FBI-2021 - Data structure for realizing a digital twin of construction processes

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Abstract

The digital twin concept originates from the 1960s, but it still took many years for the term “digital twin” to emerge. It essentially consists of a physical twin and its digital counterpart. Both are connected so that changes in the real world are also updated in the digital world. After using digital twins in several industrial sectors, it just recently found its way to civil engineering. Researchers see its potential, especially in the situational awareness it creates. This awareness can be used to improve overall efficiency in all phases of a building’s lifecycle.
The following paper develops a process-oriented model that is able to represent activities during the construction phase holistically. Where existing models lack the inclusion of the as-designed and as-built product information along with the as-planned and as-performed process information, the proposed model includes all of them. Its underlying purpose is to store information primarily from the construction phase to facilitate the analysis of performance indicators and detect reasons for delays.
A possible application could range from a retrospective analysis of the construction process to using the information during the construction to make predictions and propose alternative schedule options. This paper will describe the proposed data structure for a digital twin comprising all of the mentioned features.

Keywords: Digital Twin, Process Modeling, Construction Performance

1 Introduction

Even though the digital twin concept originates from the 1960s from the simulation methodology applied by NASA, it still took many years for the term "digital twin" to emerge. Micheal Grieves was the first to namely mention the digital twin in 2003 in one of his publications [4]. Since then, this concept has found its way into many different industrial sectors and is now a recent research topic in civil engineering. There are numerous definitions for digital twins that put their focus on varying aspects. Fundamentally, it comprises the coexistence of a physical and a digital twin interconnected with, e.g., sensors for monitoring that transfer information from the physical to the digital twin. With the help of artificial intelligence and other interpretation techniques, a digital twin can optimize and predict the future states of the monitored object [3].

In their detailed literature review on digital twins independent of the application area, Jones et al. [9] identified several research gaps that need special attention, according to their estimate. One of those gaps consists of the requirements of the digital twin that are not yet fully understood in all phases of a product’s life cycle. Many inspected papers only focused on phase-specific use cases. Contrary, a digital twin is meant to evolve incrementally, be a continuous data source over the whole life cycle, and can contain valuable information even after the existence of the physical twin. The lack of digital twins for all lifecycle phases is also a prevailing problem in the realm of civil engineering. There are existing solutions for digital twins during the design phase. Namely, BIM methods allow the development of buildings as 3D models that include all information necessary for the construction phase. Aside from the design phase, the research focus lies in supporting the operational phase with monitoring sensors that capture prevalent parameters. Shim et al. [13], Lu et al. [11], and Khajavi et al. [10], e.g., use temperature, moisture, and brightness sensors in buildings to minimize the consumed energy from heating and lighting.

The construction phase, however, remains a relatively new area of investigation in the context of digital twinning. The first to approach this topic is Sacks et al. [12], who envision a digital twin concept that assists the construction phase of a building. Their conceptual idea is a holistic approach that captures data from supply chains, equipment, construction progress, and many other related sources to gain situational awareness at any given point in time. Besides the information about building elements and products, monitoring processes on site is vital to the developed concept. By applying lean construction techniques like closed feedback loops, they envision proactive adaption of the construction schedule. Their understanding of a digital twin during the construction phase is taken as a basis to elaborate a data model that supports all for a Digital Twin in Construction relevant aspects.

As the first step of implementation, the present paper develops a process-oriented model that holistically represents activities during the construction phase. Where existing models lack the inclusion of the as-designed and as-built product information along with the as-planned and as-performed process information, the proposed model incorporates all of them. Its underlying purpose is to store information primarily from the construction phase to facilitate the analysis of performance indicators and detect reasons for delays. A possible application could range from a retrospective analysis of the construction process to using the information during the construction to make predictions and propose alternative schedule options. This paper will describe the proposed data structure for a digital twin comprising all of the mentioned features.

In the following chapter 2, related work is being introduced. At first, the Digital Twin in Construction defined by Sacks et al. [12] will be explained in further detail since it builds the fundament for the present paper. Afterward, existing process models in the context of civil engineering will be thematized. In section 3, the elaborated model for a Digital Twin in Construction is presented. Furthermore, it is stated how integrating parts of existing file formats could benefit the proposed process model. Finally, key aspects of the paper are summarized, and future steps are presented in chapter 4.

2 Related Work

2.1 Digital Twin Construction

Recent advancements in research areas like planning with BIM, lean project management, construction monitoring, and artificial intelligence make it possible to envision significant efficiency improvements on construction sites. Whereas these study fields often get analyzed separately, the Digital Twin Construction (DTC) introduced by Sacks et al. [12] tries to bring them together. It comprises a new form of planning and controlling during the design and the construction phase of a building. To enhance all sorts of ongoing processes on the construction site DTC aims to interpret various data sources simultaneously in an interconnected way rather than analyzing them one by one. This results in a holistic approach. Another distinction to existing digital twin definitions is its scope. The Digital Twin, as a whole, has to be understood as a digital representation of the complete construction site, including external factors that influence it. It does not stop with the representation of the building itself but also captures information about processes, equipment, workers, and material on construction sites and even supply chains. The goal is to gain situational awareness with all of that detailed process status information and derived knowledge, allowing proactive planning and adaption of processes on-site. An essential part of reaching this goal is the closed-loop control system, a well-known method originating from lean management. So-called Plan-Do-Check-Act cycles are the proposed way to feedback the information gathered from data analyses into constant coordination processes on-site regularly. According to the DTC concept, this type of feedback is supposed to be given at several different time scales, as depicted in graphic 1.

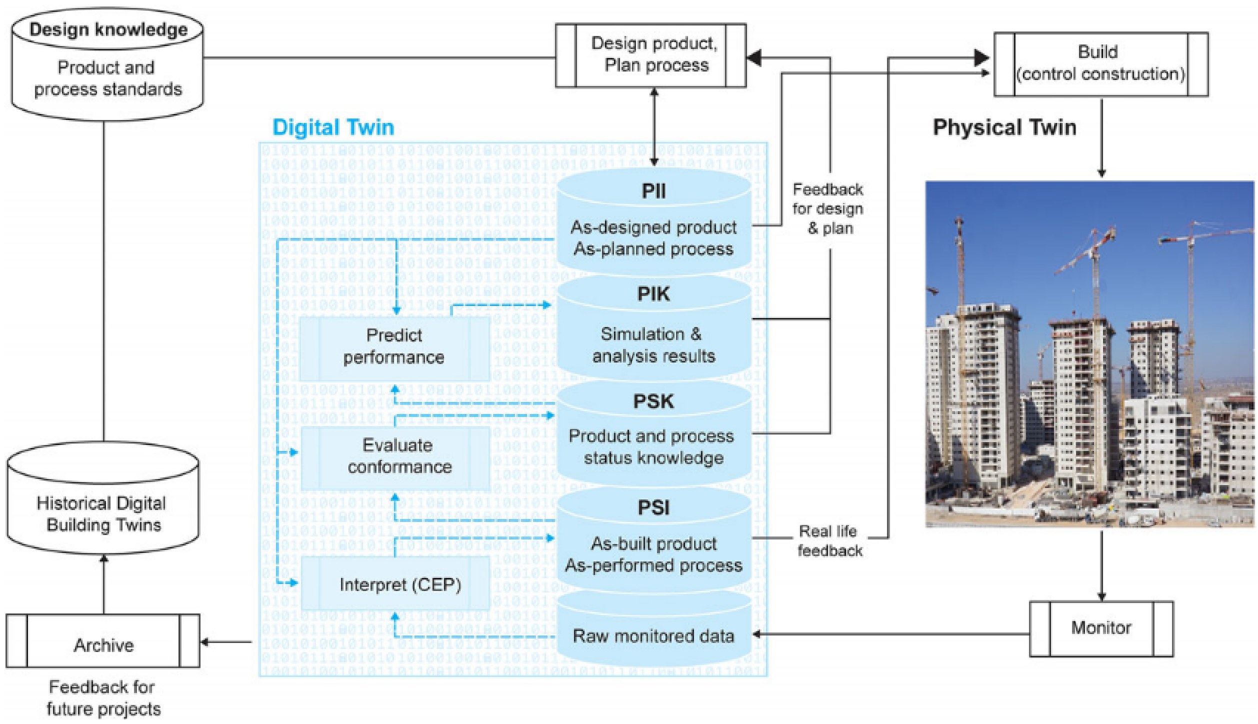

Figure 1: Workflow of the Digital Twin in Construction [12]

Moreover, the diagram shows the digital twin's essential dimensions of information. It includes the differentiation between the project intent and status. The decisive factor here lies in the current state of time. Everything that lies in the past is part of the status, whereas plans for the future states represent the intent. Furthermore, data, information, and knowledge are differentiated. They increase in their end-user value in the given order. Data is the type of information directly gathered on the construction site via, e.g., sensors and laser scanners, whereas information and knowledge result from further evaluation, analysis, and interpretation. Finally, processes and products are considered separately. This results in the four primary information clusters depicted in figure 1: the project intent information and knowledge (PII, PIK) and the project status information and knowledge (PSI, PSK).

2.2 Process Modeling in Civil Engineering

During the construction of a building or an infrastructure, the ongoing processes are of great importance when assessing a project's performance. By analyzing them, one can determine whether the construction is proceeding according to plans in terms of, for example, time and quality. Since there are numerous involved components in every process on the construction site, assessing them in a manual way is everything but a simple task. Therefore much effort is being put into developing computational methods that optimize the process management on site. Having a process information model that reflects the reality in a for the given use case suitable way is the backbone for all further analysis. There are already existing process models that describe construction processes in various ways, which form a valuable basis for designing a digital twin-specific process model.

By looking at a single construction process, the influencing factors can be defined as the persons working on the process, the activity itself, building elements with their corresponding states, and the required tools and equipment. Huhnt [6] defines their relationships in an activity-oriented way. An activity has a set of building elements in specific states as a requirement that need to be fulfilled in order to be able to start. The ones that are executing the activity are persons using certain types of equipment. Finally, a process results in building elements or referring to their status in a status change of one or multiple elements. The status of a concrete column, for example, could be described as "formwork completed", "reinforcement placed", "concrete placed", and others. These states heavily depend on the type of building element and the used construction procedure. In summary, a construction process in its simplest way can be seen as a combination of the activity, input and output components, and their state. The activity is performed on a set of components and results in a change of their states, which can range from a very fine-grained description to a simple "not started", "in work", or "finished".

Ontologies are the most fundamental way to represent objects and concepts from a specific part of the real world, including their relationships. The Digital Construction Ontologies (DICO) got developed as a part of the Diction and BIM4EEB projects. Their goal is to create interoperability between construction-related data at a technical, semantic, and syntactic level. The scope of DICO mainly consists of object descriptions related to the management and the execution of construction projects and also includes the representation of processes, which will be explained briefly. Processes in DICO are composed of one or several activities, which themselves are divided into object activities. Where activities describe the more general construction procedure, the object activities build the link to the building element on which it is applied. The activities are further described by the so-called activity flows, which can be seen as the input parameters of a process. These are the workspace, the labor crew, the material batch, the equipment, information objects, and the environmental conditions [2].

Benevolenskiy [1] created an ontology used to store process patterns for standardized processes, called the Process Pattern Ontology. He includes three main types of information in his patterns, which are the required resources, the subprocesses related to the top-level process, and applicable objects, which in his case only consist of building objects. Other than that, he gives them a description, meta-data, and time and cost-related parameters to make their intended range of application more transparent and easier to find within the pattern library. Often several variations for the same type of building object are given, for example, if a precast element is used or if it is built in-situ. Benevolenskiy's [1] concept furthermore includes the Process Instance Ontology, which is used to fill the process patterns with concrete values to instantiate processes for a specific project.

All three process-related models inspired the design of the process model for a Digital Twin in Construction, which will be presented in the following section. When explaining the developed model in detail it will be further referenced which existing process model influenced which part of the digital twin process model.

3 Data Structure

3.1 Data Modeling

The core element of the elaborated model is how processes are represented. They are organized on three different levels. The topmost level is built by the work package, which holds only basic information about the production method, e.g., if building elements are cast in place or constructed by installing precast elements. After that, the level below is constituted by the activities, closely connected to the work package since the production method determines which individual construction steps are needed. Activities detail the type of material required, performance factors, and information about the planned start and end. In the given context, particular focus is put on the performance factors. As of the current state-of-the-art, they are constant values strongly dependent on the executing construction company. Usually, every company has its own formulas and databases to determine the performance factors for a specific process of a construction project. Except for the executing company, the general construction site conditions, building, and project-specific requirements influence the performance factors. In the end, they are used to predict the time that is needed for a specific construction step [5]. Deviating from the state-of-the-art, the presented process model lays the foundation to assign and evaluate performance factors more dynamically depending on the current situation on the construction site, for example, by assessing the current accessibility of required materials, equipment, and human resources. The third and final level is formed by the tasks, which are activities related to a single building element. They are connected to the corresponding building element, holding information about the as-designed and as-built geometry. Since occasionally building elements built as one element are modeled as several items, there is a possibility for aggregation with the classes building element and building element part. Through the relationship with the corresponding activity, a task gets information about which type of material is needed. Additionally, it has access to the needed amount of material because of its direct connection with the building element. These different levels of processes resemble a combination of the processes defined by Benevolenskiy's Process Pattern Ontology [1] and by DICO [2]. Benevolenskiy's process and subprocess are similar to the work package and the activity in the presented model, whereas DICO's activities and object activities partially coincide with the activity and task level.

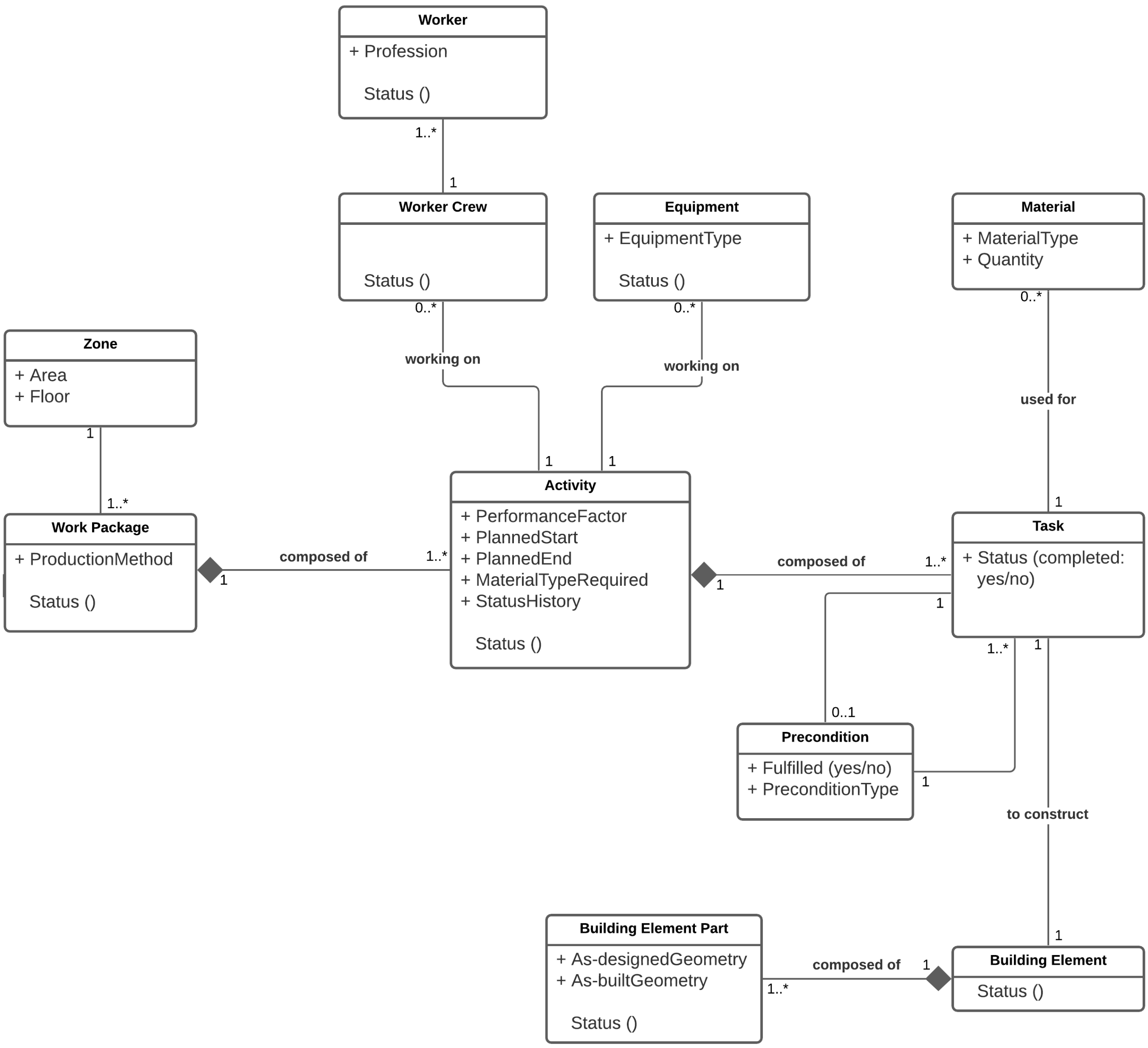

Figure 2: Data model for a Digital Twin in Construction

Tasks can also be connected to one or multiple preconditions. These conditions need to be met in order for a task being able to start. There are various types of preconditions: the availability of the needed material, worker crew, or equipment, or other tasks that need to be in a certain stage. In the case of tasks as preconditions, different types of relations, e.g., a start-to-start or an end-to-start relation, can be represented by the precondition with its required tasks and further specifications within its attributes. The same holds for activities and work packages. For the sake of clarity, the connection between the preconditions and the material, working crew, equipment, zone, and the process on the corresponding level are not shown in figure 2. Nevertheless, there are clear connection between them. Similarly to the activity flow concept of DICO which states necessary input parameters [2], here we allow different types of preconditions which show the input requirements that are necessary for a specific process to be able to start.

Furthermore, the tasks build the origin of the status concept, similar to the concept from Huhnt [6]. Every task has either the status "not started" or "finished". The status of the building elements and activities depends on the status of all tasks connected to it. Storing the history of status changes the activities, furthermore, allows the comparison of the as-planned with the as-performed information. This gives valuable insight when evaluating the construction performance. Other than that, material, workers, and equipment are part of the model. The materials are directly connected to tasks because volumetric information from the building element is needed. In contrast, workers and equipment are attached to the activity one level above since they are usually assigned to a specific type of work rather than a specific building element. Further differentiation between workers and work crews is made because, in practice, usually complete worker crews are assigned to activities rather than assigning work to each worker individually. Finally the zone describes the area in which a work package is executed. Like materials, workers, and equipment the zone can act as a precondition that needs to be available to allow the execution of a certain process.

An example of a fictitious construction project is given to clarify the difference between work packages, activities, and tasks further. For this, a floorplan of an office building (retrieved from [7]) is used to show what exemplary work packages, activities, and tasks could look like. On the uppermost level, a work package could be, e.g., *construct walls in the northern construction section on the first floor*. This would include all the walls in figure 3 within the blue area. It would already consist of how the walls will be constructed, e.g., by installing precast elements or a cast-in-place procedure. The walls in the southern construction section (yellow area) would be part of a separate work package that holds similar information. The activities one level below are directly connected to the work package. With the example from before the work package, *construct walls in the northern construction section* would have an activity for every construction step that is needed. In the case of a cast-in-place construction, an activity could be, *place the formwork for the walls in the northern construction section*. Activities for pouring concrete, removing formwork, and others would follow. All of them are concerned with the same set of walls. Every activity gets divided further into several tasks, where every task is assigned to one individual building element (see red areas in figure 3). This could result in a task like *place formwork for wall A2*. Although this division is not necessary from a schedule viewpoint, it helps with assigning the right type and amount of material to a process.

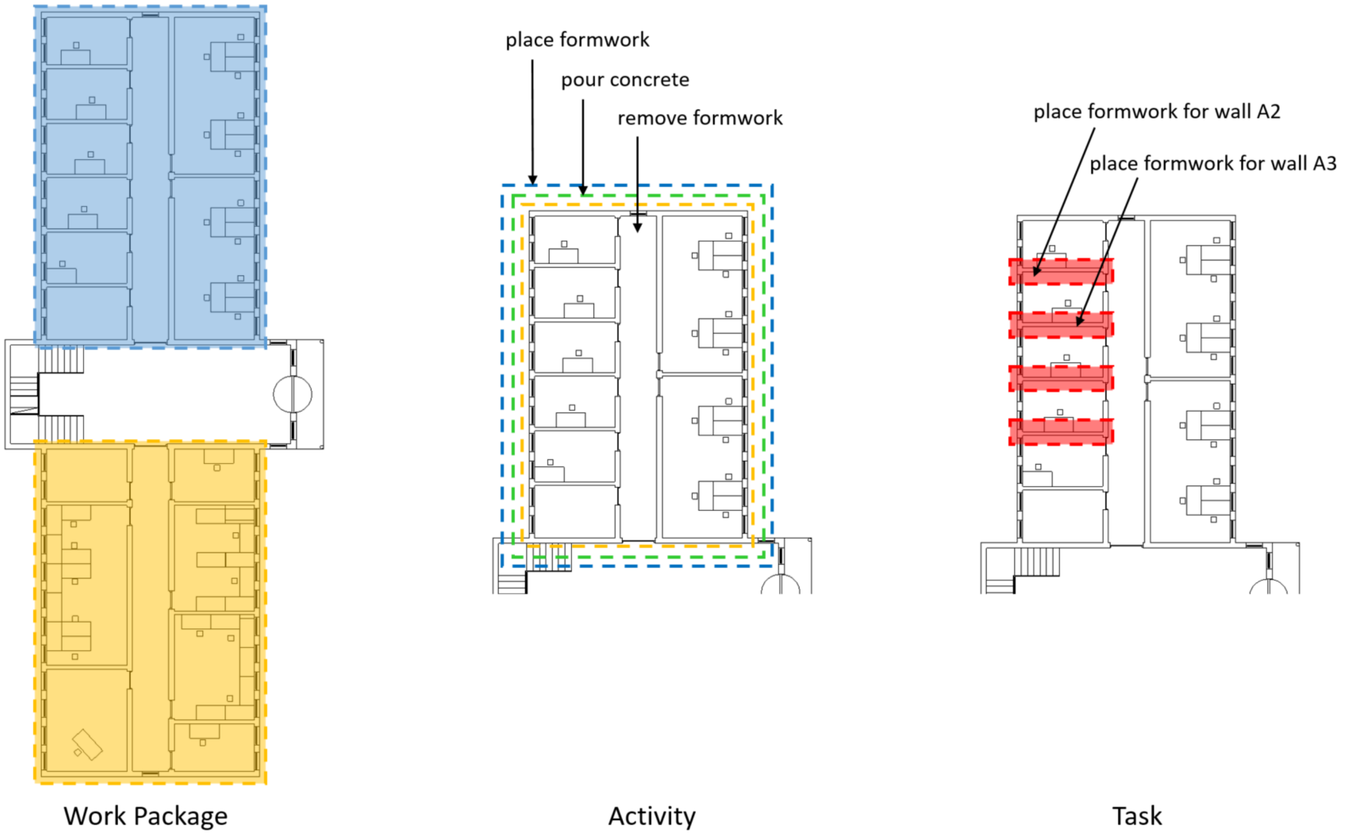

Figure 3: Different levels of processes in comparison

The proposed model has to be seen as the core elements of a construction digital twin. Depending on the use case its applied to more specific data models would need to be introduced that add domain specific elements but also have classes in common with the presented model to act as a connection point.

3.2 IFC Integration

Parts of the IFC file format can be reused to avoid defining civil engineering concepts that already have suitable models. Especially built elements are represented in a for a Digital Twin in Construction suitable way. Taking over this part would allow using IFC files as an input for the as-designed models with minimal effort. Even though the IFC format also includes definitions of processes, material, and workers, these sections of the model should be redefined to fit the digital twin requirements. Figure 4 shows a subset of the in IFC supported rooted items, which could be supported as a simplified IFC version. It mainly consists of the *ifcProject*, spatial elements which allow assigning objects to specific locations on the construction site, and built elements that allow the definition of, e.g., various types of construction elements like walls, slabs, and many others. Some of the building elements defined in IFC are specific to, e.g., maritime, road, or rail constructions [8]. Therefore they will not be relevant in the present context. The classes shown in figure 4 were specifically selected with the premise in mind to make use of the built elements defined in IFC and other than them to include only classes that are necessary to bring them into context. This primarily includes the spatial elements that define the spatial arrangement of objects within buildings and their immediate surroundings.

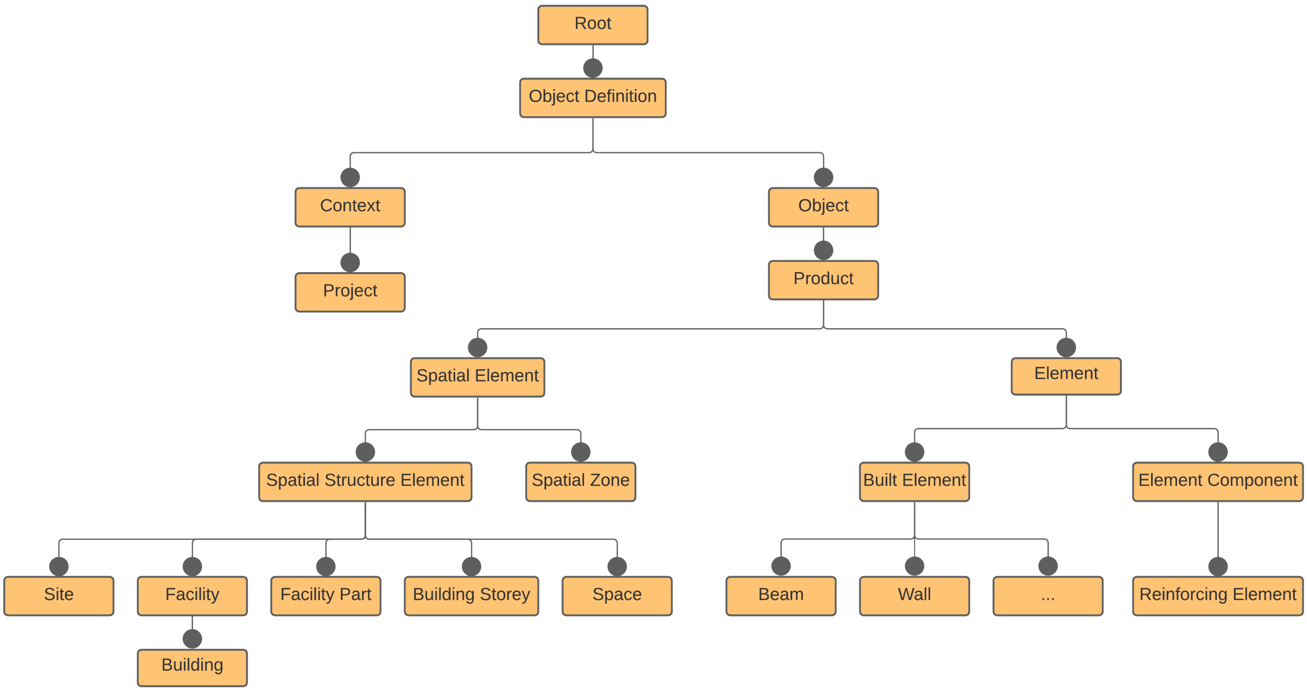

Figure 4: Simplified IFC for complementing a Digital Twin in Construction

Furthermore, simplifying the supported geometric representations should be considered. The IFC format specification includes many different geometric representations. For solid models, one can choose between explicit representations like Boundary Representation (BRep) or implicit representations like Constructive Solid Geometry (CSG) or sweep volumes. Depending on the exchange scenario, the used representation is to be adapted. The more complex geometric representations like CSG and sweep volumes generally come into play for design-to-design exchange [14]. This exchange scenario will not be of considerable relevance for the presented Digital Twin in Construction. The visualization and coordination exchange scenarios will be more relevant in the present context. For this reason, supporting mainly triangulations (*ifcTriangulatedFaceSet*) with local placement could be a feasible solution for the proposed simplified IFC version.

4 Conclusion and Future Work

This paper introduced digital twins in the realm of civil engineering and pointed out that there is substantial potential for improvement by applying digital twin concepts, especially during the construction phase. Furthermore, several process modeling approaches for construction processes were presented. These form the basis for the elaborated data model for a digital twin in the construction phase. In contrast to existing data models, it includes all vital parts of a Digital Twin in Construction, namely as-designed and as-built model as well as as-planned and as-performed model. With processes on three different levels, it can represent processes down to task-level and their main influencing factors. Additionally, it was shown how integrating existing standards like the IFC file format can benefit the model, especially for inserting model input. All in all, the presented model can build the foundation for collecting data from processes on the construction site that can be used later on to analyze construction performance closely. This could start with a retrospective analysis of the construction performance but could also evolve to a predictive analysis during an ongoing project with the means of artificial intelligence.

Since the goal of the presented data model is to be used in a digital twin environment where many different data sources come into play, it could be a reasonable step to create a new ontology, based on the model's classes and attributes, as part of the future work. Some classes could be adopted from existing ontologies, where others need to be newly defined. This ontological approach would allow to connect data from various sources and enable interoperability throughout the whole digital twin. Furthermore, the presented model has to be tested with real-world examples in order to refine it further. After that, a mapping from the IFC input files to the developed data structured has to be written, which will also be necessary for importing as-planned information like construction schedules.

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