Proceedings of the 2020 Winter Simulation Conference
K.-H. Bae, B. Feng, S. Kim, S. Lazarova-Molnar, Z. Zheng, T. Roeder, and R. Thiesing, eds.

SIMULATION IN HYBRID DIGITAL TWINS FOR FACTORY LAYOUT PLANNING

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ABSTRACT

As manufacturing companies make changes to their production system, changes to the factory layout usually follow. The layout of a factory considers the positioning of all elements in the production system, and can contribute to the overall efficiency of operations and the work environment. The process of planning factory layouts affects both installation of the changes and operation of the production system, so the effects can be utilized for a long period of time. By combining 3D laser scanning, Virtual Reality, CAD models, and simulation modelling in a hybrid digital twin, this planning process can be noticeably improved yielding benefits in all phases. This is exemplified via a novel longitudinal industrial study using participant observation to gather data. Findings from the study show that the factory layout planning process can be innovated by smart use of modern digital technologies, resulting in better solution and more informed decisions with reduced risk.

1 INTRODUCTION

Due to increased globalization and technological advancements among other factors, manufacturing companies across the world must increase their productivity and reduce any waste in order to stay competitive. The productivity of a manufacturing companies' production system is affected by a multitude of factors, for example internal logistic flow, scheduling, human operators, and the layout of all the elements inside the factory. Whenever changes are performed to a production system, a need to redesign the existing production system or design a completely new one often follows (Jung et al. 2017). Such design or redesign is often done in a project structure, which considers many different problems and factors (Schuh et al. 2011). A part of this process is the planning of facility layout, which considers where different resources of the production system, such as workstations and machines, should be positioned (Heragu 2008). The problem of positioning of these production system elements is called the facility layout problem and can, if handled well, contribute to the overall efficiency of operations leading to a reduction of total operation costs by 2-15% (Tompkins et al. 2010). The savings are realized first in the operation phase, after the layout has been planned and installed, hence the factory layout planning affects both installation and operation. Factory layout planning is most often performed in the brownfield setting, i.e. planning in an existing factory in an area that already is utilized or previously has been utilized. For example, a company investing in a new milling machine would likely like to fit the new machine in the existing facility, rather than expand or build a completely new facility. In brownfield factory layout planning settings, the availability and quality of data can vary, giving every project unique circumstances and different challenges to consider.

The aim of this paper is to help companies utilize modern technological solutions in their layout planning process, and innovating it, in order to find clever solutions and minimize the risk for problems in the installation and operation phases. This is achieved by investigating the usefulness of a hybrid digital twin model of the factory, combining 3D laser scanning, Virtual Reality, and 3D CAD in an industrial study spanning all the way from planning to operation. The remainder of this paper is structured as follows; Chapter 2 presents the theoretical framework that the work performed is based on, Chapter 3 presents the methodology applied, Chapter 4 presents the industrial study itself along with the results, Chapter 5 presents a discussion of relevant topics, and Chapter 6 summarizes and concludes the findings from the study.

2 THEORETICAL FRAMEWORK

This chapter presents the relevant theoretical framework upon which this work is based. It covers production innovation, virtual factory, digital twins, factory layout planning, 3D laser scanning, and virtual reality.

2.1 Virtual Factory

A virtual factory can be defined as a computer-based model which represents the real production system, and can be used to perform engineering activities (Lee and Noh 1997). A virtual factory can be used to recognize errors in planning prior to the implementation phase, leading to fewer mistakes in the end (Bracht and Masurat 2005). The most common reason for unsuccessful simulation studies is miscommunication 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.

2.2 Digital Twins

The digital twin concept has met various interpretations, and there seems to be no clear definition agreed upon by both academia and industry of what it means (Tao and Qi 2019). As the most basic description of a digital twin, many authors agree that it contains a physical part, a virtual part and a connection between them (Zheng et al. 2018; Tao and Zhang 2017). Often, a digital twin is a highly advanced model that in real-time replicates a real system and allows for extremely accurate and advanced calculations to support decision making. However it can be argued that the update frequency that is relevant depends on purpose of twin model. For the purpose of manufacturing layout planning, the time perspective indicate the real-time update is not needed for digital twins. Nevertheless, the concept of hybrid digital twin is used in this paper instead. A hybrid digital twin (Nåfors et al. 2020) is an adaptation of the digital twin idea but consisting of a mix of for example, as in the industrial study in this paper, 3D laser scanned data and CAD models in a simulation model. The 3D laser scanned data gives highly accurate neutral data of the measure and; the CAD models can supplement data where there is no more accurate alternative available, such as when purchasing a new machine for a production system; simulation model to give the hybrid digital twin life and some intelligence in the form of the ability of acting on its own.

2.3 Production Innovation

Innovation can defined as “the implementation of a new or significantly improved product (good or service), process, marketing method or organizational method” (OECD 2005). While there are several definitions for innovation, it is important to note that an innovation doesn’t have to be new and novel to the entire world – only to the context of which it is applied. Working in groups may be considered an organizational innovation in one area, while it has been used for many decades in other areas. Innovations can differ in size and effect, but they are always noticeable. Linton (2009) presents different terms used to describe innovation in previous research. These include: Administrative, Architectural, Breakthrough, Continuous, Discontinuous, Incremental, Product, Process, Radical, and Technical. The article also discusses fundamental and social innovations, and how they require each other in order to become impactful. Boer, Boer & During (2001) state “Technological innovation, i.e. the in-house development of new process technology, or the adoption and implementation of technology developed elsewhere, usually also requires organizational adaptation, but need not be linked to new product or new market development".

The types of innovation most closely related to the context of this paper is organizational method innovation, as the planning process needs to be efficient and consider many stakeholders in order to produce a sound solution while considered risks. With the coming of the next industrial revolution, Industry 4.0, radical technical innovation is at the doorstep which makes right now a great time to make a push for innovative ideas and solutions in the industrial area. Technical innovation in other areas regarding for example the generation and usability of data might be extremely useful for the context of brownfield layout planning with the implementation of organizational method innovation – a new way of thinking and using the new opportunities. Some examples that could be useful are Virtual Reality, Augmented Reality, Mixed Reality, Laser Scanning, 3D printing, and Big Data Analytics just to name a few.

Garner IT Glossary (2019) defines digitalization as "The use of digital technologies to change a business model and provide new revenue and value-producing opportunities; it is the process of moving to a digital business". This definition of digitalization is related to that of production innovation used in this paper, as it focuses on finding valuable use of digital technologies to provide valuable opportunities.

2.4 Factory Layout Planning

The task of planning the layout in a factory can be divided into two separate categories, optimization and design problems (Heragu 2008). The optimization type of problems are more mathematical in nature, and in turn can offer solutions to optimize theoretical layouts. The other type of problem, design problems, are more subjective in nature. Another perspective on layout planning procedures are to divide them into either construction layout methods (Tompkins et al. 1996), i.e. planning empty factories in greenfield settings, and improvement procedures, i.e. making changed layouts based on existing production systems in brownfield settings. Layout planning execution can be separated into three types with different levels of detail considered (Schenk et al. 2010):

1. Systemization of the planning principles in accordance with the planning activities and project definition.
2. Implementation of ideal layout planning in accordance with the project development planning activities.
3. Implementation of real layout planning in accordance with the project development planning activities taking real restrictions into account.

Each level of execution corresponds to a different type of layout; 1 - ideal layout, 2 - approximate layout, and 3 - real layout (Schenk et al. 2010). The ideal layout represents the best possible solution, created completely without constraints or restrictions. The approximate layout considers building parameters in particular, while the real layout considers all restrictions and is adapted from the ideal layout by a multitude of restrictions, requirements, and various factors (Schenk et al. 2010). The real layout is the one most likely to function as expected in real factory settings, as it considers many different factors, requirements, and restrictions. A summary of the different approaches and their correlation to ideal greenfield or real brownfield scenarios is presented in Table 1.

Table 1: Different approaches and their correlation to real or ideal factories

	Ideal/greenfield scenario	Real/brownfield scenario	Reference
Problem	Optimization	Design	Heragu (2008)
Procedure	Construction layout methods	Improvement procedures	Tompkins et al. (1996)
Layout	Ideal	Real	Schenk et al. (2010)

Previous research has focused on the optimization type of problems, often called the facility layout problem, where multiple algorithms have been developed over the years as summarized by Drira et al. (2007) and several other literature surveys and reviews more recently (for example Hosseini-Nasab et al. 2017; Ahmadi et al. 2017). While there is much research on the optimization problem, there is little help for factory layout planning considering all the different considerations, compromises, and challenges faced in industries. For practical help with this, the Systematic Layout Planning method provides hands-on systematic procedures, methods, and tools to use when planning layouts (Muther 1974). It has however not been completely modernized and adapted to today's factories, which are becoming more and more digitalized and connected.

2.5 3D Laser Scanning

3D laser scanning is a technology that stems from the field of terrain mapping among others and can be applied to gather un-biased spatial data in a non-contact way (Gregor et al. 2009). 3D laser scanners are mainly separated into either time-of-flight scanners or phase-shift scanners. Time-of-flight scanners are suitable for outdoor use, such as construction sites, as they capture data from objects more than 100 meters away, while phase-shift scanners are more suited for indoor use, such as most production systems, as they normally capture data from closer objects with a higher resolution (Dassot et al. 2011). 3D laser scanners operate by emitting laser beams that reflects on a surface in the direction of measurement, and by calculating the distance the beam has travelled combined with the direction it was sent, a measurement point in 3D space can be gathered (Klein et al. 2012). The type of scanners commonly used in production system scanning often have a 360-degree field of view in the horizontal axis and around 300-320 degrees in the vertical axis as illustrated in Figure 1 (Dassot et al. 2011). By controlling the direction of the measurement in a systematic manner, millions of measurement points in 3D space can be combined to generate a both detailed and neutral spatial representation of the scanned environment. Using the built-in camera, the measurements can also be complemented with RGB data that gives enhanced visual properties. The systematic manner of data capture such as this is known as a scan.

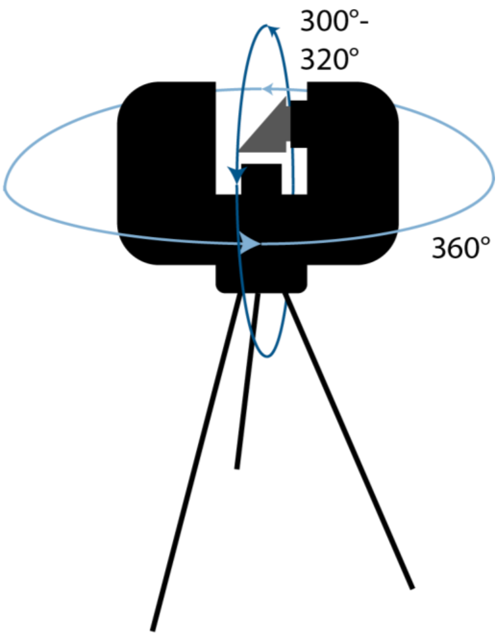

Figure 1: Visualization of a 3D laser scanner and its field of view.

2.6 Virtual Reality

Virtual reality (VR) can be defined as a computer-generated simulation of a three-dimensional environment that can be interacted with in a seemingly real way by a person using special equipment, such as a helmet with a screen inside or gloves fitted with sensors. It has been developed since the first system that presented stereoscopic 3D views while tracking head movement in 1968 (Sutherland, 1968). Two important characteristics are used to differentiate VR systems; immersion, the user's sensation that the virtual environment is real, and presence, the user's sensation of being part of the virtual environment (Liebert 2001). Immersion can be affected by for example feedback lag time, field of view, spatial audio, tactile feedback, and force feedback (Lu et al. 1999), while presence can be affected by for example a virtual representation of the user. VR systems can be classified based on their level of immersion, ranging from non-immersive VR, for example desktop systems, to fully immersive VR systems making use of a head-mounted display (Korves and Loftus 1999).

In the field of production, VR has shown potential as a collaborative tool for exchanging data and information, which can facilitate both an improved understanding as well as improved decision-making via immersive experience and visualization (Choi et al. 2015). Immersive VR systems has been used in collaborative factory planning scenarios where multiple users viewpoints are visualized with positive results (Wiendahl et al. 2003)

3 METHODOLOGY

The methodology section covers the research design and data collection methods used in this paper, action research (Bryman and Bell 2007; Oosthuizen 2002) and participant observation (Mack et al. 2005; Kawulich 2005). The choice of methodology is further discussed in the discussion chapter.

3.1 Action research

Action research is an approach where the researcher collaborates with a client in order to both diagnose a problem as well as develop a solution to it (Bryman and Bell 2007). Due to the collaborative problem-identifying nature, it is well suited for industrial scenarios where problems might be ill defined. A typical approach in action research is cyclical, where the steps plan, action, results, and reflection are performed in order as presented in Figure 2 starting with the plan phase. This approach builds knowledge into the next study each cycle, allowing an improved understanding to be gained over time. The industrial study in this paper builds on several previous studies, one of which is presented in Nåfors et al. (2017). Action research also allows the researched to apply different data collection methods in pragmatic, and allows the researcher to be a part of the studied group differently each cycle (Oosthuizen 2002).

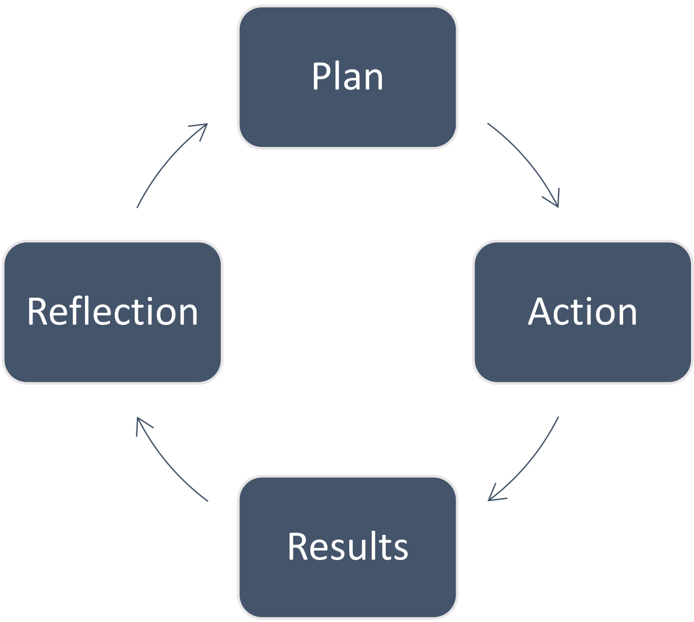

Figure 2: The cycle of action research based on (Oosthuizen 2002).

3.2 Participant observation

A researcher applying participant observation, a qualitative data collecting method, can gain insight into a specific context, behavior, and relationship (Mack et al. 2005). Participant observation can be classified into four different levels of observations (Kawulich 2005);

1. Complete observer, where the studied group does not know of the researcher who is hidden from the group.

2. Observer-as-participant, where the researcher is known by the group and has minor participation with the group but focuses on data collection.
3. Participant-as-observer, where the researcher is known by the group and interacts extensively with it.
4. Full participant, where the researcher is a member of the group.

This research applied the full participant role, as the researcher also had the expert knowledge and skills required to perform the tasks.

4 INDUSTRIAL STUDY

This section provides information regarding the case and research setup, as well as the results.

4.1 Case description

Plastal Industri AB, henceforth called Plastal, a manufacturing company producing plastic parts for the automotive industry, often re-design their layout in their manufacturing plant in Gothenburg, Sweden. As new product models and face-lifts are designed by the automotive industry annually, the suppliers must adapt their production system. For Plastal's plant in Gothenburg this means investing in new machines and changing the flow to adapt changes in product design and volume. As production cannot be stopped while the supplied companies require products, these changes must be implemented as a whole during the industrial vacation window of roughly a month, or incrementally during weekends. During this time period, old machines must be phased out, new machines must be installed, and all the parts of the new layout must be trimmed in and ready for full production the next work day. The process of planning the new factory layout would normally be performed by a team of engineers in 2D CAD based on a drawing of the facility combined with drawings of the elements to be installed during the installation period. In some cases, simple 3D CAD models would also be used.

The specific part of the factory where this industrial study took place was specified for punching plastic bumpers. The area was divided in two parts, one for front bumpers and one for rear bumpers. Both areas had a mix of robots, machines, inspection, and human tasks. The floor areas were roughly 700 m^2 for the each of the bumper production areas, and an area related to the two with forklift traffic and general use of roughly 1000 m^2 were also relevant for this study.

The work related to layout planning in this industrial study consisted of three main steps;

1. Data gathering, which consisted of 3D laser scanning and subsequent data processing, collection of both 2D and 3D CAD models and data regarding forklift and operator movements in the area.
2. Model building, where the data gathered in the previous step was combined steps in order to produce the hybrid digital twin for both desktop and VR.
3. Workshops, where the models were displayed for various stakeholders.

4.2 Results

The results from the industrial study are divided into four parts; one for each step of the work related to layout planning, and one for the feedback gathered at the end of the longitudinal study after the layout changes had been implemented and operations had been running for over six months.

4.2.1 Data gathering

The 3D laser scanning performed in this industrial study took place on a Saturday when the factory was almost empty of employees and no normal production was being performed in order to simplify the scanning procedure. In total, the scanning took around 10 hours to complete and consisted of over 60 scan positions. After processing, the resulting complete point cloud of both areas consisted of approximately 200 million points. The part of this resulting point cloud that represented the rear bumper production area is showed in Figure 3

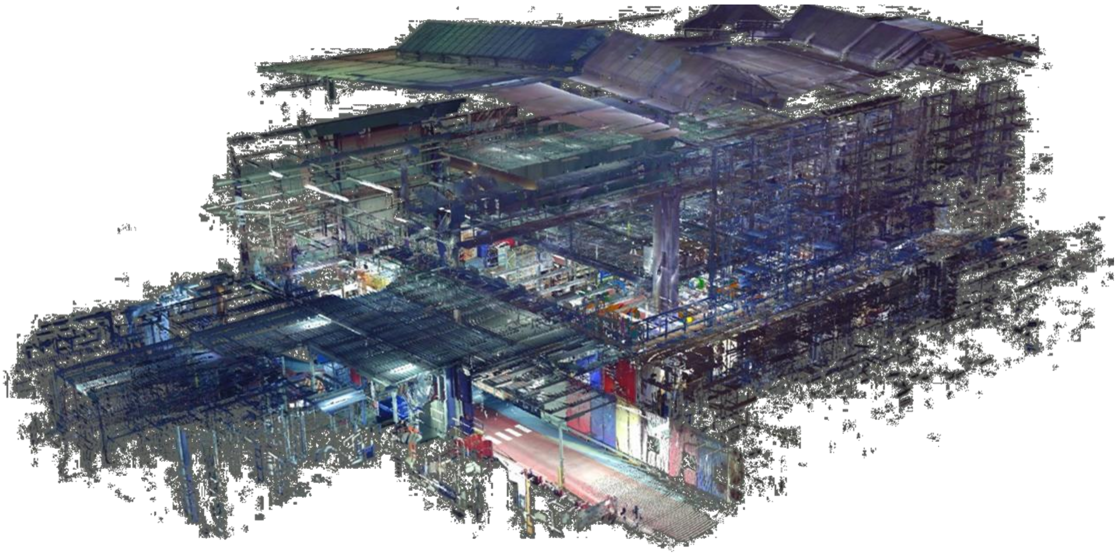

Figure 3: Result of 3D laser scanning the relevant part of the factory.

In addition to the point cloud data, a 2D CAD drawing of the future layout was also gathered along with 3D CAD models of the products that where produced in the area and simplified models of the new machines.

4.2.2 Model Building

The model building step first aligning the point cloud to the 2D CAD drawing, in this case aligning two sides, then segmenting the point cloud data to smaller pieces that could be repositioned individually, such as a pallet, a shelf, or an assembly station. These pieces were then aligned to the 2D CAD drawing of the future layout. The resulting model was sent digitally to the key contact at Plastal, who viewed it and sent further requests for changes via e-mail by taking screenshots at appropriate angles and marking and explaining changes to be made. This process was iterated until there were no more changes requested, at which point the next step started. Figure 4 shows a part of the resulting model, which contained both point cloud data and 3D CAD data. The time to build the model is hard to measure, but estimated to around three working days for one person, heavily dependent on experience.

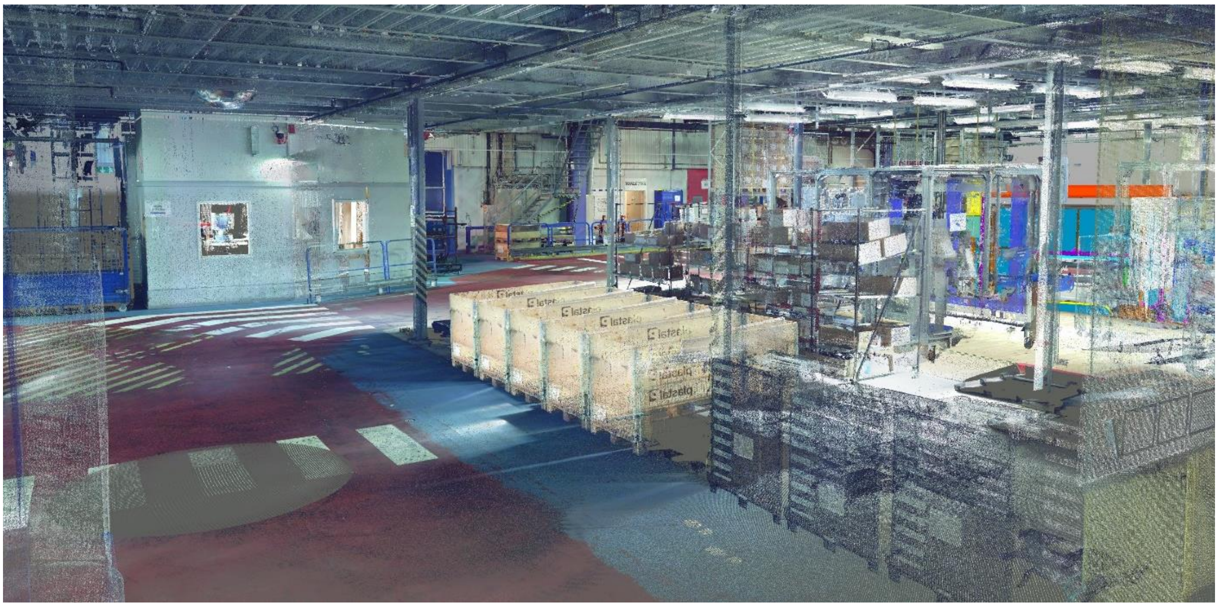

Figure 4: A part of the built model of the rear bumper production area, showing a mix of point cloud data and 3D CAD data (the colorful machines to the right).

4.2.3 Workshops

The final model of the layout, which included static planned changes, simulated employees moving around both with and without products as they would be expected to, as well as simulated forklift traffic adjacent to the production area, was displayed using VR during several workshops both with and without researcher's presence. The model was displayed for both engineers and operators, who were able to explore the model in actual scale in immersive VR using an HTC Vive setup. An example of what the VR user would see inside the headset is shown in Figure 5.

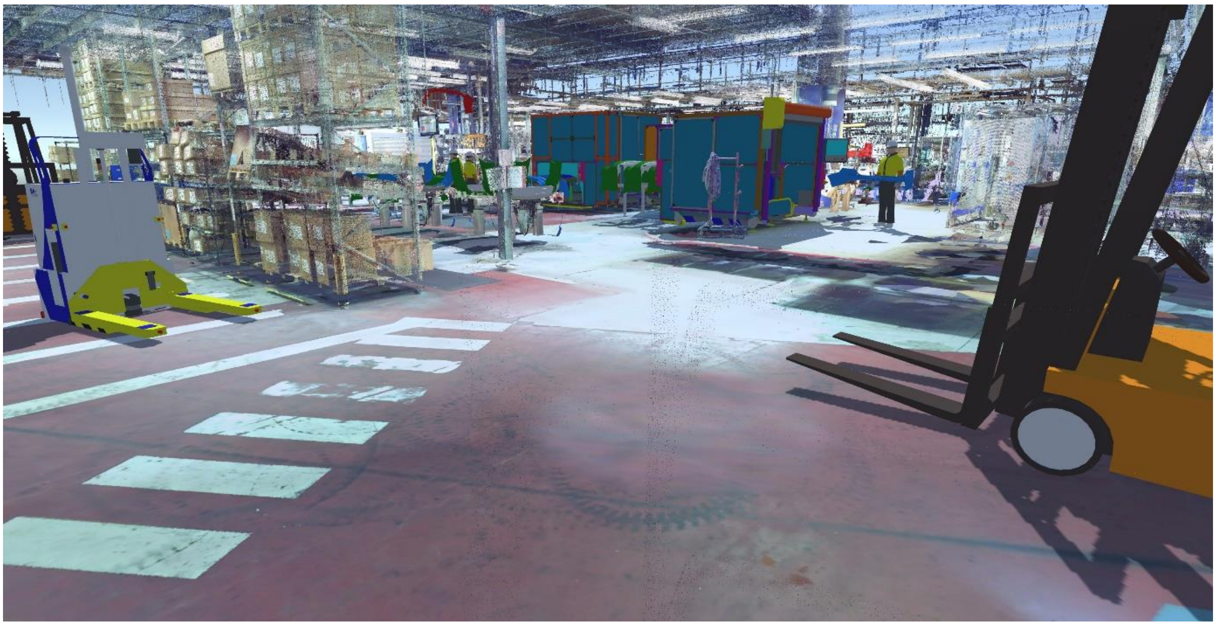

Figure 5: An example of the final model as it would appear when visualized in immersive VR. Forklifts and operators move and perform simulated tasks in the virtual model, consisting of both point cloud and 3D CAD data.

4.2.4 Experiences

The experiences from the industrial study can be divided into three parts, in accordance to the three phases of a factory layout; the planning phase where the layout is prepared, the installation phase where the changes are installed, and the operation phase where the layout is being utilized. These experiences are summarized for each phase in the following sections.

4.2.4.1 Planning Phase

During the planning phase, the following effects were identified:

- Plastal experienced that the 3D environment offered by the hybrid digital twin model was far more realistic than the 2D CAD drawings used previously. The cross-functional team that was working with the layout for the related production area in the factory stated that the feedback received for proposals made was far better than usual, stating that this was due to the feedback-giving employees (the operators who would be working in the area) simply having a better understanding of the proposals they were being presented.
- The point cloud data used in the hybrid digital twin model was considered more precise and trustworthy than the 2D CAD drawings otherwise used in the layout planning process, yielding both more quantity and quality of information thus making it easier to understand and avoid mistakes.

- The operators from the affected area were able to get a feeling for the planned layout via the VR model and could comment and give valuable improvement suggestions otherwise usually obtainable after installation already in the planning phase.
- In the VR model, is was also possible for the operators to evaluate visibility of the forklift traffic from a safety point of view as that traffic was implemented via simulation logic. The moved positioning of layout elements changed the visibility in the area, so a rough safety assessment was possible to make.
- The movement of ungainly equipment could be evaluated in the hybrid digital twin model by moving it trough gates, narrow passages and areas where the roof height was lower. As the point cloud data gathered from the 3D scanning gave accurate representations of the facility in 3D space, information that was unavailable in the 2D CAD drawing was present and aided in this matter.
- The hybrid digital twin model was highly appreciated by Plastal as detailed measurements and installation planning could be done remotely in high detail, saving the engineers from multiple control measurements and potentially impacting operations.

4.2.4.2 Installation Phase

During the installation of the layout, Plastal noticed several effects of using the hybrid digital twin in their layout planning process:

- As the layout was being installed, there were much fewer re-plans needed than normal.
- The hybrid digital twin model was used in communication with involved parties to explain what should be done and how, resulting in simpler and more effective means of communication.
- The hybrid digital twin model was also used to give contractors that prepared electrics, improved the flooring, and performed the actual moving of equipment to give them a better understanding.

As an end-effect of these, the installation process went much smoother than usual as there were fewer errors in general.

4.2.4.3 Operation Phase

The operation phase of the layout, when it is serving its purpose, started during 2019 and is ongoing as of this moment. Multiple effects of the changed way of working has been experienced:

- The operational personnel's understanding of the proposed changes and their involvement in the change process increased their engagement and anchoring the proposal throughout the organization, leading to a simpler implementation.
- The start-up phase of the layout went smoother than usual, likely due to a stronger evaluation of the layout and a more thorough planning due to the utilization of an accurate 3D environment both viewed on a screen and experienced in immersive VR.

The entire process was considered so beneficial that Plastal now are working on implementing it further throughout the organization as another test case has been setup where the engineers in Sweden are planning changes for another one of Plastal's factories located in Belgium using this way of working. This result points to strongly experienced benefits of using this way of working. Discussion

4.3 Innovation

Innovation as a topic is rather well-researched, but it seems to be a difficult topic to reach a consensus on as it differs between each genre of innovation. When it comes to layout planning, the word innovation seems completely novel. Perhaps that is one of the reasons why the process often is overlooked or not that interesting for companies. Another reason could be that it rarely generates any direct profits, but every error or mistake is costly to solve. Difficult to evaluate the advantage of using digital twin methods since avoided mistakes are not always apparent. Adjacent areas in manufacturing industries, such as product development, seems much more likely to be innovative and try new things. Some companies are very keen to explore and try new things in their production development organization as well, while other companies are less keen on doing so. It may be required sooner or later for larger companies to be bold and innovative in their production development organization in order to stay competitive. The worst case is that they learn something along the way and scrap the result.

Organizational method change does not come easy. Since the contextual layout planning processes involve people, a technical innovation that helps people share their implicit knowledge to make a better plan is one of the things that could be extremely useful. Another technical innovation could be having neutral and true data, as opposed to the manually made CAD-drawings of the facilities and components that are widely used today. How to implement and make good use of the technical innovations requires some organizational method change, and the combination of all these will lead to production innovation in the end.

4.4 Sustainability

This case study shows how innovation in the production layout planning process can give large contributions to sustainability. First of all, using 3D laser scanning gives a highly accurate and neutral 3D replica of the scan object, giving less reason for the project members to travel to factories in general. This not only saves money by better solutions and fewer mistakes during the installation phase, it also reduces the company's ecological impact as fewer flights are required. With the outbreak of the recent pandemic, reducing the need to travel has been further emphasized as engineers may be expected to work differently not only for environmental reasons. Fewer days away also lowers the expectations on the engineers to be away from their families and friends, as they can perform higher quality work from their normal workplace. The way this study used the combined model in a workshop setting allowed many people to see and get a feeling for how the future production system will look like, allowing them to give valuable feedback to those in charge of development at an early stage where changes are easier to implement and come with less of an impact. It also constitutes as a social event, giving employees the chance to speak up, as it is much easier to understand a realistic model than a simplified abstract one. This seems to be appreciated in Swedish companies at least, where workers often appreciate being involved in what is happening.

4.5 Research

The solutions tested in this case were those the researchers were the most acquainted with, 3D laser scanning, VR, and production flow simulation. There are however many more solutions that could be tested, for example Augmented Reality or scale models. In the future, these alternative solutions used in these case studies could also come from other fields such as the field of safety, where layout has a different focus, or that of hospital layout development, where humans and seasonal changes have a very large effect.

Throughout the industrial study, communication between the researcher and industrial stakeholder was a constant element, as part of the intention of the industrial study was to inspire change. By keeping communications honest and thorough, the industrial stakeholder is now able to implement parts of the method without the researcher assistance and is currently doing so while simultaneously working to spread this new way of working throughout the company.

A difficult part for research in layout planning is the longevity. It takes time to plan and execute layout changes, the lead time on ordering machines can in some cases be years, and the total time from initial change idea to a fully up and running layout can be several years. For this reason, very few studies in the area consider the installation and operation phases. This paper is one of the first to do so in the field, and the first to do so with this method. This paper therefore presents a novel contribution to the field and inspire future researchers to broaden their scope beyond the planning phase.

4.6 Next Steps

A next step in the line of this research is to combine learnings from multiple longitudinal studies in general guidelines for how the manufacturing industry can seize the value from working with hybrid digital twin models. In addition to the guidelines, further work on the software side is required if such work is to become more utilized in companies, specifically regarding the ability to use the same source of data without converting. As it was during this study, data was converted and managed through multiple different software from different suppliers to reach a satisfactory end result.

5 CONCLUSIONS

This paper has shown how the process of brownfield facility layout planning could be innovated via intelligent use of digital technologies, in this case 3D laser scanning, VR, and simulation models in order to find new value-producing opportunities and reduce several forms of waste. The implementation of these technologies in an industrial case study showed that companies can find better solutions, and evaluate their ideas in a new way, allowing them to take better and more informed decisions, reducing potential risks. This novel longitudinal study has shown that using a hybrid digital twin for factory layout planning can yield valuable feedback from stakeholders as the level of understanding of planned changes is increased. In turn, fewer mistakes and issues were noticed during installation and operation, resulting in a more effective factory layout planning project than usual. In order to fully reap the benefits of the new technologies, further investigations into how and when it should be used is in order before the process can become truly innovated, in order to generate guidelines for how hybrid digital twins should be used.

ACKNOWLEDGMENTS

The work was performed together with Plastal Industri AB and RISE AB in the DIP project (Digital tvilling för utveckling och installation av produktionssystem) mainly funded by PRODUKTION2030 through VINNOVA (Swedish Agency for Innovation Systems). The work presented in this paper has been carried out within the Production Area of Advance at Chalmers University of Technology. The support is most gratefully acknowledged.

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