Integration of BIM and Industry 4.0 - approach for rapid deployment of digital twins for modular construction

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Abstract: The automation of production processes has made enormous progress in recent years through modern communication and information technologies. Through continuous intelligent networking of components, machines, and processes in Industry 4.0 (I4.0), the production of precast concrete elements can be carried out more efficiently in terms of both time and costs. The digital twin, as a central information container, is a fundamental concept in I4.0 that collects and provides relevant data and information across all lifecycle phases of a component. As an established tool for the planning and design phase, Building Information Modeling (BIM) focuses on designing and describing buildings and infrastructure. However, BIM models are not suitable for communication and interaction in cyber-physical systems and real-time data integration. The aim, therefore, must be to combine current BIM concepts with methods from I4.0, which enable self-organized and decentralized production. For this, suitable interfaces must be developed that ensure a continuous flow of information across all lifecycle phases. This paper presents an approach for digital twins' rapid and automated creation based on implementing the asset administration shell, a digital twin framework known from I4.0. In the presented approach, an administration shell template of a component, which already contains the necessary semantic data structures, is instantiated with a corresponding BIM model's design and construction data. The concept is demonstrated and validated using a virtual precast concrete column as an example. The proposed approach thus combines BIM with I4.0 methods and ensures a continuous flow of information between planning and production.

Keywords: Digital Twin, Building Information Modelling (BIM), Industry 4.0, Modular Construction, Automation

1 Introduction

The construction industry is at the beginning of a digital transformation that will change how we plan, build and operate buildings and infrastructure. Advances in sensor technology, connectivity, cloud computing, Internet of Things (IoT) and artificial intelligence enable the built environment to become a dynamic network in which smart objects can exchange data and information. In the manufacturing industry, IoT technologies are referred to as Industry 4.0 (I4.0) and enable the networking of products, machines, and processes to realize decentralized production. In the sense of I4.0, smart products seek an optimal path through production systems by communicating and interacting autonomously with their environment. In contrast, the production of precast concrete elements resembles a roofed construction site with only a few digitalized or automated processes. The implementation of digital twins is an essential component of I4.0 for the collection, evaluation, and provision of data along the entire value chain. First works are already successfully applying the concepts of I4.0 to the construction industry, where the application of I4.0 methods is also referred to as Construction 4.0.

In construction, Building Information Modelling (BIM) is an established tool for the digital description of structures and infrastructure during the planning and construction phase. BIM models contain the logical structure of the building and other semantic properties and attributes. However, using BIM models as digital twins is a heavily debated topic in many studies. The digital models created as part of the BIM process are intended for the planning and construction phases in which mainly static data is handled. Furthermore, BIM models are not designed for human-machine and machine-machine interaction. Both of these are elementary functionalities of the digital twin in I4.0 and are indispensable for implementing cyber-physical systems. In the context of I4.0, the administration shell was developed as an information container that provides methods for interaction in cyber-physical systems, which can be used for data management and distribution. Initial applications to the industrialization of the production of precast concrete parts show that the technology can also contribute to the digital transformation of manufacturing in the construction industry. By combining BIM and the digital twin from the context of I4.0, a unique symbiotic approach can be created. However, the ultimate goal in construction must be that the flow of information remains continuous and does not become further fragmented.

This paper presents a concept for integrating IFC-based BIM models into the administration shell of Industry 4.0 in the industrialized production of precast concrete elements. BIM models contain various data that are important for creating digital twins. With regard to the industrialized production of precast concrete elements, these are mainly general dimensions as well as data on material, reinforcement, and quality of the element. These data can be used to model digital twins and enable automated, rapid deployment on completion of the BIM process and at the start of production. The concept is validated in a case study in which an implementation of the approach is first proposed and finally applied to a virtual precast concrete column.

2 State of the Art

2.1 Digital Twin in Construction

Since the introduction of the digital twin, the concept has been adopted by many industries. As a result, many different definitions exist, each differentiating between industry-specific characteristics. Boje, Guerriero, Kubicki, *et al.* [1] propose a definition for the construction industry based on the digital twins' original definition by Michael Grieves. In this definition, the digital twin consists of physical and virtual space as well as a data link connecting the two. A characteristic of a digital twin is a bidirectional data link between the physical and virtual space. In a literature review, Sepasgozar [2] examine applications of digital twins regarding their data exchange capabilities. Their analysis shows that many published implementations of the digital twin do not qualify as such but rather as digital shadows for which only unidirectional data exchange is needed. The role of BIM in digital twins is a question on which there is still no consensus in the construction industry. In the literature, the digital twin is described as either an evolution, complementary, or independent of BIM [3]. According to Davila Delgado and Oyedele [4], both concepts are unique approaches that respond to different industry needs. In general, BIM is designed to improve the efficiency of design and construction. In contrast, the digital twin is designed to accurately represent the current state during manufacturing and operations, mainly through real-time data enabling data-driven decision-making and the simulation of what-if scenarios [3]–[5]. Shahzad, Shafiq, Douglas, *et al.* [3] state in their work that the data contained in BIM can be of great use to the digital twin if integrated appropriately.

2.2 Industry 4.0 & the Asset Administration Shell

I4.0 is the digitalization of production by linking the real and virtual space by connecting products, machines, and processes through innovative communication and information technologies to cyber-physical production system [6]. Smart products know their status and can independently find their optimal path through intelligent production systems by communicating and interacting with the machines and processes. Essential to the implementation of cyber-physical systems in the sense of I4.0 is the fully automated collection of the underlying process data and the evaluation, quantification, and analysis of the collected data. I4.0 is being driven forward in Germany by the *Industrie 4.0* project initiated by the Federal Ministry of Education and Research. The asset administration shell is considered the technical implementation of the digital twin in *Industrie 4.0*. It consists of many submodels that form an overall digital representation, each submodel representing an aspect or use case. The submodels contain all relevant data required by the asset through all life cycle phases. Essential for the autonomous exchange of data between Industry 4.0 components is the unambiguous interpretability of the data by both humans and machines. For this purpose, concept descriptions are specified that clearly define the semantic meaning of the data enabling machine-readability. Semantic descriptions of the data can also be provided by external repositories such as E-CLASS. Machine readability makes it possible to transfer data autonomously in machine-to-machine communication. A special I4.0 language is used for this purpose [7].

3 Concept

During the digital BIM planning process, a central digital model is created that, in addition to a simple geometric model, contains further data and information that are added to the components in the form of properties and attributes. The level of detail of this data depends heavily on individual project requirements. However, it can be assumed that at least data regarding geometric dimensions, materials, and reinforcement will be captured as part of the detailed design. For the industrialized production of precast concrete elements, these data represent a subset of the data requirements (cf. [8]). The data captured in the BIM model can be used to create digital twins, ensuring a continuous flow of data between the design phase and production and avoiding further fragmentation. In addition, the often cumbersome and tedious modeling process is simplified and enables digital twins to be made available quickly. The approach presented in this paper integrates an IFC-based BIM model into the digital twin for the industrialized production of precast concrete parts based on the administration shell of *Industrie 4.0*. The paper builds on the extensive preliminary work of [8], who developed data requirements and an administration shell template for precast concrete parts which are used as a basis for the presented approach.

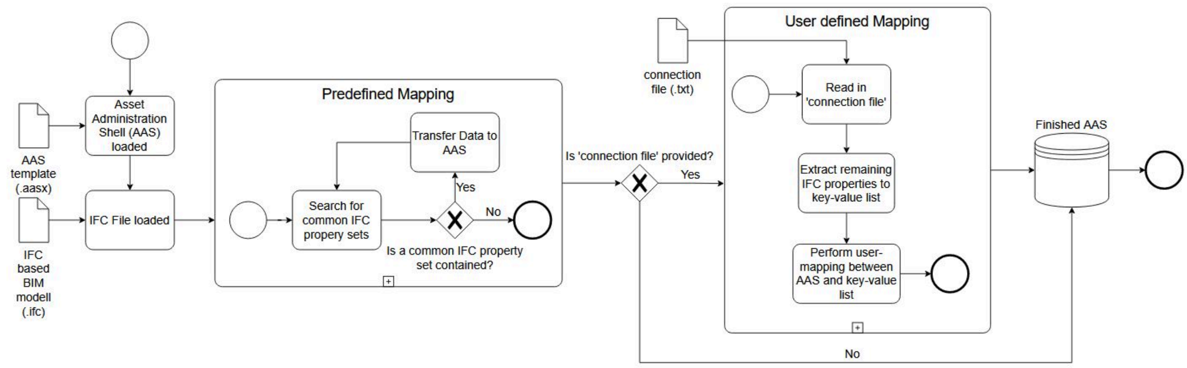

Figure 1: BPMN diagram of the proposed approach

The Industry Foundation Classes (IFC) are an open, vendor-neutral data format for the geometric and semantic description of a building. An IFC model consists of many hierarchically organized entities that model the logical structure of a building. These entities can be assigned properties that are defined as static properties directly in the schema of the IFC model or as dynamic properties that the user can freely assign. Dynamic properties are defined via a name-value-datatype list and combined into property sets which are then assigned to objects [9]. The properties of the IFC-based BIM model must be mapped to the properties contained in an administration shell-based digital twin. The prerequisite for this is an administration shell template with a data structure that conforms to the specific application requirements. Although an IFC-based BIM model cannot cover the entire data requirements of the digital twin, the data significantly contributes to simplifying and automating the deployment process. Data related to production processes and machine parameters are usually not captured in a BIM model. Therefore, they must be modeled manually or added to the administration shell by adding other external sources.

4 Case Study

As part of a case study, a Java-based implementation has been developed for the presented concept. The developed application assigns the properties in an IFC-based BIM model to the corresponding properties in the administration shell. The application is validated using the example of a precast concrete column.

4.1 Implementation

The developed application (see fig.1) consists of two components processing an IFC-based BIM model on the one hand and an administration shell on the other. The apstex IFC framework is used to evaluate the IFC files. For processing the administration shells, the BaSyx middleware from the Eclipse Foundation is used. Basyx has a Java-based SDK enabling reading and writing of administration shells. The prerequisite for the application is an IFC file and administration shell template, both being passed to the application as input. In this case study, the administration shell template developed by Kosse, Vogt, Wolf, *et al.* [8] is used. The application's functionality includes mapping material and reinforcement data and the addition of the reference to the underlying IFC file. To ensure the availability of attributes and properties, MVD's can be used. In the context of the prototypical implementation presented in this work, the availability of the properties is assumed without prior checking. The mapping is performed in two steps. The application first evaluates all statically defined IFC properties before evaluating user-defined properties. For this purpose, a mapping file is defined that is passed to the application.

Mapping of properties specified in the IFC data schema

The IFC file format provides statically defined property sets for the material and reinforcement data. These properties are mapped to properties in the administration shell. In the administration shell, data relating to material and reinforcement are available in a structured manner in submodel element collections. A submodel element collection exists for each unique element containing the properties and attributes. Especially for the data concerning reinforcement, grouping and aggregation of reinforcement types are performed prior to the mapping.

User-defined mapping

Dynamically specified properties can be used to transfer information such as production data and machine parameters, provided they have been assessed as part of the BIM process. A mapping file ('connection file') is required that specifies the assignment of the user-defined properties to the data structure of the administration shell. The mapping is specified via a text file by indicating the property name and the associated property in the administration shell, separated by a colon. Instead of the unique GUID of a property in the administration shell, the more readable idShort is used to simplify the application. To ensure a unique mapping, information on the position within the hierarchy of the administration shell is added to the mapping (e.g., Production-Transport-Transport company-Address). Before the mapping is performed, a key-value list, containing all unused IFC properties, is created.

This list is then used to perform the actual mapping (between AAS and key-value list). This procedure enables the flexible addition of information from other sources.

The progress of the process and any errors that occur are logged in a corresponding file. At the end of the process, the user receives a log containing information about the transferred data and a list of missing data.

4.2 Results

The validation of the proposed implementation is performed using the precast concrete column shown in fig 2 and 3. The column has a cast-on foundation and bracket support. The geometric dimensions can be taken from fig. 3. An IFC-based BIM model exists for the component, which, in addition to a geometric model, also contains data on material and reinforcement.

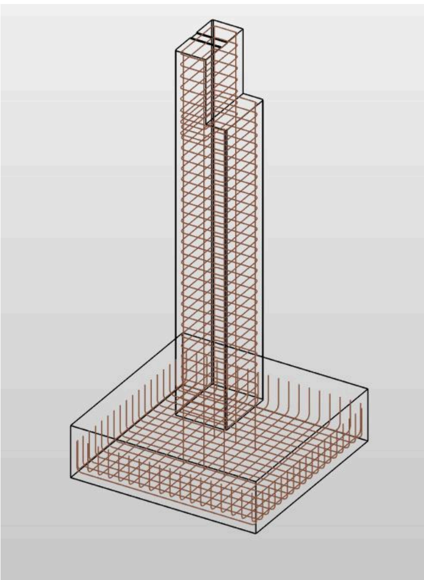

Figure 2: precast concrete column with foundation

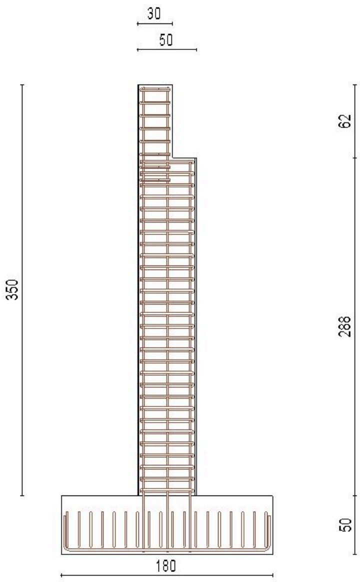

Figure 3: Dimensions of the precast concrete column with foundation

Figure 4 and 5 show the asset administration shell after successful application of the presented tool. The administration shell of the precast concrete column now contains data regarding material, reinforcement, and a reference to the IFC-based BIM model. A submodel element collection was created for each reinforcement type.

5 Discussion & Conclusion

The construction industry's digital transformation is characterized by the introduction of modern information and communication technologies. By introducing Internet of Things technologies, the built environment is interconnected to form cyber-physical systems in which participants can exchange data and react intelligently to one another. Essential for implementing cyber-physical systems is the digital

Figure 4: Instantiated Administration shell material SMC

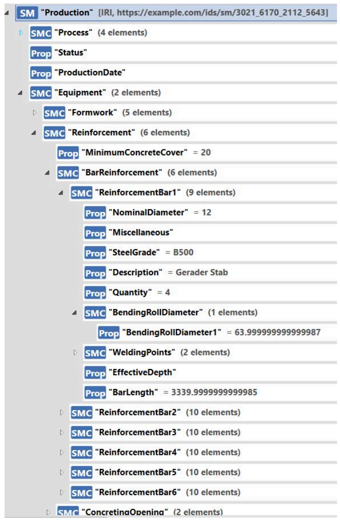

Figure 5: Instantiated Administration shell reinforcement SMC

twin. BIM is a proven and established tool for the digital description of buildings and infrastructure during the planning phase. However, due to insufficient integration of real-time data and a lack of interaction capabilities, BIM is unsuitable as a platform for an IoT digital twin. The digital twin, on the other hand, is by no means an evolution of BIM, but should rather be seen a complementary. Integrating BIM into digital twins allows for a digital model that uses current data models in construction and at the same time is able to participate in data exchange in cyber-physical systems. The approach presented in this work integrates BIM as a data basis for the creation of digital twins enabling the rapid provision of digital twins and, at the same time, contributes to keeping the flow of information continuous preventing further fragmentation. Furthermore, it is scalable and can be applied to entire buildings. An administration shell is created for each precast concrete element, which combines to form the administration shell of the entire building. Future research will extend the presented approach by a visualization component in which data is presented interactively to the user. Furthermore, the addition of further sources is planned.

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