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COLLABORATIVE SITE LAYOUT PLANNING USING MULTI-TOUCH TABLE AND IMMERSIVE VR

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ABSTRACT: *Building Information Modeling (BIM) is changing the way architects and engineers produce and deliver design results, and object-oriented 3D models are now starting to replace traditional 2D drawings during the construction phase. This allows for a number of applications to increase efficiency, such as quantity take-off, cost-estimation, and planning, but it also supports better communication and increased understanding at the construction site by means of detailed 3D models together with various visualization techniques. However, even in projects with a fully BIM-based design, there is one remaining part that is still done primarily using 2D drawings and sketches – the construction site layout plan. In addition to not take advantage of the benefits offered by 3D, it also makes it difficult to integrate site layout planning within the openBIM ecosystem. In this paper we present the design and evaluation of a user-friendly, IFC-compatible software system that supports collaborative, multi-user creation of construction site layout plans using both multi-touch table and immersive VR. By allowing temporary structures, machines, and other components to be easily added and updated it is possible to continuously produce and communicate 3D site layout plans that are aligned with the schedule and supports integration with other BIM-tools.*

KEYWORDS: *BIM, VIRTUAL REALITY, VR, OPENBIM, IFC.*

1. INTRODUCTION AND BACKGROUND

With increased focus on digitalization and efficiency within the Architecture, Engineering, and Construction (AEC) industries, detailed Building Information Models (BIM) from the design are now often available for use by the contractor. This can facilitate the tendering process and make cost estimation and planning more efficient, but above all it supports enhanced communication and understanding during the production phase in the form of detailed 3D models with corresponding metadata. Furthermore, already today there are examples of so-called *"drawingless"* projects such as Röforsbron, Slussen, and Celsius, which clearly shows that the industry is moving more and more towards a situation where traditional 2D drawings are given less space (Cousins, 2017; Johansson & Roupé, 2019). In fact, in Scandinavia, Total BIM has emerged as a concept where the BIM is the legally binding construction document and no traditional 2D drawings are delivered to the construction site (Disney et al 2022). However, there is still one document that the contractors themselves have to create and keep up to date – *the construction site layout plan*.

Currently, the site layout plan is often drawn up in 2D by default – often using Bluebeam – and although the work differs between projects, there are several recurring problems connected to it (Andersson et al., 2019). Gros (2019) investigated the work with site layout plans at one of Scandinavia's largest contractor and found that:

- Even if all of the design is done using BIM, the site plan is still usually in 2D
- Typically just one person working with the site plan
- The site plan is rarely updated and often differs from reality
- The work with the site plan is often linked to lack of time and stress
- Often poor communication and respect for the site plan (difficult to interpret plans)

However, there are also several good examples in practice which have shown the possibilities of working with site layout plans in 3D, often created and maintained in SketchUp (Jongeling, 2013). 3D offers many benefits regarding elevations and general workplace organization in the vertical dimension, at the same time as it is easier communicate and present ideas around it. Still, this approach typically requires a modeling expert responsible for updating the plan, and in the end these plans tend to be exported as static 2D images instead of being integrated with other BIM datasets (Gros, 2019).

Going beyond site layout planning in real-world projects, much research has focused on turning site layout planning into an optimization problem that can be automated, which – in many ways – is similar to using probabilistic and generative methods for automated creation of production plans and schedules (Taghaddos et al., 2021; Abune'Meh et al., 2016; Kumar and Cheng, 2015; Isaac and Shimanovich, 2021; Fischer et al., 2018). At the same time, there is also research that emphasizes the benefits of collaboration, teambuilding, and commitment, and instead advocate more focus on user-friendly software tools and various visualization techniques, for instance Virtual Reality (VR), to support the collaborative planning work (Tallgren et al., 2021, Tallgren et al., 2020). VR, in particular, can clarify aspects of the design that are difficult to comprehend from traditional 2D documents, and can better resemble real work environments – features that are useful when evaluating planning scenarios and reviewing constructability (Zaker and Coloma, 2018; Wolfartsberger, 2019). Given these properties, it is therefore logical that the use of VR has been tested also for site layout planning (Xu et al., 2020; Muhammad et al., 2019). In this context, and when compared to traditional 2D methods, VR has been shown to make the plan more effective to comprehend and to enhance the ability to detect clashes (Muhammad et al., 2019). Nevertheless, certain aspects of the layout planning are still considered to be more efficient in 2D, which tells us that instead of trying to choose between either one of these interfaces it would perhaps make more sense to try and combine them, which has been a successful approach for both urban planning and collaborative healthcare design (Faliu et al., 2019; Roupé et al., 2020). In this paper we take inspiration from these ideas and present the design and evaluation of a multi-user, multimodal system for collaborative creation of site layout plans. The system combines multi-touch table and immersive VR, but contrary to similar approaches within urban planning and healthcare design much more focus has been put on integration within the openBIM ecosystem.

2. THE COLLABORATIVE SITE LAYOUT PLANNING ENVIRONMENT

To support a multi-user, multimodal planning environment we have used BIMXplorer and further customized it. BIMXplorer is a real-time desktop- and VR-viewer that directly supports the IFC file format and creation of federated building models (Johansson, 2016; BIMXplorer, 2023). IFC import is implemented using the xBIM framework (Lockley et al., 2017), and by taking advantage of efficient occlusion culling, BIMXplorer allows large and complex BIMs to be visualized in immersive VR without the need to simplify or decimate the input dataset. The VR user interface – explained in detail in (Johansson and Roupé, 2022) – consists of a tools palette with support for sectioning, measurement, filtering, markups, BCFs, and multi-user sessions (Fig 1). In the following subsections we further describe the multi-touch as well as VR interface that were developed to support user-friendly, collaborative creation of site layout plans. Fig 2 presents an overview of the new system using a sample configuration with both co-located and remote clients.

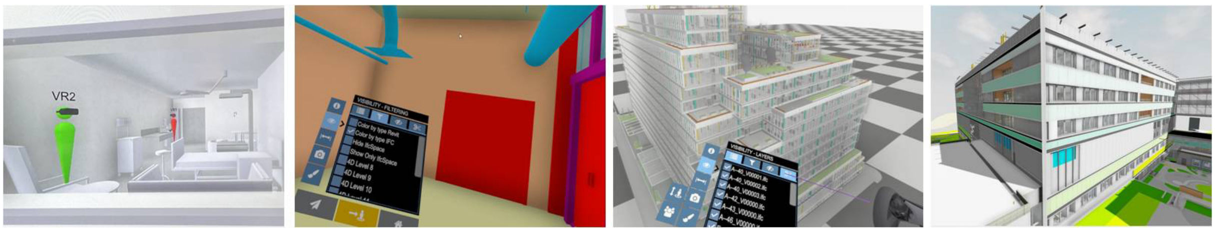

Fig. 1: Examples of different tools and models in BIMXplorer.

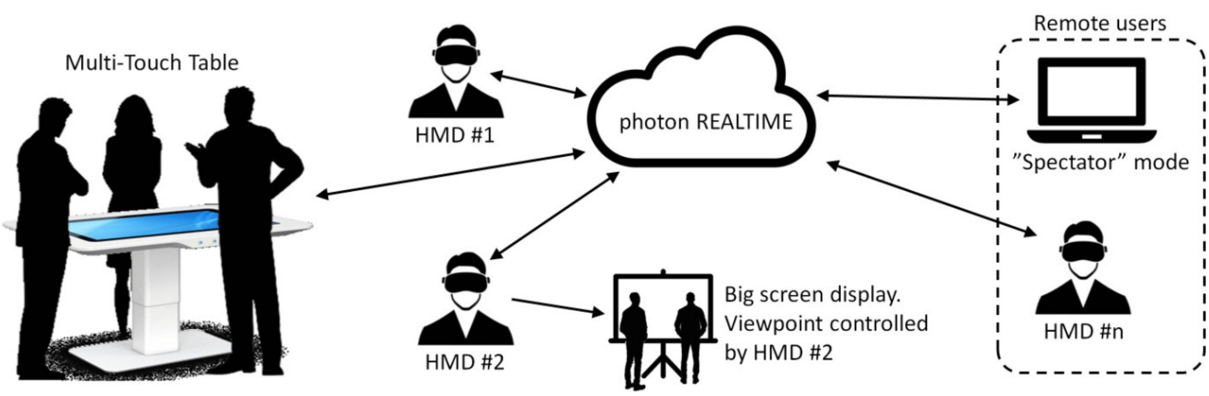

Fig. 2: System overview using a sample configuration.

2.1 Prefab database creation

Site layout planning in 3D mainly consists of placing 3D-objects that represents temporary structures, machines, and temporary placements for materials as instances in a 3D-environment. We refer to these objects as prefabs, and the motivation around the creation and organization steps was to allow easy creation from already present 3D-models or BIMs. We therefore implemented support for also importing .skp- and .fbx-files using their respective APIs, and then simply implemented a tool in BIMXplorer to select and save a single or multiple objects as a prefab, with the current view as the preview images (Fig 3, middle). Depending on the type of component it also makes sense to be able to select the center of rotation (i.e. during planning), which is why we optionally support placement of a pivot point using a standard translation gizmo. Finally, with a number of prefabs created, a user can then organize and group the prefabs in different folders and subfolder (Fig 3, right) before selecting a root-folder, which will then import and create a prefab database file (.pfd-file), which will have the same organizing structure. Assuming a very large number of prefabs are originally created, this makes it possible to select a subset for a certain planning workshop, like a template. The whole procedure is illustrated in Fig 3, where a SketchUp scene is first imported (left), followed by selection and isolation of a skip container that is save as a prefab (middle), and finally the folder structure where it is saved (right). Note however that this only has to be done once, to create a pfd-file, which can then be re-used as a template in several planning workshops.

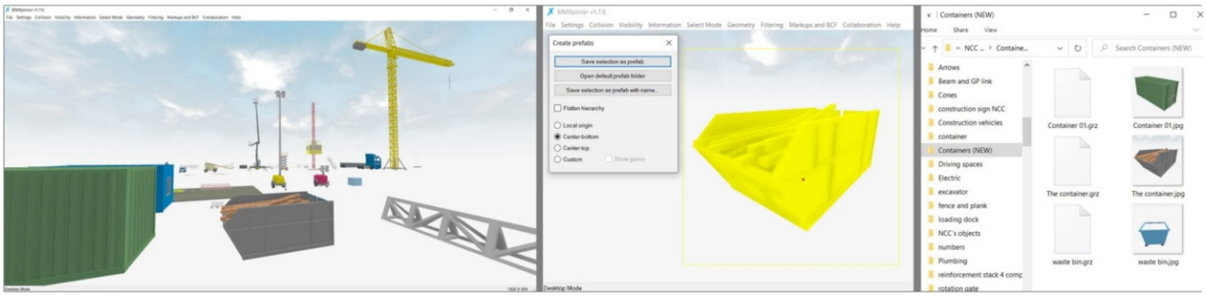

Fig. 3: The prefab creation process in BIMXplorer and file structure.

2.2 Desktop UI and touch interface

The desktop, multi-touch interface is inspired by our previous work for healthcare environment design (Roupé et al., 2020), but implemented on top of BIMXplorer and much more adopted for use in a openBIM ecosystem. The touch interaction is a custom implementation using “raw” touch events in Windows, i.e. listening to WM_TOUCH events. The actual interface follows that of StreamBIM, with two-finger pan-and-zoom, one-finger for look-around in 3D as well as scrolling in menus, and one-finger tap for selection and button pressing. No inertia is used. The UI is implemented with Dear IMGUI and has a collapsible toolbar with functionality for adding objects, sectioning, visibility and filtering, settings, and file I/O. As seen in Fig 4, sectioning is done by selecting a level/floor from IFC-data and can then be adjusted up or down. With BIMXplorer already using Dear IMGUI for the tools palette in VR, it was possible to directly re-use certain UI-element, such as for filtering and sub-model visibility. In this context, the filtering capabilities are particularly interesting as it allows for controlling visibility and colors of objects based on their properties. This makes it possible to filter out certain scenarios if the data is available in the IFC-file(s), such as subcontractor or scheduling information. For instance, if scheduling information is present, it’s possible to filter out only those objects that will be constructed at a certain point in time, making site layout and logistics planning adhere to the real construction schedule.

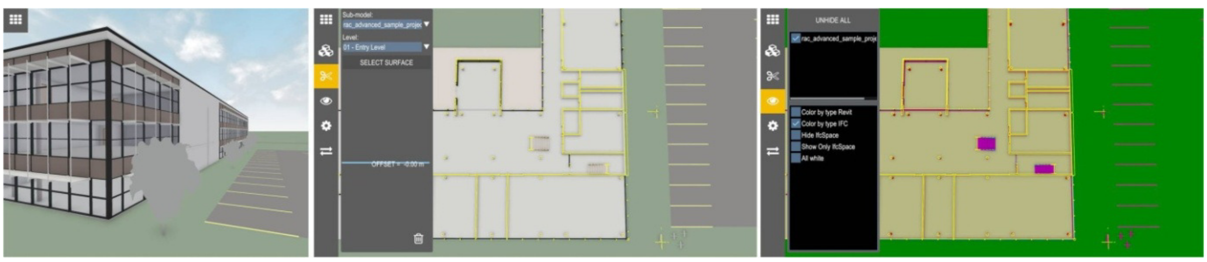

Fig. 4: The multi-touch table interface, including sectioning-by-floor, and filtering in the top-down view.

All the imported prefabs (i.e. the prefab database) are accessible in a folder structure and are added using drag-and-drop as illustrated in Fig 5. Selecting an object by tapping brings up the context menu making it possible to hide or delete the object. A selected object – or multiple selected objects – can directly be moved horizontally by dragging or rotated using the “gizmo”. By toggling one of the context menu buttons, vertical movement is activated instead.

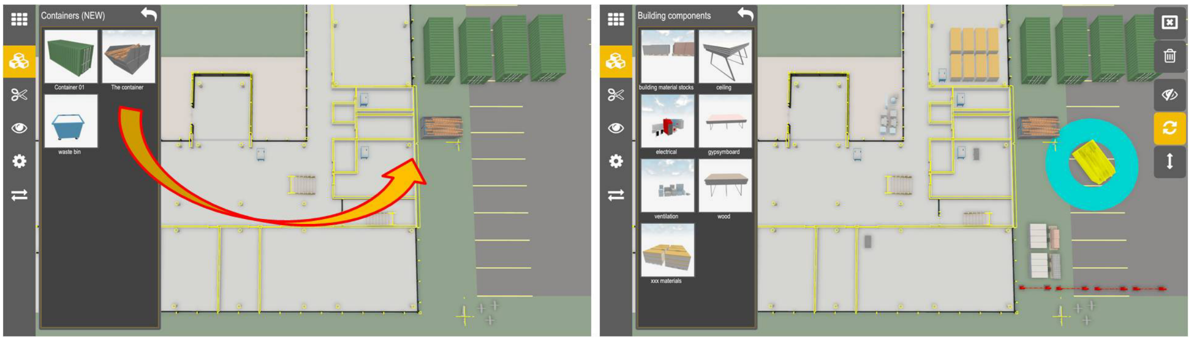

Fig. 5: Adding prefabs using drag-and-drop (left), and context menu and rotation gizmo (right)

2.3 VR interface

A similar interface for adding objects is implemented in VR as well by dragging and dropping prefabs from the tools palette, as seen in Fig 6, left. In fact, as this is done using Dear IMGUI the actual code is almost identical, which is one of the main benefits of using the same UI toolkit for both 2D desktop and immersive VR. Moving, re-placing, and rotating objects is also similar, but with gizmos more adapted for use in a pure 3D environment (as opposed to a 2D desktop interface).

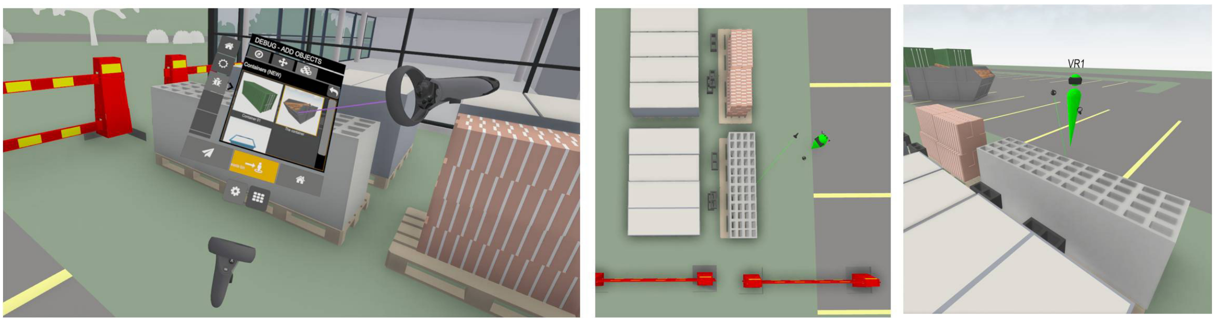

Fig. 6: Adding prefabs using drag-and-drop in VR (left), view of VR avatar in other clients (right)

2.4 Multi-user and collaborative planning

The multi-user functionality already present in BIMXplorer was extended to also support collaborative planning and adding, translation, and removal of instanced prefabs. The implementation is based on the Photon Realtime SDK and uses no other server infrastructure. All clients load the same model (.bmx-file) and prefab database (.pfd), and then call *“JoinOrCreateRoom”* (Photon API) with a previously agreed upon meeting ID. The first client that calls this function performs the actual creation of the Photon “room”, and all other clients will then join it. Every modification to the shared environment, such as adding or translating objects, creating 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 (i.e. the avatars), on the other hand, is using *“SendUnreliable”* because it is regularly updated anyway. However, in either case, no 3D-data is ever sent over the network, just IDs and transformation matrices. The only exception is 3D markups which are represented as a polyline with 3D coordinates. Still, all clients must be able to uniquely identify objects and prefab instances even if created locally on a single client. The solution was to simply let each client generate and assign a GUID when adding or creating a new object (using *CoCreateGuid*).

2.5 IFC export and openBIM

As previously stated, one of the main challenges when considering site layout planning in a modern BIM context is the need to integrate and align different data sources, from design as well as from production. In essence, this means that we can no longer only produce images and 2D-data, but instead also needs to provide 3D-data. As the solution to consume BIM-data is through the IFC file format it thus makes sense to also use that for producing data. Fortunately, the xBIM framework that is used in BIMXplorer to import IFC-files also has functionality to create IFC-files. With the underlying geometry representation in BIMXplorer being indexed triangular meshes we have chosen to use IFC4 which has support for *"IfcTriangulatedFaceSet"*. The possible options exposed for IFC-export are everything, selected, or visible, which means that it is also possible to only export a subset of the planned components as an IFC-file. This makes it possible to separate the exported IFC-files both temporally and spatially. Furthermore, by using the BCF functionality it is possible to transfer additional information, either back to the design organization or as viewpoints or "points-of-interest" for on-site mobile communication platforms, such as Dalux or StreamBIM. Example of both IFC- and BCF-export is seen in Fig 7, where the sample layout shown in Fig 5 is exported as an IFC4 file and imported into Solibri together with two BCF viewpoints. In Fig 8 the openBIM-supported model- and dataflow is illustrated.

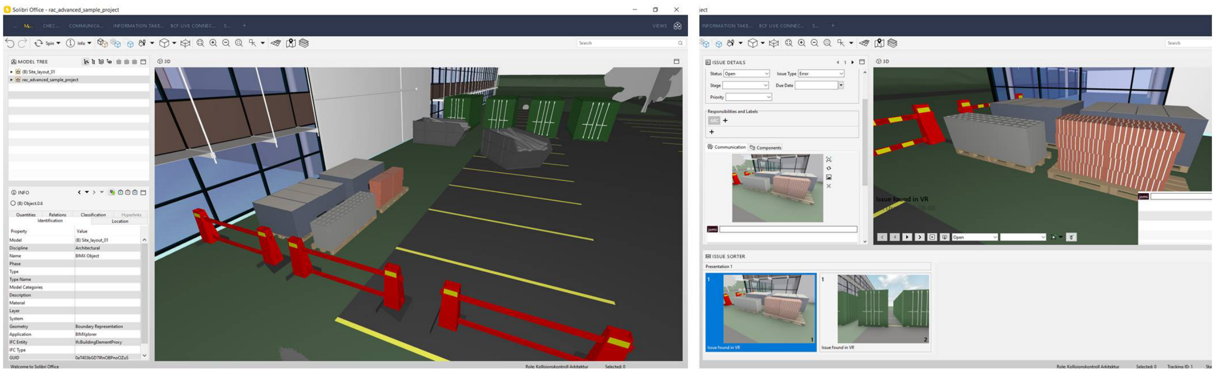

Fig. 7: The "Site component IFC" (left) and BCF (right) exported from BIMXplorer opened in Solibri.

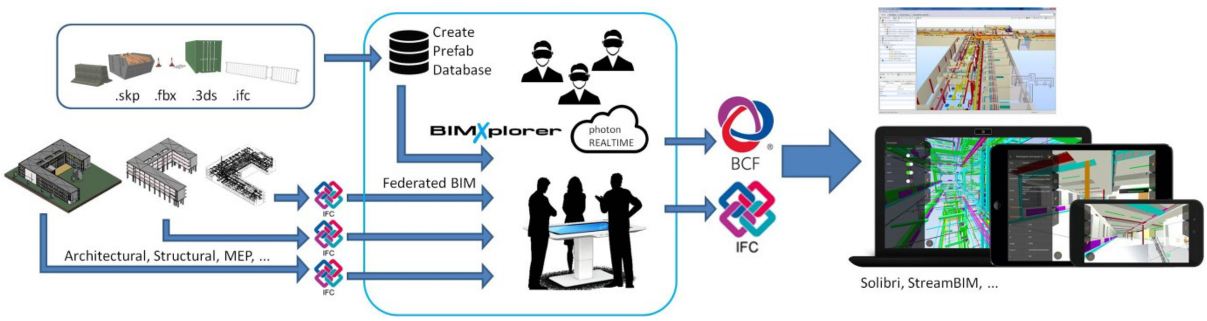

Fig. 8: Schematic illustration of the openBIM-supported 3D model- and dataflow.

3. EVALUATION

The developed system has been evaluated during a workshop session with representatives from the construction industry. The primary focus during the workshop was around safety and specifically to see if immersive VR could provide benefits in detecting hazardous situations compared to only using traditional 2D drawings. As part of that investigation the site layout planning functionality was tested and evaluated with respect to placing guardrails and temporary covers. The complete setup during the workshop can be seen in Fig 9. A single, large touch screen was used together with two VR headsets, one of them also connected to a projector. Seven (7) participants, both from design and production, took part in the exercise which lasted around three hours. The test case was the 6th floor of the Kineum project, a 27 story tall building recently constructed in Gothenburg, Sweden (Fig 10). This project was chosen due to the sheer size and complexity, but also because design documents included both BIMs and traditional 2D drawings. In the first part of the exercise the participants where ask to identify areas that can be hazardous during construction using only 2D drawings. In the second part the same was done, but this time in VR using multi-user. In the third part, safety equipment, such as guardrails and covers, was placed and updated using the site layout planning tools. However, note that the possibility of adding and moving objects in the immersive VR interface was not implemented at the time of the workshop. Still, all modifications done on the multi-touch table (add, move, delete, etc.) was updated in the VR interface. As an additional and final step, the evaluation was completed with a post-workshop interoperability test.

Fig. 9: The setup during the workshop.

Fig. 10: The Kinum project; BIM, structural-only BIM, construction, completed building (left to right).

4. RESULTS AND DISCUSSION

4.1 2D vs. VR and multi-touch table for safety review

Except for the outer perimeter, there were mainly four areas that required safety precautions; three large openings and the area around the elevator shafts. From the 2D exercise only two participants managed to identify all of them. Among the other participants there were various differences, but they all missed the triangular shaped opening, which is actually quite difficult to spot in 2D due to its somewhat uncommon shape. However, when moving on to the second part in the exercise, using VR, all areas requiring safety precautions were easily identified by all participants. On the one hand, this could be seen as an unfair comparison, considering that there were elements of collaboration with the multi-user setup. On the other hand, this was the first time using VR for four of the participants which introduce an extra layer of mental workload before navigation and interaction with the different tools are fully understood. Regardless, it was clear from the participants' response and comments that VR provided a much more immersive and true-to-scale experience that allowed all of them to easily detect all floor openings, including the one that most missed in the first part of the exercise. Still, already by inspecting the model top-down view at the touch table, openings were much easier to detect than in the 2D drawing alternative due to the 3D perspective and shading. However, VR was considered particularly valuable in complex situations that are difficult to assess through traditional methods. Furthermore, with the general understanding that every action in construction carries some level of risk to workers' safety, all participants acknowledge the unique properties of VR to understand and comprehend complex design choices from a safety and constructability perspective, thereby improving safety planning and design. Finally, in addition to simple identify the hazardous areas, the participants were also asked to use the markup tool to illustrate suitable safety measures, as seen in Fig 11.

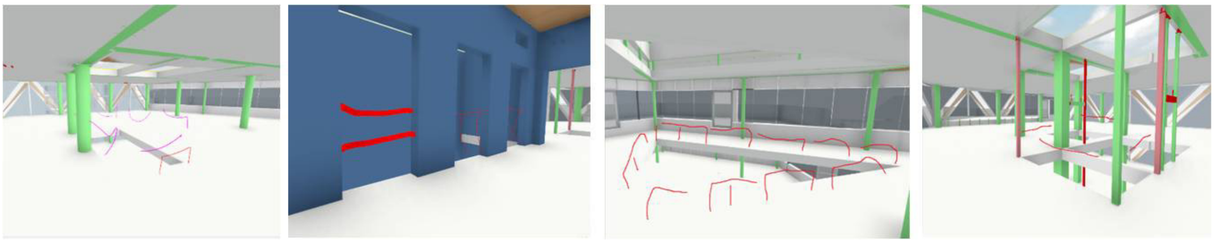

Fig. 11: Participants used the markup tool in VR to illustrate where safety measures were needed.

4.2 Planning and collaboration

In the third part, the top-down interface on the multi-touch table was used to place safety measures around the identified hazards, the results of which can be seen in Fig 12. One participant had experience from similar planning settings and specifically around the difficulties in getting people to interact with BIMs and 3D models on touch- and smartboards using desktop BIM-viewer applications and was surprised to see how easy and intuitive it was to add new components to a highly complex BIM using the multi-touch interface:

“We have always had problems in the past of getting non-experts and 'normal' people to be able to interact with these large and complex BIMs”

The main activity was around the touch-table and in that respect some participants indicated that they felt a bit isolated when immersed in VR, even if this was a multi-user session. Similar observations have been noted in previous research as well (Roupé et al., 2020; Truong et al., 2021). However, this might have been different if the functionality of adding and moving objects also in VR had been available during the workshop. Other than making markups, the VR users could only tell the other participants what to do and therefore became more of observers and reviewers, than that of creators. Still, participants around the touch-table liked that they always could see where VR viewers were. On the other hand, it was clear that immersive VR and the 1:1 scale was superior in order to understand narrow or wide space and to identify safety and constructability issues. For instance, the initially placed safety precautions for the elevator shaft section were later identified as too "light", which was not as easy to spot in the top-down desktop interface, but very obvious when seen in a first person, true-to-scale perspective. This actual combination and collaboration using multiple interaction and visualization interfaces was also identified as an efficient setting in order to increase understanding and share and exchange knowledge across professional disciplines. In particular, it was stated that the collaborative walkthrough between design and construction safety team can increase designers’ awareness and foster designer contribution for safety planning.

In addition to the request for also adding and moving components in the VR interface, there were several suggestions for improvements and also some identified issues. One suggestion that came very early during the workshop was to implement more of a polyline-drawing-tool for the guardrails, as it was found a bit inefficient and time-consuming to drag and drop all the individual sections and then place and rotate them correctly around the openings. To some degree this was also made extra cumbersome because the ray-intersection routine (i.e. hit-testing) does not use a dedicated collision shape but instead uses the actual geometry, which in the case of the guardrails consists of thin bars that are difficult to hit. The concept of a polyline drawingmode was also suggested for an area-drawing tool (i.e. surfaces). Even if 3D components are preferred as representations several participants highlighted the need to be able to also illustrate areas. Further suggestions included the possibility to group objects together to form composites and to be able to copy-paste objects (both individual and composite groups).

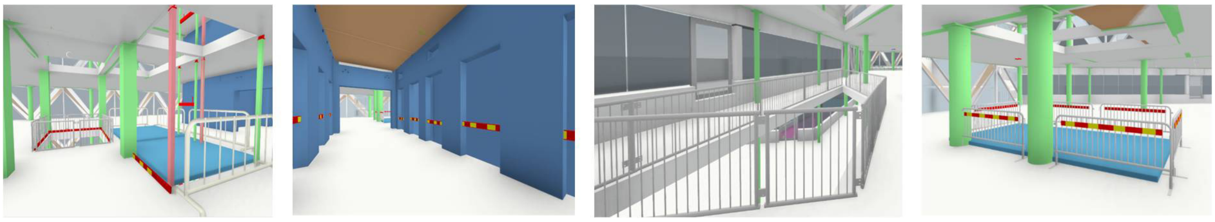

Fig. 12: Guardrails, temporary covers, and fences placed using the top-down interface on the multi-touch table.

4.3 Interoperability

All the safety equipment that was added to the project during the workshop was exported as a single IFC-file and then imported into both Solibri and StreamBIM together with other disciplines in the project (e.g. architectural, structural, MEP, etc.), which can be seen in Fig 13. In effect, this introduces a new discipline to the federated BIM – *Temporary Safety Components*. Although the IFC-export wasn't actually used during the workshop (i.e. it was imported into StreamBIM and Solibri at a later time), the functionality was discussed and the prospect of having an IFC-file with temporary structures and site objects as output sparked many ideas from the participants. For instance, it meant that all other tools that are part of the BIM palette, such as automatic quantity takeoffs and clash detection, could now also be used for temporary structures and components. However, regardless of future applications, the interoperability test successfully completed our initial evaluation which shows that, not only can non-designers collaboratively create construction site layout plans in 3D, but also directly integrate and use this 3D data together with all the other BIM sources received from the design organization.

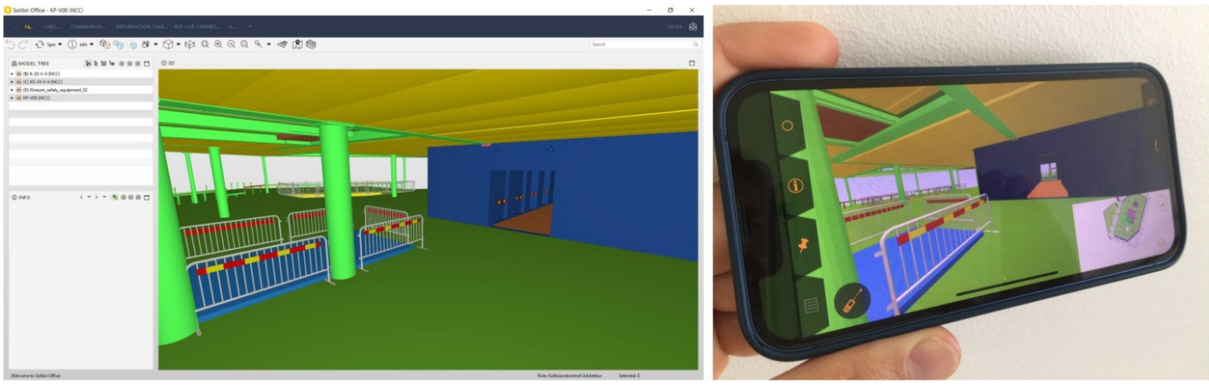

Fig. 13: The "temporary safety components" IFC-file imported into Solibri and StreamBIM.

5. CONCLUSIONS

In this paper we have present the design and technical details of a user-friendly, IFC-compatible software system that supports collaborative, multi-user creation of construction site layout plans using both multi-touch table and immersive VR. In addition we have presented an initial evaluation of this system with respect to safety review and planning and layout of temporary safety components. For the specific task of identifying hazardous situations, the presented system was found to be more efficient compared to only using traditional 2D drawings. The multiple interaction and visualization interfaces were found to complement each other and to provide an efficient environment for collaboration and knowledge sharing across different professional disciplines. In this context, the immersive VR interface was found to be superior in order for users to understand space, dimensions, and complex designs, whereas the multi-touch interface was considered very intuitive and easy to use with suitable tools for adding and modifying 3D components. With the ability to also export the planned environment as an IFC-file the system has been shown to support creation and continuous update of 3D site layout plans that can be fully integrated with a projects other BIM sources and tools.

For future work it would be interesting to implement some of the request and suggestions that were proposed during the evaluation, such as a polyline drawing tool for guardrails and grouping of components. Furthermore, it would be interesting to explore and evaluate the system with a more dedicated focus on all aspects of construction site layout planning, not only safety.

6. ACKNOWLEDGEMENT

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REFERENCES

Abune'Meh, M., El Meouche, R., Hijaze, I., Mebarki, A., & Shahrour, I. (2016). Optimal construction site layout based on risk spatial variability. Automation in Construction, 70, 167-177.

Andersson, J., et al. (2019). DIGITAL BYGGETABLERING. SBUF Report 13546

BIMXplorer (2023). www.bimxplorer.com

Cousins, S. (2017). Total BIM: How Stockholm's £1bn urban transformation project is going 100% digital. Construction Research and Innovation, 8:2, 34-40

Disney, O., Roupé, M., Johansson, M., & Domenico Leto, A. (2022). Embracing BIM in its totality: a Total BIM case study. Smart and Sustainable Built Environment.

Faliu, B., Siarheyeva, A., Lou, R., & Merienne, F. (2019). Design and prototyping of an interactive virtual environment to foster citizen participation and creativity in urban design. In Advances in Information Systems Development: Designing Digitalization (pp. 55-78). Springer International Publishing.

Fischer, M., Garcia-Lopez, N. P., & Morkos, R. (2018). Making each workhour count: improving the prediction of construction durations and resource allocations. In Advanced Computing Strategies for Engineering: 25th EG-ICE International Workshop 2018, Lausanne, Switzerland, June 10-13, 2018, Proceedings, Part I 25 (pp. 273-295). Springer International Publishing.

Gros, L. (2019). Problems and challenges to work with construction site plans (Thesis). Karlstads Universitet.

Isaac, S., & Shimanovich, M. (2021). Automated scheduling and control of mechanical and electrical works with BIM. Automation in Construction, 124, 103600.

Johansson, M. (2016). From BIM to VR - The design and development of BIMXplorer. PhD thesis. Chalmers University of Technology

Johansson, M., & Roupé, M. (2019). BIM and Virtual Reality (VR) at the construction site. In Proceedings of the 19th International Conference on Construction Applications of Virtual Reality (CONVR 2019).

Johansson, M., & Roupé, M. (2022). VR in Construction–Multi-User and Multi-Purpose. In Proceedings of the 22nd International Conference on Construction Applications of Virtual Reality (CONVR 2022) (Vol. 22, pp. 248-259).

Jongeling, R. (2013). Setting requirements in practice - Approaches and effects. Open BIM 2013 Conference. BIM Alliance Sweden

Kumar, S. S., & Cheng, J. C. (2015). A BIM-based automated site layout planning framework for congested construction sites. Automation in Construction, 59, 24-37.

Lockley, S., Benghi, C. and Cerny, M. (2017). Xbim. Essentials: a library for interoperable building information applications. The Journal of Open Source Software, 2(20), 473.

Muhammad, A. A., Yitmen, I., Alizadehsalehi, S., & Celik, T. (2019). Adoption of virtual reality (VR) for site layout optimization of construction projects. Teknik Dergi, 31(2), 9833-9850.

Roupé, M., Johansson, M., Maftei, L., Lundstedt, R., & Viklund-Tallgren, M. (2020). Virtual collaborative design environment: supporting seamless integration of multitouch table and immersive VR. Journal of Construction Engineering and Management, 146(12), 04020132.

Taghaddos, H., Heydari, M. H., & Asgari, A. (2021). A hybrid simulation approach for site layout planning in construction projects. Construction Innovation, 21(3), 417-440.

Tallgren, M. V., Roupé, M., & Johansson, M. (2021). 4D modelling using virtual collaborative planning and scheduling. Journal of Information Technology in Construction (ITcon), 26(42), 763-782.

Tallgren, M. V., Roupé, M., Johansson, M., & Bosch-Sijtsema, P. (2020). BIM-tool development enhancing collaborative scheduling for pre-construction. Journal of Information Technology in Construction (ITcon), 25, 374-397.

Truong, P., Hölttä-Otto, K., Becerril, P., Turtiainen, R., & Siltanen, S. (2021). Multi-user virtual reality for remote collaboration in construction projects: a case study with high-rise elevator machine room planning. Electronics, 10(22), 2806.

Wolfartsberger, J. (2019). Analyzing the potential of Virtual Reality for engineering design review. Automation in Construction, 104, 27-37.

Xu, S., Fu, D., Xie, Y., Hou, L., & Bu, S. (2020). Integrating BIM and VR for highway construction site layout planning. In CICTP 2020 (pp. 1068-1079).

Zaker, R. and Coloma, E. (2018). Virtual reality-integrated workflow in BIM-enabled projects collaboration and design review: a case study. Visualization in Engineering, 6(1), 4.