

REALISTIC VIRTUAL MODELS FOR FACTORY LAYOUT PLANNING

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ABSTRACT

Factory layout planning is essential for manufacturing companies when designing or redesigning production systems. Layout planning usually involves 2D CAD applications, sometimes based on faulty data. Difficulties in communicating and discussing layout alternatives using such applications can lead to critical errors, yielding inaccurate simulation models producing poor results. This paper aims to investigate and evaluate the usefulness of realistic 3D layout models in the layout planning process, addressed by an industrial study of how existing methods for visualization can be applied. This paper shows that utilizing a realistic and accurate layout model allows for fruitful discussions while several potential mistakes can be avoided. It also shows benefits in evaluating a layout and the model's accuracy in immersive virtual reality where a better perspective of the layout can be acquired. Having such evaluated layout models will enable more accurate simulation models for planned changes, based on real physical requirements.

1 INTRODUCTION

Manufacturing companies are continuously facing new challenges, which make them redesign existing production systems or design new production systems. Either way, layout planning is an essential part of the process to achieve an efficient production system (Drira, Pierreval, and Hajri-Gabouj 2007). There are prerequisites and criteria to consider when planning layouts, which makes it suitable to use virtual tools (Iqbal and Hashmi 2001). A common type of virtual tools used is layout modeling using 2D CAD applications, with data of the existing shop floor area from previous layouts or blueprints. There are problems found with working only with such virtual tools for the layout planning. One such problem is that the data can contain errors originating from measurement mistakes or undocumented changes in the production systems (Rex and Stoli 2014). Another problem is to communicate and discuss the planned layouts, which can lead to misunderstandings between employees. These problems can result in errors that are causing problems when implementing the planned layout. The differences between planned and real implemented layouts can lead to difficulties when building a valid simulation model due to a lack of proper and accurate spatial data. Hence, the simulation model might be missing many details without being noticed due to being abstract. This abstract simulation model can lead to a simulated capacity that is impossible to achieve when the real production system is running due to a lack of details and information in the model, and investments not giving the expected results.

There is a need to ensure the spatial data of the shop floor area used for layout planning are geometrical accurate and up-to-date (Lindskog, Vallhagen, and Johansson 2017). 3D laser scanning has

been shown to be a fast and efficient technology for capturing such spatial data (Lindskog, Vallhagen, and Johansson 2017). The 3D laser scanning results in point clouds that can be used for layout planning by combining them with 3D CAD models of the new equipment into realistic 3D layout models (Lindskog et al. 2016). These layout models can be communicated and discussed during the layout planning process with different stakeholders of the layout (Lindskog et al. 2016). The main challenges are to work efficiently and systematically with such models during the planning process and to ensure all parts of the production system are included. A key part of this work is to create a common mental model for all stakeholders, which should meet the virtual model and the reality (Vallhagen, Stahre and Johansson 2011).

The aim of this paper is to investigate and evaluate the usefulness of a realistic virtual factory model in factory layout planning. The aim is addressed by an industrial study of how existing methods for visualization and layout evaluation can be applied in a real industrialization project. During this study, realistic 3D layout models are created using point clouds of the existing shop floor area. These models are discussed in workshop settings with engineers involved in the layout planning and machine operators that will work within the production system. During the workshops, two alternatives of how to present the models are studied. The first alternative is to use a projector screen and the other alternative is to use a head-mounted display (HMD) for immersive virtual reality (VR).

2 STATE OF THE ART

Layout planning of production systems includes considerations of many factors and involvement of different people throughout the organization. To support layout planning there are many approaches and virtual tools available. Within this paper, the overall approach has been the virtual factory. A virtual factory can be defined as a computer-based model representing the real production system, which can be used to perform engineering activities (Lee and Noh 1997). The virtual factory can be used to recognize errors in planning prior to the implementation phase, leading to fewer mistakes in the end (Brent and Masurat 2005). The most common reason for unsuccessful simulation studies is mistakes due to mental models being internal to its holder (Musselman 1994). One way of externalizing that mental model is by creating a virtual factory, to ensure that discussions are aligned to the same model. To support this virtual factory approach, VR and 3D laser scanning are applied.

2.1 Virtual reality

In 1965, VR was first defined as “A system that can display information to all senses of the user with an equal or bigger resolution than the one that can be achieved in a natural way so that the user cannot say that the artificial world is not real” (Sutherland 1965). The first VR system was developed in 1968, an HMD was implemented to present stereoscopic 3D views using a cable connected sensing device to track the user’s head movement (Sutherland 1968). Since then, VR has attracted wide attention in both industry and academic world (Fisher et al. 1987; Loeffler and Anderson 1994; Shukla, Vazquez, and Frank Chen 1996).

The VR technology maturity has increased drastically over the years. In the production area, VR can be used as a collaborative tool for exchanging data and information, thus to better facilitate understanding and decision-making through immersive experience and visualization (Choi, Jung, and Noh 2015). Immersive VR has been shown to be a useful tool for collaborative factory planning, especially when multiple viewpoints of users are visualized (Wiendahl and Harmschriani Fiebig 2003). VR systems can be divided into four categories based on the setup difference, namely desktop systems, widescreen projection systems, immersive CAVE systems, and immersive HMD systems (Korves and Loftus 1999).

2.2 3D laser scanning

3D laser scanning is an active, non-contact, spatial measurement technology (Boehler and Marbs, 2002). Measurements are captured by emitting laser light and recording its reflection off the nearest surface along its trajectory. The laser light is either pulsed or continuously modulated to allow measurements of the distance it has traveled through either time of flight or phase shift calculations (Besl 1988). The devices are equipped with a mirror that directs the laser along a 360-degree vertical path out of its core. By storing the angle of the mirror and the measured distance traveled for each captured measurement, surface points of the surroundings can be plotted in x, y, z coordinates. The capture process of modern devices capture tens of millions of measurement points in a few minutes and the resulting data set is often referred to as a point cloud. The quality of the measurements relies on many factors but the distance to the target, the rotational speed of the mirror (rate of capture), and the surface properties of the measurand are amongst the most important.

3D laser scanning originates in the field of surveying but has since spread into many areas of use. Examples are forensics, tunnel construction, industrial production systems, and archaeology (Sansoni, Trebeschi, and Docchio 2009; Lam 2006; Bi and Wang 2010; Metallo and Rossi 2011). Common for all applications is the need to rapidly and/or accurately digitalize the spatial properties of objects or surroundings.

3 INDUSTRIAL STUDY

The industrial study was following an industrialization project at a company designing and manufacturing components for jet engines. The type of product and its related production addressed by the project is small parts used in the subsequent fabrication of larger casings. The raw material is forgings and the major part of the operations and operations time is CNC milling. This is followed by a sequence of operations for deburring, cleaning, and inspection, before the parts are used in welded sub-assemblies. The purpose of the industrialization project was to prepare for, install, and start up new production equipment to increase the capacity to meet ramp-up of production demand. Thus, it was not a new product and new processes to be designed in the project, but instead an expansion of some already existing processes and production solutions. However, the considerably higher production volumes and production rates put the solutions of layout and production flow in a new perspective. The industrialization project was assigned to use an existing shop area and can be considered as a brownfield scenario. This means that there are several physical limitations and constraints in the facilities for how to set up the new layout, to keep cost and investments at a reasonable level. There are also other products that need to be manufactured in the same area in existing equipment as well as using some of the new to be installed.

The overall process of the industrial study is divided into four steps, as presented in Figure 1. First, the shop floor area was captured using 3D laser scanning. The resulting point cloud was used together with 3D CAD models to create a realistic 3D layout model of the planned layout. This model was used to create an identical model to be viewed using an HMD setup. Following the creation of the two models, three workshops were held at the company where the models were used for evaluating the layout. How the model was used, feedback, and thoughts regarding the planned layout were gathered through observations. These observations were used as the results of this paper, which were analyzed to form the conclusions.

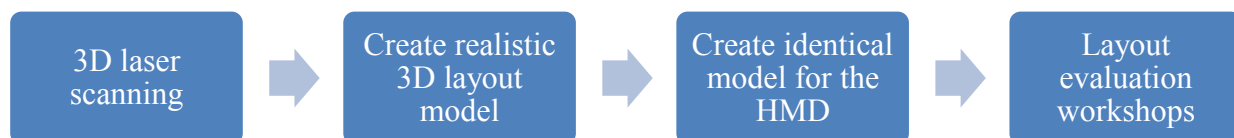


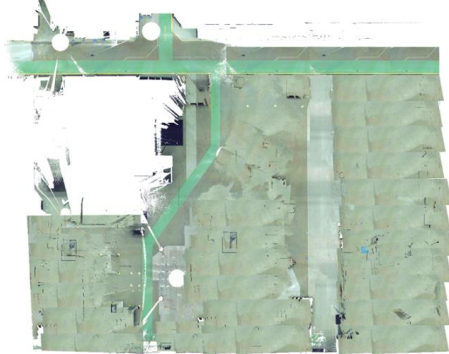
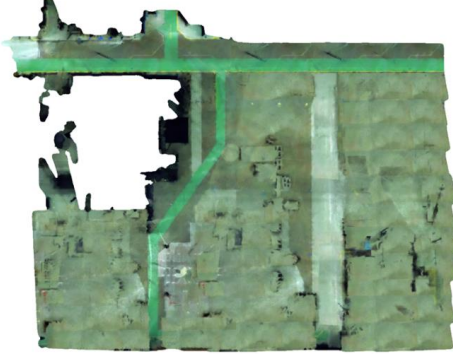
Figure 1: The process of the industrial study.

3.1 Spatial data capture and processing

3D laser scanning was used to capture the spatial data of the current shop floor area and conditions of the area purposed for the machine installation. A 3D laser scanner incorporating an RGB sensor which produces colored point clouds was used for data capture. During the data capture, the area was partly in use by older equipment, scheduled to be removed before installation of the new machines. In addition, there were material storages and material handling equipment positioned throughout the area. The measurement data associated with these objects was manually removed from the data sets in dialogue with the production engineers on-site. In total eight scan positions and a total of 226 million data points were used during the study. The eight scans took roughly one hour to perform, and about one hour to process into a point cloud using Autodesk ReCap.

To accommodate the requirements of the HMD system, an additional, lighter version of the point cloud was generated. This was to allow for higher frame rates in the taxing rendering that is inherent to the HMD system. The lighter version was achieved using mainly two strategies, density reduction of points and translation from points to simplified meshes. Density reduction was achieved using CloudCompare by filtering away points that are closer than a distance threshold to their neighbor (CloudCompare 2017). This reduces the visual quality significantly at close range but is unnoticeable from further away and was implemented mainly on the roof data and surrounding areas. Meshing and simplification operations were conducted using MeshLab (Cignoni et al. 2008). Meshing the points was done using the screened Poisson surface reconstruction filter (Kazhdan and Hoppe 2013). The resulting mesh was then simplified using the Quadric Edge collapse decimation filter. This strategy was implemented for flat surfaces such as the floor and walls. The simplified mesh was textured using color data from the point cloud. To exemplify the benefits of this operation, samples of the floor model before and after simplification and meshing, along with data sizes is presented in Table 1.

Table 1: Sample of the floor model before and after simplification and meshing.

Floor	Point cloud	Triangle mesh
		
Vertices	67,036,944	24,295
Data size	1,013 MB	21 MB

3.2 Creation of the realistic 3D layout model for a projector screen

The realistic 3D layout model to be viewed on a projector screen was created as a representation of the future production system layout in Autodesk Navisworks. To achieve a representative model, it was created in three iterations. For each iteration, a meeting was held with members of the industrialization project to ensure that all equipment was accounted for within the layout and that it met their expectations.

3.2.1 First iteration

The initial realistic 3D layout model was created using the following models:

- 2D CAD layout of the shop floor area, created by the industrialization project team
- 3D CAD models of the machines and other equipment that were planned to be installed
- 2D CAD model of the planned walkway
- Point cloud of the shop floor area after cleaning
- Point cloud of equipment that was already available and should be kept within the new layout

The point cloud of the shop floor was aligned with the 2D CAD layout, by aligning the outer walls of the point cloud with the walls of the 2D CAD layout. This resulted in a slight offset in some of the details, as exemplified with the pillar positions in Figure 2.

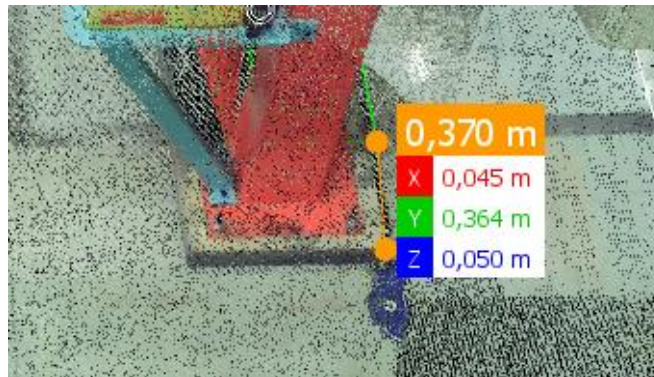


Figure 2: Differences between the aligned point cloud and the 2D CAD layout. The difference in Z is irrelevant due to 3D versus 2D, while the difference in Y represents a mismatch between the 2D CAD layout and the point cloud.

Following the alignment, the point cloud was hidden from view and the 3D CAD models were aligned to the 2D CAD layout. A corner of the 2D CAD model of the machine was chosen as the best point to base alignment on as it matched up well with the 3D CAD model of the same, and was used for all machine placements. The 3D CAD models of the barrels were placed on a model of a pallet and placed according to the 2D CAD layout. Once this model matched the 2D CAD layout, it was shown to the project leader and a facility project manager who gave feedback on which details were missing or wrong. The key feedback gathered were:

- There should be two pallets in front of each machine, required to perform the work tasks
- There should be one pallet lift for each machine

3.2.2 Second iteration

The feedback gathered of the initial model was used as the basis for changes, hence the second iteration of the model had two pallets in front of each machine as well as a point cloud of the kind of pallet lift used in the factory. Two models of machine operators in 3D CAD were added to this model to give a greater sense of scale. This model was shown in a meeting with the project manager of the industrialization project and another project manager, who gave the following key feedback and impressions:

- Three of the machines could be repositioned to give more space for other related tasks
 - The side of one of the moved machines could be used as production meeting area and as a potential workstation area next to another machine
- The pallet rack belonging to an adjacent machine should be moved in the future state

After these changes had been made according to the company's updated 2D CAD layout, a meeting was held with the same participants to confirm that the changes and updates were correct.

3.2.3 Third iteration

The third iteration of the model was created and verified during a meeting with a production engineer involved in planning the flow of products in the planned layout. After showing the model updated with the feedback from the previous iteration, the flow of products was examined together with the production engineer. The feedback from the evaluation was implemented to the model. The key feedback gathered from this meeting were:

- The working pallets should be rotated 90 degrees
- There should be one work bench per two machines
- The models used for tool measurement were not correct and should be changed
- A coordinate measuring machine and a washing machine could be added to the layout area

3.3 Creation of the realistic 3D layout model for an HMD

The realistic 3D layout model to be viewed using HMD was created using the triangle mesh, point clouds, and 3D CAD models. Those models were imported to Unity for the integration process, where everything was placed in the same position as in the model for projector screens. The triangle mesh and point cloud constitute mainly as the background environment in the model, however certain objects such as the tool wagons and pallet lifts were made from a sub-set of points. 3D CAD models of new machines were used to form the layout. Standard SteamVR API and customized scripts were used to enable the interaction functions such as navigation in the model using teleport, repositioning of interactable objects to new positions, saving and loading positions of these objects, and other functions.

3.4 Layout evaluation workshops

The two realistic 3D layout models were used to evaluate the planned layout during three workshops, which followed a structured introduced in Lindskog et al. (2016). The workshop structure is an iterative process, with the overall task of identify risks and eliminating potential problems before starting the installation the planned layout. The three workshops have different focus areas and aim, as presented in Figure 3 (next page).

Employees from the company with different competences and responsibilities were participating in the workshops, as presented in Table 2. These participants were divided to match to the focus area of each workshop, and were either working with designing the production system or will be working within the production system when implemented. Other than the workshops participants, four researchers of the research project conducting the study were present at the workshops. A company representative researcher acted as moderator of the workshops. One research was managing the realistic 3D layout models, which also included making changes to the models when needed. Two researchers were making observations and not part of the discussions. Observation notes were written during the workshops and audio was recorded.

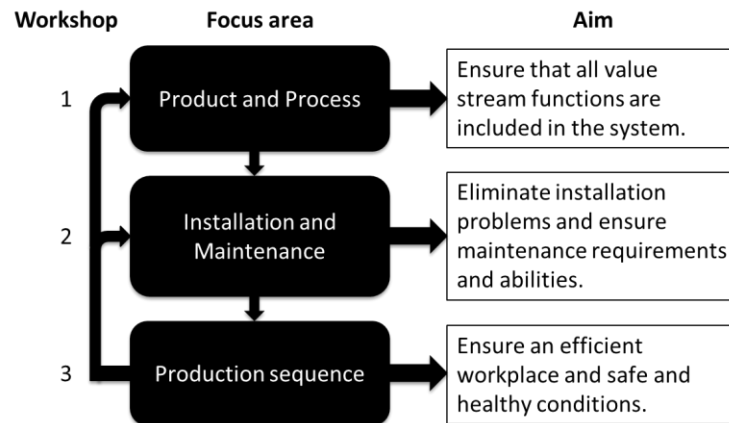


Figure 3: Structural description of the three layout evaluation workshops (Lindskog et al. 2016).

Table 2: The participants at the three workshops (excluding the research team).

Workshop	Participant	Work responsibility
1	1	Project leader
	2	Process planner
	3	Production leader
2	1	Project leader
	2	Process planner
	3	Machine acquisition
	4	Maintenance engineer
3	1	Project leader
	2	Process planner
	3	Production leader
	4	Team leader/Machine operator
	5	Machine operator
	6	Machine operator

The setup during the workshops were two parallel projectors and an HMD. The first projector was used to display the realistic 3D layout models and the second projector was used to display additional information, e.g. product or production data. An HTC Vive was used as an HMD to experience the realistic 3D layout model in immersive VR. Two hand-held controllers were provided for navigation and user interaction in the model, which was tracked by two sensor stations that also track the HMD.

The workshops were started with an introduction by the moderator. Next, the process planner, who participated in all workshops, presented the planned production flow and material flow using the model presented on the projector screen. Discussions were held between the participants with the support of the model. When a decision of repositioning or replacing any object in the layout, this was made within the model directly. Other issues that could not be solved during the workshops, were noted by the project leader for further investigation. During the second half of workshop 2 and 3, the HMD was used for presenting the layout. One participant at a time wore the HMD and held the controllers to interact with the model, while a live view was displayed on the projector screen so that the rest of the participants could experience the same view and context as the system user.

4 RESULTS

The results of the industrial study are divided into two parts, identified problems and risks with the layout, and observations made from the usage of realistic 3D layout models.

4.1 Identified problems and risks with the layout

The planned layout discussed at the workshops was found including several problems and risks, mainly concerning equipment that needed to be moved or was missing in the model. The most critical problems and risks identified during the workshops and how these were solved are presented in Table 3.

Table 3: Identified problems and risks with the layout during the workshops.

Workshop	Problem or risk	Solved during the workshop by
1	There was no defined area for incoming material, which requires a desk with a computer for material registration and space for at least four pallets.	Importing and positioning 3D CAD models of a desk and pallets.
	Five fixture wagons were missing.	Importing and positioning 3D laser scanned wagons.
	The pallets positioned in front of one of the machines blocked the possibility to walk by the machine.	Repositioning the pallets.
	Information center was missing.	<i>Not solved during the workshop.</i>
	Lockers for cleaning material and operators' personal equipment was missing.	<i>Not solved during the workshop.</i>
2	One of the machines seemed to be too close to a wall, the operation might not get the required working space.	Repositioning the machine 0.5 meters from the wall.
	The position of an air cleaning filter might be wrong, due to errors in the 2D CAD layout.	Repositioning the filter to fit the point cloud.
	The coordinate measuring machine was positioned in the wrong place.	Repositioning of the machine.
	There should be a fence between the machines and the pathway to block personal to make a shortcut.	<i>Not solved during the workshop.</i>
	Electric cars should have enough space behind the machines to change the cooling liquid.	<i>Not solved during the workshop.</i>
3	A workbench was needed to support one of the machines.	Importing and positioning a 3D CAD model of a workbench.
	Two work desks were identified as being too small.	<i>Not solved during the workshop.</i>
	Wagons for tool changing should be placed in front of the machines	<i>Not solved during the workshop.</i>
	Computer workstations for the operations are needed.	Importing and positioning 3D CAD models of workstations.
	The model lacks wastebaskets, paper rolls, baskets for used tools, lighting over working desks, and boards over the tool preparation desks.	<i>Not solved during the workshop.</i>

4.2 Observations made from the usage of the realistic 3D layout models

The realistic 3D layout models were used during the three workshops to discuss and evaluate the planned layout. There were observations made from how the models were used and accepted by the participants.

4.2.1 Realistic 3D layout model using a projector screen

During the workshops, the realistic 3D layout model was appreciated and used frequently when discussing the layout, mainly to visualize what was being talked about. For example, during discussions related to the flow of materials in the area the model was used to discuss entry and exit points for the material. To point at specific details in the model a laser pointer was used by the participants during the discussions. Top view of the layout was used to achieve an overview of the layout. In this view, the 2D CAD layout was enabled to visualize other sections of the factory as well. Changes that were discussed during the workshops were implemented within a minute and evaluated instantly, as measurements could give instant feedback.

Measurements in the realistic 3D layout model gave access to accurate and true information. Examples of topics that were analyzed using measurements were how a doorway should be placed and how this decision would affect the available wall area and comfortable working environment between a machine and a wall.

The model was used to determine space available for different equipment. One such example is the number of pallets that would be possible to store for incoming material. By importing and positioning pallets in a proposed area, the amount that would be possible to store was analyzed. This could be instantly evaluated by adding pallets to the incoming material zone until the zone was filled. Another example of the instant evaluation was to determine the proper scale of machines and equipment, as the scale of the coordinate measuring machine was in question. It was decided as having the proper scale after a human-sized model was placed next to it.

4.2.2 Realistic 3D layout model using an HMD

Viewing the realistic 3D layout model using an HMD was considered to give a better perception of proportions and distances than the projector screen. This model and way of viewing were used in both workshop 2 and 3 to evaluate the machine position that seemed potentially too close to the wall, but was not considered an issue in this model. It was also used to evaluate working height and to identify good positions for information screens based on the viewpoints of the operators. Two good and feasible positions for these were identified in a few seconds of viewing the model using the HMD. Two tables were identified as being too small when an operator stood next to them in the model, something which was not noticed using the projector screen. Control measurements of similar tables used in another part of the factory confirmed this notion.

5 DISCUSSION AND FUTURE WORK

The workshops were appreciated by the participants and the usefulness of discussions held around an accurate realistic 3D layout model was found obvious, as some problems were easily identified and solved quickly. Through the involvement of stakeholders outside of the industrialization project, such as operators in the third workshop, new problems and potential risks were identified that had not been discussed before. This should be valuable to the company, as they can solve these issues before becoming a problem in the real production system.

Utilizing 3D laser scanning was a quick way to capture the spatial data and build accurate and realistic layout models. A lifelike accurate point cloud of the facilities was built from scratch in less than an hour after the data was captured through the eight scans. Making adjustments in this model was quick and simple, however, one of the drawbacks of the 3D laser scanning is that it only captures data which can be seen. If a machine is adjacent to the wall, there will be a lack of data in the point cloud of the wall behind that machine. This lack of data will appear as a hole in the point cloud if that machine is moved.

The structure followed for the layout evaluation workshops had been used once as a method in previous research, making this paper as a validation and future development of the method. For the

industrial study of this paper, an additional iteration of the workshops might have been needed due to the number of problems and risks that were not solved during the workshops. These problems and risk should be fixed before an iteration of the workshops. The main reason these problems and risks were not solved during the workshops was that additional information was needed from persons not being able to participate.

The result of the layout evaluation can be related to the roles of the participants at the workshops and how the production flow is presented and understood. The initial plan was to use a structured way of describing the production and material flow, as in Lindskog et al. (2016). However, this was not available during the workshops, causing possible mistakes and lack of information. In a future implementation of the layout evaluation workshops method, it should be ensured that such information is available before the workshops are carried out. It is recommended to use methods like value stream mapping, or similar, to have a clear understanding of the design of the value stream, and it can also be very beneficial to use discrete event simulation (DES) to get data about for example work in progress and buffer sizes.

Presenting a realistic 3D layout model using an HMD can bring an awe effect to users through the novelty and realism of experiencing the model in this medium. This awe effect can lead to users being less critical and missing details. An example from the industrial study was a missing fence, only noticed while viewing the model using the HMD, which gave a false perception of available space. The users' impression might have been different if the fence had been in place. The fence was also missing in the 2D CAD layout, however, it was not noticed there as it was noticed for the first time during the third workshop.

A drawback of presenting the layout using both projector screen and an HMD was that it required two separated models. These models were not synchronized, any changes done in one was manually replicated in the other. A better solution would be using the same model viewed using both projector screen and HMD instead of two separate models, although no such solution existed at the time of the industrial study as far as the authors are aware.

As a next step in ensuring that the realistic 3D layout model is accurate and true to the future production system is to include results from a simulation of the system. By using simulation to analyze the flow of products and material, required space and capacity can be made visible in the model. Uncertainties discussed during the workshops, such as the number of pallets needed or the capacity of the overhead cranes, could be analyzed and decided upon based on facts rather than assumptions. The next step in developing this workshop method is to include DES in the creation of the realistic 3D layout models, which is planned for an upcoming study. By combining DES with the models, several scenarios can be tested and evaluated during the workshops and the simulation can be visually accurate. The potential benefits and drawbacks of using an HMD in the previously mentioned combination would also need to be researched.

By using the approach presented in the industrial study, several issues with the planned layout was identified and fixed while creating the realistic 3D layout model. Realizing and solving these issues early on allows for a more accurate simulation of the future production system, yielding better results and a better basis for decisions.

6 CONCLUSION

The industrial study shows that a realistic 3D layout model can be used to enable fruitful discussions around an accurate model instead of each person's mental model during layout planning. The industrial study shows potential in evaluating layouts and their corresponding accuracy in immersive VR, where involvement comes naturally as little to no interpretation is needed to understand what is being discussed or evaluated. Working systematically with realistic 3D layout models allows for quick implementation and accurate evaluation of changes, however, it must be done at the right time and by involving the right people to achieve the best possible results.

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