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Using Collaborative Immersive Environments and Building Information Modeling Technology for Holistic Planning of Production Lines

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Abstract. Large and complex building projects need many different experts from different engineering disciplines for different matters. But these experts each use their own IT tools that produce a lot of heterogeneous data. This leads to a strong fragmentation of competencies, what causes problems for interdisciplinary collaboration, because the data might be inconsistent, redundant or there are no interfaces to combine the data. These problems in collaboration increase the risk of planning mistakes that might significantly impair the overall project success. So only one database should be used for all engineering tasks to improve the transdisciplinary collaboration. The Building Information Modelling (BIM) working methodology enables the digital collaboration of virtual production planning and architecture tasks for developing a building. By means of lean optimization in combination with early integration of future-oriented production facilities, process-relevant production data can be included in the planning phase before construction begins. This article presents a real time immersive 3D virtualization system using the digital twin of complex buildings with a modern production line as the single source of truth and creates a consistent integrated data model, that enables transdisciplinary collaboration of all involved engineering disciplines. In this way, a continuous comparison can be made between the real construction project and its digital twin in an interactive, intuitive and collaborative manner. The same model is also used by production planners to optimize the material flow and in general the value chain of a production line through a holistic planning, which brings many benefits for all stakeholders.

Keywords. Transdisciplinary collaboration, immersive environments, building information modelling, virtual reality, production planning, smart factory, digital engineering

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Introduction

As modern factories are becoming more complex, they require more experts from different engineering disciplines to collaborate. This challenge is growing with the complexity and size of the project, as the number of interfaces needed to enable the interdisciplinary collaboration of the different engineering teams and their tools increases, because planning modern factories requires a broad range of competences [1]. Especially, the collaboration of architects and production planners is becoming increasingly important because the production process and the building directly impact each other [2]. As the environments of production need to be fast adapting, production planning becomes a constant, interdisciplinary task of enterprises, so it is necessary that there exists a consistent database for the digital factory that represents the present state of the production facility to perform further planning and optimization [3]. The BIM (building information modeling) working methodology enables virtual production planning and architecture digital collaboration and lays the groundwork for the digital factory [4, 5] by centralizing project information in a shared digital model. Its physical counterpart will not emerge until digital planning and virtual commissioning are successfully implemented. Process-relevant production data can be included in the planning phase before construction begins, using lean optimization in conjunction with early integration of future-oriented facilities [7]. With many different experts working together on joint projects, as in architecture and engineering, the importance of providing flexible work procedures and environments increases. Since BIM is meant to enable collaboration between different specialists, it is also important to find a suitable process for those experts to collaborate. The computer-supported cooperative work (CSCW) domain explores how computer technology can improve collaborative work and enable novel kind of collaborative work. Johannsen et al. [6] defines the four basic categories of collaborative work along the space and time dimensions as depicted in Figure 1. Regarding the space dimension, collaborative work can be conducted either co-located, when all participants are in the same location or distributed when collaborators join a Collaborative Virtual Environment (CVE) from different locations. Along the time dimension, synchronous collaboration takes place when all collaborators are participating simultaneously, at the same time, and asynchronously if they conduct their work at different times. For instance, immersive CVEs can be used to support collaborative design reviews in remote collaboration setups among architects, engineers, and other stakeholders, enabling them to work together on building designs regardless of their physical location. Furthermore, they can review and discuss 3D models of building designs in real-time, but also asynchronously in global teams with different time-zones. This can help to reduce travel costs, improve collaboration efficiency, and enable more effective communication among team members.

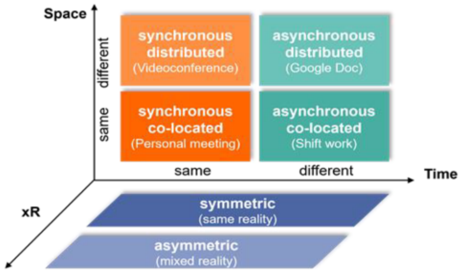

Figure 1. CVE matrix based on space, time and XR technologies dimensions [7].

Extended Reality (XR) technologies, such as Virtual Reality (VR) and Augmented Reality (AR) are immersive technologies that merge the physical and digital worlds and are well suited for the work on spatial data, especially including not yet existing or not visible metadata.

As CVEs can be implemented to be used within the same level of immersion, for instance in VR, but also allow cross-level collaboration, for instance between AR and VR, we extend the CSCW matrix with the XR dimension [7], adding the symmetric and asymmetric categories. In symmetric collaboration, all participants perceive the CVE in the same way, for instance in AR, while in asymmetric CVEs a subgroup of collaborators can experience the same CVE for instance in VR and another subgroup in AR. The term CVE in this paper refers to collaborative immersive environments that use XR hardware for the collaborative sessions. In the architecture domain, asymmetric CVEs can be used to support construction coordination and planning, enabling team members to visualize and coordinate complex building components, such as mechanical, electrical, and plumbing systems, and identify potential issues in the early stages. While one part of the collaborators is on-site, another can join remotely using VR technology to immerse into the construction site environment. The on-site team meanwhile participates with AR devices, allowing them to interact with the virtual avatars of the remote collaborators and see their virtual annotations while still being able to see the real construction site. The combination of immersive technologies and digital copies of buildings or machines for collaboration is often referred to as the industrial metaverse.

This article focuses on the interface between factory planning (including the building construction) and production planning. So therefore, the goal is to integrate BIM into the factory planning process and precisely display the correlation between production (logistics, output, sequences, etc.) and the production building to precisely plan the building and use the space efficiently. Finally, the integration of the data in a single virtual and semantic model called "virtual twin" and discuss the benefits of using it in immersive collaborative sessions will be discussed.

1. Relevant work

There have been many projects and attempts to integrate immersive technologies in engineering processes in recent years. Especially the topic digital twin has been a very popular theme in engineering research with big tech companies that presented new solutions in the last years. Nvidia for example released their Omniverse toolchain, that is meant to enable engineers to collaboratively create 3D worlds to simulate environments for production purposes as well as training purposes for autonomous robots [8]. The software VREX also is used for collaborative visualization of 3D models or pointclouds in the area of BIM [9].

Architectural authoring software programs such as Revit [10] and Archicad [11], which are widely used in the industry, allow semantically rich modeling of buildings in 3D and serve as BIM interface to the virtual representation in the collaborative immersive environments exchanged through an open format (IFC). EPLAN [12] now also has a module for 3D planning. Complete 3D planning of all trades would be the ideal basis of a digital twin, although a prerequisite that is often not met is the semantic linking of data sets. For example, components in the building geometry must be able to be assigned in the plans of the cabling. In existing building construction, the poor data situation creates major challenges. Many big software companies provide specialized platforms for production planning such as Siemens has the Tecnomatix suite. It covers especially the production processes, kinematics as well as logistic aspects of the production line [13]. Another example from academic research is Beisheim et al. [14] that describes a System to use the AutomationML data format to create an accurate digital twin of a production system, that is able to perform virtual commissioning with real time interfaces to commercial PLC-software and accurately calculated physics of the production system. All these examples focus on the production machines itself, trying to simulate them as accurately as possible.

2. Implementation of the virtual factories

In this section, two applications for the virtual twin of a production facility, where the planning process was supported by collaborative virtual environments, are described. The two use cases differ in that one of the production areas is to be integrated into a new building to be constructed, which is referred to as a greenfield, and the second is to optimize an existing production site, while production is ongoing, which is referred to as a brownfield. Both applications are developed with the virtual engineering software PolyVR [15]. This software has the goal to serve as an integrator of the planning data of machines, production line or building and visualize this data in collaborative virtual environments.

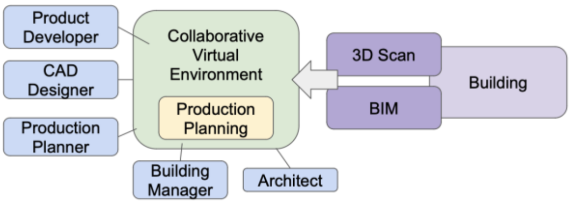

Figure 2. Methodology for creating CVE`s.

In its core, PolyVR has a virtual reality engine with collaboration module, many interfaces to planning data such as CAD, ECAD, automation code as well as different simulation modules. The clustering capabilities of PolyVR allow flexible software configuration of different hardware systems for distributed visualization on computer clusters and can thus be used on visualization clusters for high immersive VR environments such as CAVE and Powerwall and can be deployed also on VR headsets or on the web. This is particularly attractive for SME-oriented applications. PolyVR handles the representation of the building and the machines as a virtual twin, including semantic understanding and simulations. The software is being developed at the Karlsruhe Institute of Technology and is available on GitHub under the GPL3 license [16].

2.1. Greenfield

This section presents the application use case of a project, in which the whole process of planning a building as well as the construction process with the development and continuous updates of a virtual twin is accompanied. Currently, in the application of greenfield, most planning data is generated in a digital form. But this data is composed of a platitude of different heterogeneous file formats. The challenge of handling and congregating the information which originates from various domains of building planning to create the complete virtual twin is becoming increasingly complex. The appearance of redundancies, inconsistencies, missing semantics and lack of interfaces to link corresponding data sets is continuously multiplying. A necessary solution to these upcoming problems is an IT software tool, which links the data of all phases of the building planning and construction, while at the same time procures this information and makes it accessible to the involved stakeholders.

The planning of the new production shop floor was divided into three task packages: First task, the previous production was analyzed and data available to date was compiled. In addition to each workstations and machines geometries, data of the manufacturing processes was also collected. For some stations, log data was available from which many process-relevant parameters such as production times could be derived. Further data was collected manually, in order to obtain a complete description of the manufacturing. The second task was the virtual mapping of the new store floor layout. Since the production was to be expanded, another machine and a driverless transport system (AGV) were added. Subsequently, the virtual manufacturing was integrated into the 3D BIM model of the building. The third task in production planning was to set up the value stream simulation, based on the changes made to the shop floor layout. Various simulation modules from PolyVR were used for this purpose. While some of the commonly used export formats store 3D data such as the architectural building model as IFC, other planning formats only store their information details in 2D formats such as DWG and DXF like the plans for electrical lines or heating, ventilation and air conditioning (HVAC). For the integration into the virtual twin a better semantic understanding of each planning dataset and their information needed to be automatically built. From the 2D plans, the required information was selectively filtered and additional information such as height and floor number was semantically combined to visualize the planning of the two-dimensional data in the virtual 3D building. An approach to automatically generate 3D ducts in the virtual twin for the HVAC system was implemented to visualize the required space.

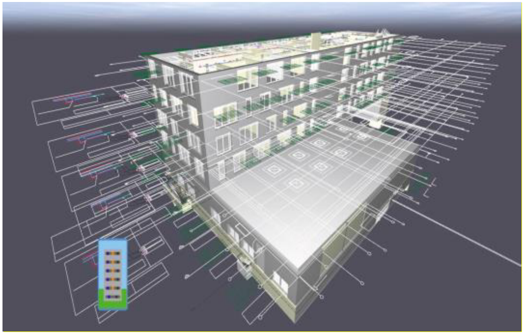

Figure 3. The building model is a combination of 3D and 2D data from various disciplines.

For the manufacturing shop floor within the planned building, 3D models of the machines were directly imported through the CAD exchange format STEP and placed at their planned installation locations. Within the virtual scene, these locations could be moved via drag and drop to manually test different layouts in a quick way. Along the predefined steps of the manufacturing processes on the shop floor routes could be traced to simulate material flows. These flow paths could be made configurable to enable the planning of automated guided vehicles (AGVs). To accelerate the user's experience between the oftentimes hour-long manufacturing steps, a time-lapse mode with factors between 10 times and 1000 times faster than real time was implemented.

During the construction of the planned building, 3D scans and 360° panoramic photos were used to both log the current progress of the construction as well as a possibility to note deviations from the planning data. Through superimposing the 3D scans within the CAD models, the differences could be shown visually and deviations calculated through algorithms. One of the examples, which came up, was the wrongly inferred vehicle height clearance. This was corrected through the virtual measurements of scanned data. Another benefit of the 3D scan and the panoramic pics is the possibility to allow for virtual tours of the construction sites without the need to visit the construction site physically.

Figure 4 Shop floor and material flow simulation.

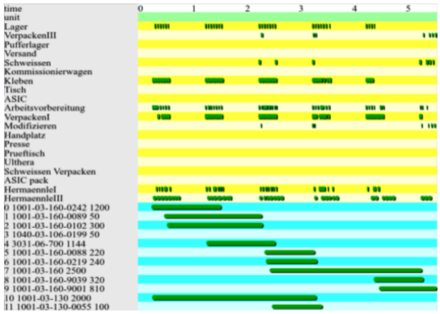

Figure 5. Utilization of the stations and processing span of the orders.

2.2. Brownfield

In contrast to the application of greenfield where most of the planning assets are currently created in a digital form and handling difficulties lie mostly in the data compatibility and integration of such, in brownfield the challenges of historical data and already existing physical environments arise. To get a better understanding of the preexisting topology within the building, oftentimes 3D scanners are used. These create a rather data heavy three-dimensional comprehension of the physical space.

In the application of our use case, an existing sheet metal processing hall from the company Schneider Electric was internally 3D scanned to assist in the development and creation of a planned virtual twin. Based on this virtual twin, collaborative work and discussions were encouraged and boosted. Information about the delivery, storage of materials and placement of new machines were made possible to discuss with customers and suppliers. Further optimizations in the area of the shop floor processes were enabled. One of these shop floor processes is the material flow simulation. Within the virtual scene, the material flow was visualized and calculated. To improve this material flow, the possibility for the deployment of AGVs was assessed to automate the transport of half-parts and finished parts.

To generate this virtual twin a virtual scene with the 3D scans was set up, as shown in Figure 6. From the information of the 3D scans, rough models were manually designed and textured to serve as movable placeholders of the physical installations such as the high-bay storages and the individual manufacturing machines. With the possibilities to duplicate or scale various placeholders, different machine configurations could be considered and evaluated. From the predefined manufacturing steps and their corresponding machine, material flows and material paths would be recalculated and automatically adapted to changes in the layout. These paths and their changes could be visualized and simulated in real time using virtual reality in a cave as shown in Figure 7.

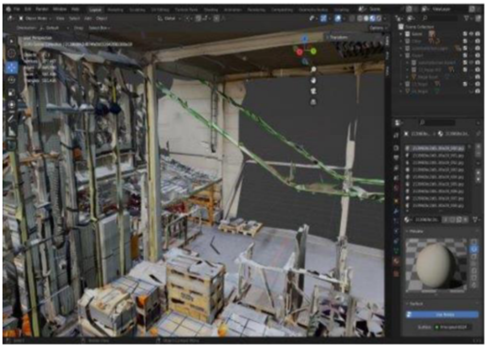

Figure 6. 3D point cloud of sheet metal processing plant.

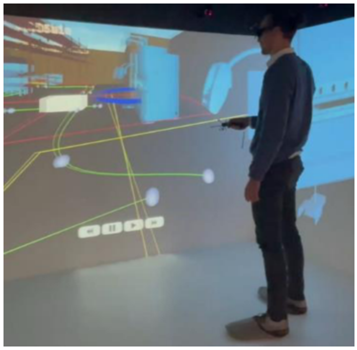

Figure 7. Collaborative virtual reality session in a CAVE.

3. Discussion of benefits and limitations of collaborative immersive production planning for enterprises

As presented in the last section, we created a virtual representation of a future and existing factory also integrating the building planning information (BIM model). With the help of PolyVR we created a single virtual place, where all heterogeneous data of the construction and production planning were brought together in the term of “single source of truth”. The virtual twin is not static, it provides variable configuration possibilities, as well as simulates different processes, such as the value stream.

The result was used for immersive collaborative meetings among various stakeholders to review discrepancies, discuss potential problems, bottlenecks, and optimizations, discuss the construction or redesign process, and make decisions. The collaborative sessions were conducted in a CAVE, but also using VR headsets from remote locations. In case immersive hardware is not available, the first project was also delivered as a 3D web application, and for the second project, sharing the 3D display via a teleconferencing system also brought benefits for discussion with remote partners.

Collaborative immersive environments are ideal for planning modeling scenarios because of the ability to experience buildings or facilities at scale and realistic manner, before they exist. They give the user an idea of what it might look like in reality, which means that design errors can be corrected at an early stage. In order to achieve the lowest possible error rate, a transdisciplinary process is preferable. This ensures that all responsible teams are involved and that potential misunderstandings are avoided.

In addition, the costs that can arise if not all people are taken into account from the beginning can be shown by a practical example. During the planning of a new center, virtual inspections of the building were carried out at a power wall with a wide variety of people such as janitors, engineers, experts, etc. at iterative steps, and the resulting reviews were integrated into the planning. After the building project was completed, it was found that the access to the storage room was too small and too narrow for

conventional care trolleys. As a result, custom-sized trolleys had to be procured. A cleaning professional would have been able to identify this problem in the virtual model and point out the discrepancy in the design.
One of the main advantages of using immersive technologies is the improved understanding through enhanced visualization of the site. It can provide a comprehensive and accurate representation of the existing site, enabling stakeholders to understand the layout and identify potential issues before starting the planning process, to make informed decisions. This can help to reduce misunderstandings and avoid costly mistakes. Once a virtual twin of the factory is available, it can also be used for training. For instance, employees can be trained in the construction/production process or the assembly of the machine, while waiting for it's the delivery.

CVEs can help project managers to track progress, identify potential issues, and make informed decisions about resource allocation. This can help to ensure that projects are delivered on time and within budget. For instance, a company has used VR collaboration environments to present the planned factory to the bank to get a loan for its production. All the details, not only about the architecture of the building, but also about its use, where the delivery is taking place, where the warehouse, manufacturing areas are, where the machines are assembled and commissioned before shipment to the customer, as well as the planning of office space and workplaces for each employee in the company, were communicated to investors in a clear manner.

As we showed through both use cases, using immersive environments for collaboration can significantly improve efficiency. CVEs can be used to simulate and optimize factory layouts and workflows, helping to identify potential bottlenecks and develop strategies to improve efficiency. This can help to increase productivity and reduce costs. Increased safety is a very important factor concerning production planning. CVEs can be used to simulate and test different scenarios, helping to identify potential safety hazards and develop strategies to mitigate them. This can help to improve overall project safety. In our application, the safety distance between the machines in the shop floor are integrated in the configuration logic. If one machine is moved too close to another, the user will receive a warning by highlighting the machine boundaries in red. Saving time and optimizing of the construction and production princess are leading automatically to reducing the costs. Costs can be increased by allowing teams to identify and resolve issues before construction begins, reducing the need for rework and minimizing the risk of costly mistakes. In the operational phase, the virtual twin of the factory can be used for planning reconfiguration measures to reduce production downtime. Furthermore, using collaboration immersive sessions from remote locations, can reduce travel time and costs.

The flexibility of collaborative immersive environments can be further enhanced using an asynchronous mode (as discussed in section 1). Independent of location and time - from the “where” and “when” the work has to be processed - distributed and asynchronous collaboration setups foster the most flexible work conditions. Literature on Mixed Reality CVEs [17] recommends building CVEs enabling all categories of collaborative work, as depicted in Figure 1, and furthermore allowing flexible transitions between them.

Allowing asynchronous collaboration means gaining more flexibility to conduct group work. Team members do not have to make appointments in order to continue the group work, but they can also continue group tasks when others are absent. Asynchronous collaboration tends to reduce required meetings and with it also the administrative effort for collaborative work. For instance, during a factory planning, several experts from different domains can co-work from different locations and without being restricted by time zones or work schedules.

During asynchronous collaboration, the processes have to be logged, so that they can be retraced by other collaborators when they rejoin the group work. This allows the retention of knowledge, which can be accessed and viewed at other times. For instance, a physical task can be recorded by a user and later visualized with an avatar when the user is not present within the CVE [18]. The knowledge can also be accumulated across all participants for a specific group task, creating immersive databases of knowledge. Furthermore, the logs can be used to automatically generate documentations of processes, which is usually a laborious task in the practice and will significantly save time.

Finally, asynchronous CVEs implement various tools which allow users to view changes applied by others over time. Similar to version control systems, asynchronous CVEs enable the interaction with multiple versions of the conducted work, for instance the creation of alternative work branches and a backup and recovery mechanism. Overall, using CVEs for factory planning can help to improve understanding, visualization, project management, reduce costs, enhance efficiency, and increase safety. In brownfield sites, it can also help to ensure that the factory is designed to meet the needs of the business and can adapt to changes in demand or production requirements, while minimizing disruption to existing operations.

4. Conclusion and Future Works

The main goal of the CVE is to improve the collaboration between the different stakeholders, as for example to synchronize different engineering teams. CVEs enable teams to work together on a single, centralized platform, allowing for better communication and collaboration. This can help to reduce errors and improve overall project efficiency. Using true scale of views, comparisons can be made based on planed data and a 3D scan, allowing the current status to be compared with the planed status at any time and corrections to be made during the construction phase. In addition, simulations can be created based on real-data to make projects even more accurate and efficient. Moreover, these digital data are to be used to generate automatically a detailed virtual twin for achieving a full virtual commissioning.

BIM and CVEs allow intelligent models to be created with multidimensional data structured in such a way that experts from a wide range of disciplines can access it in real time, independently of location. Using this powerful backend, it is possible to digitally map each section or object and track it through its lifecycle - from planning to design to construction and finally to implementation. However, when bringing together engineers, designers, academic researchers, and so on, it is important to ensure that the CVE offers an adequate entry level for everyone so that new users in particular are not overwhelmed by this technology from the very beginning. In this context, another area of virtual reality may be of interest. It would not only be possible to view the whole architecture virtually, but also to extend the CVE with the real environment and to use augmented reality, which allows to map the generated digital content with the reality. Finally, it should not remain to be mentioned that in order to be able to use such a structure, it is very much dependent on how well virtual models are available or can be generated. In the future, this problem could be solved by using AI-generated high-resolution model sets from text, images or video, as photorealism becomes increasingly important. For example, lighting scenarios can be simulated to ensure that workers are not disturbed by reflections in the future environment or complex energy supply systems such as heat and light in the factory can also be taken into consideration in order to integrate eco-efficiency aspects in the future. Therefore the aim should not only be to combine heterogeneous data, but also to bring together and encourage transdisciplinary collaboration between architects, production planners, engineers, and other stakeholders.

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