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Design and Application of a Digital Factory Model for Factory Restructuring

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Abstract

Factory planning has the task of designing products, plants, processes and the building of a factory. The requirements to the factory planning and the building concerned have changed in the last years. Regular restructuring gains more importance in order to maintain the competitiveness of a factory. Restrictions regarding new areas, shorter life cycles of product and production technology as well as a VUCA (Volatility, Uncertainty, Complexity & Ambiguity) world cause more frequently occurring restructuring measures within a factory. The interfaces between factory planning and building planning are crucial in conversion processes to optimally meet the new requirements of a factory building and to react to short-term adjustments. Because of the high adaptation rate of factories described above, a methodology for restructuring factory buildings based on an up-to-date digital factory model is conceived and designed for practical application in factory restructuring projects. The emphasis is on decision making in building conversion processes of factory buildings. The aim is to shorten the decision-making process on the construction site. This requires the application of a methodology that reduces the deficits of the existing approaches. Finally, it will be shown how to best use the digital factory model in practice. It is about designing a mobile application to meet the needs of factory planners on site. An Augmented Reality (AR) application is designed and created with focus to the UI to provide decision support for planning variants. The time and cost expenditure are represented in the AR tablet solution based on a Building Information Model (BIM).

Keywords: Augmented Reality; Building Information Modeling; Digital factory twin; Factory planning

1. Introduction

Factory planning describes the systematic, goal-oriented process for planning factories, structured in successive phases. This process extends from the initial idea to the commissioning of production and is carried out with the aid of tools and methods. The planning of the factory building can be derived from the production task. The demands placed on factory planning and the building in question have changed in recent years, and restructuring is becoming increasingly important [1–3]. Restrictions regarding property, shorter lifecycles of product and production technology, as well as a turbulent environment cause more frequently occurring reconstruction measures within a factory [4]. As a reaction to the increasing changes in the corporate environment and the associated need for regular adaptation, factories have been planned for several years to be more adaptable [5]. But conversion in factories is a complex and resource-intensive process.

The conversion process is a part within the life cycle of the factory. In the life cycle, after an initial planning phase of the factory, the construction and ramp-up of the factory is followed by the operating phase. In this phase, as mentioned, restructurings occur frequently. The conversion process can be divided into three phases: Knowledge phase, preparatory phase and reconstruction phase. In the further course of this paper, the focus is on decision making in the preparatory phase. A challenge is the clear and comprehensible communication of planning contents on the construction site [6]. Under the

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assumption that current digital planning data of a factory is available, a digital building model can be used to support construction site meetings and to facilitate decision-making. There are various existing approaches that address the use of digital building models in factory planning.

Melcher et al. describes an approach for factory layout mapping using semi-automated processes with the help of drones. It deals with the evaluation of area conditions, but it is not a portable solution to make decisions on site [7]. Bussemer et al. has also recognized the recurrent restructuring in manufacturing [8]. This work identifies the restructuring targets and the corresponding elements. However, structural changes are not covered. Näser and Wickenhagen, on the other hand, have investigated how the building information modelling (BIM) approach can be integrated into factory planning. Among other aspects, the restructuring of existing workplaces in an existing factory building are considered. The connections between the factory planners and different technical planners are elaborated. Here, too, the focus is not on decision-making on site through the use of portable visualization techniques [9]. In the Schoenefelder and Schmalstieg approach, which took account of augmented reality (AR) on site in the factory, the focus was, however, on building acceptance. The decision making during conversion on site was not taken into account [10].

In general, there are different visualization techniques to use the digital building twin of the factory to be able to make faster and sounder decisions in the preparatory phase. In this study an approach for an AR application was chosen in contrast to e.g. a virtual reality (VR) application. For use in the factory, an Augmented Reality application is much more flexible due to the location-independent hardware. For the production area there are already approaches which address the use and design of AR applications [11], [12]. In the building sector there is a lack of consideration of AR applications from the perspective of human factors, usability questions and design guidelines. There are no scientific methods, especially regarding the use of AR for decision support in factories. Most known approaches of using AR applications in factory planning address production specific problems [13].

Thus, A method is developed to prepare digital building models for an AR application for construction meetings on site. The method focuses on designing a suitable user interface (UI) for a tablet application. The guiding principle is to support the quality of decisions on site with model-supported construction meetings. This study can be used to include digital models of the factory building into the conversion process.

2. Methodology

A three-step approach is used in the present study to investigate the application of a digital model of a factory building on site. The three-step approach makes it possible to introduce the later user step by step to the desired result. It follows the top-down principle and guides the user through clarification of the general nature of digital twins (first step), via the design of a suitable UI, to a specific AR application (third step). In each step the actual goal is approached step by step by means of deduction. In addition, the activities can be clearly divided into classification, design and development activities.

- Classification of digital twins in the factory
- Design discovery through mock-up
- Development of a construction site appropriate AR application

In the first step, the layer model of the digital twins is presented. The digital twin of the building is classified and the connections to the other digital twins are mentioned. The basic components of the digital building twin are derived and illustrated. In the second step, a mock-up selection is suggested to identify an appropriate design for the user interface of the AR application. In the third step, workflows are proposed that take different file formats into account. It also discusses criteria that support the selection of the AR Engine.

2.1 Classification of digital twins in the factory

In the first method step the user must become aware of the type of digital twin he is using. Different types of digital twins contain different information and must therefore be processed differently in AR applications with regard to the UI and data formats [14]. It is proposed to use the developed layer model of the digital twins for classification.

The digital twin of the product is located on the lowest level of the layer model (cf. Figure 1). The aim of digital product twin is to capture all the information about a product over its entire life cycle [15].

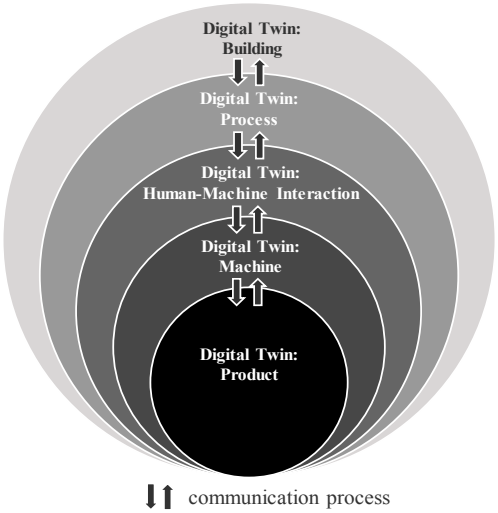

Fig. 1. Layer model of digital twins

The digital twin of the machine or production cell is located on the second lowest layer. The next level in the layer model of digital twins in Figure 1 is human-machine collaboration. The superior level of human-machine interaction digital twin is the digital twin for the production process. From the author's point of view, the superordinate level of digital twins represents the digital twin of the building. From digital product twin upwards, the applications and research approaches are continuously decreasing. Nevertheless, there are the first approaches which use digital building twins in the factory [16]–[18]. Based on the definition of a digital product twin from Gausemeier [15], the

digital building twin can be derived from this. The digital building twin is structured analogously (cf. Figure 2). In the layer model of the digital twins (cf. Figure 1), the building twin is superior to the other twins because it spans the superordinate coordinate system. The building twin assigns a unique x-y-z coordinate to each point in the space and thus also to each machine or product. All subordinate digital twins can thus be spacial referenced by the digital building twin.

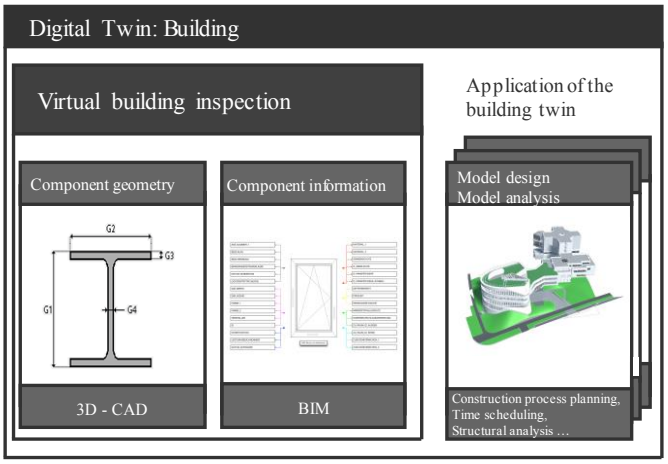

Fig. 2. Derivation of the digital building twin

Visualisation techniques such as AR and VR make it possible to experience the geometric dimensions of a building together with component information. The building twin then serves as the platform for applications such as construction process simulation, time schedules, structural calculations, etc. [19].

After presenting the different digital twins, the user can classify his digital twin and derive the requirements for a UI of an AR application. It is proposed to consider the principles mentioned in DIN EN ISO 9241-110: Ergonomics of human-system interaction. The principles for dialogue design contained therein are:

- Adequacy of tasks
- Self-descriptiveness
- Controllability
- Expectation conformity
- Fault tolerance

In addition, the individualization in the DIN EN ISO 9241-110 is addressed [20]. This is deliberately omitted as there is no purpose for subsequent adaptability of the UI for this use-case. In addition, the visual structuring of information should be considered. These are depending on the use case: Placement of information, required information, consistent placement of areas, density of information displayed, differentiation of groups, sequencing, application of conventions and functional grouping [21]. Based on this the next step presents how to find a suitable UI for an AR application.

2.2 Design discovery

The goal is to design an appropriate user interface (UI) for an AR application. Subsequently, the following requirements were derived from the principles for dialogue design and should be considered when designing the UI for the mock-up:

- Comprehensible information architecture
- Comprehensible navigation concept
- Easy interaction
- User assistance
- Consistency of elements

There are different ways to present a UI in advance. The simplest form is the paper mock-up. Also digital mock-ups are used for the development of UI's in the context of AR [22]. For the selection and implementation of mock-up variants, reference is made to preparatory work by Ligman et. al [23]. The user must decide for a mock-up regarding his available time, abilities and budget.

2.3 Development of a construction site appropriate AR application

There are a variety of data formats for digital building models or BIM models: DWG, DXF, IFC, RVT, NWD. At this point of the method it is necessary to find out which formats are available and which format is required for the creation of the AR application in the software used. Based on this, various workflows can be performed to ensure fast availability for the AR application and to improve performance for the different file formats. Subsequently, suitable workflows are developed based on the common data formats DWF, RVT and FBX. The applied workflows with tools used and the associated import file formats and performance optimizations are displayed in table 1.

Table1: Workflows and import file formats

Workflow	Source file	Intermediate format	Target format	Performance optimization
1. Scene-Convert in 3ds Max	.FBX	.MAX	.FBX	Conversion of Autodesk materials to standard materials
2. NuGraf64 /Polytrans convert	.DWF	.BDF	.FBX	Reduction of polygons
3. Direct Import	.FBX	-	.FBX	-

The first workflow is converting Autodesk materials into standard materials to use the FBX in Unity without adjustments. Therefore, the Scene converter in 3ds Max was used. If the source file is a DWF (second workflow) there is the possibility to decrease complexity by reducing the nodes (structure) of a geometry of the digital building twin during import with NuGraf64. This means the AR application runs more smoothly, especially with less powerful devices. When converting Nurbs formats into polygon formats, it is possible to specify the maximum deviation of the tessellation from the specification of the exact mathematical model of the Nurbs surfaces. This allows the polygon number of meshes to be very finely dosed and optimized. This is faster and better than

reducing the polygons in FBX files. In the third workflow, when importing the FBX directly, there is no possibility to convert materials or improve performance. However, this is the fastest workflow. A post-processing of the materials in Unity may be necessary to improve the visual impression.

There are also different AR Engines that can be used. Each has its own advantages and disadvantages. There are differences in the performance, the costs, the integration and markers suitable for use. For the respective application it is suggested to choose a suitable AR Engine based on the mentioned criteria. When selecting AR Engines, reference is made to the survey of Rana and Patel [24].

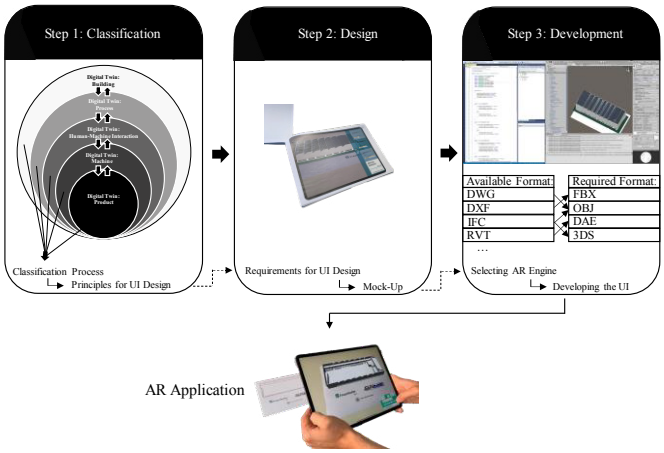

Fig. 3. Method Overview

The three steps in the overall context of the method are shown in Figure 3. The also explained sub steps can be found here. The results of the mock-up can be used to start developing the UI. Based on the available data formats of the digital building twin and the data formats that can be used by the development environment, a workflow (cf. table 1) must be selected and executed.

3. Application of the purposed method

The presented three-step approach is carried out and experiences with the implementation are described. The starting point is a BIM model of a factory.

In the first step a pure building model for the evaluation of the method is identified. Due to the task to create an AR application for the representation of conversion scenarios with cost and time overview, the following design principles were identified: Customization to task, self-descriptiveness and controllability. The focus was also on an understandable navigation concept and the applicability on different devices to be able to address a broad group of users and not to be limited in terms of hardware.

In the second step, based on the aim that the AR application should enable the user to get an overview of the different conversion variants of a factory at the construction site a paper mock-up (static design template) is developed. The paper mock-up was used in the implementation case, as this enables a cost-effective and fast query of the UI. The UI can also be designed differently if the same principles and requirements for the UI are considered. Therefore, a survey is conducted among potential users to compare and rank different designs. A variety of sketches of the UI to be developed are used. The paper mock-up visualizes the content and demonstrates the essential functionality in a static way. It displays the structure of the information and supports the design review of the layout. The best rated UI proposal can then be used to develop the AR application in the final step. A total of 15 people is interviewed with the paper mock-up and a selection of 9 different UI proposals are presented. First the font colour of the UI is queried and then the different UI variants with varying amounts of information and arrangements. The goal is to discover how to arrange the UI to ensure a clear overview of the overall impression, to arrange the display of information in a meaningful way, to adjust the amount of information ideally to the decision support and not to restrict the field of view too much.

The best rated proposal for a UI is shown in Figure 4. It shows the augmented building model on the floor plan. The UI is in the lower right corner with the indicated 3 conversion scenarios (S1-S3). The UI's font colour has prevailed in the survey as white. In addition, a minimalistic and clear presentation was preferred. Other UI suggestions were often too loaded with information or the field of view was restricted by a too large UI. At the end of the survey, the interviewees were also able to draw up their own sketches for a proposal for the UI. However, no sufficient sketches with suggestions for improvement were made. General suggestions for improvement, such as the suggestion that no transparency should be used for the background of the UI or that too many colours would be a handicap, are considered in the subsequent implementation of the UI.

Fig. 4. Best rated UI for an AR application supporting decision making

The use of an easy and quick to create paper mock-up has proven to be useful. Digital mock-ups that were more complex to create would have taken more time in the present implementation.

The third step follows: Development. Before the actual app development takes place, a preliminary comparison of AR Engines is carried out. Due to the initial situation, the design of an AR application with restructuring scenarios of a factory the AR engines Vuforia and XZIMG were tested and compared. After detailed tests Vuforia was selected for the development of the prototype. The decisive factor in the comparison was the stability during augmentation to a DIN A3 floor plan. This

criterion is fundamental for use on construction site. During the development of the UI, the above principles and requirements were further specified and applied as follows: The ability to quickly import planning changes, scalability of the UI and platform neutrality.

To ensure the application can be used during construction, it is necessary to add changes. A class for saving object lists and time lists was used for this purpose. The time lists are linked to the slider in the UI. Depending on the type, the connected game objects are shown or hidden. The script is designed to be drag and drop customizable. When planning changes occur by technical planners, changes can easily be integrated into the application even from BIM planners themselves.

A scalable UI is developed in Unity. The UI automatically scales by requesting how many dots per inch (DPI) the device has. The correct button size and usability in portrait or landscape format is ensured. The responsiveness of the UI enables it to be easily operated and readable on different devices with different resolutions and different DPIs. The responsive design concept was the template for the implementation [25]. In the present application, the output format of the digital twin was a Revit model (.RVT). This was exported as FBX. Then the first workflow (see table 1) was carried out to transfer the Autodesk materials directly to Unity. This meant that no subsequent processing of the materials in Unity was necessary. This workflow worked error-free except for components with glass. To fix that, the transparency of windows and glazed doors in Unity had to be subsequently adjusted.

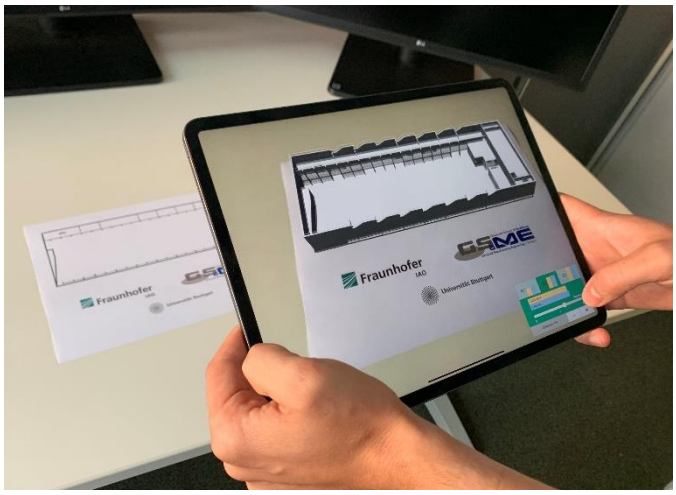

Fig. 5. AR application during operation

In the following, the principle of using the application and the application itself is presented. The prerequisite for the application is to have the current planning status available both as a digital 3D model and as a paper plan (floor plan). In most cases, the floor plan can be extracted from the 3D model. If the application is built according to the method shown above and the current floor plan is printed, the application can be used. The application augments the digital building twin on the floor plan (see Figure 5). The designed UI is displayed on the bottom right of the tablet. This makes it easy to reach with the thumb. You can see 3 tabs with time and cost information. The selected scenario is displayed in the tab as dark green. Different features can be activated by the UI like the time slider to display the construction progress or gradually adjustable transparency of the surrounding building. The corresponding geometric objects of the digital building model are linked to the UI and displayed augmented. The time and cost information are always displayed depending on the selected scenario. Thus, it is possible to take a decision regarding the different conversion scenarios. The decision can be made on the sound basis of the displayed information. A comparison of the conversion scenarios can be executed not only regarding costs and time, but also regarding the spatial and structural execution and visual impression. The three-dimensional augmentation provides an impression that cannot be achieved with a two-dimensional floor plan. Figure 5 also shows the UI. Displayed information and buttons have been kept as simple and clear as possible. The results of the paper mock-up were applied. The application is self-explanatory. As soon as the time slider is activated, the roof of the factory is blanked out and the conversion scenarios inside become visible. The comparability is guaranteed by the fact the time slider saves its position, so it is possible to compare the construction progress of all scenarios e.g. after 3 months. Only the total cost of the scenario is displayed. A breakdown to trades is possible, however, has been rejected in this case as not to burden the user with too much information and thus impair decision-making.

4. Results and Discussion

Altogether the approach presents a method, which enables to design a UI in a systematic way for AR applications that run performant and can be provided quickly. After the classification of the digital twin, by using the layer model of the digital twins, there is a better possibility to dedicate to the respective characteristics and specifications regarding information representation, information content and file formats. The approach by stages considers design guidelines and design references from established sources. During the implementation of the design guidelines it turned out that it is always necessary to emphasize which guidelines are fulfilled by which elements in the UI design. Based on design guidelines, a possibility to evaluate a UI proposal by means of a mock-up is presented. The paper mock-up used was quick to perform, but it does not consider realistic colour reproduction as it appears on the display at the final stage. In addition, workflows are presented which enable the time-saving creation of AR applications suitable for construction site. A workflow with a scene converter in 3ds Max is presented, which allows a simple and fast conversion of proprietary materials into standard materials. A post-processing of the materials is not necessary, which saves up to 80% of time depending on the size of the building and the project compared to the manual transfer of materials in Unity. Through the 2nd workflow (see table 1) especially with very handy devices required for construction sites, the difference in performance is high. There are other data formats and associated workflows which have not been considered in this paper. A comprehensive comparison was therefore not possible. The performance and the loading times of the application are short. The augmentation is displayed without jerking although the first workflow was used (cf.

table1). The workflow to reduce the model geometry was not applied because the model used was not very large and therefore did not cause any jerking. The main result is that the expansion stages have already to be considered during modeling the factory in the BIM software. This not only means the respective floors are displayed only once during the construction sequence simulation without redundancies occurring what brings performance improvements. Sectional modeling also has a strong effect on the subsequent editing of the model in Unity. Initially, this effect was ignored. A time-consuming adaptation of the BIM model was necessary afterwards. This procedure is strongly evident in the performance of the application and for the implementation of the method. With the running application construction meetings can thus be supported visually and informatively. It was discovered that the use of the prefabricated UI is too limited in some cases. Some planners want additional display options. The overall result is a method for obtaining a user-friendly AR application which is flexibly extensible. The responsive design concept employed has proven to be valuable in practice.

5. Conclusion

In recent years, the planning of conversions in factories has become increasingly important. The approach contributes to faster decision-making during conversions by enabling AR applications to be designed in a structured way. The UI is dealt with in a focused manner. A paper mock-up was selected in the implementation case. Since a digital mock-up for evaluating the UI is also possible, it is necessary compare the results in future research when using a digital mock-up specially to consider the realistic colour rendering on a display. Also, an extension of the considered data formats and the workflows connected with it would create a practical addition to the existing work. This requires a comprehensive comparison that considers different data formats and identifies processing times and performance differences of the application. In addition, an extension of the functionality and display options is advisable to extend the range of application. Industrial AR has become an integral part of Industry 4.0 concepts [26]. However, the AEC industry, relative to other industries, has been slow in adopting AR/VR technologies[27]. This work contributes to advance the use of AR in the construction industry.

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