job planning session with a total of eight participants who took turns to use three different VR headsets that were all available in the same “VR room” at the site office. An additional screen was connected to each headset so that those standing outside could see what the different people were doing in the VR model (see Fig 6). This session had also been preceded by previous constructability reviews and job planning sessions in VR, however on other parts of the project and without multi-user functionality.

Fig. 6. Job planning with several users simultaneously in the VR model. (From: Project A)

The focus in this case was framework supplement on a single floor and the responsible supervisor started with a review (in VR) regarding how progress was planned on this floor and in what order the different disciplines would go and which moments were considered the most challenging. This then turned into more discussions about specific places and other participants took turns to be inside the model at the same time. In order to exemplify the type of discussion that was going on between the participants, below is an excerpt from the conversation during the meeting:

#1: Here we will have to put a screen on the outside because we will never get access here with the drywalling. I see that now...
#2: Yeah, it's really tight there…
#1: [takes measurements in the model] ...there's not even enough space for a screwdriver so that's the way we'll have to do it....

#1: ...here we also need to build screens first, because this is insanely tight. Here we have to go first and THEN the installers. Just have to make sure they don't sneak start here...
#2: Ohh, yeah, it's tight all the way here!
#1: Yeah, it's very tight
#3: There's so much installations here...
#3: What if we could go in with a rail before they even cast...? Nah, the ceiling is too high here...

To what extent the use of VR – and multi-user VR – in job planning generally improves the end result is difficult to give a definitive answer to, as it is possible that a "traditional" session using 2D drawings or BIM would have worked just as well. However, many discussions during the meeting are about size and space, and in that aspect we know that VR contributes to a better understanding. From the questionnaire, it is also a very positive rating that is given regarding *understanding of the project*, *details*, as well as *understanding the work of other professional groups and disciplines*. Furthermore, there are several examples in this particular project of design and constructability issues first discovered in VR (discussed more in sub-section 3.6). Together, all these factors point to added value in using VR during job planning and design and constructability review. What can be said with certainty, however, is that the possibility of being several people in the same VR model is considered a clear added value compared to only being able to be one person at a time.

3.4 Remote multi-user

Three of the projects took advantage of the possibility to perform multi-user meetings fully remote. The first was a bridge project (E) which was reviewed among development and construction engineers, and although this was mainly considered to be a technology test, some minor issues and clashes regarding the reinforcement was discovered. These issues could then be sent back to the design team as a BCF. However, being a bridge project it allowed the VR technology to be evaluated in an infrastructure-context, both in terms of functionality but also in terms of what types of models and information content that can be expected. Notable observations here is that teleport navigation have less usage when doing constructability review for a bridge and also that sectioning-by-floor doesn't make sense in this context. Instead, it is expected that sectioning along the road- or alignment curve would be the corresponding use for infrastructure project with IFC4x3 in the future.

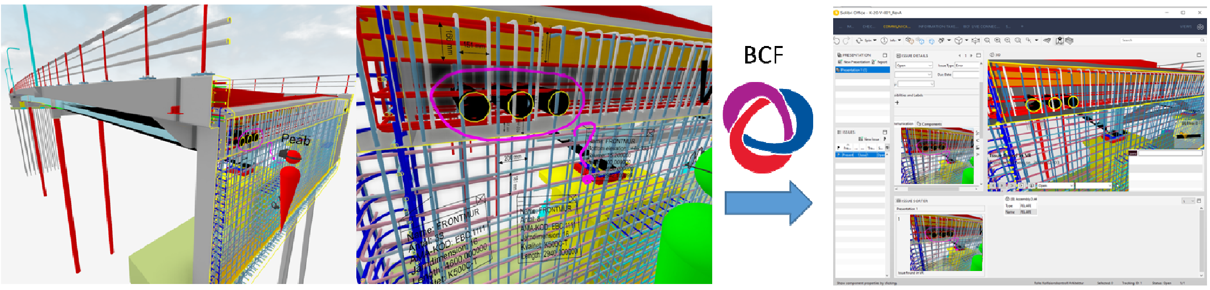

Fig. 7. Design issues detected in VR can be sent back to the design team as BCF-files (Project E).

The second occasion with multi-user was an informative meeting around the production sequencing in project G. The meeting was planned to start with testing and evaluate the possibilities of using VR as a tool during the project. However, as the VR multi-user worked so well the originally planned meeting (i.e. Zoom meeting) didn't happen and instead the sequencing was discussed only in VR. As the federated model was very well structured, with properties in each object indicating the sub-contract, it was possible to use the filtering functionality (discussed more in detail in sub-section 3.5) to color-code and turn them on/off in VR. This essentially allowed for a simplified 4D model, albeit without animations (Fig 8).

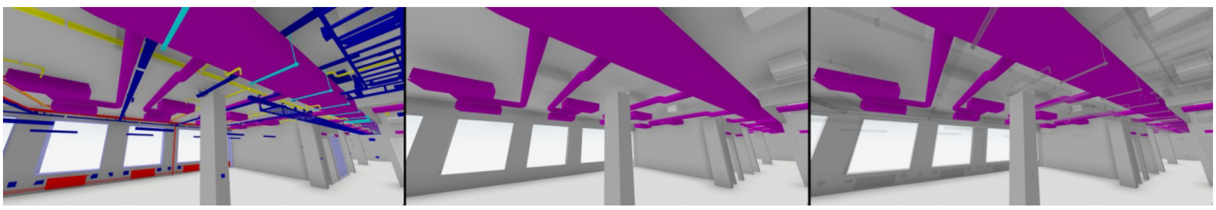

Fig. 8. Illustration of sequencing using color-coding and filtering from IFC-properties. (From: Project G)

In project D, design and construction were ongoing (in parallel) and the VR-session involved two MEP-designers connecting from their office, two MEP- and VDC-coordinators at the site office, and two researchers. In addition to this, one VDC-specialist connected to the meeting in "spectator" mode, i.e. without a HMD. The primary focus was MEP-coordination at a single floor where ordinary clash detection and coordination had just been completed, but during the meeting several other parts of the project, such as the main installation room, were also reviewed, see Fig 9. Below is an excerpt that shows the dynamics that arise during the meeting, despite everyone being in different physical locations.

#1: So, then we can sneak into the main installation room right here. It's probably a bit interesting...
#2: Damn, it's going to be a high ceiling here...
#1: This was insanely cool to fly around in here!
#2: Crazy big! In the model, it doesn't look like that otherwise. I mean, when you look at a normal screen...
#3: I found here, here it seems to be a big issue! I can gather you here...
#3: It feels like a lot of things are colliding here. If you look down here...
#4: Yeah, we haven't really done any [design] collaboration in this area. Still a couple of months away...

However, on the floor that was the primary focus, no immediate problems with the installations were discovered. Still, this session clearly shows the possibilities of having people from both production and design jointly review and discuss the project in VR without even having to leave their own workplace. Also, compared to the co-located sessions, we see no major differences in behavior among participants, either in questionnaire response, or from the observations.

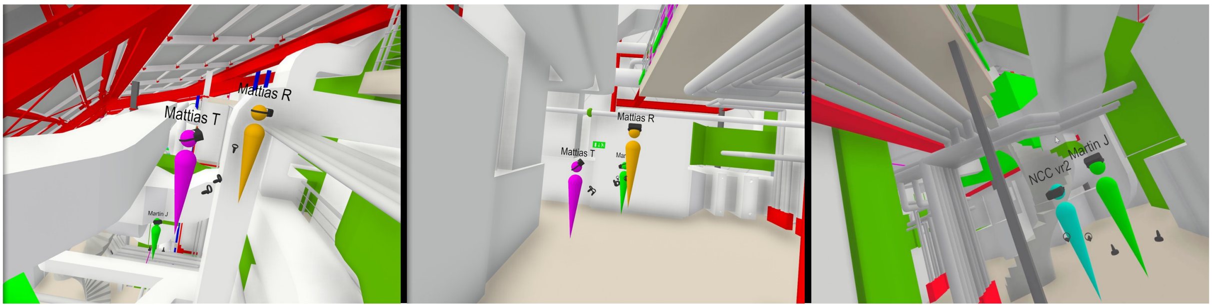

Fig. 9. Constructability review with multiple users simultaneously in the VR model. (From: Project D)

Overall, it can be stated that the possibility of being several people at the same time in the VR model provided a clear added value and contributed to increased understanding and communication between the participants. Compared to when several people take turns putting on the VR glasses and entering the model, communication and understanding is facilitated by being able to see where the others are, what they are looking at and pointing on, and scaling 1:1 and stereo vision also means that *"everyone sees the same thing"*. Even in cases where all participants connected from widely different locations, observations together with comments and reactions from the participants show that they act very much like standing next to each other and looking at the same things in the model.

Previous research on multi-user VR has highlighted the importance and effects of realistic avatars on user experience (Pakanen et al., 2022). However, the data from our study doesn't identify that as particular important. Nothing was ever mentioned negatively regarding the simplicity of the avatars. In fact, the only thing explicitly commented about the avatars was a question regarding why one of them had ordinary glasses (i.e. spectator mode), and that some participants expressed it was a cool thing that a user inspecting the mini-model will appear as a "giant" to those being in scale 1:1. Other than that, participants reacted surprisingly normal in the interactions with each other and with primary focus on the tasks (e.g. design review, planning). Typically they gathered around a specific issue, like a clash and then discussed verbally while also using pointing, selection, or markups to further aid the discussion. It is thus suggested that request and need for realism is instead strongly connected to the application and main purpose with the use of the technology. With the focus in this context being on use of VR for design and constructability review, planning, work preparation, and general information about the project, things like photorealism is of less importance. In fact, material and colors are instead asked to be more symbolic or schematic to illustrate discipline, or functionality (e.g. fresh air inlet). With that focus it is perhaps logical that the avatars are of more symbolic character. Also, site personnel in Scandinavia today are getting more and more used to the concept of BIM and the BIM-tools that are often used on site are more ”engineering software” with focus on geometry and data (Disney et al., 2022). That is, high level of detail appears to be more important than high level of photorealism. It is still possible that more realistic, human-like, avatars would improve the user experience, level of presence, communication, and social interaction (Pakanen et al., 2022), however, it is clear that the current approach is ”good enough” and does not negatively impact the multi-user experience.

3.5 OpenBIM, properties, and filtering

In Scandinavia, BIM-projects are typically synonymous with IFC-files from the contractor perspective. In fact, only in rare cases do contractors and the on-site organization even have access to the native BIM models. There are multiple reasons for this, such as contractual and the need for a neutral collaboration format, but also that almost all clash detection and model review for non-infrastructure projects is done in Solibri or BIMCollab Zoom, using IFC. As such, it is clear that any VR system that needs to be used on a regular basis in a construction-context needs to have support for IFC. Furthermore, it is clear that the concept of properties and metadata is starting to become common knowledge throughout the on-site organization, much thanks to the use of software like Solibri, Dalux, and BIM360. Features found in those systems, such as filtering, are then requested, or even expected to be found in the VR system. As already discussed, in these contexts, realism, materials, and textures are of less importance, while instead geometric detail and color-coding are features that are considered important and often asked for.

From a data management perspective, issues (e.g. design issues) are handled differently in all the projects, ranging from simply exchanging BCF-files to using more integrated cloud-based solutions (e.g. BIMcollab Cloud). However, the common denominator is that BCF can be used as a transfer format between different systems, and the possibility to take snapshots in VR and export as BCF was considered very useful and also important in order for a smooth integration with all the other BIM-systems. Still, several participants also asked for the possibility to import BCF-issues from other systems into VR for further inspection

3.6 Design, constructability, and planning review

In project C, the focus was a large installation space that involved both new and existing installations. Here, rule-base color-coding was applied in order to clarify between *existing-to-keep*, *existing-to-remove*, and *new installations*. The work in this area was to begin the following week and the MEP subcontractor fitter reviewed the VR model for about an hour together with the project manager. They went through the planned execution in detail and discovered several places in need of modifications. Above all, they discovered that in several places it was not an optimal design from a production perspective, and the installation fitter then asked if it was possible to move or draw new pipes and ducts directly in the VR model. That was not possible in the software, but the fitter was then creative on his own and used the markup tool with an excessively "thick" pen to simply draw the alternative piping in 3D (see Fig. 10). After this was drawn up, a number of screenshots were taken of the model and these were then used as print-outs the following week during the actual execution.

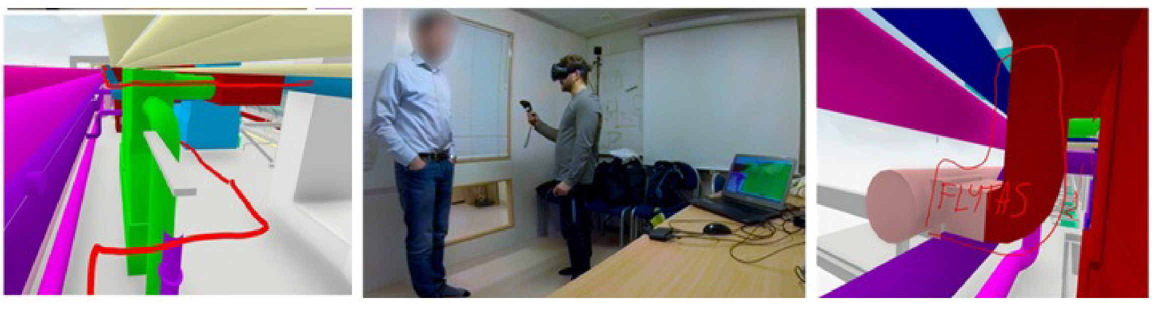

Fig. 10. Review and sketch of more production-adapted MEP installation. (From: Project C).

This scenario is interesting for a number of reasons; First, it is an actual example of Production-Oriented Views (Johansson & Roupé, 2019) created fully in VR, by the installation fitter, and then used on-site; Second, it shows the potential – and also the *need* – of bringing construction-knowledge into the design process. Ideally, this VR review session should have been held already during the design stage; Third, it highlights the importance of being able to color-code objects on-demand based on properties, in this case illustrated by the need to easily distinguish between different installations; Fourth, it appears that VR, as an user-friendly interface to the BIM, “encourage” users to actually edit or change the model in case of errors. This last point is also brought up several times in project H, from different MEP disciplines, where they basically ask *“Can I move this?”*.

The multi-user VR job planning session in project A (section 3.3) had been preceded by similar planning and review sessions, however without the multi-user functionality. Also then, it was a lot about sequencing and whether lack of space meant that the planned execution order had to be changed. In addition, the following major issues were detected in the model (which then had to be updated in the design):

- Too small openings in prefabricated wall elements (logistical/transport problems otherwise)
- Too low railings (safety issues)
- Wrong type of radiators on one floor (106 pcs)

Important to note here is that conventional BIM model review and clash detection in Solibri had already been performed without these issues being detected. Here, the radiators are perhaps the most interesting. Being a high-rise office building, the sill height is the same on all floors, except for one. However, design had assumed the same sill height and just copied and used the same radiator layout on all floors, which wouldn’t work with a lower sill height. From a 2D plan view this is impossible to spot, and clash detection will not find it either. Instead, one of the construction workers reviewed this floor in VR and instinctively though *“I can’t mount the brackets behind those radiators”*.

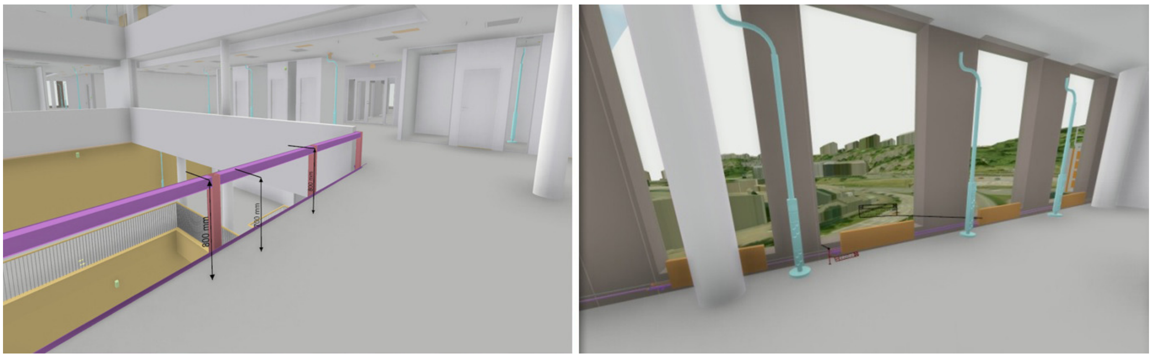

Fig 11. Errors found in VR such as too low railings (left) and wrong type of radiators (right) (From: Project A)

Similar examples that have been found in other projects during this study include wrong components (e.g. fire door instead of normal door), lack of space (e.g. spaces around doors, stairs ending to close to a wall or door), and constructability issues and general design errors (e.g. wrong connections between walls and roof). Beyond that, a lot of (physical) clashes have been identified. However, these clashes are often in places where there hasn’t yet been a “final” clash control. Overall, it appears that clash control (e.g. Solibri) work well in most cases and that it is not primarily to detect "physical" collisions that VR should be used for. However, as the above examples show, a clash-free model does not automatically guarantee that there are no problems or that the design is sound from a constructability perspective. Ideally, clash detection should therefore run in parallel with constructability reviews and in this context VR is highlighted as a suitable tool by the respondents.

4. CONCLUSIONS

In this study we have investigated the use of single and multi-user VR in order to better understand benefits and use cases in a construction-oriented context. As gathered from eight real-world projects, our data and analysis show that there are great benefits and opportunities by letting construction personnel use VR technology for design and constructability review, sequencing, and job planning. By involving staff with knowledge and experience from construction production, many issues have been identified and resolved before reaching the actual production stage. In some cases, it has been pure design errors or constructability issues, while in other cases it has been about changing the sequencing order between disciplines, or identifying alternative solutions that would be better from a productivity perspective. The primary benefit of VR compared to non-immersive alternatives is found in the 1:1 scale and stereo vision, which gives a much better understanding of size, space, and details – this at the same time as the miniature model with by-floor sectioning still can offer easy overview and orientation similar to a traditional 2D plan view. In addition, our observations suggest that participants inspect immersive VR-models much like they inspect real environments, using egocentric cues and interactions.

Regarding multi-user VR, this feature was rated very high by all of the participants, and it is clear from our results that it improves communication, understanding, and collaboration. Even in remote sessions, there appears to be a surprisingly high sense of presence among participants, mainly facilitated by them being able to see where the other users are, what they are looking at and pointing at. Also, multi-user interactions do not seem to require realistic avatars in order to be efficient.

Furthermore, with increased on-site use of BIM-viewers like Dalux, BIM360, and StreamBIM, site personnel are getting more used to the concept of BIM, federation, and properties, and are now starting to request features like BIM-properties, filtering, and color-coding also in VR. Such features can be provided by directly supporting OpenBIM and IFC which additionally solves many problems with BIM and VR reported in previous research, such as interoperability and data management issues. In relation to this we also see that high level of detail in combination with schematic coloring is more important than realism and textures when used in a construction-oriented context. Still, directly supporting federated, high-detail BIMs can be a challenging task for a graphics application to manage in real-time, especially with stereo rendering and VR. However, as we have shown with BIMXplorer, this can be solved by occlusion culling and modern, GPU-driven rendering techniques.

For future work it would be interesting to explore the use of VR technology with a construction-oriented focus already during the design stage by bringing in knowledge and experience from production. Although we see in this study that the VR technology allows design issues – or even better solutions – to be found before reaching the actual production stage, it would be preferable to identify it already at the design stage. Here, multi-user capabilities can make it easier to gather the required competence without the need for everyone to meet at the same physical location.

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