Fabrication Information Modeling: Closing the gap between Building Information Modeling and Digital Fabrication

Martin Slepicka[1], Simon Vilgertshofer[1] and André Borrmann[1]

[1]Chair of Computational Modeling and Simulation, Technical University of Munich, Germany

martin.slepicka@tum.de, simon.vilgertshofer@tum.de, andre.borrmann@tum.de

Abstract -

Additive manufacturing (AM) is no longer a new technology and is already being used profitably in many sectors of the economy. AM is also becoming increasingly popular in the construction industry, and more and more research is focused on unlocking new building materials for AM. As a digital fabrication method, AM provides many new opportunities for the design of innovative and complex architecture and also has the potential to increase the productivity of the construction industry. However, the planning effort can increase accordingly and only experts in this field are able to apply this technology to construction projects. A methodology to improve planning efficiency has already been developed for the construction industry in the form of Building Information Modeling. In BIM, however, only conventional manufacturing processes have been taken into account so far, meaning that computer-aided manufacturing processes such as AM are still considered separately. Even more importantly, the granularity of product and process information is normally not sufficient for automated manufacturing. For this reason, this study proposes a framework, Fabrication Information Modeling, which can be used to generate BIM-supported fabrication information for the use of AM in the context of construction projects. Additionally to an expected reduction in planning effort, FIM would also provide the means of realizing an end-to-end digital chain from the first draft to the production of a construction project.

Keywords -

Building Information Modeling (BIM); Fabrication Information Modeling (FIM); Additive Manufacturing (AM); Automated Construction.

1 Introduction

The construction industry plays a key role worldwide, as it has a far-reaching impact on almost all other sectors of the economy and generally on everyone's quality of life. However, if we look at the technological development of the construction industry in recent decades, we see that it has lagged behind the progress of comparable industries (e.g. mechanical engineering) in certain areas. Modern methods and more efficient materials are used only to a limited extent, so productivity in the construction industry has been stagnant for years [1].

However, digital manufacturing methods, such as Additive Manufacturing (AM), have been enjoying increasing interest in the construction industry in recent times and their advantages have been recognized more and more. Using these technologies significantly more complex geometries or internal structures as well as variable material compositions for functionally activated components can be realized. But as products and construction projects become more and more complex, the corresponding planning and production effort also continues to increase, so that measures must be taken to compensate for this additional effort [2].

In order to better handle the ever-increasing planning complexity in the construction industry, the BIM methodology has been developed and is becoming more and more established for conventional construction. With this approach, all activities in the planning, construction and maintenance of buildings can be digitally represented and efficiently executed. Among other things, it is possible to model conventional construction processes beforehand on the basis of the digital building model. The granularity of the process description, however, typically remains on a rather coarse level, not going beyond complete tasks as 'place formwork' or 'pour concrete'. For digital manufacturing methods, such as AM, however, no such mechanisms have yet been implemented in BIM. For taking full advantage of a closed digital chain from design to fabrication, a much more precise or complete process description is necessary. Whereas in conventional construction, the predominantly manual work processes are described on a comparatively coarse level, as this information is typically interpreted by human workers, automated fabrication processes must include every detail and to be executable by the corresponding machines.

To realize a closed digital chain between digital design and digital manufacturing, this paper brings the concept of Fabrication Information Modeling (FIM), introduced by [3], into the context of civil engineering. Similar to BIM itself, FIM represents a planning cycle of its own in which manufacturing information is generated iteratively on the basis of BIM data and can then be represented digitally and executed in reality. Within this iterative design process not only the creation of fabrication information for a given BIM model will be possible but also interfaces for as-designed and as-built simulations will allow for optimization of the fabrication information and pre-built planning of post-processing information.

2 Background

As already mentioned in the previous section, the majority of manufacturing in the construction industry today is manual work. A continuous digital chain from design to manufacturing is thus not given even when BIM is applied. A fact that can be changed by integrating Digital Manufacturing (DM) methods into the BIM process. However, this turns out to be very difficult, even though both BIM-based design and DM are based on similar computer-aided methods and tools. BIM and DM each have a different focus, require different levels of detail, and provide constraints to each other. For similar reasons, Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) have long been handled separately in the mechanical engineering industry and only recently have been more closely connected in the wake of "Industry 4.0" concepts [4]. In the construction industry, automated manufacturing has been limited by, among other things, scaling problems and the lack of useful, processable materials, but attempts are now being made to develop comparable concepts to "Industry 4.0" [5].

However, research on this topic has so far mainly focused on the identification of manufacturing parameters, data exchange scenarios for such planning processes and a (semi-)automatic derivation of DM parameter sets and machine control code [6, 7]. A holistic system that can deal with different processing mechanisms and different framework conditions does not yet exist. The first question to be answered, though, is what exactly DM is. Zhou et al. define DM as a computer aided manufacturing process that combines handling of product, process and resource information, implementation of product design, function simulation and rapid prototyping as well as performing rapid production and quality control [8]. According to this definition, Fabrication Information Modeling (FIM) itself is a DM method but focused on the needs of the construction industry. In this paper, the concept is applied on Additive Manufacturing (AM) techniques, as they allow for a very high degree of automation. Accordingly, FIM is designed as a framework and underlying data structure for the generation and application of fabrication information to automate and digitize construction processes that can be executed using AM. Although AM methods are to be considered predominantly (cf. section 2.1), formative manufacturing, e.g., bending of rebars, and subtractive manufacturing, e.g., for removal of excess material in post-processing steps, must also be considered (cf. section 2.4).

The following sections provide a brief overview of the techniques and tools involved.

2.1 Additive Manufacturing (AM)

Additive Manufacturing (AM) is an overarching term for all methods in which components are created by the computer-controlled addition of material, usually layer by layer. For the manufacturing process, a AM print head is continuously moved into positions which describe the component geometry, and material is applied there accordingly. Objects printed in this way are characterized by a very high degree of geometric freedom [9].

AM methods that are particularly of interest for use in the construction industry are those that can process concrete or steel. Most of these methods – if classified according to the material distribution method – can be divided into the group of particle bed methods or extrusion methods. These two methods each come with their own advantages and disadvantages, as described below.

Particle bed methods: In particle bed processes, a flat layer of non-self-setting material (liquid or powder) is always first applied to the substrate (ground or previous layer) and then allowed to set only at desired points, either with a binder, chemical or physical selective activation. These steps are then repeated layer by layer until the print is ready. In a final step the excess material that has not been activated or bound is removed.

An important advantage of this technique is that the particle bed already provides a support structure and thus offers a very high degree of geometrical freedom and can produce objects with a very high surface resolution [10]. In some cases, however, it is problematic to remove particle bed residues from the finished printed component, e.g. if closed structures are to be created. Because of the particle bed, the possible construction space is limited in these processes and must be stabilized by outer walls.

Extrusion methods: Extrusion methods are those in which material is deposited in layers according to the specified geometry in a computer-controlled manner, usually by extrusion through a profiled opening [9]. However, the depositing process can take very different forms, depending on the specific variant and the material used.

An advantage of this method is that the desired object can be printed at high speed as well as in a particularly material-saving manner [10]. In addition, depending on the path guidance system, in-situ printing can be performed at building scale or printing can be performed in the existing building [11]. However, with this method, the material is not supported during printing and may have to be stabilized by extra support structures or the geometrical freedom is significantly limited.

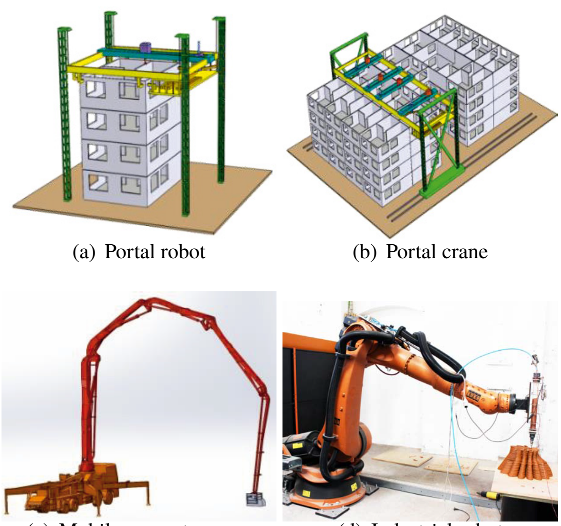
2.2 Transport mechanisms

Depending on the material, different transport systems, including mechanical screw conveyors or pneumatic pumping systems, can be used, which is why the material supply must also be planned for each AM application. If liquid or pasty material is used (as is the case with concrete), pumping systems via pipes and hoses are usually used [12]. In such a case, it must be planned for that the concrete must have a certain composition so that it is both **pumpable**, and subsequently **extrudable** and **constructible** [13]. For solids, they can be fed in the form of a wire or filament mechanically via a spindle, or as a powder mechanically by screw conveyors or pneumatically in a gas stream. For AM, therefore, not only must the material quantity be planned correctly, but volume flows must also be coordinated and controlled as a function of the print head movement. In the case of particle bed methods, using solids as the feedstock for material supply also adds a distribution mechanism that can be used to create a flat particle bed. For this purpose, a roller or a rake is often used, with which a particle heap applied at the edge is distributed over the entire installation space.

2.3 Machinery

Depending on the AM method, it is additionally possible to exchange the motion apparatus. This mainly concerns the extrusion methods, since in the particle bed processes only horizontal travel is necessary due to the particle bed and the installation space is limited. In particle bed processes, therefore, only gantry robots are used to move the print nozzle. However, there are different print head systems here, e.g. with a single nozzle or a multi-nozzle system, which must be controlled differently accordingly.

In the case of extrusion methods, the tool path can be made much more complex than in the case of particle bed methods, since the material is applied directly during the extrusion process and can thus be moved in all spatial directions — limited, of course, by material properties and the effect of gravity. For the extrusion method the selection of the machine for end effector positioning is decisive for how complex and spacious the print path for the production of an object may be. Various machine systems with different degrees of freedom of movement are available for the end effector positioning. Among them, gantry robots, single-axis mobile portal cranes, mobile concrete pumps, and industrial robots as well as a combination of these systems can be considered (cf. fig. 1), each with the corresponding advantages and disadvantages [12].



(a) Portal robot (b) Portal crane

(c) Mobile concrete pump (d) Industrial robot

Figure 1. Selection of possible manipulators for use in additive manufacturing [12]

2.4 Subtractive and Formative Manufacturing

In the context of this paper, the FIM concept is applied on AM methods. In various cases, however, a combination of AM with other techniques can be very useful. These include subtractive manufacturing methods, which remove material inversely to AM, e.g. by drilling, milling, turning or grinding tools. Furthermore, formative manufacturing methods should be mentioned, in which material is worked into a new shape by various tools, e.g. by bending.

Hack and Kloft have shown in a real-scale demonstrator how all three techniques can be used together to produce a steel-reinforced free-form wall [14]. For this purpose, the concrete core is manufactured with an AM process and provided with bent reinforcing steel (formative). Subsequently, the reinforcement is again covered with the same AM method and finally, in a finishing step, the surface is smoothed subtractively.

2.5 Machine control

Depending on the AM-method to be used, a certain movement pattern (toolpath) must be programmed into the corresponding machine and the associated material flows must be coordinated with this movement. In this context, the term machine control describes a sequence of instructions for machine tools or industrial robots, with which digital numerical information is converted into real axis movements [2]. For Digital Manufacturing Methods, these instructions are in general derived from geometric representations of the object that is to be manufactured, e.g. from the geometric information of a BIM model. This derivation involves two processes, a slicing operation that cuts a 3D geometric representation into 2D Slices (layers) and a path planning operation that generates a continuous pathway (toolpath) onto these layers based on how the inner structure of the object to be manufactured should look like. For both processes several algorithms already exist and may be chosen for typical hardware configurations and manufacturing methods.

A toolpath then has to be translated into machine specific control code. While some machines (predominantly CNC-machines) are able to interpret the Standard DIN 66025/ISO 6983, commonly known as G-Code, others are controlled with code written in a vendor specific programming language (most industrial robots). Another possibility to realize machine control is via "robot frameworks", like e.g. Player, YARP, Orocos, CARMEN, Orca, MOOS, the Microsoft Robotics Studio and Robot Operating System (ROS). All of these frameworks provide a collection of software tools, libraries, and conventions that can be used to control specific robots.

However, the processes described above (slicing, toolpath planning and machine control) cannot be carried out in just any way. Depending on the AM method, material and machine system used, the approaches can differ greatly and have different requirements for the component design, so that these steps can usually only be carried out by specially trained personnel. If a common platform or database is not used to support design and manufacturing, the two areas will inevitably be separated. In a holistic planning process, such as that promised by FIM, manufacturing problems can be addressed as early as the design stage by means of information feedback, thus reducing planning and communication efforts.

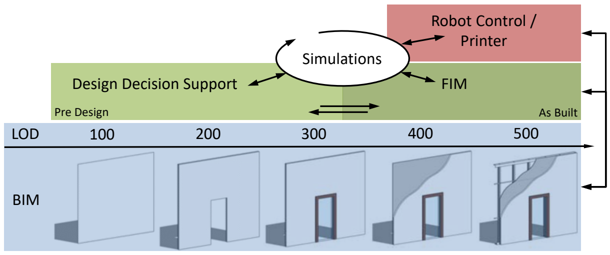


Figure 2. Positioning of FIM between digital design and digital manufacturing.

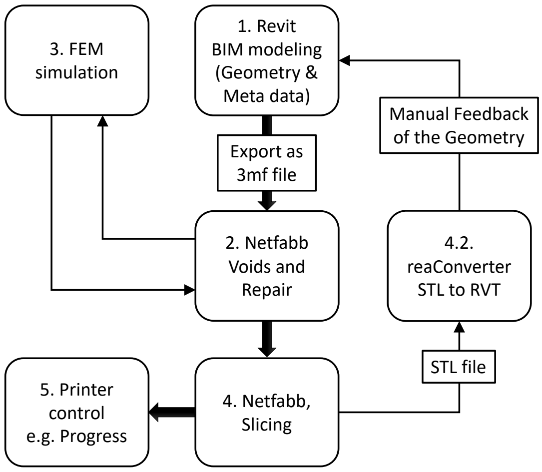


Figure 3. Data exchange Example: Separate software solutions for CAD and AM [16]

3 Fabrication Information Modeling

As described above, the gap between digital design and digital manufacturing is one of the obstacles preventing the wider use of AM methods. As a BIM-based DM methodology, FIM provides a common interface between these two disciplines and creates a shared planning and data basis. Figure 2 shows that FIM is positioned between BIM modeling and digital manufacturing. It is also shown that FIM is already linked to the early design phase of BIM via a so-called Design Decision Support System (DDSS) [15]. Fabrication Information Modeling (FIM) therefore describes, analogously to BIM, a methodology for the fabrication aware integrated design, construction and management of components in the context of an overall building using digital methods.

Even if the detailing in FIM takes place at component level, components that are related to each other in BIM must still be detailed in a linked way. Only through common boundary conditions for individual FIM modelings cross-component functional areas and a seamless assembly of the individual parts can be realized. At the component level, BIM data is used to model the parameters and processes involved in a fabrication aware manner and to detail the geometry to represent the material distribution as accurately as possible. For this purpose, we focus on formalizing all the information that has been summarized in section 2 to enable FIM to automate many of the detailing processes described above and to provide as much information as possible for the early design phase.

Without FIM, the presented conversion processes are tedious and involve different software solutions that are based on diverging data structures. Accordingly, a lot of file format conversions must be performed and by doing this, data gets lost on the way. In a study by Kruse, several scenarios of using BIM data to generate toolpaths and the corresponding machine control code were examined [16]. One of the respective data exchange scenarios is depicted in fig. 3, other examples only differ in certain details. In this particular example, first a BIM model was created (1) and the geometrical data was then exported to a 3MF-file to be processed further (semantic data is already lost in this step). Then the inner structure is generated (2), the resulting geometry sliced and the toolpath is planned according to the specified AM-Method (4) using a software which is specialized in preparing CAD models for 3D printing, in this case Autodesk Netfabb. If sophisticated simulations and optimizations are needed, the model can be exported for a detailed FEM analysis (3). After another export, the generated toolpath is finally translated into machine specific control code (5) which controls the machine movement for the printing process.

As can be seen quite clearly, this process consists of various individual steps and requires file conversions during which data gets lost. FIM is intended to improve this situation by creating a data basis that is made available to all operations involved in the planning process via appropriate interfaces. Through a carefully considered choice of the data structure and additional extensions, further operations are also made possible, such as the inclusion of as-built data for subsequent processing steps. If, for example, the fabricated object is captured directly during manufacturing process and the obtained as-built data is fed back into the FIM model, a digital twin (DT) can be realized. Usually, for the collection of Digital Twin data, the object is measured precisely with the help of sensors after manufacturing. Measuring the object during the manufacturing process and storing the data in the FIM thus provides a more precise and more correct digital replica than in many other interpretations of the term "digital twin".

Figure 4 shows the proposed process structure on the basis of the data just described. It is worth mentioning that data exchange does not necessarily have to be file-based. The data structure of FIM can also be defined in the form of a database (such as a graph database or a triple store) that can be accessed via web services.

Due to the fact that FIM is supposed to incorporate diverse AM methods, which can be very different in their complexity, the underlying data structure must be flexible enough to be able to incorporate different parameter sets. It may also be necessary to be able to switch between different parameter sets or to have the option of storing multiple sets if the suitability of different AM systems is being investigated during the design phase or if multiple methods are being used to manufacture a component.

These parameters that are to be modeled can be divided into three categories, the material parameters, process parameters and machine parameters. **Material parameters** describe the material composition and the expected properties of the material in the finished state. It should be noted that several materials can be used (e.g. concrete and steel) or one material can be graded in different ways (e.g. by changing the concrete mix ratio). **Process parameters** describe all adjustable values involved in the manufacturing process (possibly multiple parameters for several AM methods), such as speeds or tool dimensions. These parameters have to be coordinated during the design process. Last but not least, the **machine parameters** have to be considered. These simply describe the machine system to be used and thus define limit values for the process parameters.

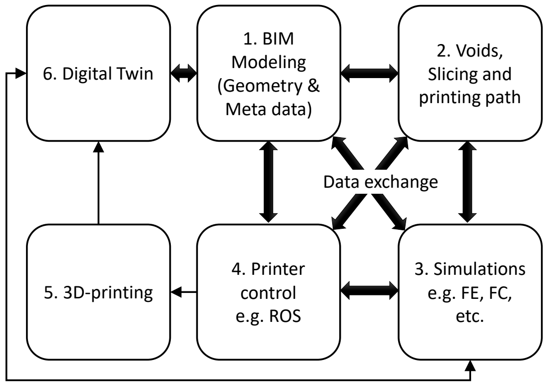


Figure 4. Data exchange scenario based on FIM.

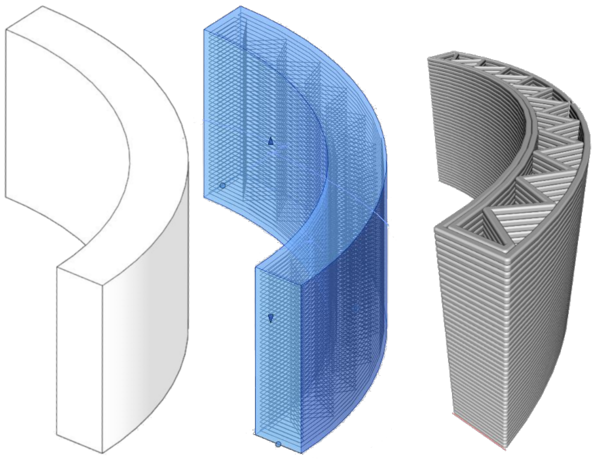


Figure 5. Detailing Example: BIM Model of a Curved Wall (left), generated printing path (middle) and generated 3D-Geometry representing the as-designed material distribution (right).

For detailing via the generation of a printing path, we created a prototype that can be used to create an interior structure in different variants for a BIM component controlled by a set of parameters fig. 5. The path planning tool was created in the Dynamo graphical programming interface for the BIM modeling software Revit. In addition, an exporter was implemented to add the path geometry to the existing IFC file for data exchange (see section 4). Furthermore, an algorithm was developed that can convert the generated printing path into a solid model via a sweep

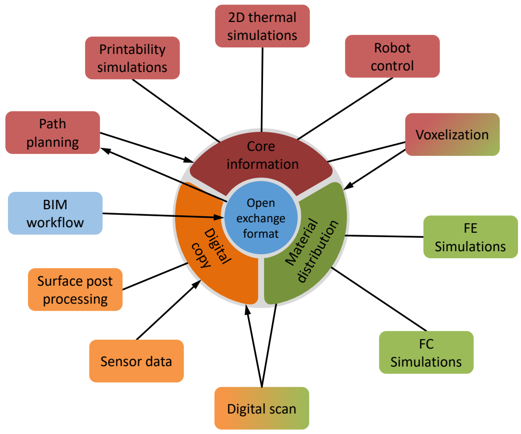


Figure 6. FIM data structure using an open interoperability standard.

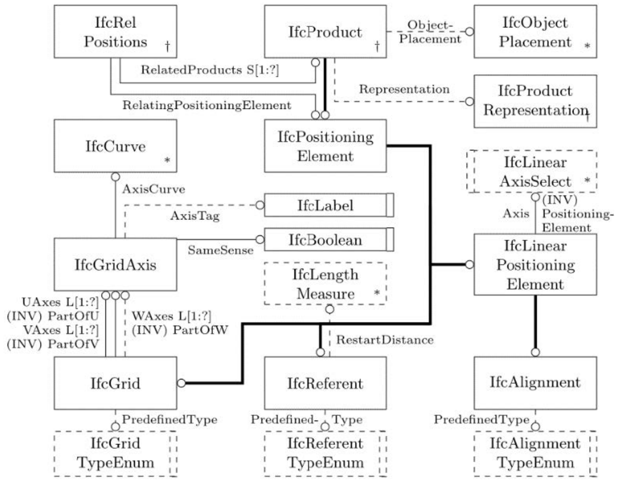


Figure 7. EXPRESS-G diagram of positioning entities from IFC4x3_RC1 that are relevant for FIM [21].

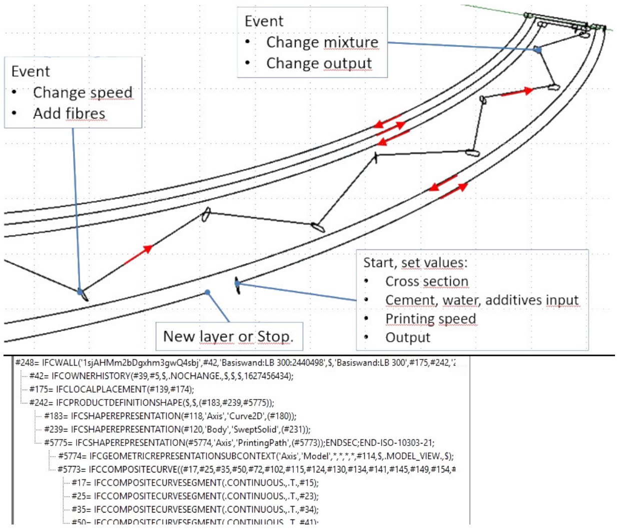


Figure 8. Visual Representation of an alignment curve and partial tree view of the corresponding IFC-file (same example as fig. 5).

operation, for the representation of the material distribution. In fig. 5, these levels of detail are lined up side by side.

A very well suited basis for the description of FIM data are open interoperability standards, such as STEP [17] or IFC [18]. The IFC standard is of particular interest in this context, as the most widespread and established format for open BIM data exchange [19] and corresponding importers and exporters exist for most BIM-capable software. In the following section, the IFC standard is used as an example to illustrate the underlying data structure of FIM. Similarly, the STEP standard would be a suitable choice, especially due to the fact that some implementations for AM have been studied already [20]. But due to the better availability of export/import tools and further reasons explained in section 4, we prioritize the IFC standard for our studies. However, this does not exclude subsequent investigations of the STEP standard.

4 FIM data structure

In principle, FIM can be implemented in any data model that can represent the parameters and geometries mentioned in section 3 (cf. fig. 6). However, since one of the objectives of the FIM methodology is a better integration of AM methods into BIM, it makes sense to consider an IFC representation of the involved data. For this, however, the question arises whether the IFC standard can represent all necessary manufacturing information, or whether an extension is necessary.

Comparing an AM process with a road construction project, many parallels can be discovered. The toolpath of AM is comparable to the Alignment along which a road is planned. Comparable to road construction, a lot of parameters must be referenced to the alignment (in case of AM the toolpath) and exactly for this purpose several Classes have been defined in the latest version of the IFC standard (IFC 4.3, cf. fig. 7).

A description of the printing process along the printing path can therefore be defined in the IFC format without definition of additional classes figs. 7 and 8. The printing path itself can be represented as `IfcAlignment`, a derived class of `IfcLinearPositioningElement`, which can be used to linearly position other objects to its axis. The axis is in turn described by the toolpath geometry (in this case via the class `IfcCompositeCurve`, the IFC version of a polycurve). Non-constant, linearly referenceable parameters that can change during the printing process, such as the material composition, the printing speed or the extrusion rate, can be linearly referenced along the `IfcAlignment` as common in road or railway design, e.g. via `IfcReferent` or via `IfcOffsetCurvesByDistance`. With `IfcReferent` its attribute `RestartDistance`, a parametric length measure, can be used along the corresponding alignment to, among other things, reassign a parameter value e.g. by means of a property set, or to append additional information at a specific position. Similarly, a list of distance values (offset) along the alignment can be specified with `IfcOffsetCurvesByDistance`. These distance values to the alignment can also be "misused" for AM purposes, e.g. to describe a changing parameter value. All constant parameters, such as machine parameters (machine type, arm length of the robot, etc.), can be represented as Property Set and the material parameters via `IfcMaterial` on the `IfcProduct` level.

Additionally to the information necessary for the AM process itself (toolpath and referenced parameters),the aforementioned information can be used to generate the more detailed geometrical description of the object that is to be manufactured, in the sense of as-designed geometry. To perform this detailing, the expected filament cross-section can be drawn along the tool path via a sweeping operation. This results in a three-dimensional geometry which very accurately represents the material distribution of the planned AM component and can be used for simulation purposes (e.g. for component optimization). In the IFC standard, such a geometry can be represented e.g. implicitly via an `IfcSweptSolid` instance, or, if this is implemented as part of the `IfcTunnel` extensions, as a Voxel model via the potential future extension in the form of the `IfcVoxelData` class.

Similarly to the "as-designed" material distribution model, "as built" information can be stored by scanning the object during the manufacturing process to capture the interior of the built object and referencing the data to the 3D representation of the object (preferably as voxel information). Using this data, already planned post-processing steps can be adapted to the exact geometry and further performance simulations can be executed.

The resulting data structure can be described as follows (cf. fig. 6). First, the data structure resulting from the BIM modeling is adopted (e.g. in the IFC standard) and the information necessary for applying the corresponding AM method (core information, shown here in red) is derived from the corresponding data and incorporated into the existing data structure. Based on the core information, a more detailed 3D model, the planned material distribution (shown here in green), is generated and integrated into the existing data structure for possible simulation purposes. This data set is optimized until it is ready for production and is finally expanded during printing to include the scan data, i.e. a digital copy (shown here in orange). The diagram also shows various interfaces to other operations.

5 Conclusion

AM represents an excellent method of producing prototypes quickly and inexpensively. Considering that a building is in most cases unique due to the individual conditions of its location and the decisions made during design, it is therefore only natural that 3D printing also represents a forward-looking technology for the construction industry. With significantly increased design freedom, there is the possibility that the appearance and function of modern buildings and their components will be fundamentally altered. However, the resulting additional expense is a major obstacle to increased use of additive manufacturing methods. Especially the combination of AM and BIM methods, as discussed in section 2, can remove this obstacle and bring many advantages analogous to the "Industry 4.0" concept. If FIM is implemented as described in sections 3 and 4, the planning effort, which is currently only manageable by planners with the appropriate expertise, would be significantly reduced. This could make AM technology much more attractive for the construction industry.

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