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Towards the digital factory twin - design guide for creating a 3D factory model

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Abstract

Shorter product lifecycles are also leading to even shorter planning times for the development of production systems. In most companies, the restructuring is carried out within a few weeks during the annual holidays. Digital tools such as simulations or the digital twin are used to avoid delaying the restructuring during this time. However, the introduction of a 3D model of the factory is often the first point of failure for many companies. This article proposes a six-step process model that enables the transition from 2D to 3D design. The process model was evaluated in a research project.

Keywords: digital twin, virtual engineering (VE), factory planning, digital mock-up

1. Introduction

Shorter product lifecycles and increasing dynamics pose challenges for the product creation and production system planning. Due to the multiple changes in the factory environment, production systems need to be adapted or rebuilt more and more frequently (Löffler, 2011; Nåfors *et al.*, 2017). As the factory planning becomes increasingly complex, driven by shorter product lifecycles and the dynamic nature of modern manufacturing environments a more integrated and agile approach is required. This, in turn, highlights the critical role of interoperability and tool integration in supporting the entire factory lifecycle (Tolio *et al.*, 2013). Recent industrial trends have increasingly focused on increased digitalisation to improve competitiveness in such a market environment (Schönsleben *et al.*, 2017). That's why virtual representations of the factory are often used to support factory planning (Stark, 2022).
For many companies, the challenge is that production adjustments cannot be carried out during ongoing operations and therefore only a few weeks are available for changes during the annual shutdown. Error prevention in the form of a virtual check is essential to eliminate errors in advance and ensure that everything runs smoothly (Lindskog *et al.*, 2013; Debevec *et al.*, 2020). The virtual 3D-model can also be used as the basis for a digital twin of the factory. In this way, the planning of the production system can be further optimised (Dai *et al.*, 2020).
Especially mid-sized organisations face the challenge of creating the basis for a Digital Factory Twin, a 3D model of the factory. However, the creation of a 3D model of your factory is a real challenge for mid-size companies. A particular focus is the conversion of existing 2D factory planning into 3D factory planning. There is also the question of how to organise collaboration on an overall model.
This paper addresses this challenge and presents a process model for creating a 3D model of the factory. The process model is intended as a tool for factory planners to migrate existing 2D design to 3D design, thereby laying the foundation for the implementation of a digital factory twin. The paper is structured as follows: This paper begins by defining terms such as digital factory twin and describes the benefits

and challenges of digital factory design (Chapter 2). Next, it examines the state of the art and describes methods that support digital factory design and enable 3D design (Chapter 3). As existing methods are inadequate, this paper develops a methodology. A research design is used to ensure that the development of the methodology is comprehensible and methodologically sound (see Chapter 4). The process model (Chapter 5) for creating a 3D model and the evaluation of the methodology (Chapter 6) is then presented. Finally, the results are discussed and the need for further research is described (Chapter 7).

2. Problem analysis

This chapter begins with a delineation of existing definitions in the context of the digital twin. It then discusses the potential benefits and existing challenges of 3D-based factory design.

2.1. Definition of terms

There are several terms related to the digital representation of the factory that are used in a similar context but have certain differences. The Digital Factory (DF) represents the basic concept of improving the optimisation and simulation of production processes and the collaboration between stakeholders in factory operations planning (Sacco et al., 2007). The Digital Mock-Up (DMU) is a collection of 3D models that digitally represent a physical entity (Stark, 2022). The Virtual Factory (VF) extends the DMU to represent the individual products and networks of companies throughout the factory life cycle (Sacco et al., 2010). The Digital Factory Twin (DFT) complements the VF with a connection between the entities of the real factory and the virtual factory via synchronisation of data (Grieves, 2015). DMUs thus form the basis for the VF and the DFT. The term DFT is defined differently in the literature. There are studies that have analysed the distinction between the term DFT and similar terms, for example as part of an SLR (Cieply et al., 2023). The discussion on the differentiation from other terms primarily centres on the extent to which data is exchanged between the physical and cyber worlds. In a digital model, there is a manual connection between the two worlds. The digital shadow has an automatic link between the physical and cyber worlds, but a manual link between the cyber and physical worlds. In comparison, the digital twin has an automatic link in both directions (Cieply et al., 2023).

2.2. Benefits of data-driven factory planning

The factory planning with a DF has many advantages over the conventional method. Virtual production tools offer reduced development time, supported product and process development through simulation, resource efficiency, and improved product quality (Schuh et al., 2011).With the help of a DMU, interactions between 3D models can already be investigated in the digital planning stage (Stark, 2022). In addition, data can be extracted from the VF that make it possible to optimise the energy supply in order to conserve resources and save energy costs (Stoffels et al., 2013). DMUs offer many benefits over 2D representations of factories. The DMU of the factory helps to extract additional information, since, for example, collisions or the space requirements of machines are better represented or only become visible in the 3D view (Lindskog et al., 2013). The 3D representation of the factory allows people to become familiar with the model more quickly. Thus, even employees or stakeholders who are not directly involved in factory planning can use the model to identify potential problems and risks (Lindskog et al., 2013; Nåfors et al., 2017; Nåfors and Johansson, 2021). The concurrent engineering of complex models has also been made more achievable through recent progress in modeling and simulation tools, DFT technology, and the interactive and collaborative capabilities inherent in immersive virtual reality (VR) (Cohen et al., 2019). Multi-user VR technology also enables collaboration between different stakeholders without physical boundaries (Yildiz et al., 2020).

Practical applications have demonstrated the usefulness of a VF in improving the organisation and execution of the schedule. It reduces production downtime by identifying problems before they occur, improves production forecasting, and enhances overall production process planning. It also increases operator productivity and eliminates idle time and congestion (Debevec et al., 2020).

DFT will be crucial to the future of manufacturing (Rosen et al., 2015). The current challenge in implementing DFT is that the technical solutions require, for example, high initial investments and data integration with corresponding standardisation of factory data. Another challenge is the maintenance of

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simulation models, as their creation is often very resource- and time-intensive. It emphasises the need for dynamic simulation of physical systems and offers the possibility of using virtual models to actively control and adapt physical entities to changes in the environment. By creating a 3D model of the factory, production processes can be monitored, optimised and adapted in real time (Yildiz et al., 2020).

2.3. Challenges of data-driven factory planning

Factory design faces several challenges due to today's changing business environment. Shorter product lifecycles require production systems to be adapted repeatedly (Nåfors et al., 2017; Löffler, 2011). The overlapping life cycles of products, production technologies and production equipment also lead to a more complex factory planning process (Dér et al., 2022). As the factory planning becomes increasingly complex there is a need for digitalisation like a virtual representation of a factory to increase the competitiveness (Schönsleben et al., 2017; Stark, 2022). Simultaneously, within the realm of the manufacturing industry, a growing need to adeptly manage the co-evolution of products, processes, and factories emerges. This involves the reduction of ramp-up and design times and optimizing the reconfiguration and evaluation of manufacturing facilities. Seamless integration and simultaneous generation of product, process and factory models is the key challenge (Azevedo and Almeida, 2011). Another challenge in factory planning is coordination with product development (Disselkamp et al., 2023). Factory planning projects also involve a large number of different stakeholders, which results in an increased organisational effort due to the need for effective coordination between them (Oehme et al., 2013). The exchange between stakeholders generates a lot of information that needs to be captured without loss, as it is the basis for important decisions. To ensure this and enable collaboration, project participants should be integrated into the project as early as possible (Kerkenberg, 2016). These mutual information flows lead to an increase in complexity in factory planning and to rising coordination costs (Kampker et al., 2012). In addition, data integrity, data timeliness and a holistic view of all factory planning components are critical challenges for fast and effective planning (Loos et al., 2012). To surmount these coordination challenges, stakeholders can collaboratively engage within a centralized 3D model of the factory. However, practical implementation often deviates from this ideal, as stakeholders tend to join the project at different times, occasionally necessitating recourse to a 2D factory plan (Kampker et al., 2012). A plausible rationale for this divergence may stem from the incomplete progression of the transformation towards a DF. According to a survey of 700 companies from 2022, 64 % of the companies are still at the beginning of this transformation (Geissbauer et al., 2022). Using 2D applications for layout modelling in factory planning can lead to data inaccuracies, communication challenges, and discrepancies between planned and actual layouts. These issues can result in errors during implementation and hinder the accuracy of simulation models, potentially leading to unexpected results (Nåfors et al., 2017).

The increasing complexity of factory planning, combined with current environmental influences, requires innovative approaches to address these challenges. One such approach could be the introduction of a factory DMU that improves collaboration, coordination, and information sharing, while laying the foundation for a comprehensive digital transformation in factory planning.

3. State of the art

Given the challenges and issues identified in factory design that underline the need for a DMU, it is crucial to take a closer look at the current state of the art and existing approaches in this field. This section provides a comprehensive overview of the requirements for designing a DMU and the available methodologies that have been developed to address these challenges.

There are several requirements for the design of a DMU. The DMU needs to be visualised as accurately as possible. In addition, all the objects required for the design should be available and each element should have a detailed description for the calculation of various attributes. Furthermore, the modelling system should provide flexible capabilities to modify the DMU to accommodate changes in machinery, layouts and other facilities (Zafor et al., 2015).

The design of a factory DMU is often not explicitly addressed in the literature. Building a DMU tends to play a minor role in creating a VF (Choi et al., 2015; A. Dalstam et al., 2018; Yildiz et al., 2020),

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although it is a crucial foundation (Choi et al., 2015; Yildiz et al., 2020). Stark focuses mainly on creating DMUs for products, and only touches on the role of the factory in passing (Stark, 2022).

Zafor et al. developed a method that divides the construction of the DMU into eight phases: 1) Planning, 2) Analysis of object factory, 3) Design and Preparation of digital factory, 4) 3D CAD modeling and Simulation modeling, 5) Digital factory construction, 6) Validation and Modification, 7) Application, 8) Effects Analysis & Extensions. However, these individual phases are not further explained (Zafor et al., 2015).

Another method for designing a 3D factory was developed by Salehi and Wang, based on the V-model, with the aim of improving the information quality of the digital factory. This approach is divided into three main phases - system design, system implementation and system integration - each with two sub-phases, including requirements analysis, laser scanning, data processing, process simulation, results analysis and integration into the digital factory (Salehi and Wang, 2018a). Based on these phases, a process was developed to create a 3D factory using 3D laser scanning and CAD modelling. The process consists of six steps: The first phase, **Project Preparation**, includes a requirements analysis and laser scanning strategy. By identifying requirements and preparing for laser scanning, the foundation is laid for the creation of a hybrid 3D model. The next phase, **point cloud model generation**, begins with the planning of the 3D laser scan. This includes defining the scan route, estimating the number of scans required, planning personnel, defining scanner parameters and positioning reference objects. During the actual scanning process, several scans are taken at different locations in the factory. Once the scanning process is complete, the scan data is transferred to a computer, registered, and aligned to create an overall data set. The results are checked, adjusted and the model is exported in various data formats. The processing of the scan data includes coordinate translation, which matches the origin of the point cloud model to the position on the Earth's surface in the DTX-Solutions© Virtual Globe. This is followed by coordinate transformation, which involves aligning the coordinate axes by rotating them around the x, y and z axes. The subsequent format conversion of the point cloud 3D model is aimed at adapting the data format to the specifications of the web-based renderer. In the third stage, the point cloud model is visualised in a web browser. In the fourth step, CAD models are integrated into the point cloud model. In the fifth step, the hybrid 3D model is placed on the virtual globe with the corresponding environment and environmental information. In the final step, the results are used in the context of digital factory planning (Salehi and Wang, 2018b).

The critical analysis of the literature presented shows that there are already existing process models for DMUs. However, these are inadequate, as Zafor et al. focus primarily on the geometric (re)modelling of factories using CAD. In addition, the process of designing a DMU is only described superficially.

In their work, Salehi and Wang focus mainly on scanning methods and their integration into the development process in the form of the V-model. However, it remains unclear how the process can be further processed and used for factory planning after the scanning process.

Therefore, this paper addresses these two shortcomings by considering both the scanning of parts of the factory and the post-processing and creation of individual 3D CAD models to create a complete 3D model of the factory that meets the performance requirements of the industry.

4. Research design

The research design of the thesis is divided into an ***overarching*** and a ***specific methodology***. Blessing and Chakrabarti's Design Research Methodology (DRM) is used as the ***overarching methodology*** (Blessing and Chakrabarti, 2009). Type 5 of design research projects were selected for this approach. The chapters of this paper are based on the DRM framework and the four stages. This chapter explains the research question. Chapters two and three provide a condensed overview of the initial descriptive study I. Chapter five relates to the prescriptive study, while chapter six describes the descriptive study II. This study investigates the following research question:

> ***How can small and medium-sized companies create a 3D model of the existing factory and enable long-term cross-departmental collaboration?***

The design guideline was developed as part of a research project using Österle and Otto's Consortium Research Methodology as a ***specific methodology*** (Österle and Otto, 2010). The Consortium Research Methodology is divided into four phases: *Analysis*, *Design*, *Evaluation* and *Dissemination*. In the *analysis phase*, the research objective is defined, and a consortium is formed. As part of this research, the consortium consists of a research institute and two user companies. A research plan was drawn up, including a literature and tool review. Different scanning methods and tools were then tested in the *design phase*. An initial modelling was then carried out in both companies, using different tools in each case. In the third phase, the *evaluation* was carried out as part of the design of a factory building. The results were then summarised in expert workshops. *Dissemination* began in the final *phase*. To this end, regular rounds of best practice exchange were set up in the companies. In addition, the results were published in professional magazines. This paper concludes the scientific exploitation. In addition, documentation has been provided for the maintenance of the 3D model by the companies and for the training of the employees within the organisation.

5. Proposed solution

This chapter presents the process model for creating 3D factory planning. The model is divided into six steps (Figure 1). The process model is aimed at planners who have previously planned in 2D and intend to migrate their existing process to 3D planning to create the basis for the digital factory twin. A key challenge of the approach is to reuse existing company data and models to reduce overall effort. For this reason, existing data such as product and machine data and equipment are reused.

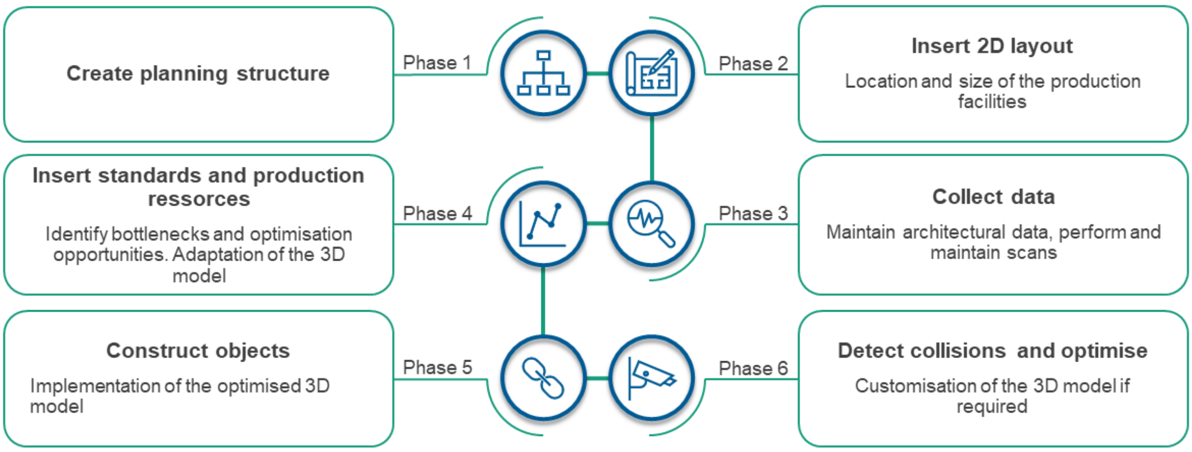

Figure 1. Procedure model for creating 3D factory planning

5.1. Phase 1 - Create planning structure

The first planning step serves to prepare the actual planning. A clear allocation of roles is essential for collaborative planning. This must be combined with appropriate role and rights management. Particular attention is devoted to access rights and the processing of the data created:

- **Access rights:** In many companies, data from product development is restrictively shielded from external and other areas of the company. This must also be considered in factory planning. In principle, data (in this case the 3D objects) can be assigned to departments or released individually. In large design teams, it is useful to allocate the data created to the relevant departments and the users to one or more departments, and to use this to control rights management.
- **Processing rights:** As in classic product development, a distinction must be made between development statuses. In the context of the methodology presented here, three statuses are proposed: *In Progress, Released, No longer in use*. In addition, a subdivision into write and read rights is useful to avoid unintentional changes in the development process.

Once the roles and rights management have been defined, the actual planning structure is created (Figure 2). The proposed structure of the 3D-model of the factory is divided into five hierarchical levels ("Structure" column in Figure 2). This enables a graduated modelling depth from the plant and building structure to individual assembly lines or shelfs ("Comment" column in Figure 2). For example, a crane system is created on the third hierarchy level below the line. A work centre is created as a sub-element of planning on the fourth level. The division into hierarchy levels offers the option of linking rights

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management to the levels. This also offers performance advantages, as only individual parts of the factory floor can be loaded, thus reducing the size of the overall model.
A distinction is made between three different roles for editing (factory planner, TGA (technical building equipment) planner, work planner). In the "Edit content" column in Figure 2, different roles are assigned to the various structure elements, which can then edit the individual elements on a project-specific basis. The structure for a new planning project is created exclusively by the Plant Structure Planning department to ensure a standardised planning structure across all projects, which guarantees transparency and traceability throughout the entire development phase and thus considerably reduces the training effort for new employees, for example.

Structure	Comment	Edit content	Create
Plant 10	e.g. Paderborn	Only structural elements	
Line 1100	Range	Only structural elements	
Building structure Hall 15	Building	Factory planning	
TGA Line 1100	Technical building equipment (TGA) per line	TGA planner	
Crane systems 1100	Crane systems are processed per line	Factory planning	
Systems 1100	Systems, such as test bench per line	TGA planner	
Planning 10500	Planning at the lowest cost centre	Only structural elements	
Layout 10500	2D footprints		Plant structure planner
TGA 10500	Workplace		
Equipment 10500	Everything that has an equipment number		
CXS 10500	Company Excellence System		
Tools 10500	e.g. welding curtains	Work planner	
Logistics 10500	Will be subdivided again		
Handling 10500	e.g. trolleys → everything that is moved		
Bearing 10500	Fixed shelf		
REGAL TYPE 1	Example for lowest level		

Figure 2. Hierarchy levels for collaborative 3D factory planning

5.2. Phase 2 - Insert 2D layout

Based on the planning structure created in phase 1, the 2D layout can be converted into a 3D layout in phase 2. The explanations given in this paper refer to surface layouts. However, it is possible to insert various other layouts, such as overhead conveyor layouts and overhead crane layouts The 2D layouts must be aligned with the factory zero point. The factory zero point is used to align the 2D layout in 3D. To do this, a reference object is drawn at the origin of the 2D layout, which can then be used to align the 2D layout in the 3D environment. This means that if the 2D layout is changed, the new layout can be inserted seamlessly. Otherwise, the new layout must be repositioned at great expense. The 2D layout then represents the base of the overall 3D layout as a result.
The 2D layout can be enriched with additional data and information, such as workplace data, escape routes, data on electricity, water, ventilation, and lighting as well as building and construction plans with information such as pipework or structures.

5.3. Phase 3 - Collect data

In the third phase, the overall model must be enriched with 3D data to create an initial factory DMU. There are basically four options for this: Reusing, Importing, scanning, and constructing. The four elements of data acquisition are presented below:

- **Reusing:** Existing models can be reused to reduce the effort required to create a DMU. These can be existing 3D models of the product, machine parts, shelving or containers.
- **Importing:** Different types of data can be imported in relation to the planning case. Greenfield planning enables the entire 3D hall to be imported in collaboration with architects. The model can then be enriched with data from machine manufacturers or suppliers (e.g., shelving). This

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type of data acquisition has the advantage that the overall 3D model can be enriched quickly and is highly accurate. The disadvantage is that, depending on the file format, importing the model is time-consuming. In addition, post-processing of the models is often necessary, as otherwise the performance of the model becomes too low.

- **Scanning:** Compared to design in product development, the challenge in the development of production systems is that existing infrastructure is reused (also known as brownfield planning). As there is usually no historical 3D data available for these elements that can be imported, scanning these elements (e.g., shelves) using a laser or camera is a common option. This has the advantage that the physical object can be modelled accurately in a short space of time. The disadvantage of these models is their limited accuracy and the time required to familiarise oneself with the tools and scanning processes. To support the selection of a suitable tool and reduce the familiarisation effort, fact sheets were created for various scanners and scanning methods (an example is shown in Figure 3).
- **Constructing:** Another option is to reconstruct the required objects. This is necessary if a very high level of detail is required, or the model is frequently reused. However, this process is very time-consuming compared to scanning (more information on constructing in step 5).

2 Intel RealSense ™ Depth Camera

Brief product description

The Intel RealSense™ Depth Camera is an advanced 3D depth camera that enables precise depth measurements and has a high accuracy in capturing movements and gestures. It was developed for applications in computer vision, robotics and automation.
The Intel RealSense cameras are available in several models, including the D400 series, the L500 series and the T265. Each camera has its own features and specifications, but all offer high-quality depth sensing capabilities.

Device type

- Budget devices

Illustration

Technological parameters

Accuracy	---	**Weight**	From 60 g
Max. scan size	---	**Connections**	USB 2, USB C*3.1
Software	Opensource SDK	**Compatibility**	Windows, Linux, Android, macOS
Price	From 272 €		
Technology	Camera based	**Website**	https://www.intelrealsense.com/depth-camera-d435/

Figure 3. Example profile for a scanner

5.4. Phase 4 - Insert standards and production resources

In phase four, the factory DMU is extended to incorporate standards and production resources.
Production resources are essential for facilitating the manufacturing of products in the factory. Production resources include, for example, tools, jigs and fixtures, test equipment, transport equipment, and work safety equipment. Since production resources are used in many different fields of production, they are usually included in a library of the software used to create the factory DMU. The library can then be used to insert these production resources into the DMU during the enrichment of the planning.
The term 'standards' refers to components used in manufacturing processes that are developed exclusively by the in-house Factory Structure Planning department. These standards are implemented in the factory to simplify the processes. An example of this are transport containers with company-specific dimensions. The use of these uniform transport containers leads to a simplification of the logistics processes in the factory.

5.5. Phase 5 - Construct objects

Once the standardised elements have been created, the overall model of the DMU can be further enriched. The challenge here is to strike a balance between a high level of detail and the performance of the model. This also requires the manual customisation of some objects. Imported models run the risk of having a high level of detail that affects the overall performance of the model.

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The extent to which standards restrict the performance of the model must also be checked. The repeated use of containers or shelves can have a significant impact on the performance of the model.
The DMU is then further detailed and combined with existing simulations. These development results are used to make changes, which in turn are implemented in the model.

5.6. Phase 6 - Detect collisions and optimise

The 3D model can then be used to detect collisions between individual planning objects, examine material movements and optimise the factory layout. The use of 2D layouts has often led to errors due to the limited perspective (e.g., a supposedly correctly planned staircase that collides with objects that are not directly visible).
The leap into the third dimension opens new possibilities for planners, such as a simplified collision check, the planning of workplace layouts in virtual reality and the validation of system concepts through virtual commissioning. 3D factory planning simplifies collision checks.

6. Evaluation

The methodology presented was applied as part of the Datenfabrik.NRW research project. The research project pursues the approach of optimising the engineering, operation, logistics and IT infrastructure of production in a data-driven manner. Both greenfield and brownfield planning was carried out by the two companies involved in the project. Both companies manufacture capital goods with a high degree of vertical integration. Production covers the entire manufacturing process, from the cutting of raw materials and the forming of components to final assembly. Both companies scanned and reconstructed parts of the factory, as well as importing and post-processing data. The programmes from Dassault (3D Experience Platform) and Siemens (Line Planner) were used as the basis for planning.
The project provided valuable insights for optimising the methodology. Various file formats for importing data from plant manufacturers or scans were analysed. It was found that the JT format is particularly suitable for handling plant data, as it is suitable for large-scale components. In addition, performance was improved by simplifying 3D models with a high polygon count and by colour matching transparent components. Performance has been further improved by removing radiuses and holes below a certain diameter.
Furthermore, experience was gathered on the effort involved in scanning building components and importing data. The main effort involved in integrating architectural data is coordinating a suitable file format with the architecture firm. The greatest effort involved in scanning is familiarisation with the respective tools. After successful training, a two-metre wide and high shelf can be scanned and post-processed by an experienced employee in approx. 1-2 hours. The post-processing work consists of cropping the model and removing incorrectly recorded point clouds. Compared to scanning, the design effort for the same shelf is two to three times higher.
An application was used to compare the DMU model with the real hall to analyse the DMU model on the real hall in production. This enables local staff to be involved and their expertise to be incorporated into the assessment of the design status.

7. Conclusion

In this article, a process model was developed for the development of a DMU for a factory. The process model consists of six steps. In the first step, the role and rights management are defined and a structure for the 3D model is created. In the second step, the existing 2D layout of the factory is integrated into the DMU. In the third step, this is supplemented by imported machine and factory building models and enriched with scans. In the fourth step, manufacturing standards are integrated into a library that enables standardised and cross-project use of frequently used elements. Missing objects are constructed in the fifth step. Finally, the DMU is checked for collisions and further optimised based on further development results.
The use of a DMU also provides important insights into the effects of product adaptations on production and thus enables early adaptation of the product based on production requirements (integrative product development). In process planning, material flow and process simulations can be carried out based on

the DMU. Furthermore, change plans can be checked and, if necessary, revised in the DMU before they are implemented (e.g., virtual commissioning). In addition, 3D factory design provides the ability to conduct a virtual tour of the factory, making it a tool for stakeholder communication and change management.

Further research is needed to integrate the DMU model into a digital factory twin. Enriching the DMU with live data allows, for example, forecasting or retrospective analysis and elimination of logistical bottlenecks based on historical data. Further research is needed to improve the versioning of the models, enabling not only historical states to be represented, but also future planning changes to be incorporated into the overall factory model at a defined point in time. In addition, the extent to which the economics of digital factory design can be assessed in comparison to conventional factory design with significantly reduced tooling costs needs to be analysed.

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References

A. Dalstam, M. Engberg, D. Nåfors, B. Johansson and A. Sundblom (2018), “A STEPWISE IMPLEMENTATION OF THE VIRTUAL FACTORY IN MANUFACTURING INDUSTRY”, paper presented at 2018 Winter Simulation Conference (WSC). https://doi.org/10.1109/WSC.2018.8632234.

Azevedo, A. and Almeida, A. (2011), “Factory Templates for Digital Factories Framework”, Robotics and Computer-Integrated Manufacturing, Vol. 27 No. 4, pp. 755–771. https://doi.org/10.1016/j.rcim.2011.02.004.

Blessing, L.T.M. and Chakrabarti, A. (2009), DRM, a design research methodology, Springer, Dordrecht, Heidelberg. https://doi.org/10.1007/978-1-84882-587-1.

Choi, S., Kim, B.H. and Do Noh, S. (2015), “A diagnosis and evaluation method for strategic planning and systematic design of a virtual factory in smart manufacturing systems”, International Journal of Precision Engineering and Manufacturing, Vol. 16 No. 6, pp. 1107–1115. https://doi.org/10.1007/s12541-015-0143-9.

Cieply, J., Disselkamp, J.-P., Dyck, F., Alturk, W., Kühn, D.-I.A. and Dumitrescu, D.-I.R. (2023), “A systematic literature review on the Digital Twin of the factory in the context of the product and factory lifecycle”, Procedia CIRP, Vol. 119, pp. 834–840. https://doi.org/10.1016/j.procir.2023.02.168.

Cohen, Y., Faccio, M., Pilati, F. and Yao, X. (2019), “Design and management of digital manufacturing and assembly systems in the Industry 4.0 era”, The International Journal of Advanced Manufacturing Technology, Vol. 105 No. 9, pp. 3565–3577. https://doi.org/10.1007/s00170-019-04595-0.

Dai, S., Zhao, G., Yu, Y. and Bao, Q. (2020), “The Evolution from Digital Mock-Up to Digital Twin”, in Tallón-Ballesteros, A.J. and Chen, C.-H. (Eds.), Machine learning and artificial intelligence: Proceedings of MLIS 2020, Frontiers in Artificial Intelligence and Applications, IOS Press, Amsterdam. https://doi.org/10.3233/FAIA200781.

Debevec, M., Simic, M., Jovanovic, V. and Herakovic, N. (2020), “Virtual factory as a useful tool for improving production processes”, Journal of Manufacturing Systems, Vol. 57, pp. 379–389. https://doi.org/10.1016/j.jmsy.2020.10.018.

Dér, A., Hingst, L., Nyhuis, P. and Herrmann, C. (2022), “A review of frameworks, methods and models for the evaluation and engineering of factory life cycles”, Advances in Industrial and Manufacturing Engineering, Vol. 4, p. 100083. https://doi.org/10.1016/j.aime.2022.100083.

Disselkamp, J.-P., Cieply, J., Dyck, F., Grothe, R., Anacker, H. and Dumitrescu, R. (2023), “Integrated product and production development - a systematic literature review”, Procedia CIRP, Vol. 119, pp. 716–721. https://doi.org/10.1016/j.procir.2023.06.198.

Geissbauer, R., Bruns, M. and Wunderlin, J. (2022), PwC Digital Factory Transformation Survey 2022.

Grieves, M. (2015), “Digital Twin: Manufacturing Excellence through Virtual Factory Replication”.

Kampker, A., Osebold, R., Trautz, M., Burggräf, P., Krunke, M., Meckelnborg, A., Leufgens, I. and Rogel, D. (2012), “Innovative Fabriken interdisziplinär planen”, wt Werkstattstechnik online 102, 186-192.

Kerkenberg, T. (2016), “Digitale Fabrikplanung für zukunftssichere und Industrie 4.0-fähige Produktionssysteme”, Zeitschrift für wirtschaftlichen Fabrikbetrieb, Vol. 111 No. 3, pp. 104–108. https://doi.org/10.3139/104.111490.

Lindskog, E., Berglund, J., Vallhagen, J. and Johansson, B. (2013), “Visualization Support for Virtual Redesign of Manufacturing Systems”, Procedia CIRP, Vol. 7, pp. 419–424. https://doi.org/10.1016/j.procir.2013.06.009.

Löffler, C. (2011), Systematik der strategischen Strukturplanung für eine wandlungsfähige und vernetzte Produktion der variantenreichen Serienfertigung. https://doi.org/10.18419/opus-4453.
Loos, M.N., Ovtcharova, J. and Heinz, S. (2012), “Fabrikplanung im Fokus”, Bautechnik, Vol. 89 No. 4, pp. 257–263. https://doi.org/10.1002/bate.201201547.
Nåfors, D. and Johansson, B. (2021), “Virtual Engineering Using Realistic Virtual Models in Brownfield Factory Layout Planning”, Sustainability, Vol. 13 No. 19, p. 11102. https://doi.org/10.3390/su131911102.
Nåfors, D., Lindskog, E., Berglund, J., Gong, L., Johansson, B. and Vallhagen, J. (2017), “Realistic virtual models for factory layout planning”, in Chan, W.K., D'Ambrogio, A., Zacharewicz, G., Mustafee, N., Wainer, G. and Page, E.H. (Eds.), WSC'17: 2017 Winter Simulation Conference WSC turns 50: simulation everywhere! December 3-6, 2017, Red Rock Casino Resort & Spa, Las Vegas, NV, 12/3/2017 - 12/6/2017, Las Vegas, NV, IEEE, Piscataway, NJ, pp. 3976–3987. https://doi.org/10.1109/WSC.2017.8248107.
Oehme, D., Wagner, U., Riedel, R. and Müller, E. (2013), “Optimization of Engineering Processes in Factory Planning”, IFAC Proceedings Volumes, Vol. 46 No. 9, pp. 353–358. https://doi.org/10.3182/20130619-3-RU-3018.00406.
Österle, H. and Otto, B. (2010), “Konsortialforschung”, WIRTSCHAFTSINFORMATIK, Vol. 52 No. 5, pp. 273–285. https://doi.org/10.1007/s11576-010-0238-y.
Rosen, R., Wichert, G. von, Lo, G. and Bettenhausen, K.D. (2015), “About The Importance of Autonomy and Digital Twins for the Future of Manufacturing”, IFAC-PapersOnLine, Vol. 48 No. 3, pp. 567–572. https://doi.org/10.1016/j.ifacol.2015.06.141.
Sacco, M., Pedrazzoli, P. and Terkaj, W. (2010), “VFF: Virtual Factory Framework”, paper presented at 2010 IEEE International Technology Management Conference (ICE). https://doi.org/10.1109/ICE.2010.7477041.
Sacco, M., Redaelli, C., Constantinescu, C., Lawson, G., D’Cruz, M. and Pappas, M. (2007), “DiFac: Digital Factory for Human Oriented Production System”, in Jacko, J.A. (Ed.), HCI applications and services, Lecture Notes in Computer Science, Vol. 4553, Springer, Berlin, pp. 1140–1149. https://doi.org/10.1007/978-3-540-73111-5_125.
Salehi, V. and Wang, S. (2018a), “Using point cloud technology for process simulation in the context of digital factory based on a systems engineering integrated approach”, in Maier, A., Kim, H., Oehmen, J., Salustri, F., Škec, S. and Kokkolaras, M. (Eds.), Product, services and systems design, DS, Curran Associates Inc, Red Hook, NY.
Salehi, V. and Wang, S. (2018b), “Web-Based Visualization of 3D Factory Layout from Hybrid Modeling of CAD and Point Cloud on Virtual Globe DTX Solution”, Computer-Aided Design and Applications, Vol. 16 No. 2, pp. 243–255. https://doi.org/10.14733/cadaps.2019.243-255.
Schönsleben, P., Fontana, F. and Duchi, A. (2017), “What Benefits do Initiatives Such as Industry 4.0 Offer for Production Locations in High-wage Countries?”, Procedia CIRP, Vol. 63, pp. 179–183. https://doi.org/10.1016/j.procir.2017.03.356.
Schuh, G., Aghassi, S., Orilski, S., Schubert, J., Bambach, M., Freudenberg, R., Hinke, C. and Schiffer, M. (2011), “Technology roadmapping for the production in high-wage countries”, Production Engineering, Vol. 5 No. 4, pp. 463–473. https://doi.org/10.1007/s11740-011-0324-z.
Stark, R. (2022), Virtual Product Creation in Industry: The Difficult Transformation from IT Enabler Technology to Core Engineering Competence, Springer Berlin Heidelberg, Berlin, Heidelberg.
Stoffels, P., Boussahel, W.M., Vielhaber, M. and Frey, G. (2013), “Energy engineering in the virtual factory”, in 2013 IEEE 18th Conference on Emerging Technologies & Factory Automation (ETFA 2013): Cagliari, Italy, 10 - 13 September 2013, 9/10/2013 - 9/13/2013, Cagliari, Italy, IEEE, Piscataway, NJ, pp. 1–6. https://doi.org/10.1109/ETFA.2013.6648083.
Tolio, T., Sacco, M., Terkaj, W. and Urgo, M. (2013), “Virtual Factory: An Integrated Framework for Manufacturing Systems Design and Analysis”, Procedia CIRP, Vol. 7, pp. 25–30. https://doi.org/10.1016/j.procir.2013.05.005.
Yildiz, E., Møller, C. and Bilberg, A. (2020), “Virtual Factory: Digital Twin Based Integrated Factory Simulations”, Procedia CIRP, Vol. 93, pp. 216–221. https://doi.org/10.1016/j.procir.2020.04.043.
Zafor, H.A., Dhar, J.C., Saha, S., Nahar, S.K. and Iqbal, M. (2015), “Constructing a virtual factory using 3D Studio Max”, paper presented at International Conference on Mechanical, Industrial and Materials Engineering 2015 (ICMIME2015), 11.-13.12.2015, Rajshahi, Bangladesh.