Construction Robotics (2022) 6:87–99
https://doi.org/10.1007/s41693-022-00075-2

REVIEW

Fabrication information modeling: interfacing building information modeling with digital fabrication

Martin Slepicka[1] · **Simon Vilgertshofer**[1] · **André Borrmann**[1]

Received: 22 February 2022 / Accepted: 3 July 2022 / Published online: 22 July 2022

Abstract

Digital manufacturing methods have been successfully used in different industries for years and have since had a positive effect on the development of their productivity. These methods offer significantly greater design freedom and make it possible to develop shape-optimized and function-activated components. In the construction industry, however, these technologies are only being used reluctantly, even though additive methods could make resource-efficient construction possible. The possibly decisive disadvantage of these methods is that a significantly higher granularity of product and process information is required, thus significantly increasing the planning effort. A circumstance that the framework described in this study, fabrication information modeling (FIM), could significantly mitigate by linking digital fabrication and BIM-based digital building design via a digital chain. For this purpose, FIM provides a methodology with which the information of a digital building model can be detailed, component by component, in a fabrication-aware manner. Based on the open exchange data format IFC, the FIM framework integrates seamlessly into the BIM context and enables automated detailing of the design information.

Keywords Building information modeling (BIM) · Fabrication information modeling (FIM) · Additive manufacturing (AM) · Automated construction

1 Introduction

The construction industry is of enormous importance for the global economy and generally influences the quality of life of all people. Construction projects account for about 13% of global GDP and employ about 7% of the working population (Mckinsey Global Insititute 2017). Despite these figures, the construction industry performs comparatively poorly in annual productivity growth. While productivity in the manufacturing industry increases by around 3.6% per year, in the construction industry, it is only around 1%.

Several reasons have been identified for these poor statistics, which have existed for years. Innovations take a long time to adopt (Mckinsey Global Insititute 2017). In the construction industry, for example, it has long been common to work with 2D modeling tools, and in some places, this is still the standard.

In contrast, 3D modeling has long been the standard in the manufacturing industry. Many mechanisms have already been developed to replace laborious and time-consuming manual work with fast and automated processes. With the concepts of Computer Integrated Manufacturing and later Industry 4.0, the manufacturing industry is also establishing ways to create a complete digital chain from design to production, including production planning, production monitoring, resource and project management (Lee et al. 2015; Makris et al. 2014). However, an important innovation being adopted step by step in the construction industry is the Building Information Modeling (BIM) methodology. It is based on the continuous use of digital data throughout the life cycle of a building (cf. Borrmann et al. 2018). Although

---

Simon Vilgertshofer and André Borrmann have contributed equally to this work.

✉ Martin Slepicka
martin.slepicka@tum.de

Simon Vilgertshofer
simon.vilgertshofer@tum.de

André Borrmann
andre.borrmann@tum.de

[1] Chair of Computational Modeling and Simulation, Technical University of Munich, Arcisstr. 21, 80333 Munich, Germany

BIM enables a higher level of digitization, automated manufacturing methods are not yet supported by this technology. Finally, since most work tasks on construction sites are still performed by hand in a tried-and-true manner, process automation, e.g., through the use of digital manufacturing technologies such as Additive Manufacturing (AM), could give the constructions industry's weak productivity a boost again.

However, automation in construction was constrained by scaling issues and the lack of viable, processable materials, among other factors. Over the past decade, many of these critical problems have been solved, and research on additive manufacturing in construction continues to advance (cf. Buswell et al. 2018). Since AM methods, such as "Contour Crafting" (Khoshnevis 1999) or Dshape (Dini n.d.), have become established, AM has attracted increasing interest in the construction sector. Many more methods and materials have been available since the first developments for AM in construction, and more new technologies are still being added. The industry has also recently recognized more and more the advantages that AM can offer. With AM, much more complex geometries and even internal structures with graded material compositions can be realized. However, in addition to other problems of the technology, such as the large-scale application of the implemented methods, the corresponding planning, and production effort is also significantly more complex, so measures must be taken to compensate for this additional effort (Hehenberger 2020).

Modern modeling methods, such as BIM, are essential to cope with this increased planning effort resulting from digital manufacturing. BIM offers the possibility of developing comprehensive end-to-end models across different stages (LoD) containing geometric **and** semantic information. This approach allows all building design, construction, and maintenance activities to be digitally represented and efficiently executed However, the BIM methodology needs to be extended to integrate digital manufacturing. Much more information needs to be modeled for a complete process description of an automated manufacturing process than for a rough description of manual tasks that human workers can interpret.

Therefore, to successfully establish Digital Manufacturing (DM) in the construction industry, the manufacturing methods need to be made more accessible, but also modeling methods for the corresponding fabrication information need to be seamlessly integrated into existing systems such as BIM. In this context, Duro-Royo and Oxman (2015) have already introduced the term Fabrication Information Modeling (FIM) for all industries as "[...] a methodology designed to bridge the gap between virtual design tools and advanced digital fabrication tools", based on selected examples. Slepicka et al. (2021) implemented an FIM framework specifically for the construction industry to generate manufacturing information for relevant digital manufacturing methods based on BIM data. Similar to BIM, this FIM implementation represents a planning cycle. The manufacturing information is generated iteratively based on BIM data and independently of the machine system used. Via various interfaces, the manufacturing information can then be used to support digital workflows, e.g., in various simulation and optimization processes, or directly for manufacturing by interpreting the information for the corresponding manufacturing system.

In this conference extension paper, based on (Slepicka et al. 2021), the FIM framework is described in detail, use cases are outlined, and a future outlook on the industrial application is given.

2 Background

FIM was designed as an interface between BIM-based digital design and Digital Manufacturing (DM) to enable a digital chain from design to manufacturing. Although both BIM and DM are based on similar computer-aided methods and tools, this is not a simple task. Both digital methodologies have a different focus, require different levels of detail, and are mutually dependent. In addition, DM does not represent a single manufacturing method but encompasses different technologies, with different parameters and constraints. Therefore, an overview of the relevant technologies is provided to describe the FIM framework, i.e., the data structure and data transfer methodology.

2.1 Digital design and digital manufacturing

BIM already represents a methodology by which a building model is created across the various planning phases to form a holistic model, enriched with high-quality geometric and semantic information, and used for construction and building maintenance (Borrmann et al. 2018). However, only traditional manufacturing methods have been supported when using BIM models in actual construction. For these—predominantly manual—manufacturing methods, it is at least necessary that construction plans can be derived from the digital model, which the workers can interpret. In order to use digital manufacturing methods, on the other hand, a much more detailed description of all the construction processes involved is required since automated manufacturing systems do not have sufficient independent interpretation capabilities. However, research on this topic has mainly focused on identifying manufacturing parameters, data exchange scenarios for such design processes, and a (semi-)automatic derivation of DM parameter sets and machine control code (Dörfler et al. 2013; Lu et al. 2015). FIM aims to bridge this gap between digital design and manufacturing by realizing a digital chain. Figure 1 illustrates this chain

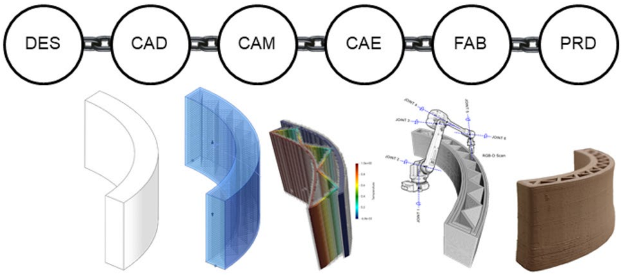


Fig. 1 Digital chain from design to manufacturing (after Duro-Royo and Oxman 2015)

from the design draft (DES) over computer-aided design (CAD), manufacturing (CAM), and engineering (CAE) to fabrication (FAB) and finally to the finished product (PRD).

Zhou et al. (2011) define Digital Manufacturing (DM) as a computer-aided manufacturing process that combines the handling of product, process, and resource information, the implementation of product design, function simulation, and rapid prototyping, as well as the implementation of rapid production and quality control. Many technologies are summarized under this umbrella term. However, for the explanations below, it refers primarily to those technologies that can automatically generate or process components based on digital data—using predominantly **additive** but also **subtractive** or **formative** methods. Due to the large scale of construction projects, methods belonging to the class of AM methods are particularly suitable for the construction industry. In addition, additive processes offer a very high degree of geometric freedom, as these methods also allow the internal structure of a component to be designed almost freely. However, subtractive and formative methods can also be of interest for post-processing or supporting processes. For example, it is possible to use subtractive processes to remove excess material after the AM process and formative processes to bend reinforcing steel into a precisely fitting shape (cf. Hack and Kloft 2020). Within the scope of this paper, only the AM methods are described in more detail.

2.2 Additive manufacturing methods and machinery

All AM technologies consist essentially of a moving apparatus (Machinery), an AM tool, and devices for material feeding (Transport mechanisms) (Slepicka et al. 2021). The tools are designed for different material deposition methods and specialized for different materials. However, methods that can be used to process construction materials (especially concrete, steel, and wood) are particularly suitable in the construction industry. These methods can be classified according to two essential and fundamental methods of material deposition, independent of the material supply and the movement apparatus. First, the **particle bed methods** need to be named. They involve selective activation (chemical or physical) of specific areas in a particle bed surface with activatable material. On the other hand, there are **extrusion methods** in which material is applied layer by layer via an extrusion nozzle. A review of these processes has been summarized by Paolini et al. (2019).

While in most particle bed processes, the motion apparatus (usually a gantry system), the tool, and the material supply are combined into one overall system for process-related reasons, extrusion processes can be combined with different motion and supply apparatuses. Machines with different Degrees of Freedom (DOF) for their movements, such as gantry systems (3 DOF), industrial robots (6+ DOF, cf. Zhang et al. 2015), or others (cf. Näther et al. 2017), can be used for movement, and different pumping and mixing systems for material supply. Depending on the motion apparatus used, the planning of manufacturing information becomes more difficult as the number of DOF increases. However, at the same time, the geometric possibilities in 3D printing also increase with more DOF.

To manufacture a component additively, it is necessary to continuously control the machines of the AM system since the material is to be continuously conveyed and distributed in a targeted manner during the process. Consequently, corresponding machine parameters must be controlled during the manufacturing process using a defined scheme, the printing path, which describes the machine movement. However, this printing path can look very different depending on the AM system. The printing path can be generated using various modeling methods. A previously designed 3D model is often translated into a printing path using 3D slicing and subsequent 2D path planning methods (Ding et al. 2016).

As mentioned earlier, some AM technologies already exist for practical application in construction, but it still takes specialists to use the machines employed. For such systems, the manufacturing information must be extensively modeled, and specialists must constantly monitor the machine during construction. This circumstance can be significantly improved with an interface linking digital design (geometric and semantic modeling) and digital manufacturing (modeling and executing fabrication information).

3 Fabrication information modeling

We define FIM as the representation of information necessary for the automated manufacturing of building components. It includes a fine-grained description of the artifact to be manufactured and the manufacturing process, including the types of machines employed and the dynamic parameters of their application. At the same time, the FIM is independent of the specific machines used—it is thus vendor-neutral.

It forms a layer of abstraction between high-level design information (BIM) and low-level machine instructions. This paper illustrates the FIM concept by applying it to an Additive Manufacturing process.

Using FIM, it is possible—within certain limits—to automatically derive manufacturing information from BIM data. By choosing BIM data structures as a basis for FIM, unnecessary data conversions will be avoided, and a consistent transition from design to manufacturing information can be ensured. Furthermore, this also allows "As-manufactured" information recorded during manufacturing with FIM to be used without conversion for subsequent BIM use cases, such as building maintenance.

Part of the FIM concept presented in this paper is that a printing path—enriched with enough additional information—can be applied to any machine system with suitable translation algorithms. In this sense, the FIM data can be translated for each machine system into machine or robot control instructions (digital numerical information, cf. Hehenberger 2020) that can be interpreted and converted into robot movement. If this information is stored in the FIM data structure, it can be used for simulations and referenced to sensor data. A significant advantage of FIM is that the modeled control data and intermediate results, such as layer data, can be used directly for various purposes with appropriate interfaces or interpreters. If the data are used directly for robot control, sensor data can be fed back into the FIM model during manufacturing and consulted for corrections.

The following will detail how manufacturing information can be derived from BIM data, how it can be structured, and how it can be used directly for manufacturing and other purposes.

3.1 FIM application range

To significantly reduce the manual effort required to create FIMs, an integral part of the framework is the objective to automatically derive the FIM representation from the BIM representation by applying rules and patterns that reflect the manufacturing knowledge.

However, an important question is at what stage of development a digital building model must be for manufacturing information to be (automatically) derived from it. Is it during or after the design phase has been completed? We consider both options. On the one hand, the geometry of the components to be printed must already be defined to create printing paths via slicing and path planning (see Sect. 2). However, on the other hand, a part can also be explicitly modeled for 3D printing in the early design stage using parametric design to take full advantage of AM (cf. Martínez-Rocamora et al. 2020).

Since this approach requires expert knowledge of AM methods, there are efforts to implement a BIM-based Design Decision Support System (DDSS) allowing even inexperienced designers to consider AM methods (Li and Petzold 2021). Fabrication Information Modeling (FIM) is not simply the creation of manufacturing information but a framework in which all parameters are iteratively optimized, different variants are evaluated comparatively, and feasibility is verified. It is a methodology for designing, constructing, and managing components in a manufacturing-aware manner for use with digital methods, such as AM. Figure 2 illustrates the involvement of FIM along a project's timeline and locates the framework between BIM modeling and digital manufacturing.

It is important to note that, due to the limited construction space of AM machines, the design of the manufacturing information for large-scale projects must be carried out on a component-by-component basis. Therefore, the actual FIM modeling does not take place on a project level but individually for each coherent printable section.

3.2 Information gap between BIM and fabrication

While the design of a component focuses on its form, function, and purpose, manufacturing a component depends more on the process description, including the development over time, material distribution, structure, and others. In addition, the design of a building focuses more on the functional composition of individual components (e.g., walls, doors, windows) than on the exact construction of the individual components. Therefore, unlike a manufacturing model, a BIM model does not usually require a detailed description of the structural makeup of individual components; it is sufficient to model the appearance of the components. For this reason, a transformation and enrichment of the information must be performed during the transition from BIM to FIM (cf. Fig. 4).

AM methods, as already described, offer the possibility of fine-tuning the material distribution in a component. This way, material gradations and purposefully placed cavities can be generated, which can significantly increase the functional spectrum of the corresponding component. If cavities

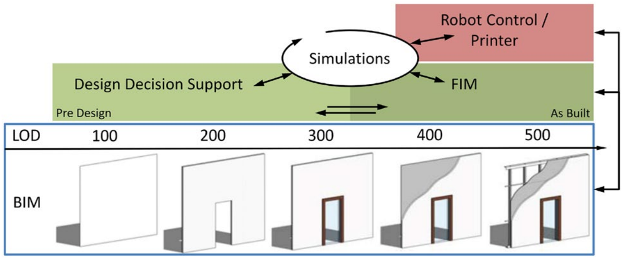


Fig. 2 Application range of FIM, interfacing digital design and digital manufacturing (cf. Slepicka et al. 2021)

are planned in a particular arrangement using so-called infill patterns, the component's thermal or sound insulation capacity can be increased, for example. Better thermal insulation performance can be expected with all three wall structures shown in Fig. 3.

One of the main tasks in creating the manufacturing model is to model suitable infill patterns for the corresponding component according to the functional and shape specifications from the design model. In addition, the robot movement of the AM system required for the realization of these structures must be derived, and corresponding material flows coordinated to ensure optimum print quality. As already described (cf. Sect. 2), the motion of the AM machine is described by a printing path that can be generated from the design model using various slicing and path planning algorithms. For example, the printing path shown in Fig. 4 was derived directly from the BIM model of the curved wall using a specially implemented algorithm.

Once generated, the printing path representation—an essential part of the manufacturing model—can be used to represent the manufacturing process (motion of the print nozzle) and describe the external shape and the material distribution. Furthermore, it is possible to reference non-constant parameters linearly, e.g., nozzle velocity or material flows, along with the path geometry, which can be used, e.g., to describe material gradations (varying concrete compositions) in the component or to perform 2D simulations. A 3D model can also be derived from the printing path utilizing a segment-wise sweep (assuming that the filament is deposited uniformly). It can be used for more sophisticated 3D geometry analysis and mechanical simulations for preliminary performance checks (Wassermann et al. 2020).

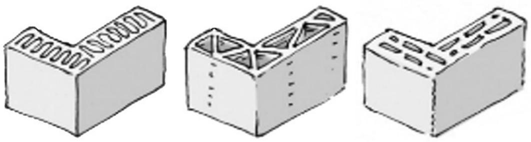


Fig. 3 Different infill patterns for the interior structure (after Kloft et al. 2020)

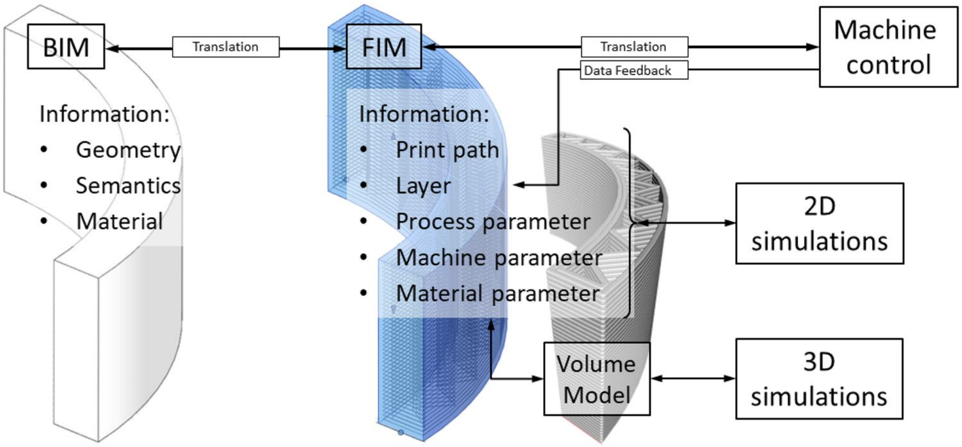
3.3 Automated detailing

As indicated in Sect. 1, the previously described manufacturing model can also be modeled without the FIM methodology; in other words, manufacturing can be performed separately from design, which is precisely the way AM technology is often used: First, an object is designed computer-aided, then this geometry data is converted into manufacturing data using other software, and finally printed by the appropriate AM system. A serious disadvantage of this procedure is that the corresponding software is changed several times—usually accompanied by a change in data representation—and thus, design and production are entirely decoupled. With this decoupling, it is not possible to feedback data and makes additional data exchange with, e.g., simulation software, difficult (Slepicka et al. 2021). This approach is acceptable for small projects and rapid prototyping if erroneous print results can be tolerated. For large-scale projects, such as those in the construction industry, the time and material required for manufacturing are very high, so it makes sense to manufacture only with an optimized data set.

The ability to detail components in a manufacturing-oriented manner, derived from and in conjunction with digital building models, is a vital advantage of the FIM methodology. Thoughtful choice of data structure and additional extensions (cf. Sect. 4) also enable other operations, such as adding as-built data for subsequent processing steps (Slepicka et al. 2021). When detailing the manufacturing model, the boundary conditions implied by the applied AM method can be directly fed back to the design model.

For example, walls can be divided into segments in the digital building model, but these segments do not meet manufacturing requirements. For example, in the case of a wall corner, the wall is modeled as two separate but adjacent wall

Fig. 4 FIM interfacing BIM with the fabrication mechanism and simulation functionality



segments with the BIM modeling tool *Autodesk Revit* (cf. Fig. 5, left), but this is not the case after manufacturing. For fabrication with AM, these two walls must be connected to form a contiguous corner using FIM and have to be considered one overall component. Furthermore, the increased design freedom provided by AM can be used at this point to improve the function of such a wall corner. For example, heat loss can be prevented more effectively at this point if the corner is round (cf. Fig. 5, right). In addition to the general shape of the wall corner, a specific cavity structure provides another thermal insulation effect (see also Dielemans et al. 2021). Different infill patterns that enable the component's increased insulation functionality was discussed in Sect. 3.2 and illustrated in Fig. 3.

Another advantage of the FIM methodology is that many of the detailing processes described earlier can be automated. However, it should be noted that the different AM methods may be of different complexity to control and may require different parameter sets. In FIM, however, the corresponding parameter sets for the different methods can be managed similarly. These parameters to be modeled can be divided into three categories: **material**, **process**, and **machine** (Slepicka et al. 2021). The machine parameters describe the specific limitations of the machines used. They represent value ranges within which the corresponding machine can operate and can be taken from the manufacturer's data sheet (cf. Sect. 4.3). The material parameters essentially represent the material composition, i.e., they describe the mixing ratio of the individual material components and can, for example, represent different types of concrete. In the case of AM, this is realized via material flows. The values remain constant if only one material is used throughout the printing process and change just if a material change is carried out in certain sections of the component (cf. Sect. 4.2). The process parameters describe values that affect the printing process (e.g., speeds or conveying rates). These values are usually non-constant but can be referenced linearly along the printing path since they depend on the print head's position, regardless of which AM method is used (cf. Sect. 4.4).

Nevertheless, some restrictions must be made for this. If AM systems differ too much, e.g., due to different fundamental principles or if the available build space differs significantly, it may be necessary to create different FIM variants. A more important fact is that since AM processes can produce objects with very complex geometries, the possible applications of these processes are very diverse. However, at the same time, there are also many different ways of setting the parameters. Therefore complete automation of data generation is only possible in certain scenarios, e.g., when modeling a specific component type using predefined parameterizable infill patterns (cf. Sect. 3.2 and Figs. 3 and 4).

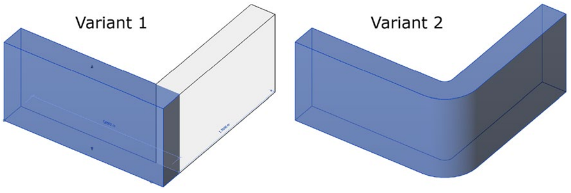


Fig. 5 BIM model of a wall corner modeled as two separate segments (left) and form optimized for 3D printing as a single component (right)

However, not only the choice of the AM System or the variety of application scenarios may cause difficulties. For specific design reasons, the FIM model must be checked for feasibility, e.g., if high overhangs are planned. At the same time, different slicing methods must be evaluated in comparison if necessary (see Sect. 2). In the case of high overhangs, for example, it is advisable to define non-planar layers since the number of support structures can be reduced (Mitropoulou et al. 2021). Process-related adjustments may also be necessary, e.g., a C2 continuous printing path (no kinks in the path geometry) is preferable to allow the robot to move as smoothly as possible (preservation of acceleration, cf. Ravankar et al. 2018). Likewise, it may be advantageous to develop a velocity profile in conjunction with the print path, for example, to take advantage of the curing time of the concrete to achieve an optimal layer-to-layer bond (Babafemi et al. 2021; Wolfs et al. 2019). All of these constraints represent optimization problems that cannot simply be solved in one detailing step when creating the FIM model but have to be solved in many iterations of the model.

3.4 FIM use cases

For FIM, similar to the BIM methodology, use cases can be defined as the purpose for which the corresponding data are created and used. These use cases allow FIM-related tasks to be better structured and possible interfaces to be clearly illustrated. Figure 6 presents some of these use cases, visualizing many of the processes described in the previous sections. Starting from a BIM model, shown as the central item in Fig. 6, all other manufacturing-related information and tasks are built around it in separate data branches. The FIM data can be divided into three categories, as shown in Fig. 6. The first category is the core information, which is necessary to be able to perform a manufacturing process. The second category is focused on the material distribution, which is derived from the core information and represents an "as-designed" solid model. Finally, the third category is the digital copy, i.e., data collected during or after manufacturing. It represents an "as-manufactured" model.

The core information in this context is the printing path and all parameters that can be referenced. As mentioned earlier, various path planning methods are used to create this information; velocity profiles can be created and other

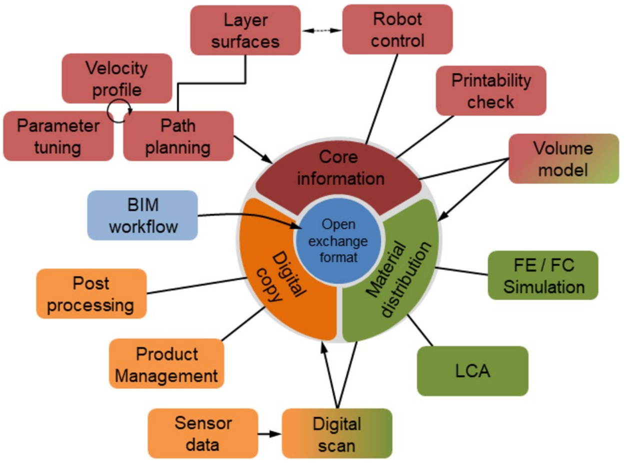


Fig. 6 FIM use cases

parameters adjusted in separate steps. For complex, multi-DOF robotic systems, a different design of the layer geometry can also be performed (see Sect. 3.3), on which the path planning is subsequently based. Once this information has been created in sufficient detail, it can either be used directly to derive machine control code and a process plan or compiled into a solid model (material distribution, "as-designed" model) for simulation purposes.

Using the "as-designed" model, complex simulations, such as finite element (FE) or finite cell (FC) methods, can be performed to estimate the functional capabilities of the component, or a life-cycle analysis can be carried out. In addition, this model represents a reference model of sorts, i.e., the "nominal" state of the component, which can later be compared with the "actual" state. This comparison can be made provided sensor data are returned to the FIM model during or after manufacturing ("as-manufactured" model). Corresponding mechanisms for creating a digital copy of the printed part are part of ongoing research work and, therefore, not yet fully integrated into the FIM data structure. However, as a component manufactured by AM methods is built up layer by layer, there is a unique opportunity to scan the component's interior using sensors. Such data can then be used to generate a Digital Twin (DT) and provide a much more complete picture of a component than if only a pure surface scan of the finished component is performed. If necessary, this can also be used to identify possible weak points in the component and to plan possible post-processing steps.

4 FIM framework

As mentioned before, FIM represents an interface between BIM and DM. At the same time, this also means that the data generated during the corresponding modeling process must be easily accessible to various software systems—such as CAD, CAM, or robot control software. In Sect. 3.3, a key advantage of FIM was that manufacturing information could be modeled based on digital building data (a BIM model) with no unnecessary conversions. These are the main reasons to design the FIM data structure based on the well-established BIM data model named Industry Foundation Classes (IFC). The open, international standardized data model IFC (ISO 16739) allows the exchange of vendor-neutral building information models across different software platforms (cf. Borrmann et al. 2018, pp. 81–126). Other comparable data models, such as STEP (ISO 10303), are also conceivable and have already been evaluated for use with AM (Rodriguez and Alvares 2019).

Nevertheless, IFC offers more advantages, as explained in the following. One is that many data structures needed to enable the mechanisms described in Sect. 3 are already implemented in IFC. It is worth mentioning that data exchange does not necessarily have to be file-based. The data structure of FIM can also be used to build a database (such as object-oriented databases, graph databases, or a triple store) that can be accessed via web services.

The actual modeling of FIM data happens for a building model component by component, i.e., separately for each individual AM component that a continuous print can create. Each such component is thus represented in a separate FIM project since the construction plans of other components in the same BIM project are not directly relevant to its production. However, components nearby (e.g., physical contact) may impose constraints, such as the type of interface to that component. To address this, dependencies from FIM to FIM must be linked across projects. Only through shared constraints for individual FIM modeling can cross-component functional areas and a seamless assembly of the individual parts be realized. Mechanisms that enable such a linkage have not yet been implemented for FIM but have been investigated in the context of multi-level of development (LOD) models (Abualdenien and Borrmann 2019; Abualdenien et al. 2020; Chindanonda 2019). Thus, linking different FIM projects is possible (cf. Sect. 4 for data structure reference). In the same way, it is conceivable that different FIM variants can be linked, for example, when adaptive detailing strategies are applied, and different variants are compared and evaluated (cf. Zahedi and Petzold 2018).

The FIM data structure is presented in more detail in the following, subdivided according to the different parameter classes. A FIM model created for a component represents a separate project (`IfcProject`), and each contains the description of a component (`IfcProduct`). Furthermore, different materials (cf. Sect. 4.2), AM machines (cf. Sect. 4.3), and processes (cf. Sect. 4.4) can be modeled and related to the component. The construction site environment (`IfcSite`), which describes the surrounding of the component, was not considered in the current FIM concept and is therefore not modeled.

4.1 Printing path and layer

As an integral part of a FIM model, the implemented data structure for the representation of printing paths is described first. Since the printing path describes the layer-by-layer motion sequence of the printhead, the corresponding geometry can be represented as a curve and modeled separately for each layer. The printing path is usually irregularly curved for components with complex internal structures, which is why it usually has to be modeled in segments rather than as a continuous curve. In addition, each layer can be described by a surface representing a slice through the component to be printed. How this cut is executed can be modeled in a separate design process, as indicated in Sect. 3.3, and need not necessarily be planar.

In the FIM data model, the curve geometry is represented as `IfcCompositeCurve`, which is a curve composed of different curve segments. However, the curve alone cannot fully represent complex motion patterns, such as those of an industrial robot. It can only be used to describe the position of the printing nozzle, but a direction vector is also required for its orientation. Nevertheless, suppose the composite curve is connected to the layer surface (shared parameter space, see Fig. 7). In that case, the surface's normal vector can act as an orientation vector at the corresponding parameter positions of the curve. Therefore, for resolving complex geometries, `IfcCompositeCurveOnSurface` is used.

In this way, one layer at a time will be represented. The entire component, represented as `IfcProduct`, printed layer by layer, can then only be understood as an assembly of the individual layers (cf. Fig. 8). In the FIM data structure, a layer is thus represented as a separate element, which can be assembled with other layers via an aggregation relation to form the complete part. In the IFC data schema, there is currently no separate entity for this element, but for the time being, the class `IfcProxy` can be used here as a workaround. Figure 9 shows an example IFC file for this, in which a wall (in the file an `IfcWall`) with a zigzag inner structure was represented in assembled layers. This assembly was later used to test 3D printing with clay at a model scale.

4.2 Material parameters

How different building materials can be represented is already part of IFC via the class `IfcMaterial` and can be used analogously, provided that the material composition remains constant over the entire print object. `IfcMaterial` can describe homogeneous or inhomogeneous substances and represent material properties via PropertySets (buildingSMART 2021). One or more materials can be assigned to a component. However, if the material in the component is graded, a representation with a simple assignment is no longer possible. A precise representation of material transitions is not yet provided in IFC.

However, a material mixture (e.g., concrete) can also be described as one or more material flows that vary across the

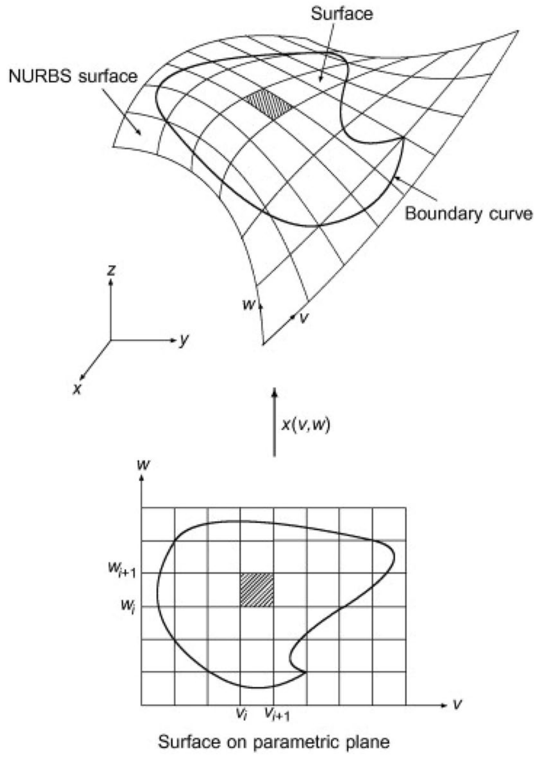


Fig. 7 Curve on a NURBS surface using the same parameter space—here *v*,*w*. (taken from Zienkiewicz et al. 2013)

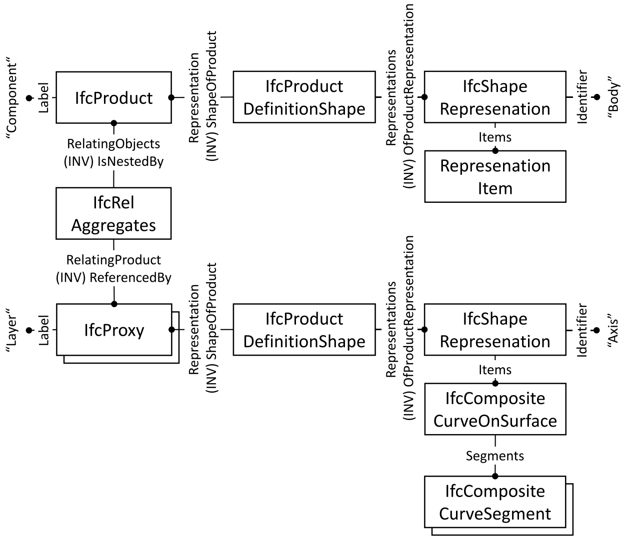
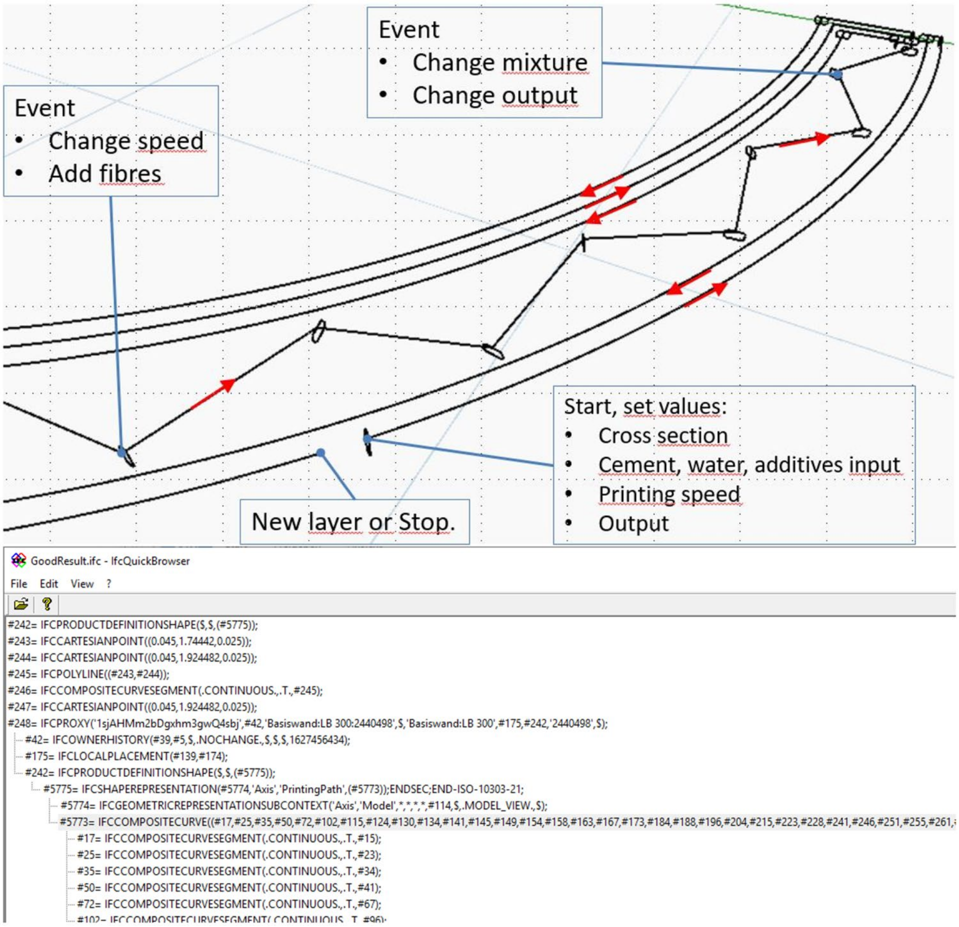


Fig. 8 EXPRESS-G diagram of the component representation



```
#242= IFCPRODUCTDEFINITIONSHAPE($,$,(#5775));
#243= IFCCARTESIANPOINT((0.045,1.74442,0.025));
#244= IFCCARTESIANPOINT((0.045,1.924482,0.025));
#245= IFCPOLYLINE((#243,#244));
#246= IFCCOMPOSITECURVESEGMENT(.CONTINUOUS.,.T.,#245);
#247= IFCCARTESIANPOINT((0.045,1.924482,0.025));
#248= IFCPROXY('1sjAHMm2bDgxhm3gwQ4sbj',#42,'Basiswand:LB 300:2440498',$,'Basiswand:LB 300',#175,#242,'2440498',$);
  #42= IFCOWNERHISTORY(#39,#5,$,.NOCHANGE.,$,$,$,1627456434);
  #175= IFCLOCALPLACEMENT(#139,#174);
  #242= IFCPRODUCTDEFINITIONSHAPE($,$,(#5775));
    #5775= IFCSHAPEREPRESENTATION(#5774,'Axis','PrintingPath',(#5773));ENDSEC;END-ISO-10303-21;
      #5774= IFCGEOMETRICREPRESENTATIONSUBCONTEXT('Axis','Model',*,*,*,*,#114,$,.MODEL_VIEW.,$);
      #5773= IFCCOMPOSITECURVE((#17,#25,#35,#50,#72,#102,#115,#124,#130,#134,#141,#145,#149,#154,#158,#163,#167,#173,#184,#188,#196,#204,#215,#223,#228,#241,#246,#251,#255,#261,
        #17= IFCCOMPOSITECURVESEGMENT(.CONTINUOUS.,.T.,#15);
        #25= IFCCOMPOSITECURVESEGMENT(.CONTINUOUS.,.T.,#23);
        #35= IFCCOMPOSITECURVESEGMENT(.CONTINUOUS.,.T.,#34);
        #50= IFCCOMPOSITECURVESEGMENT(.CONTINUOUS.,.T.,#41);
        #72= IFCCOMPOSITECURVESEGMENT(.CONTINUOUS.,.T.,#67);
        #102= IFCCOMPOSITECURVESEGMENT(.CONTINUOUS.,.T.,#96);
```

Fig. 9 Example FIM model for an extrusion print of a curved wall. Only one print layer is displayed (cf. Slepicka et al. 2021)

printing path. In this way, it can be derived directly from the FIM model how the conveying rate of the material supply must be controlled. How this is realized in the FIM data structure is analogous to the variable process parameters and is described in detail in Sect. 4.4.

4.3 Machine parameters

Machine parameters are used to describe AM systems in detail. Each system has different properties affecting logistics, material usage, build speed, and other parameters. The parameter ranges within which the corresponding machine can operate are particularly interesting to the manufacturing process. For example, robotic systems have a specific maximum range of motion, limiting the build space and thus defining the maximum component size. Extrusion systems, for example, may be limited in their ability by the material feed system's minimum or maximum feed rate, the maximum axis speed, and acceleration. As should already be apparent, these parameters strongly influence the printing path and process parameters. The machine parameters represent limit values that must be considered when modeling the printing path and the process parameters. For this reason, different FIM variants may have to be generated for machines with very different limit values.

Depending on the AM system, one or more machines may be involved. In the case of an extrusion system, an extruder tool, a machine for motion, and a material feeder is needed. Each machines is described in FIM using the IFC class `IfcConstructionEquipmentResource` (cf. Fig. 10). This class is intended to describe construction equipment and can be used directly to describe AM equipment. For a more detailed description, the corresponding machine parameters are appended to the previously mentioned class as `IfcPropertySet`. Subsequently, an `IfcPropertyBoundedValue` can simply be created for each of the previously mentioned value ranges. Furthermore, the machine can be assigned to a print task (cf. Sect. 4.4) by the relation `IfcRelAssignToProcess` and thus indirectly associated with the print path.

4.4 Process parameters

For the design of the printing path, the elements provided by the IFC data model for roadway/railway design are employed, particularly the alignment entities. While road

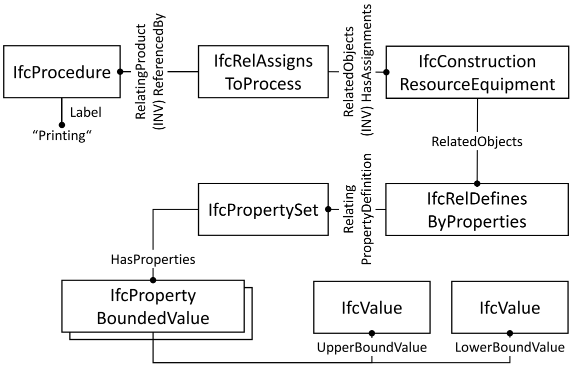


Fig. 10 EXPRESS-G instance diagram of relevant entities describing an AM machine and its assignment to the respective processes

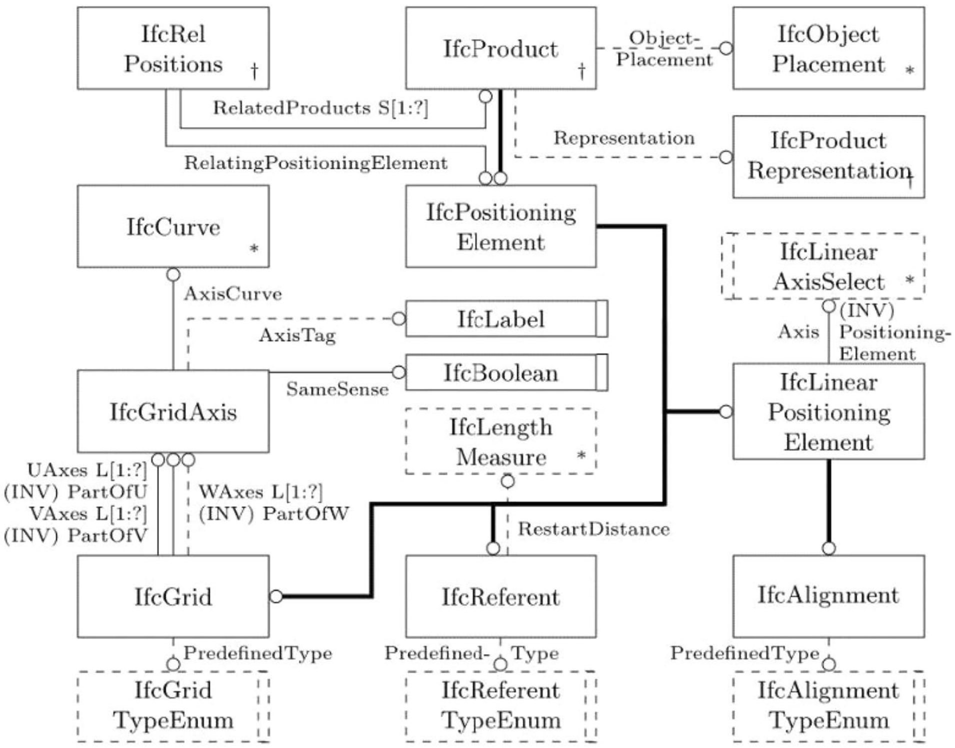
planning involves planning parameters, such as superelevations or elevations, AM process planning requires planning nozzle velocities, material flows, and printing sequences. Parameters, i.e., the nozzle velocity or the material flows, can therefore be linearly referenced to the path geometry, just as the superelevation is referenced to the roadway. For such referencing, some classes have been defined in the current version of the IFC standard (IFC 4.3, see Fig. 11). Therefore, no new IFC classes must be defined to represent non-constant process parameters.

The printing path, modeled layer by layer as an `IfcCompositeCurve` (cf. Sect. 4.1), can be defined as an `IfcLinearPositioningElement` and be used to position other objects to itself linearly. Any non-constant parameters that can change during the printing process, such as the printing speed or the extrusion rate, can be referenced along with the positioning element, i.e., the print path.

There are several options for this, which can be applied depending on the type of parameter change, e.g., the IFC class `IfcReferent` can be used to trigger parameter changes at specific points in time. Alternatively, a functional gradient can be represented along the printing path by linearly referencing another `IfcCurve` representing the parameter variation over the entire parameter range of the printing path (cf. Fig. 12).

Another process parameter that must be modeled is the print sequence. Sequencing is essential when further segmentation of the printing path's layers is necessary, e.g., if there are openings in the component. Usually, these segments cannot be printed in direct succession. As with the other process parameters, there are already defined IFC classes for sequence modeling. For this purpose, the entire component to be printed is assigned to an `IfcProcess`, more precisely an `IfcProcedure`, which describes a coherent set of instructions. Just as the component is divided into individual layers (cf. Sect. 4.1), the corresponding procedure is divided into individual tasks (IfcTask), each assigned to a layer or a layer segment. The execution order of the individual tasks is then modeled via the `IfcRelSequence` relation (cf. Fig. 13).

Fig. 11 EXPRESS-G diagram of positioning entities from IFC4x3_RC1 that are relevant for FIM (Jaud et al. 2021)



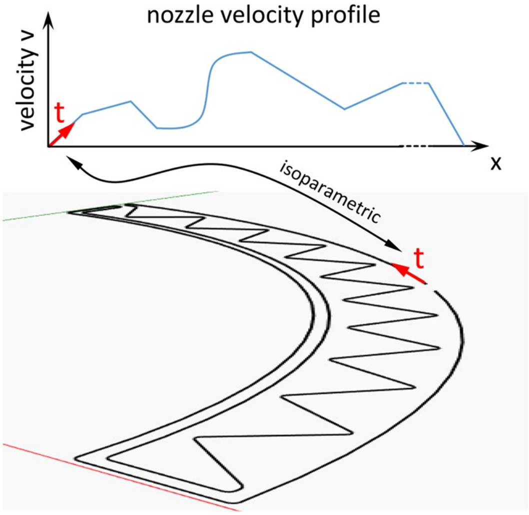


Fig. 12 Qualitative example of non-constant parameter modeling using an `IfcCurve` that is "isoparametric" to the print path

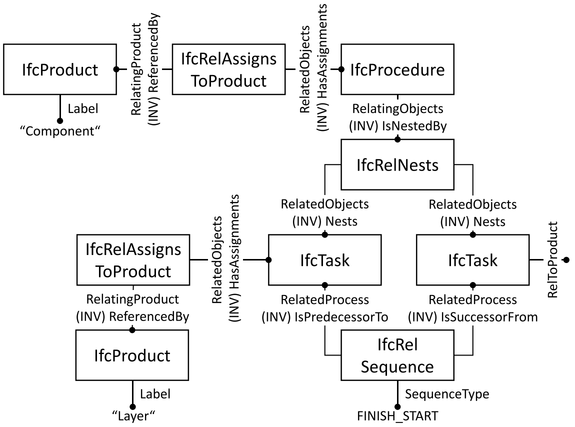


Fig. 13 EXPRESS-G instance diagram of relevant process modeling entities

5 Proof of concept

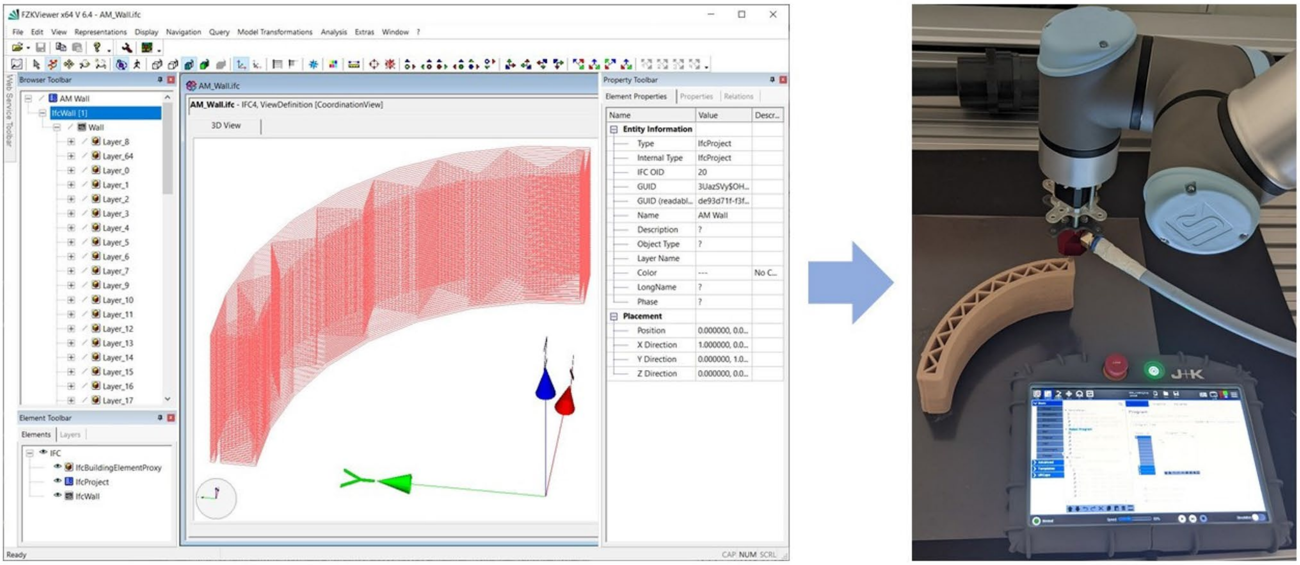
To illustrate the generation of a FIM from a BIM representation, a software prototype for the automated generation of a printing path was created by Slepicka et al. (2021) that allows the creation of an interior structure in different variants for a BIM component controlled by a set of parameters (cf. Fig. 4). The path planning tool was developed for the BIM modeling software *Autodesk Revit* using its graphical programming environment (*Dynamo*). In addition, an exporter was implemented to create an IFC model for data exchange based on the data structure described in Sect. 4. These data were then used for model-size prints using a *UR10e* robot with a clay extruder tool (see Fig. 14). As depicted in Fig. 14, we implemented a tool that automatically translates the curve geometry into an executable robot control script written in *URScript*. In addition, we have also tested other robot control options based on this model, i.e., a direct translation to G-Code and online robot control via a socket connection and piecewise transmission of curve segments embedded in *URScript* snippets. A significant advantage of the proposed IFC data structure is the ability of reading the data in different ways, with different control frameworks (e.g., the Robot Operating System, ROS) and interpreting it for different concrete printing systems. For example, the path can be read as individual segments that are translated into specific control statements (e.g., in *URScript* with `moveL`—linear movement—or `moveC`—circular movement—commands). Another interpretation method is to decompose the path into individual waypoints and send them to the robot piece by piece, with a freely selectable degree of resolution. For real-time data exchange with the robot, the robot's position can be controlled, for example, at a clock frequency of 500 Hz based on the model data. The model can be updated with feedback information at the same frequency.

Furthermore, an algorithm was developed to convert the generated printing path into a solid model representing the material distribution via a sweep operation. This 3D representation was converted into an STL file and used for 3D thermal simulations (cf. Aninger 2022). Although the results met expectations, we have not yet verified the results in an appropriate experiment.

6 Conclusion and outlook

AM technologies are said to have many advantages. This technology is expected, among other things, to help make construction significantly more resource and time-efficient by automating what used to be primarily manual work processes. Thanks to the high degree of geometric freedom, components can be optimized in terms of shape, and functions can be integrated, saving material in many places and limiting the use of composite materials. However, although this technology has been attracting increasing attention over the past 20 years, it is only used in isolated cases in construction projects. Unfortunately, the increased geometric freedom is accompanied by a much greater design effort, as indicated in Sects. 1 and 2, for which there are currently no sufficiently supportive software solutions. Currently, when AM is used, production planning must be carried out in a separate step in addition to the conventional construction planning.

With FIM, all planning processes required for building with AM can be integrated into the regular BIM



Name	Value	Descr...
Entity Information		
Type	IfcProject	
Internal Type	IfcProject	
IFC OID	20	
GUID	3UazSVy$OH...	
GUID (readabl...	de93d71f-f3f...	
Name	AM Wall	
Description	?	
Object Type	?	
Layer Name		
Color	---	No C...
LongName	?	
Phase	?	
Placement		
Position	0.000000, 0.0...	
X Direction	1.000000, 0.0...	
Y Direction	0.000000, 1.0...	
Z Direction	0.000000, 0.0...	

Fig. 14 Created IFC model (left) and printed model (right)

workflow. Provided that decision support tools are used (cf. Sect. 2.1), AM-related constraints can be incorporated in the early design phases. Due to the IFC-based data structure, unnecessary data conversions are eliminated, and the generated model data are directly linked to the building model, which can significantly reduce this additional workload by avoiding unnecessary work steps.

In contrast to other AM solutions, FIM also exposes intermediate steps such as slicing and path planning and makes the corresponding data available to the designer. Accessing this data makes it possible to make subsequent changes to AM paths that have already been created, for example, if additional cavities are required for piping or cable ducts. Furthermore, using the FIM data as direct input for the manufacturing system with a suitable interface is possible. This way, machine information can be fed back to the FIM directly during printing. Based on this feedback, it is possible to adapt the planned paths to any defects in the currently printed object, adjust the model accordingly, and, if possible, learn from the recorded defects for future AM projects. In addition, interfaces to simulation software and data feedback mechanisms are being developed for FIM. These interfaces allow direct evaluation of manufacturing data before starting the production process. Therefore, FIM could accelerate the development of AM and make its use in the industry more attractive.

Acknowledgements The research presented is part of the Transregio 277 'Additive Manufacturing in Construction—The Challenge of Large Scale', funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation)—project Number 414265976—TRR 277.

Funding Open Access funding enabled and organized by Projekt DEAL.

References

Abualdenien J, Borrmann A (2019) A metamodel approach for formal specification and consistent management of multi-LOD building models. Adv Eng Inf 40(1474–0346):135–153. https://doi.org/10.1016/j.aei.2019.04.003

Abualdenien J, Schneider-Marin P, Zahedi A, Harter H, Exner H, Steiner D et al (2020) Consistent management and evaluation of building models in the early design stages. ITcon 25:212–232

Aninger A (2022) *From fabrication information models to simulation models* (Master's thesis, Technical University of Munich). Retrieved from https://publications.cms.bgu.tum.de/theses/2022_Aninger_FromFIMtoSimulationModels.pdf

Babafemi AJ, Kolawole JT, Miah MJ, Paul SC, Panda B (2021) A concise review on interlayer bond strength in 3D concrete printing. Sustainability 13(13):7137

Borrmann A, König M, Koch C, Beetz J (2018) Building information modeling: Why? what? how? Building information modeling. Springer, pp 1–24 buildingSMART (2021) Industry Foundation Classes, version 4.3 RC1, documentation. Retrieved January 15, 2022, from https://standards.buildingsmart.org/IFC/DEV/IFC4_3/RC1/HTML/

Buswell RA, Leal de Silva WR, Jones SZ, Dirrenberger J (2018) 3D printing using concrete extrusion: A roadmap for research. Cement and Concrete Research 112(October 2017):37-49. Retrieved from https://doi.org/10.1016/j.cemconres.2018.05.006

Chindanonda P (2019) IFC Extension: Multiple Levels of Development Model Container

Dielemans G, Briels D, Jaugstetter F, Henke K, Dörfler K (2021) Additive manufacturing of thermally enhanced lightweight concrete wall elements with closed cellular structures. J Facade Des Eng 9:59–72

Ding D, Pan Z, Cuiuri D, Li H, van Duin S (2016) Advanced design for additive manufacturing: 3D slicing and 2D path planning. New trends in 3d printing, 1–23

Dini E (n.d.) D-Shape is a particle bed 3D printing process at architectural scale. Retrieved 2020-10-20, from https://dshape.com/what-is-it/

Dörfler K, Rist F, Rust R (2013) Interlacing. Rob Arch 2012, pp 82–91. Springer

Duro-Royo J, Oxman N (2015) Towards Fabrication Information Modeling (FIM): Four Case Models to Derive Designs informed by Multi-Scale Trans-Disciplinary Data. MRS Online Proceedings Library (OPL), 1800

Hack N, Kloft H (2020) Shotcrete 3D printing technology for the fabrication of slender fully reinforced freeform concrete elements with high surface quality: a real-scale demonstrator. In: Bos FP, Lucas SS, Wolfs RJ, Salet TA (eds) Second RILEM international conference on concrete and digital fabrication. Springer, Cham, pp 1128–1137

Hehenberger P (2020) CNC-Technik und Programmierung. Computerunterstützte produktion, pp 86–117. Springer

Jaud Štefan, Esser S, Borrmann A, Wikström L, Muhič S, Mirtschin J (2021) A critical analysis of linear placement in IFC models. ECPPM 2021-eWork and eBusiness in Architecture, Engineering and Construction: Proceedings of the 13th European Conference on Product & Process Modelling (ECPPM 2021), 15–17 September 2021, Moscow, Russia, p 12

Khoshnevis B (1999) Contour crafting-state of development. Solid Freeform Fabrication Proceedings, pp 743–750

Kloft H, Gehlen C, Hack N, Henke K, Lowke D, Mainka J (2020) Additive Manufacturing in Construction (AMC) - The Challenge of Large Scale (Tech. Rep.). Retrieved from https://www.tubraunschweig.de/trr277/trr-277-home

Lee J, Bagheri B, Kao H-A (2015, jan) A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems. Manufacturing Letters 3:18-23. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S221384631400025X. https://doi.org/10.1016/j.mfglet.2014.12.001

Li C, Petzold F (2021) Integrating Digital Design and Additive Manufacturing Through BIM-Based Digital Support. PROJECTIONS. In: Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) (Vol. 1)

Lu Y, Choi S, Witherell P (2015) Towards an integrated data schema design for additive manufacturing: Conceptual modeling. International design engineering technical conferences and computers and information in engineering conference (Vol. 57045, p V01AT02A032)

Makris S, Mourtzis D, Chryssolouris G (2014) Computer Aided Manufacturing. CIRP Encyclopedia of Production Engineering, 254–266

Martínez-Rocamora A, García-Alvarado R, Casanova-Medina E, González-Böhme LF, Auat-Cheein F (2020) Parametric programming of 3D printed curved walls for cost-efficient building design. J Constr Eng Manag 146(5):04020039

Mckinsey Global Insititute (2017) Reinventing construction: a route to higher productivity. Mckinsey Global Insititute(February), 168. Retrieved from http://www.mckinsey.com/industries/capitalprojects-and-infrastructure/ourinsights/ reinventing-construction-througha-productivity-revolution

Mitropoulou I, Bernhard M, Dillenburger B (2021) Nonplanar 3D Printing of Bifurcating Forms. 3D Printing and Additive Manufacturing

Näther M, Nerella VN, Krause M, Kunze G, Mechtcherine V, Schach R (2017) Beton- 3D-Druck -Machbarkeitsuntersuchungen zu kontinuierlichen und schalungsfreien Bauverfahren durch 3D-Formung von Frischbeton. *Projekt Beton-3D-Druck Abschlussbericht. Hg. v. Forschungsinitiative Zukunft Bau. TU Dresden. Dresden*

Paolini A, Kollmannsberger S, Rank E (2019) Additive manufacturing in construction: A review on processes, applications, and digital planning methods. Additive Manufacturing 30(July):100894. Retrieved from https://doi.org/10.1016/j.addma.2019.100894

Ravankar A, Ravankar AA, Kobayashi Y, Hoshino Y, Peng C-C (2018) Path smoothing techniques in robot navigation: state-of-the-art, current and future challenges. Sensors 18(9):3170

Rodriguez E, Alvares A (2019) A STEP-NC implementation approach for additive manufacturing. *Procedia Manufacturing* 38(2019):9-16. Retrieved from https://doi.org/10.1016/j.promfg.2020.01.002

Slepicka M, Vilgertshofer S, Borrmann A (2021) Fabrication Information Modeling: Closing the gap between building information modeling and digital fabrication. In: Proceedings of the 38th international symposium on automation and robotics in construction (isarc)

Wassermann B, Korshunova N, Kollmannsberger S, Rank E, Elber G (2020) Finite Cell Method for functionally graded materials based on V-models and homogenized microstructures. Adv Model Simul Eng Sci (7):49. https://doi.org/10.1186/s40323-020-00182-1

Wolfs R, Bos F, Salet T (2019, may) Hardened properties of 3D printed concrete: the in uence of process parameters on interlayer adhesion. Cem Concr Res 119: 132-140. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S0008884618310482. https://doi.org/10.1016/j.cemconres.2019.02.017

Zahedi A, Petzold F (2018) Utilization of simulation tools in early design phases through adaptive detailing strategies. CAADRIA 2018 - 23rd International Conference on Computer-Aided Architectural Design Research in Asia: Learning, Prototyping and Adapting 2:11–20

Zhang GQ, Mondesir W, Martinez C, Li X, Fuhlbrigge TA, Bheda H (2015) Robotic additive manufacturing along curved surface—a step towards free-form fabrication. In: 2015 ieee international conference on robotics and biomimetics (robio), pp 721–726

Zhou Z, Xie SS, Chen D (2011) Fundamentals of digital manufacturing science. Springer, New York

Zienkiewicz O, Taylor R, Zhu J (2013) Automatic Mesh Generation. In: Zienkiewicz O, Taylor R, Zhu J (eds) The finite element method: its basis and fundamentals (seventh edition), 7th edn, pp 573–640. Butterworth-Heinemann, Oxford. Retrieved from https://www.sciencedirect.com/science/article/pii/B9781856176330000174. https://doi.org/10.1016/B978-1-85617-633-0.00017-4