Automation in Construction 168 (2024) 105792

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Fabrication Information Modeling for Closed-Loop Design and Quality Improvement in Additive Manufacturing for construction

M. Slepicka [*], A. Borrmann

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

ARTICLE INFO

Keywords:
Building Information Modeling
Fabrication Information Modeling
Cyber-Physical Systems
Additive Manufacturing

ABSTRACT

Additive Manufacturing (AM) has emerged as a disruptive technology with the potential to revolutionize the construction industry by integrating digital design with automated manufacturing. This paper presents and extends Fabrication Information Modeling (FIM), a comprehensive framework tailored for automated manufacturing in construction. FIM facilitates the seamless integration of digital design concepts with automated manufacturing processes, enabling precise control over fabrication information and enhancing construction efficiency and quality. This paper demonstrates its potential to optimize construction processes through a detailed exploration of FIM's capabilities, including data preparation, path planning, simulation integration, robot control, and data feedback. By enabling a circular data flow between digital modeling and manufacturing, FIM is able to bridge the gap between digital design and physical construction, revolutionizing how construction projects are conceived, planned, and executed. The paper concludes by highlighting the challenges and future research directions in advancing FIM-based construction systems, emphasizing its transformative potential in driving innovation and sustainability in the construction industry.

1. Introduction

Additive Manufacturing (AM), a potentially disruptive technology for the construction sector, has gained popularity in recent years, due to its potential to revolutionize the industry. This innovative technology involves chaining digital design with automated manufacturing. This shift towards automation aligns with the broader trend in the construction-related research, Construction 4.0, emphasizing the need for increased digitization in the construction process [1,2]. It provides the means to rethink how buildings and structures are conceptualized and built [3–5], and offers the potential for increased speed and decreased labor requirements [6]. These are advantages that could alleviate some of the labor shortage problems currently increasing in Germany due to demographic change.

Moreover, sustainability considerations play a significant role in the growing interest in AM for construction [1]. Researchers and industry professionals actively explore the technology's potential to reduce material waste, manual labor and energy consumption, aligning with global sustainability goals [7,8]. The ability to create structures with optimized geometries and minimal waste underscores the environmental benefits of AM in construction (AMC) [9]. AM's inherent capability for customization and adaptability in design empowers architects and builders to explore innovative and unconventional structures, pushing the boundaries of traditional construction methods [3].

However, despite the transformative potential, the construction industry is still reluctant to adopt digital manufacturing methods, such as AM, as the technology does not yet provide a significant competitive advantage [10,11]. This is mostly due to the fact that AM in construction is still regarded to be in its infancy (fundamental research), and many challenges still persist. As described in Section 2.1.3, in particular, the material properties of construction materials are not well-suited for 3D printing necessitating an adaptive design approach [12,13]. Thus, a feedback loop facilitated by parametric pattern-based path planning and streamlined fabrication information management becomes crucial. As shown in this paper, the challenges tied to AM in construction can be addressed by enabling adaptive design and data management, allowing full access to the fabrication information in real-time.

In this context, this paper presents Fabrication Information Modeling (FIM), a framework developed based on an open exchange data format suitable for design and manufacturing that can facilitate the seamless integration of robotic manufacturing technologies, such as AM, into construction processes. As an intermediate layer between digital design and automated manufacturing, FIM incorporates customized control methods, aiming to increase the precision and efficiency of printing processes. FIM aims to be a unified framework incorporating all construction-related automated manufacturing methods, which includes additive and subtractive techniques.

---

[*] Corresponding author.
E-mail address: martin.slepicka@tum.de (M. Slepicka).

https://doi.org/10.1016/j.autcon.2024.105792
Received 18 April 2024; Received in revised form 18 September 2024; Accepted 18 September 2024

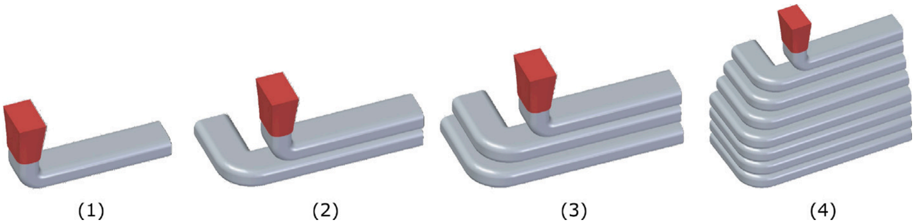


Fig. 1. Functional principle of depositing methods according to [14].

1.1. Research objectives

The primary goal of this paper is to illustrate the FIM framework, which bridges the gap between digital design (BIM) and additive manufacturing (AM). The framework aims to enable seamless, bidirectional information transfer between these two domains without the need for conversion. To achieve this, it must be possible to semi-automatically derive fabrication information from the digital design. This information should always be accessible and adaptable while preserving the "as-designed" data as ground truth. Additionally, the framework should include methods for integrating sensor data feedback to allow real-time monitoring and control of the printing process. However, this paper focuses specifically on extrusion-based AM methods, and the feasibility of applying FIM to other AM methods will need to be explored in future research.

1.2. Research outline

In the following, first, an overview of existing AM technologies related to construction is given in Section 2. In the Overview, particular emphasis is put on describing the hardware related to the various AM methods and the current digital methods to provide the fabrication information. Then, in Section 3, the proposed FIM framework is described conceptually. Subsequently, the implementation work that was performed in the scope of this paper is described. First, the data structure is illustrated, and the individual subsections are explained in detail, highlighting the corresponding capabilities. Then, in Section 5, the implemented methods for the FIM-based Cyber-Physical System (CPS) are illustrated, and key elements for closing the digital-to-physical-to-digital loop are identified. For each method, the implementation is roughly described, and experimental data is provided. Finally, in Section 6, the results are discussed in the context of the previously raised research objectives.

2. State of the art

2.1. Additive manufacturing in construction (AMC)

The term AM, often referred to as "3D printing", covers various technologies that can be used to manufacture objects in an automated, computer-controlled manner. Usually, with AM, the material application is performed layer by layer. While AM systems could only process plastics initially, more and more materials are now processable using AM methods. This technology began to raise attention for the construction industry when typical construction materials (concrete, steel, and wood) were added to the list of materials AM can process. Today, the field of AM in construction is highly dynamic, and many ongoing research projects aim to advance the respective technologies [15,16]. Current research focuses on refining AM technologies, exploring new materials, and addressing technical challenges.

The following sections will describe prominent AM methods and the corresponding hardware for AM in construction to illustrate the diversity of AM technologies in the construction sector. Furthermore, a description of software solutions to control the corresponding hardware is provided. As part of related research, many AM methods were investigated to extract standard features to create a data structure suitable for integrating automated fabrication (AM) with digital design [17]. Based on research into the data structure, this work develops a framework for cyber manufacturing, i.e., automatically deriving manufacturing information from BIM models and using this data directly for robot control.

2.1.1. Methods and materials

The primary materials used in construction are concrete, steel, and wood, of which mostly concrete and steel have been of interest in developing AM systems. The following section will also focus on concrete and steel, two materials that differ significantly concerning their properties and the way they are processed. Concrete, a mineral material, has a high compressive strength, and steel, a metallic material, has a high tensile strength, which is why both materials are often combined in construction. Naturally, processing the two materials with AM methods requires different specialized tools. Yet, the AM methods developed to process these materials have some similarities and can be grouped into two categories: the deposition methods and the particle-bed methods. These categories group AM methods according to their functional principle.

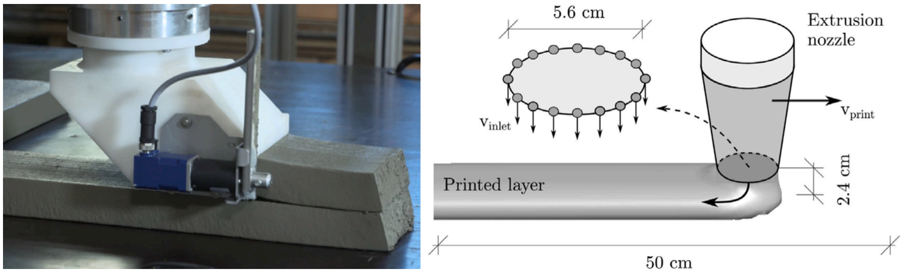
As will be apparent by the following overview, there are numerous applications for AM in the construction industry. The individual brief descriptions in the following paragraphs also will make it clear that these methods, although similar, require different hardware (cf. Section 2.1.2) and differ accordingly in terms of computer-aided control (cf. Section 2.2.2).

Deposition methods: The deposition methods include, e.g., Extrusion-based 3D Concrete Printing (E3DCP), Shotcrete 3D printing (SC3DP), and Wire and Arc Additive Manufacturing (WAAM). These methods apply the processed material by a deposition process, as indicated by the category name. First, if not already the case, the material to be printed is brought into a ductile state. Then, the material is continuously transported to and deposited at the desired location layer-wise, as illustrated by Fig. 1.

In all the named examples (E3DCP, SC3DP, and WAAM), the material is applied by an extrusion nozzle that is moved in space by a robotic actuator. However, in the case of E3DCP, freshly mixed concrete is pumped to and gently deposited on the desired location by the nozzle, which can also be actively controlled depending on the exact method. Different variations have been developed concerning the concrete deposition strategy for this method. Two notable deposition strategies are the *infinite brick* and the *layer pressing* strategy (cf. Fig. 2).

With Shotcrete, freshly mixed concrete is pumped to the nozzle, then accelerated by compressed air and sprayed onto the desired area. However, various process parameters must be coordinated for a stable shotcrete process [20], as illustrated in Fig. 3. During WAAM, a steel wire is mechanically transported to the nozzle, melted in the nozzle by an electric arc, and the resulting steel droplets are applied to the desired location [21].

Particle-bed methods: The particle-bed methods include, e.g. Selective Cement Activation (SCA), Selective Paste Intrusion (SPI)



(a) Infinite brick [18]. (b) Layer pressing [19].

Fig. 2. Two different deposition strategies for the extrusion-based concrete 3D printing method.

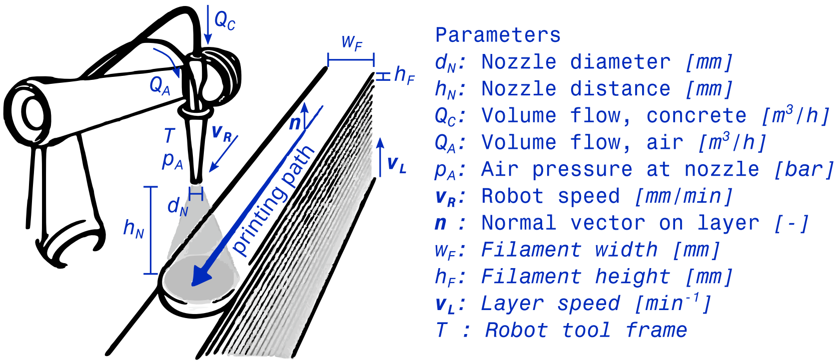


Fig. 3. Shotcrete 3D printing (SC3DP) method, including controllable process parameters, after [20].

[14,22], and Laser Powder-Bed Fusion (LPBF) [23]. With these methods, objects are manufactured in a two-step process. First, powdered material is applied in thin layers on the target area (matrix). Then, the matrix is selectively bound by a chemical or physical process. Lastly, the unbound matrix material is removed to extract and clean the manufactured object. The whole procedure is illustrated in Fig. 4.

All the named examples for particle-bed methods follow the same steps, but each method's matrix material and binding process are different. In SCA, the matrix material is composed of fine aggregates (e.g. sand) and a binding agent (cement), and the binding process is chemical. The cement gets "activated" in the desired locations by selective application of an activator liquid water droplets [22]. With SPI, the matrix material is just aggregate materials (e.g., sand or fine gravel) bound by selective intrusion of cement paste [14]. During LPBF, metal powder is applied in thin layers and then bound physically by melting the metal utilizing direct energy deposition (DED), e.g. with a focused laser beam [23].

Method combinations: A fact that has not been addressed so far is the possibility of combining different AM methods. With one AM method, only one material can be processed. Material composites are often used in construction for optimal component performance, e.g., reinforced concrete. There are various approaches to **reinforcement integration** in concrete 3D printing, such as adding steel, glass, or carbon fibers to the concrete mix, robot-assisted insertion of short rebars, or automated application of reinforcement material [24–26]. Another study investigates the combination of a particle-bed method (SPI) with a deposition method (WAAM) [27].

Finally, also the Injection 3D Concrete Printing (I3DCP) method [28] has to be mentioned; it is described in this section, as it does not strictly fit in either AM category named in this paper. With the I3DCP, a fluid material can be deposited within a reservoir of another fluid material. The method has characteristics of both categories, depositing and particle-bed methods. In addition, the method enables breaking free from the usual layer-by-layer manufacturing method; with I3DCP, the material to be deposited can be freely distributed spatially. However, this imposes another degree of freedom, that needs to be covered by the digital workflow (cf. Sections 4.3 and 2.2.2).

2.1.2. AMC hardware

In order to apply the AM methods described in Section 2.1.1 in practice, various hardware setups can be utilized. All AM methods, however, require at least a **material feeding system** (material supply), a **motion system** (manipulator), and an **material application system** (print head). Additionally, the **build platform** and the **environment** around the AM machine can also be assumed to be part of the system. Optionally, other utilities may be used in more complex AM systems, such as different kinds of sensor systems, mobile platforms, or additional tools. In the following paragraphs, a select set of commonly utilized hardware systems is named and described to illustrate how diverse AM systems can be, even if they are classified under the same functional principle.

Material supply: A reliable transportation mechanism must be provided to supply the print head of an AM system with a continuous feed of material. Depending on the applied method and material (cf. Section 2.1.1), there are different possibilities, either active or passive systems. In the case of WAAM, e.g., a wire spindle is minimally required, from which the print head can draw the steel wire. For the concrete printing methods (depositing and particle-bed systems), the material feeding system can be further subdivided into mixing and pumping machinery. At least two scenarios are possible for the mixing system [29]. One solution is a separate mixer that supplies the AM system with concrete in batches. The other solution is an in-line mixing system (integrated into the conveying system) that continuously supplies the system. In both variations, either with a separated mixer or integrated, the pumping system conveys the freshly mixed concrete or cement paste towards the print head. Standard concrete pumps can be utilized for the pumping mechanism. It is worth mentioning a related study in which the use of the retractable arm of truck-mounted boom pumps as a manipulator of the AM system was investigated [30] (next paragraph). When using the SC3DP method, an air compressor must

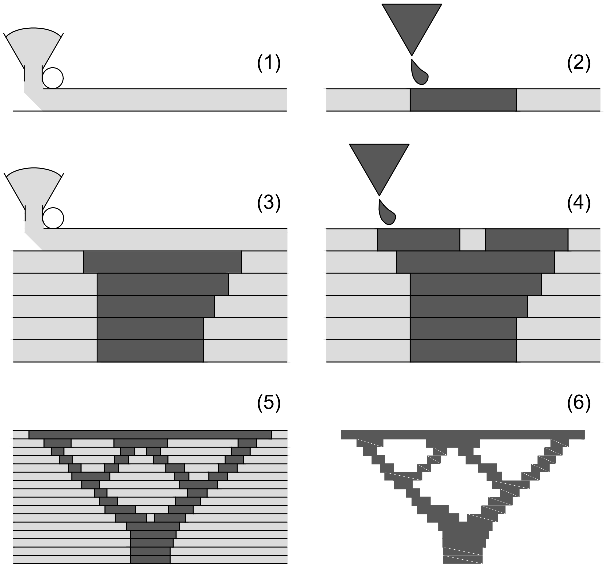


Fig. 4. Functional principle of particle-bed methods according to [14].

also be provided to regulate the spraying mechanism. In addition, in the case of concrete printing, the material feeding system can als

Manipulator: The print head motion must be computer-controllable for manufacturing using any of the mentioned AM methods (cf. Section 2.1.1). In order to realize the print head motion in AM systems, a large variety of robotic manipulators from different vendors may be utilized depending on the AM method. For whole 3D movement, a manipulator with at least 3 degrees of freedom (DoF) is required, e.g., a gantry robot or a movable print platform in combination with a movable print head (1+2 DoF). However, for more geometric freedom, in the case of non-horizontal or non-planar 3D printing (cf. Section 4.3), robots with more DoFs are required, such as articulated robot arms with 5 or more DoFs. In many research projects, 6 DoF robot arms are used. With particle-bed methods, gantry systems are usually employed; due to the particle bed that can only be applied in horizontal layers, the extra DoFs are unnecessary. Depending on the system, an additional linear axis can move its particle dispenser (next paragraph). In other systems, both tools are fixed on the same mount. Fig. 5 depicts various robot systems used in research projects.

Print head: The final key component of an AM system is the print head, the tool used to control the material application. Depending on the AM method and material, the print head may look and function quite differently. Both simple passive designs as well as complex individually controllable contraptions are available.

In the case of particle-bed methods, there are two types of material application: the particle-bed application and the selective binding. Therefore, the print head consists of two separate tools; depending on the system, they can be individually controlled. A dispensing and compacting tool for the particle-bed application is employed to spread the matrix material in thin layers within the build space of the AM system. For example, Fig. 6 illustrates the functional principle of a scatter and compacting roller used in an SCA machine and specifies its control parameters. For the selective binding process, e.g., nozzle systems with one or more nozzles for dispensing liquids (chemical activation or binder intrusion) or a focusable energy source, such as a plasma arc, laser, or electron beam (DED), are used. Here, the controllable parameter is the volume flow (liquid dispensing nozzles) or the energy input (DED), which has to be coordinated with the movement of the manipulator.

For WAAM, as part of the depositing methods, the print head combines an electric arc torch and a wire feeder, which can be attached to the chosen manipulator. It is controlled by setting the wire feed rate and the applied voltage to the torch. In the case of SC3DP, the print head is a robot-mountable shotcrete system [31]. However, the control of the SC3DP is not quite simple; many parameters, such as the applied air pressure, concrete flow rate, distance of the nozzle to the target area, and robot speed, have to be coordinated [20], as illustrated in Fig. 3.

Many different print head variations have been developed for extrusion-based concrete printing systems following different concrete application strategies (cf. Section 2.1.1). In all variations and with all strategies, however, concrete is pushed through a nozzle, shaping the concrete, and then deposited at the nozzle's location. The most straightforward system is a robot mountable tube with one end attached to the concrete pump and the other outfitted with a fixed nozzle. More sophisticated versions of this include, e.g., an integrated auger screw in the print head to fine-tune the volume flow. For some concrete mixtures, however, this fine-tuning method is not applicable (cf. Section 2.1.3). For reinforcement integration, systems have been developed that insert a fiber into the extruded filament, increasing the flexural strength of the printed component [32]. Another notable print head variation is the Gradation-Ready Extrusion System (GRES). This robot-mounted near-nozzle mixing solution can change the concrete mix gradually during the printing process [33].

Optional tools and combinations: In addition to the three main components described in the previous paragraphs, it is possible to outfit the AM system with optional equipment, either for process optimization or enabling data feedback. For process optimization, the additional tools can be passive, such as trowels mounted on an E3DCP print head, or actively controlled, such as a tilt-turn table for WAAM [21] or mobile platforms for any mountable AM system [34]. Both passive and active additions may impose additional conditions regarding machine control.

For data feedback, various sensor systems can be utilized. Optical sensors, such as cameras (RGB, thermal, or depth), laser profilers, or terrestrial laser scanners, can capture the "as-printed" geometry during or after manufacturing. Depending on the utilized AM method, other sensors, such as a voltmeter to measure the actual voltage at the WAAM tool or in-line pressure sensors to measure the pressure gradient between the pumping system and extruder in a E3DCP system can be

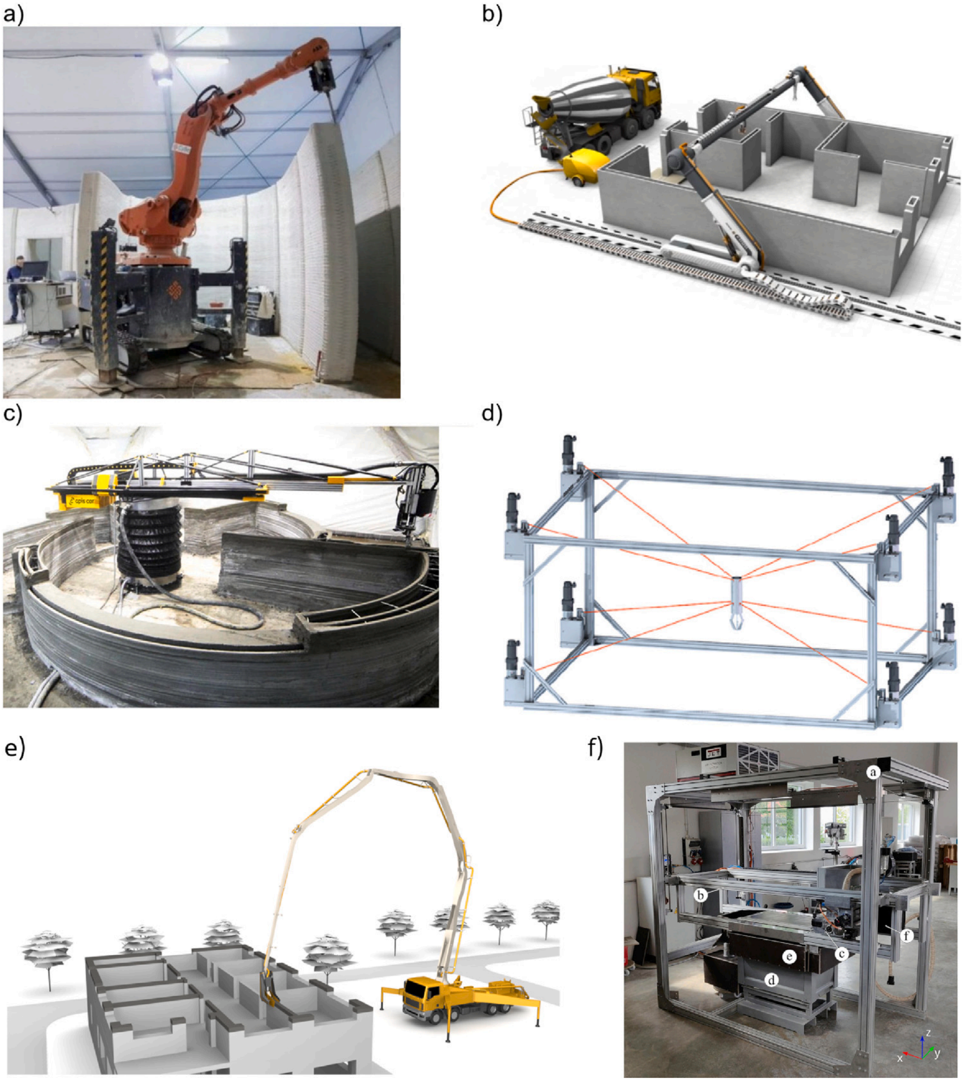


Fig. 5. Different robotic manipulators utilized in AM methods for construction [18,22,30]. (a) to (e) illustrate robots that can be used in depositing methods, and (f) shows a lab-scale particle-bed printer. (a) shows a 6 DoF robotic arm manipulator, (b) a portal robot, (c) cylindrical robot, (d) cable-driven parallel robot, and (e) a modified boom pump.

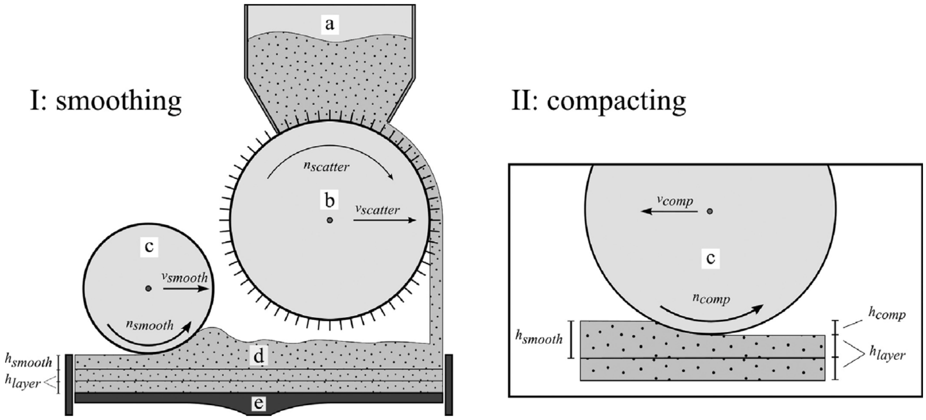


Fig. 6. Functional principle of the particle-bed preparation using a scatter and compaction roller [22].

used, e.g., for feedback control. Additionally, auxiliary utilities may be needed, e.g., if sensors must be aligned with the robot trajectory independent of the robot's end-effector [35].

All sensors and utilities will likely have different interfaces. While some sensor or utility systems can be accessed via well-implemented SDKs, others have to be hooked up with a microcontroller that can

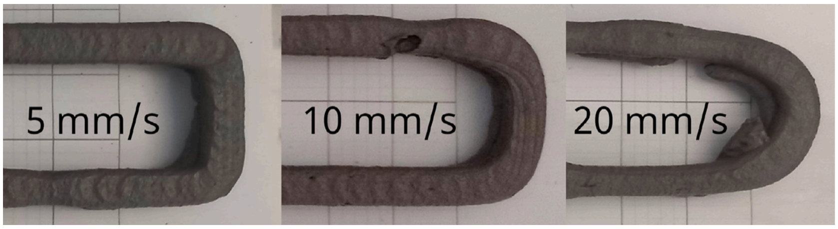


Fig. 7. Three contour prints of a rectangular component performed using different robot velocities are illustrated. With a faster velocity, the corners get more and more distorted.

interpret the sensor signal or control the utility, e.g., a custom build camera mounting system [35].

2.1.3. Challenges in AMC

AM's often-proclaimed advantage is the possibility of manufacturing components fast and resource-efficient, even those with complex shapes (cf. Section 1). However, it is often neglected that 3D printing can quickly fail if, for example, the digital model is inadequate, the machine is not calibrated correctly, the wrong or defective material is used, or environmental effects disrupt the process. In large-scale applications of AM, e.g., in construction, print failures have a much more significant impact, as 3D printing at this scale consumes a lot of time and material. In that sense, AM is not a rapid prototyping technology for the construction industry. Unlike in model-scale prototyping, failed prints cannot be reprinted at will.

Process reliability for AMC is a critical issue that needs to be resolved to raise the acceptance of the technology in the industry. In this context, challenges include material property optimization, ensuring structural integrity, and addressing issues related to scalability for large-scale construction projects. Moreover, standardization and regulatory frameworks are still evolving, not only in the construction sector [36].

For AM, concrete, for example, has to have contradicting rheological properties; it must be simultaneously pumpable, extrudable, and buildable. That means the concrete must be fluid enough to be transported through pipes and squeezed out of a nozzle without tearing; however, as soon as the material is applied, it must be structurally stable to support its weight, the pressure of the printing nozzle, and consecutive material layers [37].

Another issue of concrete, related to its rheological properties, is that it can be displaced by the printing nozzle after deposition due to friction, as illustrated in Fig. 7. The effect is proportional to the nozzle speed, dependent on the support by lower layers, and is directed tangentially to the nozzle movement. Thus, this effect is most substantial in sharp turns of the toolpath and gets stronger in higher printing layers as long as the material is still soft below. As the concrete's structural buildup (solidification) in E3DCP takes some time, this must be resolved by adapting the movement of the AM system, e.g., moving slower when the curvature is large (cf. Section 4.3). Different parameters (material, process, or even geometry) are often interrelated and strongly affect each other, as in the example described. It is often not easy to predict how the parameters are related, especially if the component's geometry is a factor.

Depending on the AM method, also different constraints must be applied. For example, the extrusion of fiber-reinforced concrete poses strict limitations regarding the repositioning of the tool during the print. In this case, the print head must be passive; using an auger screw to control the material flow would disturb the alignment of the fiber reinforcement, or, in the worst case, the fibers would clog the print head [38].

The described issues are only an excerpt of a long list of challenges. Besides the already mentioned advantages, all the different AM methods (cf. Section 2.1.1) and machine systems (cf. Section 2.1.2) have their own set of limitations related to material properties, environmental effects, and interdependencies of subsystems. For all these reasons, it is vital to provide a versatile digital workflow based on a data structure that allows full access to interlinked datasets of the domains involved at any time in the design and manufacturing process. It is vital to enable a circular data flow, not only for process control but also for capturing "as-built" deviations that could not be avoided. A suitable data structure and the corresponding framework to provide said capabilities is described in Sections 3 and 5. Before that, the conventional digital thread and its shortcomings are investigated in the following section.

2.2. Data flow in AMC

For Additive manufacturing, in general, a digital model is used to manufacture a component utilizing automated robotic fabricators, adding material, usually in a layer-wise manner (cf. Section 2.1). However, the way in which the digital model is used, i.e., the data flow, must be clarified.

First, digital design methods must provide a digital model with a certain level of detail (cf. Section 2.2.1). Then, the digital model must be translated into machine-interpretable code to control the robotic fabricators providing a digital-to-physical data flow (cf. Section 2.2.2). Using the control code, the corresponding component can be manufactured.

2.2.1. Digital design in construction using BIM

In construction, projects usually involve a wide range of stakeholders from different fields of expertise. Traditionally, project information was communicated between the stakeholders through technical drawings. Now, digital methods are increasingly adopted in the Architecture, Engineering, and Construction (AEC) industry to address the various limitations inherent to this form of information exchange. A methodology that has now been widely accepted by the industry is Building Information Modeling (BIM). It aims to digitize design, construction, and operation processes, replacing traditional drawings with comprehensive digital representations stored as building information models. This approach streamlines coordination, integrates simulations, controls construction, and facilitates data handover, leading to increased productivity and quality.

A BIM model is an extensive digital representation of a building, incorporating geometric and semantic data [39]. Providing semantics, such as building element types, properties, and materials, in an interconnected way enables many design processes in construction to be automated [40]. In construction, the design of a building is an iterative process in which the design requirements of different domains (Architecture, structural elements, HVAC, electrical, etc.) must be coordinated and integrated [41]. Among other activities, quantity assessments, collision checks, and the generation of simulation models or construction plans can be performed BIM-based. At the same time, redundancies and inconsistencies among specialists can be avoided, enhancing planning quality and efficiency.

For information exchange between the different domain experts in construction projects, the exchange data format Industry Foundation Classes (IFC) was established. IFC is an open and neutral data model used in the architecture, engineering, and construction (AEC) industry to facilitate interoperability and data exchange between different

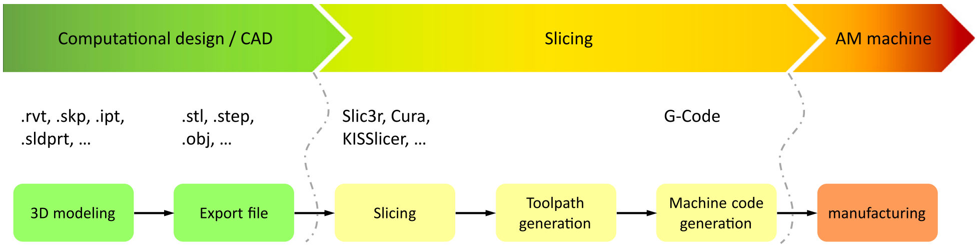


Fig. 8. Conventional digital workflow for AM, after [43]. Depicted is a linear workflow requiring two file format conversions, indicated by the dotted lines.

software applications [42]. It is an ISO-standardized data model for representing building and construction data, encompassing geometric, spatial, and non-graphical information about building elements, materials, and properties. IFC files enable seamless collaboration and communication among stakeholders throughout the entire building lifecycle, from design and construction to operation and maintenance, by providing a common language for exchanging comprehensive building information models (BIM).

IFC provides a comprehensive data model defining numerous classes for representing geometric and semantic information. A notable feature of the IFC data structure is the objectified relationships with which semantically relevant relations can be further detailed. The data model is organized into four layers (Resource, Core, Shared, and Domain layer) for better maintainability [42]. In the core layer, which is the most general, the basic structure is provided as fundamental relationships and common superclasses that may be specialized in the higher layers (Shared and Domain), which contain shared and domain-specific class definitions. The most basic schemes are defined in the Resource layer and are available throughout the entire IFC data structure. Among others, geometric elements (points, vectors, curves, etc.), higher-level geometric models (B-Rep, swept solids, etc.), elements for describing materials, and other utilities are defined in the Resource layer.

2.2.2. Digital-to-physical workflow

In order to print an object with an AM system, the corresponding fabrication information, i.e., the machine path, tool parameters, and used method, must be readily available (pre-processing, cf. Fig. 8). Usually, to provide this information, a geometric model is first generated in CAD software (cf. Section 2.2.1) and then exported as a triangulated facet model (STL file format). The facet model is then processed into machine paths and tool parameters by slicing software [43,44]. Alternatively, skipping the geometry generation, machine paths, and the corresponding tool parameters can also be generated directly utilizing generative algorithms [40]. After that, the generated toolpaths and parameters must be translated into machine-interpretable code to control the AM system's hardware. With fully developed AM systems, the machine-interpretable code, often G-Code, can then be fed to the centralized control unit, which executes the 3D print.

However, the just-described workflow is not always efficient or even feasible for the following reasons:

- In the conventional workflow, as indicated by the dotted lines in Fig. 8, data conversions are necessary. Firstly, the export of the geometric information of the component to be printed in a format compatible with the slicing software. Secondly, the export of the machine-interpretable control code, usually G-code. In each conversion step, data may be lost. Furthermore, converting data back into the original data format can be difficult.
- Printed building components in the construction domain frequently entail specific criteria concerning structural integrity or additional functionalities like thermal insulation. The design intricacies of these components are closely intertwined with their intended functional capabilities. To address this early on, numerical methods are commonly employed during the design phase to assess a component's anticipated performance [40]. However, numerical methods cannot only be used during the design phase but also during the manufacturing process to predict material behavior based on data feedback. Yet, the previously described data format conversions make integrating numerical methods and data feedback mechanisms challenging.
- As illustrated in Section 2.1.2, most AM systems combine multiple systems (Print head, manipulator, and material feed). Not all of these systems have a central control unit that can be easily controlled via a standardized numerical control code, e.g., G-code. For Example, an articulated robot arms' control unit is usually programmed using a vendor-specific programming language to utilize the robot's full potential, e.g., KRL for KUKA robots or URscript for UR robots. Not all slicing software can export control code for industrial robots. Similarly, the other equipment (print head, material feed, sensors, and other utilities) possibly have different control interfaces.
- The most commonly used intermediate file format STL [43,44] for preprocessing the digital model into fabrication information has some significant disadvantages. Although the data structure of STL files is simple, making it easy to read and write, it may contain redundancies (large data files), is only able to represent an approximation of the component's CAD model, and cannot represent semantic data [40]. Semantics, or the meaning of information, is crucial for understanding and processing data in construction planning and modeling, as it enables meaningful relationships and properties of a building to be captured and interpreted [45] (cf. Section 4).

As an alternative to the conventional workflow, automated scripts for CAD systems can be implemented to perform the slicing and toolpath generation. Using the CAD system that was used to create the digital model of the component to be printed eliminates the need to export the geometric model into one of the typical file formats for the slicing software. Very convenient for this purpose are visual programming environments available for several CAD systems, such as Grasshopper for Rhino or Dynamo for Autodesk Revit [43]. For example, the extensive plugin library for Grasshopper includes various numerical simulation tools, slicing utilities, and tools to export robot control code or directly send instructions to the robot via a TCP/IP connection [43,46]. In that sense, Rhino-Grasshopper plugins are suitable for planning and executing complex robot procedures and communicating with the AM tools for an AM process. The AM data (geometric model, numerical control code, and feedback data) can be generated and manipulated during the runtime of the respective script and later exported in separate files. In addition, with a script implemented in the two previously mentioned visual programming environments, a BIM model can be used as the data source.

Utilizing AM in construction also imposes new design and engineering requirements, which must be coordinated during building design. In this sense, AM activities, such as path planning and robot and performance simulation, must be part of the construction planning iterations and should, therefore, be integrated into the BIM methodology. A linear workflow from the digital model to the fabrication information, as depicted in Fig. 8, is only possible if the digital model is already in its final design stage and suitable for 3D printing.

2.2.3. Physical-to-digital workflow

A linear workflow and static machine control are feasible for well-defined manufacturing conditions, e.g., simple geometry, suitable environment, and easily predictable material behavior. Yet, as indicated in Section 2.1.3, such conditions are rarely available for AMC, which necessitates applying feedback control. For this, the physical reality must be **monitored**, the captured data **interpreted**, and subsequently, the interpreted data is **stored**, providing a physical-to-digital data flow. In sophisticated manufacturing systems, the interpreted data can be used in a closed loop control system to alter the machine control code to optimize the manufacturing process (**closed-loop control**).

For the first part, the monitoring, sensors must be installed to collect real-world information and convert it into digital data. In the context of AM, various parameters may be relevant, such as parameters related to the environment (temperature, humidity), to the process (pump pressure, robot position, and velocity), or to the printed component ("as-printed" data, such as geometric features). Depending on the required information, various sensor types are available [13]. For example, the robot's position and velocity can be monitored by motor feedback systems built into the robot control unit. The geometric features of the printed component are usually captured using optical sensors, such as RGB cameras, Lidars, or Laser scanners. Each sensor may have a different output; for example, optical sensors provide video feeds, pictures, or point clouds [12,47], while other sensors provide time-series data [12].

After collection, the physical data needs to be processed and converted into a digital format that can be stored and analyzed by computer systems. This may involve preprocessing to clean, filter, or format the data for further use. Once converted, the data needs to be represented digitally (stored) in a way that it can be associated with the modeled process or component data (cf. Sections 4.3 and 4.4).

For closed-loop control, the captured sensor data must be interpreted with appropriate tools depending on the data type. For video feedback, e.g. image processing algorithms may be needed. By comparing the interpreted sensor data, the "as-printed" data, with the "as-designed" data of the digital model, deviations can be identified (deviation map), and appropriate measures to counteract can be taken.

2.3. Circular data flow

In principle, digital-to-physical and physical-to-digital combined would describe a circular data flow that integrates computing, communication, and control (cyber-world) with the dynamic physical world [48]. The underlying concept has emerged in the manufacturing industry and is referred to as Cyber-Physical Systems (CPS).

In the physical-to-digital workflow, the captured data can also be used to update the digital model to track any deviations in the physical form from the original design. This process, known as Digital Twining (DT), involves using the updated model to provide a circular data flow. This way, a bi-directional dynamic mapping between the digital model and the physical world is realized [48].

A CPS is broadly characterized as a network where physical and digital elements are intricately linked to facilitate an intelligent control loop marked by adaptability and autonomy [49]. In contrast, a Digital Twin (DT) represents a precise digital replica of a physical asset continuously updated with real-time sensor data, allowing for monitoring, analysis, and simulation of the physical entity's performance and condition [50]. Combined, both concepts could enhance the capabilities of manufacturing systems by offering optimized solutions [48]. However, a seamless bidirectional information flow between the digital and physical world must be available to apply the CPS and DT concepts to AMC effectively, which is not the case if the conventional digital workflow is applied.

3. FIM framework

The concept of Fabrication Information Modeling (FIM) was first introduced by Duro Royo as "a novel framework and methodology for materially and geometrically complex design, as a way to combine form generation, digital fabrication, and material computation in seamless digital design processes" [51]. Slepicka et al. [17] adopted this idea and applied the concept to the construction industry in a BIM context. The current aim is to develop and extend the framework further to become a cyber–physical system, allowing seamless circular data flow (cf. Section 2.3).

A Fabrication Information Model (FIM) is designed to represent information essential for the automated manufacturing of building components, encompassing detailed descriptions of the component to be built and the manufacturing processes. FIM is a vendor-neutral abstraction layer bridging high-level design data (BIM) and low-level machine instructions (tool paths, velocity profiles, etc.). Utilizing FIM enables automatic derivation of manufacturing details from BIM data, ensuring consistency and avoiding unnecessary data conversions. Moreover, FIM allows seamless integration of "as-manufactured" information for subsequent BIM use cases like building maintenance. While the FIM concept is agnostic of any automated fabrication method, potentially ranging from robotic bricklaying to timber prefabrication, the focus of this paper is on applying it to additive manufacturing. For additive manufacturing, FIM enables the seamless translation of printing paths into machine control instructions, allowing for simulations, sensor data feedback, and direct usage of control data for various purposes with suitable interfaces as illustrated in Fig. 9. The FIM model acts as an intermediate layer, encapsulating the additional fabrication information on the component level.

As described in Section 2, AM methods in construction are very diverse and require different types of hardware. Each of these may require different parameter sets to be modeled. Furthermore, to enable the production of components with complex geometries or adaptive manufacturing strategies, the manufacturing process must be represented in detail but in a flexible way. Also, direct data feedback from various sensor systems and integration of simulation methods should be possible. And lastly, the modeling of the manufacturing information should be integrated into the digital design so that it can influence the design iterations.

Factoring in all the requirements listed above, it became imperative to develop a unified data structure (cf. Section 4) that aligns well with digital design but can also fully represent the fabrication information for the manufacturing process while allowing full data access at any time. Slepicka et al. [17] identified IFC, the BIM exchange data format (cf. Section 2.2.1), to be a suitable data model for the underlying data structure of FIM. This paper illustrates the refined and further developed FIM data model. Section 4 depicts and describes the most important classes and their relationships in the FIM data model as well as how the data is structured and supposed to be utilized.

Along with the data structure, methods for data utilization and interfaces to existing software solutions were developed (cf. Section 5). In this scope, a workflow to semi-automatically derive fabrication information from BIM models was developed, a pattern-based path planning approach. Moreover, tools utilizing FIM data for robot control and simulation purposes were implemented. Finally, a methodology for FIM-based scan planning and sensor data feedback was investigated and prototypically implemented.

4. FIM data structure

Slepicka et al. [17] developed a data structure based on the Industry Foundation Classes (IFC) data schema (cf. Section 2.2.1). For FIM, the IFC data schema offers a lot of flexibility. As the data format is already well established in the industry, many open-source tools can be resorted to. Furthermore, with IFC, it is possible to provide multiple geometric

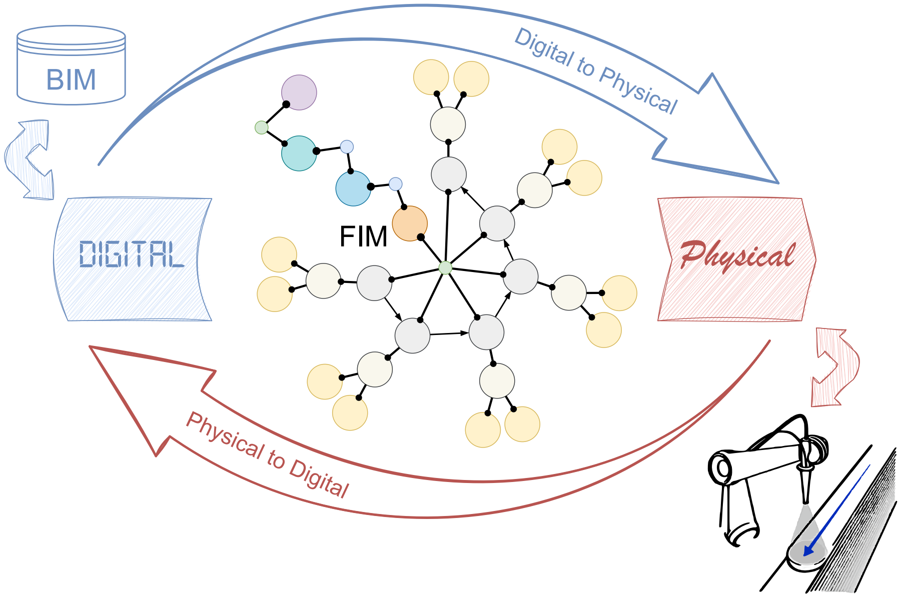


Fig. 9. Schematical description of a FIM-based Cyber-Physical System (CPS).

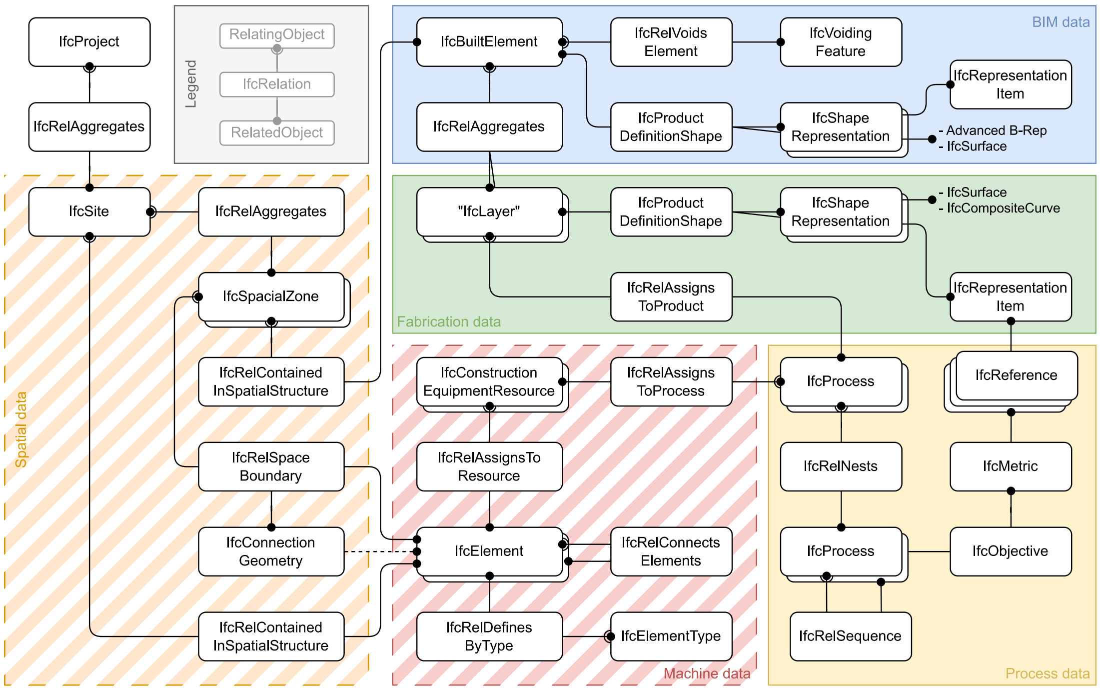


Fig. 10. Partial instance diagram of the FIM data structure for representing one component; only the most important entities are depicted.

representations for one element. Instead of converting a component's geometry into a print path, this IFC capability allows the print path to be added to the model as an alternative geometric representation. Additionally, the IFC data model, which is an object-oriented data schema, offers multiple options for how to store the data. The data can be stored file-based in different formats, such as STEP Physical File (SPF), JSON, or XML, which are plain text formats especially useful for long-term data storage. Alternatively, it can also be stored in the form of an online graph database, either using the encoding of the Resource Description Framework (RDF) [52] or by means of a Labeled Property Graph (LPG) [53].

The FIM data structure, initially proposed by Slepicka et al. [17], has since been refined and extended as illustrated in Fig. 10. To maintain readability, some entities that are not important for comprehension were omitted, such as local placement entities or the explicit items for the shape representations.

To explain the functionality, the data structure shown Fig. 10 can easily be sectioned into functional groups, as indicated by the colored areas. Left unmarked is the root node, `IfcProject`, which is the entry point. It contains general information about the manufacturing project, such as data ownership, the date and type of the last modification, and the date of the first creation.

4.1. Spatial data

Connected to IfcProject by the aggregation relation IfcRelAggregates is the spatial structure (orange box in Fig. 10), comprised of two classes, not counting the relations. The first class, IfcSite, describes the construction site, i.e., the area where the construction project takes place. For more context, the IfcSite can have geometric representations and a placement. Additionally, it can be referenced to geographic coordinates (longitude, latitude, and height elevation) or detailed via an IfcPropertySet. In a broader sense, IfcSite describes the environment around the AM system, which can significantly impact the system's performance. If sensors are installed to capture environmental data, they can be modeled to be contained in this space (IfcRelContainedInSpatialStructure).

On the construction site, one or more manufacturing systems (cf. Section 4.5) can be installed and referenced by IfcRelContainedInSpatialStructure. Each may define a workspace (IfcSpatialZone) by IfcRelSpaceBoundary, i.e., the reachable limit of the AM systems manipulator, which can be used, e.g., to set up clearance zones for human workers. Contained within (IfcRelContainedInSpatialStructure) are, on the one hand an IfcProduct representing the component to be manufactured (blue box, cf. Section 4.2) and on the other, IfcElements representing the manufacturing robot (red box, cf. Section 4.5).

The spatial data corresponds to the manufacturing system used. As previously indicated, it is helpful for preparation and setting up the system. Also, printability checks can be performed if the workspace is available by testing if the component is fully enclosed. If multiple components are manufactured with the same system, the spatial data can be shared in an external resource and linked to the component model by IfcExternalReference.

4.2. BIM data

The component model or the BIM data section (blue box in Fig. 10) is the most essential part of the data structure. It represents the extracted component information from the original BIM model that describes the component to be manufactured. At the heart of it is the IfcBuiltElement, or, when instantiated, the more descriptive subtypes, such as IfcWall or IfcColumn. For linkability, the IfcBuiltElement is always copied from the BIM model to the FIM model, retaining its GUID. The geometric description is also copied and converted into a B-Rep if not yet in that format. The B-Rep geometry format has multiple advantages for use in FIM, as the corresponding surfaces of the B-Rep can be topologically broken down and used for different purposes (cf. Sections 5.1 and 5.2). To make the surfaces available, they are linked to a separate IfcShapeRepresentation and labeled according to the topology. An exterior Wall, for example, can be topologically broken down into *top*, *bottom*, *interior*, *exterior*, and *side* surfaces.

In contrast to traditional construction methods, AM can create components with completely enclosed void structures. This extra design freedom, however, requires a higher model granularity for FIM, i.e. not only the exterior shape of an artifact but also the interior must be represented. With the IFC schema, this is possible by describing voiding features (IfcVoidingFeature), i.e., elements that are "subtracted" from another element by IfcRelVoidsElement. This process can be done either in the data preparation for FIM or during path planning (cf. Section 5.1). The voiding features can also define spaces (by IfcRelSpaceBoundary), which enables the design of function integration. When the FIM model is finalized, the voiding features can be transferred back to the BIM model to make the void spaces available for other design decisions, such as installing cable ducts and pipes.

Depending on the component type and the manufacturing method, different path planning methods can be applied to generate the fabrication information using the shape representations.

4.3. Fabrication data

The fabrication data (green box in Fig. 10) is meant to describe the motion of the AM system and its tool behavior. Usually, a toolpath is employed to control the motion of a machine. Depending on the system and utilized tools, there may be some variations in path design. However, for most additive manufacturing methods, a layer-wise material application process is used (cf. Section 2), with IC3DP currently being the only exception (cf. Section 2.1.1).

For the layer-wise methods, the component to be printed can be decomposed (by slicing) into discrete layers with a specific height. Inversely, in the manufacturing process, thin slices are basically stacked on top of one another to form the component. In the data structure, this is modeled by representing the component as an assembly of layers, i.e., the IfcBuiltElement is decomposed (IfcRelAggregates) by a list of layers (IfcLayer). However, It must be noted that the type "IfcLayer" does not yet exist; It is a proposed datatype for the AMC domain. Additionally, to account for layers divided by an opening and to enable spatially free movement (e.g., for the I3DCP method, Section 2.1.1), another element type must be proposed: IfcPrintSection. With IfcPrintSection, a print layer can be subdivided into separate parts, or 3D curves describing spatially free movement can be contained. Each print section may define a section that can be printed continuously without disruption, e.g., caused by a required repositioning. Instead of the IfcLayer and IfcPrintSection types, currently, the proxy type IfcBuildingElementProxy must be used.

Due to the nature of AM manufacturing, the geometrical shape representation of the layers can be simplified, as proposed by Slepicka et al. [17]. In most AM methods (except I3DCP), the manufacturing tool will only be moved relative to the top surface of each layer along a specific path. Thus, providing the IfcLayer entity with only the slicing surface and the toolpath (curve geometry) is enough to adequately describe the layer's geometry. At the same time, the tool movement is described; the curve defines the position (and nozzle direction), and the surface defines the orientation of the tool (it should be oriented along the negative normal of the surface). In conventional 3D prints, usually planar slicing is applied using planes aligned parallel or sometimes angled to the printing platform. Retrieving the normal vector in such a use case is trivial. However, with the proposed data structure FIM also supports non-planar and non-parallel slicing. An additional advantage of the surface shape representation is the possibility to utilize the surface geometry of each layer as a reference for "as-printed" geometry capturing (cf. Section 5.4).

A convenient way of expressing the curve geometry for the toolpath is in the form of a pcurve (IfcPcurve). Pcurves are defined in the UV parameter space of an associated surface (the layer surface). Discretizing a pcurve yields UV coordinates. The corresponding XYZ coordinates and normal vector can be obtained by evaluating the associated surface for each set of UV coordinates.

For I3DCP, the toolpath can be represented by IfcPrintSections with a 3D curve geometry as shape representation. As the method does not apply the material in layers, using surface representations for representing the tool orientation is impractical, so other means must be implemented. A possible candidate to represent a change of direction in relation to the tool path is the class IfcOffsetCurveByDistances, for which a list of IfcPointByDistanceExpressions is given. Each point-by-distance expression relates vector coordinates (the offset) with a point on the referenced curve by distance. The offset vector can also be interpreted as tool orientation. Between each distance expression, the values are linearly interpolated.

As described in Section 2.1.1, other parameters besides robot positioning must also be controlled in an AM process. Usually, the interdependent parameters of an AM system, as those shown in Fig. 3, are all related to the layer surface and toolpath. Some of these need to be modeled separately, such as the robot's velocity profile. Others are derivable, such as the filament height, which is constrained by the

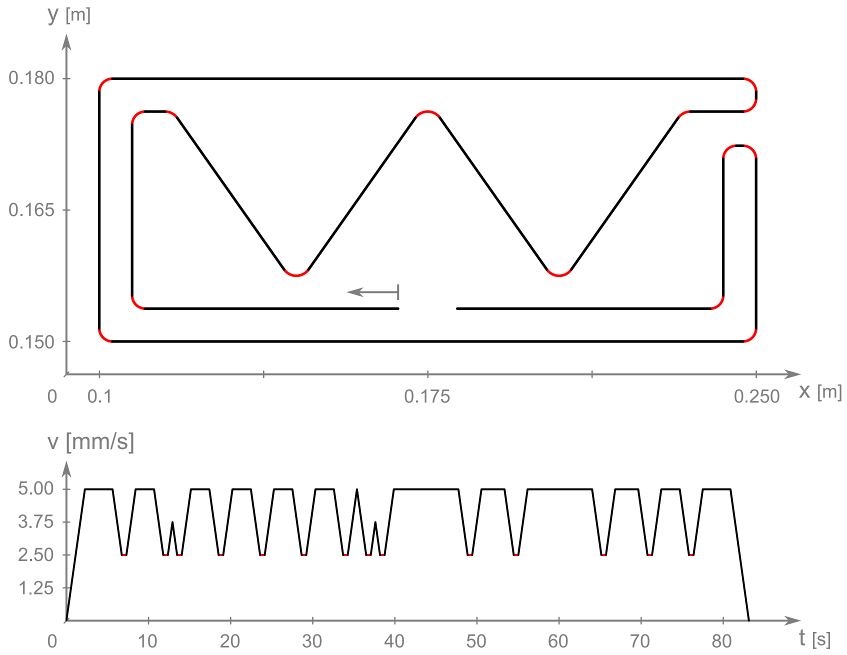


Fig. 11. An exemplary toolpath (top) along with the corresponding velocity profile (bottom). The surface area between the t-axis and the velocity profile equals the toolpath's curve length.

layer surfaces of two consecutive layers. Beyond that, other parameters are correlated more complexly with multiple control variables, such as the material flow, which depends on the robot's speed, layer height, and filament width. The velocity profile, however, is critical, it must be represented, as it describes how the toolpath must be followed. In robot control terms, the velocity profile is the time scaling function that turns a path into a trajectory (cf. Section 5.3).

All parameters can conveniently be modeled as additional "geometric" shapes in FIM. For example, the velocity profile can be represented using a curve geometry in 2D coordinate space, similar to a mathematical graph (cf. Fig. 11). For simplification, if the acceleration is assumed constant during velocity changes (trapezoidal time scaling), a polyline is well suited to describe this parameter. Composite curves with NURBS curve segments can be used for more complex time scaling (e.g., S-Curve time scaling). Instead of defining a position, the XY coordinates can also be interpreted as time and velocity. For example, the speed profile, illustrated in Fig. 11, is designed to limit the acceleration of the tool. If an object travels along the shown path, it experiences radial acceleration as it passes through the arcs (with a magnitude dependent on the object's speed and the curvature of the arc). As described in Section 2.1.3, strong acceleration can cause issues in extrusion-based 3D printing; therefore, it has to be limited by reducing the tool speed. However, the parameter "geometries" must be labeled appropriately to ensure correct use of the data later on, especially if multiple parameters have to be modeled depending on the AM method. Other parameters that do not directly relate to the toolpath must be modeled differently. Nonetheless, it is still possible to model, for example, event-based parameter changes using process data (cf. Section 4.4).

4.4. Process data

Depending on the complexity, a manufacturing process can be sufficiently described using only BIM and fabrication data. The AM system would sequentially read and interpret the fabrication data in such a scenario. However, this sequential way of interpreting the data is not very flexible; reacting to sensor feedback and fine-tuning the flow of information would not be provided, and more complex manufacturing processes would not be manageable.

With the defined data structure for describing processes (yellow box in Fig. 10), tasks, procedures, and events can be defined to enable a more flexible process design. For this purpose, the IFC format provides the abstract class `IfcProcess` with the subtypes `IfcTask`, `IfcProcedure`, and `IfcEvent`. `IfcTask` describes an identifiable unit of work, such as *"print layer"*, which can be as granular as the user desires. Similarly, `IfcTask` describes a logical set of actions following or causing an event (`IfcEvent`). For more granularity, all process types can be nested by sequences of subprocesses. Using the relation `IfcRelSequence`, processes can be related to each other, defining the sequence of events depending on the sequence type.

Each process can be directly assigned to an `IfcProduct` (component to be manufactured, or its individual layers), `IfcResource` (machine system) and `IfcControl`. Fig. 12 illustrates a use case for assigning processes to layers. By sequencing the processes assigned to layers, the order in which the layers are built can be modeled. Assignment to machine systems enables the user to define which machine performs which task, e.g., if there is more than one AM system in reachable distance to the component. `IfcControl` can model things, such as the cost of an action (material usage) or the request for an action (collection of data). Thus, also Sensor activity can be predefined in the FIM model.

Finally, the described data structure for processes cannot only be used to predefine processes. It is also possible to track the manufacturing status and equipment with the process data or to insert new events during the manufacturing. Processes can be modeled without specifying the exact execution time during FIM design, which can be added to the respective process instance during manufacturing.

4.5. Machine data

The machine data part of the data structure (red box in Fig. 10) describes the AM hardware that is to be used to manufacture the modeled component. As proposed by Slepicka et al. [17], the AM system is described using the class `IfcConstructionEquipmentResource`. However, for more modularity and to enable precise modeling of the AM subsystems as described in Section 2.1.2 (manipulator, pump, mixer, build platform, and print head), the data structure was refined. With the refinement, the individual parts of the AM system can now be modeled with separate elements (`IfcElement`). A generalized IFC class

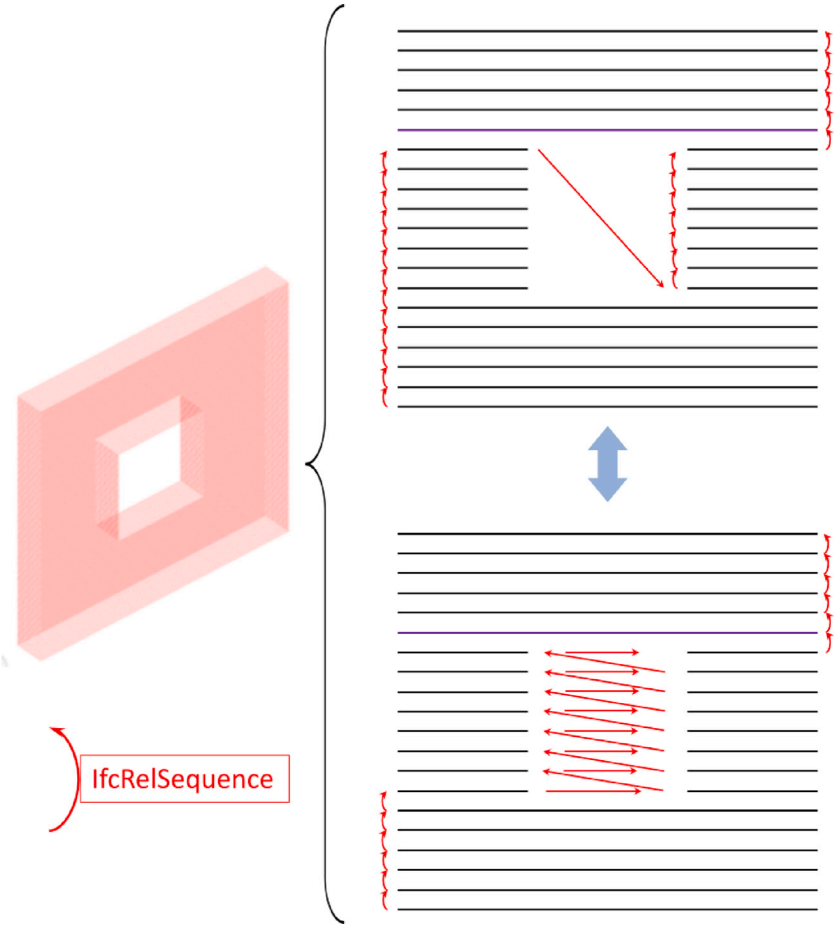


Fig. 12. Different sequencing possibilities for an object with a branched geometry. Illustrated is a wall with an opening for a window on the left and schematically the layer sequence on the right. The example is not printable and is only shown to illustrate sequencing.

is available for each of the mentioned subsystems, e.g., `IfcPump` for the pump subsystem of a deposition system, which can be specified by a user-defined type (`IfcRelDefinesByType` and `IfcElementType`). Machine-specific parameters can be integrated by defining an `IfcPropertySet` for the `IfcElementType`. All subsystems can be interlinked using the relation `IfcRelConnectsElements`. This way, complex machine systems, including pipes and wires, can be modeled if necessary for project planning.

Finally, the workspace of the AM system can be defined. Usually, the manipulator and build platform define the usable space. With the relation `IfcRelSpaceBoundary`, the defining elements can be associated with the `IfcSpatialZone` described in Section 4.1.

Much like the spatial data, the machine data is specific to a manufacturing system. If multiple components are manufactured with the same system, the machine data can be externally referenced with `IfcExternalReference`.

5. Implementation of a FIM-based cyber-physical system (CPS)

The central idea behind FIM is to provide a framework able to store and modify all relevant information for digital design and automated manufacturing with interfaces for all involved activities (cf. Section 3). With the data structure described in Section 3, full data access is guaranteed while being able to update the data at any time. It is possible to consistently interlink high-level geometric and semantic information with low-level machine instructions and feedback data from various sources.

Fig. 13 illustrates the prototypical implementation of a FIM-based Cyber-Physical System (CPS), integrating the concepts of CPS and DT (cf. Section 2.3). Several related studies have identified and investigated different methods and technologies vital to closing the illustrated loop between digital and physical reality, as described in Section 2.3. As part of the digital-to-physical activities, data preparation and path planning (cf. Section 5.1), simulation and prediction (cf. Section 5.2), and robot control (cf. Section 5.3) are highlighted. Data feedback and process control (cf. Section 5.4) are portrayed on the physical-to-digital side. Currently, all the described methods and technologies have been investigated separately; the loop has not been fully closed yet.

In the following sections, the individual implementations are explained, and experimental validation is shown.

5.1. Data preparation and path planning

As described in Section 3, FIM is designed to be integrated into digital design for construction when utilizing the BIM methodology. In order to apply FIM, a BIM model must be available in its later design stages, i.e., 3D model geometries must already be developed to a certain extent. To start modeling the fabrication information and thus increasing the model granularity component by component, the BIM model needs to meet some requirements depending on the AM method to be used. For example, components to be printed need to be small enough to fit into the workspace of the AM system. Li and Petzold [54] aim to support designers already in the early design phase to integrate

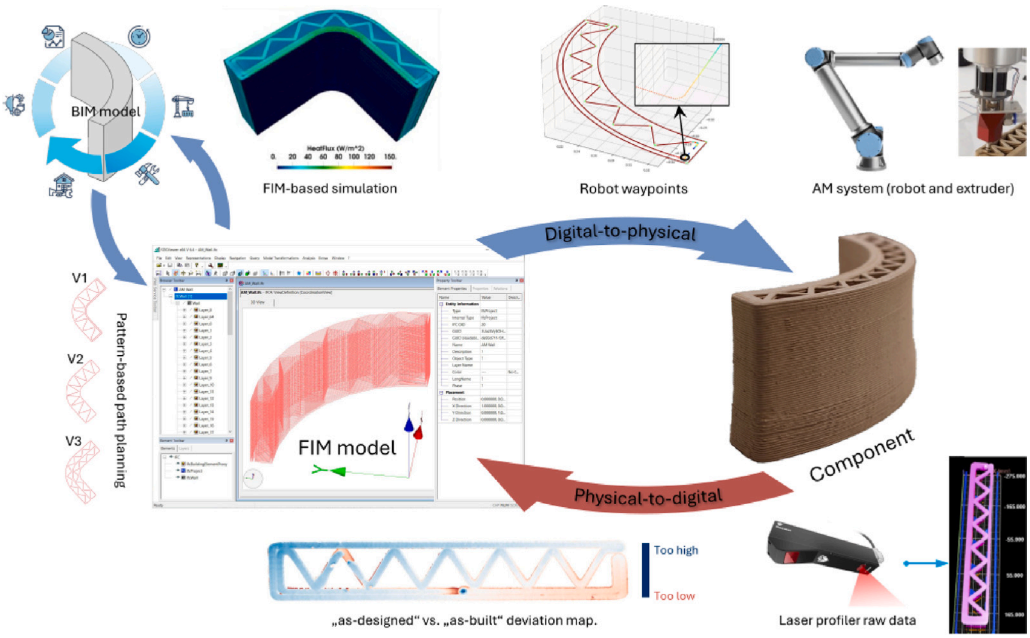


Fig. 13. Implemented methods for a FIM-based Cyber-Physical System (CPS), analogous to Fig. 9.

AM design requirements by developing a Design Decision Support System (DDSS) for BIM. Generally, when designing components for AM, greater care must be taken to ensure model quality.

Implementation

A common practice in designing for AM is to model the component to be printed, including the cavities, before using slicing software to generate the toolpath. In the context of FIM, this is also possible, the cavities could already be modeled during BIM design. However, to correctly identify the modeled cavities later, they should be modeled as separate voiding geometries, as described in Section 4.2. It is more recommendable to model the details later with FIM. This is especially the case when the structure should be topologically optimized [55], as this activity is usually outside the scope of BIM. Another strategy to generate cavities is to utilize parametric design patterns with which the toolpath can be directly generated relative to the contour of the component, indirectly generating the cavities.

If requirements are met, the component data must be extracted from the BIM model to finally utilize FIM. Depending on the BIM modeling software, different approaches may be taken. One possible solution is to use the software's IFC exporter to store the BIM model in the IFC format. Then, using an IFC reader, a component can be selected and extracted for FIM. However, if the software's IFC exporter is poorly implemented, this approach can cause issues, e.g., if the component's geometry is getting approximated for the export. Another approach is to utilize the BIM software's API to access the data directly. This way, the software's geometric kernel can also be used via API to translate the component's geometry into the required format and initialize the path planning, as described in Section 4.2.

Path planning is a central activity in the context of AM, needed to transform the component's geometry into robot instructions. As a proof of concept, a pattern-based path planning tool for deposition methods was developed using the graphical programming interface *Dynamo for Revit* for FIM. With *Dynamo*, the BIM model's data is accessible, and a geometric kernel is available for path-planning operations. Finally, modules can be loaded via *Dynamo*'s Python interface to export the FIM data to an external resource (e.g., as a file or in the form of an online graph database, cf. Section 4).

In regular 3D printing, when generating the toolpath, the contour of the provided 3D geometry is usually traced to form a shell; then, the interior is filled with a specific pattern to ensure the stability of the component. In the same way, the generation of the toolpath can be done for depositing AM methods in construction. First, assuming a layer height is specified, the individual `IfcLayer` instances must be created, assigning each layer a surface (e.g., a horizontal plane). Then, the component's contour can be extracted by intersecting the B-Rep of the BIM data (cf. Section 4.2) with the layer surfaces. The toolpath can be generated layer-by-layer with the contour and a parameter-based pattern algorithm. Different algorithms can be provided for variable designs (e.g., zigzag, lamella, honeycomb infills, or combinations).

Experimental validation

The implemented algorithm was tested on a mock-up BIM model containing a one-room house with different corner designs, as shown in the center of Fig. 14. With the Dynamo implementation quickly various FIM variants could be generated for different BIM model components, as illustrated in Fig. 14, left and right. In the shown example 3 parameter settings were chosen (Variant V1, V2, and V3) and applied to all corner designs (only the chamfered and filleted corner are shown). With FIM, the individual components can be selected for extraction. With parametric pattern-based path planning, different variants can be generated quickly. In Fig. 14, for each variant, the print path for the first printing layer is displayed.

5.2. Simulation integration

When modeling a component, it is essential to be able to estimate its performance. For example, it is possible to design the inner structure of a component to increase its thermal insulation properties. This can be of interest in wall corners to improve the heat flux in an exterior corner (cf. previous example Fig. 14).

Implementation

In this context, Oztoprak et al. [56] developed a method to automatically derive simulation models from a FIM model for a 3D FCM simulation framework (Adhoc++). As indicated in Fig. 10, a FIM model provides a semantically enriched geometric representation of a component which enables utilizing parts of the data for multiple purposes. The tool path shape representations can be used in a procedural modeling approach to produce an accurate volumetric model of the printed

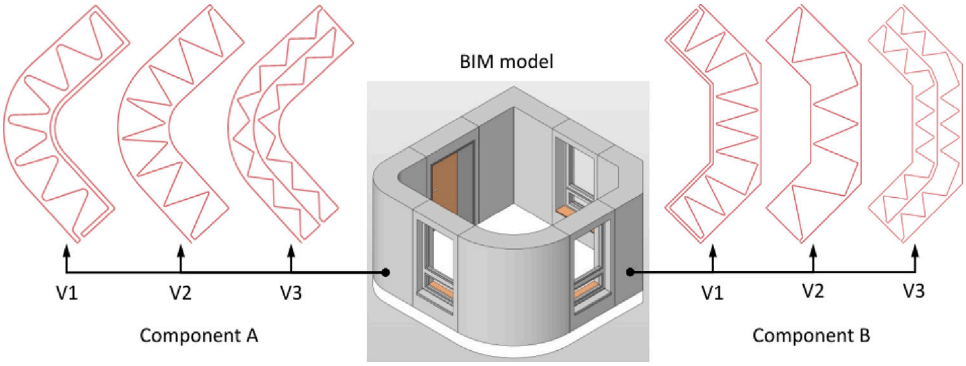


Fig. 14. Different toolpath variations extracted from a mock-up BIM model.

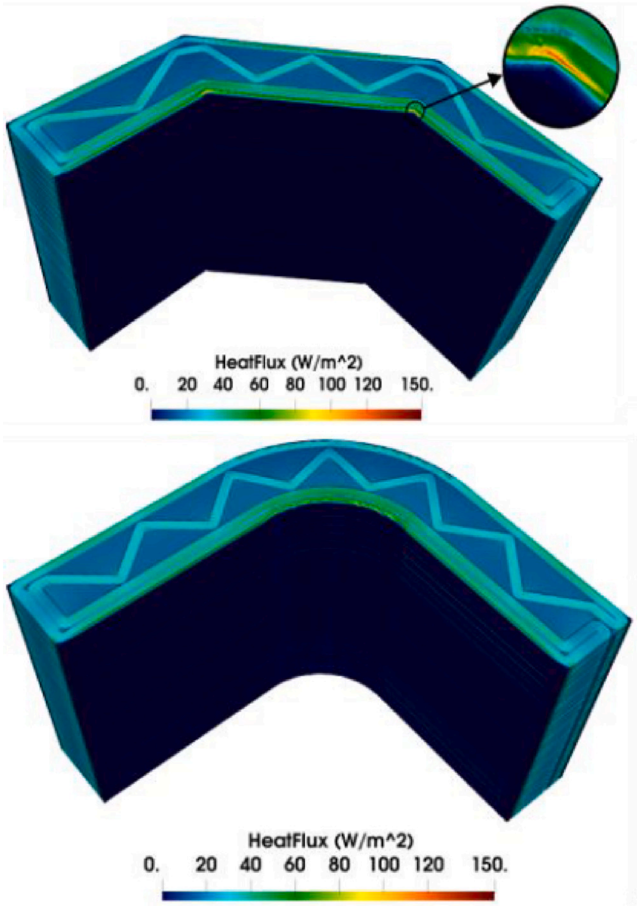


Fig. 15. Simulation results of a heat flux simulation based on FIM variant models [56].

component. Additionally, with the help of the labeled surface representations of the `IfcBuiltElement` (cf. Section 4.2) and a discretization algorithm, relevant surfaces of the volumetric model were extracted in a discretized form for boundary condition application.

Experimental validation

With this method, generating simulation models from FIM is now a streamlined process. To illustrate the usefulness of this approach, a parameter study was performed comparing different FIM variant models. Different wall corner variants in a mock-up BIM model were extracted with FIM, and various patterns were applied in the subsequent path planning (cf. Fig. 14). For all variants generated, a heat flux simulation was performed. An excerpt from the results is shown in Fig. 15.

Robot simulation is another type of simulation that can be performed with FIM. It is, however, closely related to robot control and will be shortly discussed in the next section.

5.3. Robot control

The most essential part of AM is the machine control. As described in Section 2.1.2, different hardware parts are usually combined to form an AM system. Only if all involved machine parts of the AM system are perfectly attuned to each other can good print quality be expected. For this purpose, the fabrication information must be designed meticulously unless some feedback control is installed (cf. Section 5.4). Without feedback control, the quality of the product can only be as good as the quality of the fabrication information.

As mentioned in Section 4.3, three shape representations are available in each `IfcLayer` or `IfcPrintSection` instance for describing the robot motion, a surface for the tool orientation (or in the case of I3DCP an offset curve), a curve for the tool path, and another curve for the velocity profile. Together, these three elements describe the trajectory of the manipulator. Additionally, further shapes may be available to control more parameters if needed.

Implementation

A robot controller typically accepts a steady stream of discrete poses (desired robot configurations) to generate the movement. Depending on the connection, up to 1000 poses per second can be transmitted. In order to translate the three FIM elements describing the robot's trajectory into a stream of poses, the geometries have to be discretized in accordance with the robot connection. That means if the robot connection allows, e.g., a transmission rate of 500 Hz, the following algorithm must be applied:

1. Discretize the velocity profile with a resolution of 2 ms.
2. Integrate between discrete points using the trapezoidal rule (distances between poses).
3. Use the resulting values to discretize the toolpath (XYZ coordinates).
4. Use discrete toolpath points to extract the corresponding normal vector from the layer surface (Z vector; X and Y vector inferred by current pose).
5. (If nozzle direction is constrained) Extract the tangent vectors of the toolpath at the discrete points (Z and X vector; Y inferred).

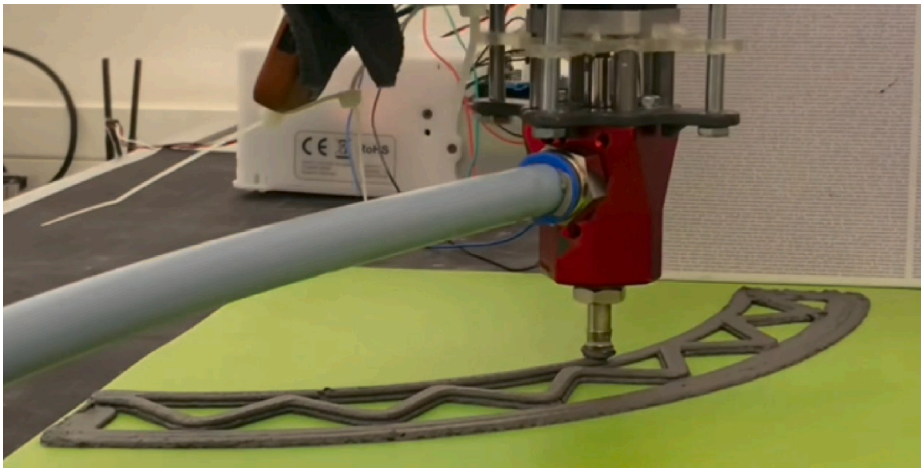


Fig. 16. Small-scale 3D print using a UR10e articulated arm robot, a Stoneflower3D clay extrusion kit and the described RTDE control framework [57].

Depending on the controller, the poses can be transmitted as is (cartesian coordinates) or as robot joint angles. For the latter, the joint coordinates must be calculated using inverse kinematics. Yet, more information about the robot system is required to correctly set up a robot connection and choose the right parameters for the inverse kinematics. This information can be modeled in FIM as described in Section 4.5. Additionally, references to external sources, such as robot description files in the URDF format, can be set up within the FIM data structure.

Different methods can be applied to establish the connection to the robot controller. A very convenient method is using an open-source robot control framework, such as ROS. With ROS, the simulation toolbox Gazebo is also available for performing robot simulations, as indicated in the previous section.

Experimental validation

The FIM-based robot control has been tested in multiple small-scale 3D printing tasks using a UR robot and an extrusion-based clay printing system. Fig. 16 shows a test print performed using the RTDE tool. For the test print, an IFC file containing the FIM model of a component was provided. Via IfcOpenShell, the FIM information was read and directly used for robot control.

Alternatives

Another viable option is to use more direct interfaces. For example, the so-called Real-time Data Exchange (RTDE) control interface can be used for UR robots. In a previous study, Slepicka et al. [57] implemented a control framework that utilizes the RTDE control interface. With RTDE, data packages can be sent to the robot controller via TCP/IP with a maximum transmission rate of 500 Hz. On the robot side, the input registers that receive the sent data can be accessed by running a small robot control program. The robot can be moved according to the trajectory by accepting the joint angles in the input registers. As discussed in this section, the control framework was set up to directly interpret FIM fabrication data (cf. Section 4.3). The apparent advantage is that no file conversion is necessary to convey the trajectory to the robot; it can be controlled directly based on the FIM data. Currently, the applicability range of the RTDE framework is limited to UR robots. However, the same principles, i.e., the core of the RTDE control, can also be applied to other robot systems, such as KUKA. Instead of the RTDE interface for UR robots, another interface, e.g., KUKAVARPROXY or RSI for KUKA systems, can be used [58]. The developed RTDE control represents a lightweight FIM-based alternative compared to other control frameworks.

5.4. Data feedback

As described in Section 2, all AMC methods and machines have their own set of advantages as well as limitations. Due to various process-related limitations and reliability issues, it is unavoidable that the “as-built” reality of the physical object will deviate from the “as-designed” reality in the digital model; it can only be limited by process control. In this context, it is essential to enable a circular data flow, as discussed in Section 2.1.3, not only for process control but also to allow capturing any deviations that could not be avoided. So, in order to close the loop in automated construction (cf. Fig. 13), methods for automated quality inspection and corresponding control must be implemented. Slepicka et al. [59] investigated which information is needed for establishing information exchange from the “as-built” object (physical) to the “as-designed” data in the FIM model (digital) and when data feedback is possible based on selected use cases. The term “Digital Twin” (DT) is often introduced in this context. Various conceptualizations of the term DT exist, all centered around the core idea that a DT serves as a digital replica of an existing or future real object or process, continually updated to reflect its current state.

However, delivering and storing a continuous data stream for all sensor types is impossible due to sensor and computation restrictions. For feasibility, the captured data must be balanced between being abstract enough and providing an adequate level of detail for its intended purpose [59]. A more discretized data-capturing approach must be chosen if the captured dataset is large and the information extraction complex. Fig. 17 conceptualizes different data-capturing approaches that must be integrated into FIM.

The online strategy is feasible for capturing small data packages at a time from which features can be extracted reasonably fast; for example, when measuring control values for feedback control. Epoch-wise strategies apply when more contextural information is required to extract certain features or attributes, such as classification tasks. Finally, the pre-assembly strategy applies if process information must be additionally considered. An Epoch can be described as a pre-defined set of instructions, e.g., one epoch may be to print one full layer.

Implementation

Two methods were developed based on FIM in separate studies. The first method was implemented to integrate online feedback control into extrusion-based clay 3D printing using an RGBD camera [35]. For this purpose, a special camera mount was created to rotate an attached sensor (the RGBD camera) based on FIM data, independently from

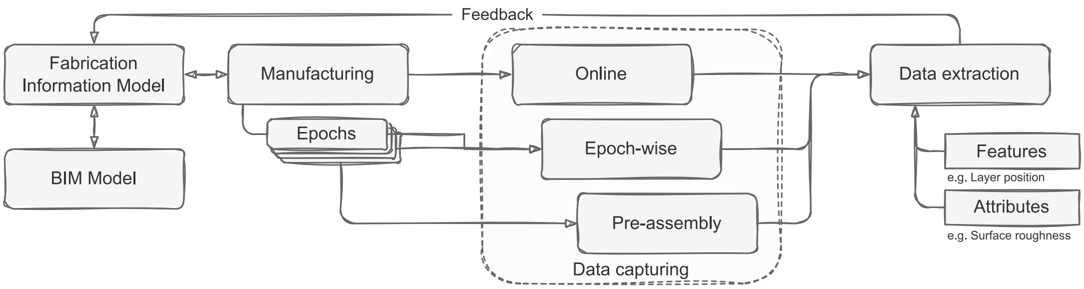


Fig. 17. Schematical description of different data capturing strategies, after [59].

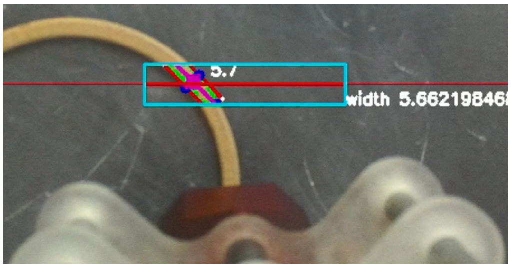


Fig. 18. Online measurement of the printed filament width. Top-down view from a nozzle-mounted RGB camera.

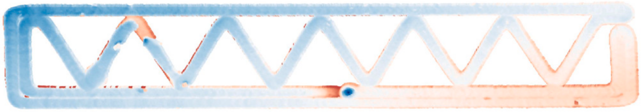


Fig. 19. Deviation heat map of layer 14 of 21 of a lab-scale test print using a clay extruder [60].

the robot system, to be aligned perpendicular to the printed filament throughout the printing process. The camera feed was evaluated with computer vision methods to extract the printed filament width to feed a PID controller regulating the volume flow of the printer. With this method, only the extracted feature (filament width) was stored in the FIM model; the video samples were discarded after extraction.

The second method is an epoch-wise quality control method utilizing a laser profiler [60]. With the laser profiler, after finishing a print layer (one epoch), a point cloud was captured of the printed filament in order to measure height deviations in relation to the modeled layer surface (cf. Section 4.3). For feedback into FIM, a deviation map can be created; it describes pixel-wise height deviations as illustrated in Fig. 19. To generate the heatmap efficiently, the laser profiler is moved along a path with a specific offset to the layer surface in the FIM model. This way, the points do not have to be orthogonally projected onto the surface to measure the distance.

Experimental validation

Both methods were tested in multiple small-scale clay printing scenarios.

The online feedback control was used to regulate a printing process that was performed with intentionally wrongfully set extrusion parameters. The system was able to detect the current filament width, and by utilizing a PID controller, the extrusion rate could be corrected adequately (cf. Fig. 18).

The epoch-wise quality control was used to create deviation maps comparing “as-designed” with “as-printed” geometries. As illustrated in Fig. 19, a printing defect and the layer-to-layer transition (bottom) are clearly visible. Also, a calibration issue could be detected and corrected; the robot carrying the laser profiler was slightly tilted compared to the printing robot (less than 1°).

6. Conclusion

This paper described Fabrication Information Modeling (FIM), a comprehensive fabrication data framework for application in Additive Manufacturing in Construction (AMC). and displayed its capabilities in different use cases. Through the integration of digital design concepts with automated manufacturing processes, FIM offers an extensive platform for storing, accessing, and exchanging relevant information. With FIM being closely linked to BIM-based digital design, it enables the integration of fabrication-related processes across various design iterations of construction projects, and the semi-automated extraction of fabrication information (cf. Fig. 14).

The discussed workflow activities, including data preparation and path planning, simulation integration, robot control, and data feedback, demonstrate the sophisticated capabilities of FIM in optimizing construction processes. FIM aims to enable precise control over manufacturing processes, accurate performance estimation, and real-time monitoring of as-built data, thereby enhancing construction efficiency and quality. All methods shown in this paper could be applied without the need to perform data conversions; data accessibility is always guaranteed.

An overarching goal in developing FIM is to enable a circular data flow between digital modeling and manufacturing, i.e., to close the digital-to-physical and physical-to-digital loop. While significant progress has been made in developing and implementing the FIM-based CPS, by prototypically implementing sensor data feedback, several challenges remain to be addressed. These include optimizing data exchange mechanisms, ensuring compatibility with diverse manufacturing systems, enhancing real-time feedback mechanisms, and a full closure of the entire digital-physical-digital circle. The missing links for the full loop closure are mechanisms for automated defect detection, and for adapting the ongoing manufacturing process based on the detected defects. Future research efforts may address these challenges to further improve the effectiveness and scalability of FIM-based construction systems.

Overall, the findings presented in this paper underscore the potential of FIM as a powerful tool for advancing cyber–physical construction systems, with implications for improved efficiency, quality, and innovation in the construction industry. As indicated in Section 1, FIM is supposed to be applicable to multiple automated manufacturing methods, such as AM, robotic bricklaying, robotic timber frame assembly, and others. In this paper, however, the focus was on AM, the applicability of FIM to other manufacturing methods must be validated in future studies.

Another noteworthy advantage of FIM is the possibility to utilize the FIM model as a ‘digital component passport,’ i.e. as a comprehensive digital representation or DT of the real component, including the manufacturing history of the component. The FIM model can be extended at any time, and is suitable for long-term storage, due to the IFC-based data format. In facility management, the FIM model could help identify issues and a possible fix in case the component performance is compromised.

CRediT authorship contribution statement

M. Slepicka: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **A. Borrmann:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Martin Slepicka reports financial support was provided by German Research Foundation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

The authors gratefully acknowledge the funding of the TRR 277 (www.tu-braunschweig.de/trr277) by the German Research Foundation (DFG) – TRR277/1 2020 – project number 414265976, and the support of the Priority Program 2187 by the DFG – Project 423969184.

References

[1] E. Forcael, I. Ferrari, A. Opazo-Vega, J.A. Pulido-Arcas, Construction 4.0: A literature review, Sustainability 12 (22) (2020) 9755, http://dx.doi.org/10.3390/su12229755.

[2] C. Boton, L. Rivest, O. Ghnaya, M. Chouchen, What is at the root of construction 4.0: A systematic review of the recent research effort, Arch. Comput. Methods Eng. 28 (2021) 2331–2350, http://dx.doi.org/10.1007/s11831-020-09457-7.

[3] D. Briels, M. Renz, A.S. Nouman, A. Straßer, M. Hechtl, M. Dahlenburg, B. Knychalla, P. Sonnleitner, F. Herding, J. Fleckenstein, E. Krakovská, K. Dörfler, T. Auer, Monolithic AM façade: multi-objective parametric design optimization of additively manufactured insulating wall elements, Front. Built Environ. 9, http://dx.doi.org/10.3389/fbuil.2023.1286933.

[4] D. Briels, S. Kollmannsberger, F. Leithner, C. Matthäus, A.S. Nouman, O. Oztoprak, E. Rank, Thermal optimization of additively manufactured lightweight concrete wall elements with internal cellular structure through simulations and measurements, Buildings 12 (7) (2022) 1023, http://dx.doi.org/10.3390/buildings12071023.

[5] R. Dörrie, V. Laghi, L. Arrè, G. Kienbaum, N. Babovic, N. Hack, H. Kloft, Combined additive manufacturing techniques for adaptive coastline protection structures, Buildings 12 (11) (2022) 1806, http://dx.doi.org/10.3390/buildings12111806.

[6] D. Thomas, Costs, benefits, and adoption of additive manufacturing: a supply chain perspective, Int. J. Adv. Manuf. Technol. 85 (2016) 1857–1876, http://dx.doi.org/10.1007/s00170-015-7973-6.

[7] A.C. Bekker, J.C. Verlinden, Life cycle assessment of wire + arc additive manufacturing compared to green sand casting and CNC milling in stainless steel, J. Clean. Prod. 177 (2018) 438–447, http://dx.doi.org/10.1016/j.jclepro.2017.12.148.

[8] C. Van Sice, J. Faludi, Comparing environmental impacts of metal additive manufacturing to conventional manufacturing, Proc. Des. Soc. 1 (2021) 671–680, http://dx.doi.org/10.1017/pds.2021.67.

[9] M.P. Tinoco, É.M. de Mendonça, L.I.C. Fernandez, L.R. Caldas, O.A.M. Reales, R.D. Toledo Filho, Life cycle assessment (LCA) and environmental sustainability of cementitious materials for 3D concrete printing: A systematic literature review, J. Build. Eng. 52 (2022) 104456, http://dx.doi.org/10.1016/j.jobe.2022.104456.

[10] S. Demirkesen, A. Tezel, Investigating major challenges for industry 4.0 adoption among construction companies, Eng. Constr. Archit. Manage. 29 (3) (2022) 1470–1503, http://dx.doi.org/10.1108/ECAM-12-2020-1059.

[11] F.Y. Ling, G.T.H. Heng, A. Chang-Richards, X. Chen, T.W. Yiu, Impact of digital technology adoption on the comparative advantage of architectural, engineering, and construction firms in Singapore, J. Constr. Eng. Manage. 149 (12) (2023) 04023125, http://dx.doi.org/10.1061/JCEMD4.COENG-13743.

[12] Y. Cai, J. Xiong, H. Chen, G. Zhang, A review of in-situ monitoring and process control system in metal-based laser additive manufacturing, J. Manuf. Syst. 70 (2023) 309–326, http://dx.doi.org/10.1016/j.jmsy.2023.07.018.

[13] Q. Fang, G. Xiong, M. Zhou, T.S. Tamir, C.-B. Yan, H. Wu, Z. Shen, F.-Y. Wang, Process monitoring, diagnosis and control of additive manufacturing, IEEE Trans. Autom. Sci. Eng. 21 (1) (2024) 1041–1067, http://dx.doi.org/10.1109/TASE.2022.3215258.

[14] D. Weger, C. Gehlen, D. Lowke, Additive fertigung von betonbauteilen durch selektive zementleim-intrusion, in: Proceedings of the Ibausil, ISBN: 978-3-00-059950-7, 2018, pp. 1–16.

[15] B. Mallikarjuna, M.N.S. Hareeswar, P.C. Sharath, Applications of Additive Manufacturing in Construction and Building Industries, Springer, Singapore, 2024, pp. 251–272, http://dx.doi.org/10.1007/978-981-99-5949-5_12, (Chapter 12).

[16] Y.W.D. Tay, B. Panda, S.C. Paul, N.A. Noor Mohamed, M.J. Tan, K.F. Leong, 3D printing trends in building and construction industry: a review, Virtual Phys. Prototyp. 12 (3) (2017) 261–276, http://dx.doi.org/10.1080/17452759.2017.1326724.

[17] M. Slepicka, S. Vilgertshofer, A. Borrmann, Fabrication Information Modeling: interfacing building information modeling with digital fabrication, Constr. Robot. 6 (2) (2022) 87–99, http://dx.doi.org/10.1007/s41693-022-00075-2.

[18] V. Mechtcherine, V.N. Nerella, F. Will, M. Näther, J. Otto, M. Krause, Large-scale digital concrete construction – CONPrint3D concept for on-site, monolithic 3D-printing, Autom. Constr. 107 (2019) 102933, http://dx.doi.org/10.1016/J.AUTCON.2019.102933.

[19] J. Reinold, V.N. Nerella, V. Mechtcherine, G. Meschke, Extrusion process simulation and layer shape prediction during 3D-concrete-printing using the Particle Finite Element Method, Autom. Constr. 136, http://dx.doi.org/10.1016/j.autcon.2022.104173.

[20] H. Kloft, H.W. Krauss, N. Hack, E. Herrmann, S. Neudecker, P.A. Varady, D. Lowke, Influence of process parameters on the interlayer bond strength of concrete elements additive manufactured by Shotcrete 3D Printing (SC3DP), Cem. Concr. Res. 134, http://dx.doi.org/10.1016/j.cemconres.2020.106078.

[21] J. Müller, J. Hensel, WAAM of structural components—building strategies for varying wall thicknesses, Welding World 67 (2023) 833–844, http://dx.doi.org/10.1007/s40194-023-01481-y.

[22] D. Talke, B. Saile, N. Meier, F. Herding, I. Mai, H. Zetzener, A. Kwade, D. Lowke, Particle-bed 3D printing by selective cement activation – Influence of process parameters on particle-bed density, Cem. Concr. Res. 168 (2023) 107140, http://dx.doi.org/10.1016/J.CEMCONRES.2023.107140.

[23] J. Diller, C. Radlbeck, D. Siebert, J. Blankenhagen, D. Gubetini, F. Oberhaidinger, M. Mensinger, Additive manufacturing in construction—Implementing powder-bed fusion of metals using a laser (PBF-LB/M) and shape optimization in the construction design process, in: Eng. Proc, MDPI, 2023, p. 10, http://dx.doi.org/10.3390/engproc2023043010.

[24] V. Mechtcherine, R. Buswell, H. Kloft, F.P. Bos, N. Hack, R. Wolfs, J. Sanjayan, B. Nematollahi, E. Ivaniuk, T. Neef, Integrating reinforcement in digital fabrication with concrete: A review and classification framework, Cem. Concr. Compos. 119 (2021) 103964, http://dx.doi.org/10.1016/J.CEMCONCOMP.2021.103964.

[25] N. Freund, I. Dressler, D. Lowke, Studying the bond properties of vertical integrated short reinforcement in the shotcrete 3D printing process, in: F.P. Bos, S.S. Lucas, R.J. Wolfs, T.A. Salet (Eds.), Second RILEM International Conference on Concrete and Digital Fabrication, Springer International Publishing, Cham, 2020, pp. 612–621, http://dx.doi.org/10.1007/978-3-030-49916-7_62.

[26] R. Dörrie, M. David, N. Freund, D. Lowke, K. Dröder, H. Kloft, In-process integration of reinforcement for construction elements during shotcrete 3D printing, in: Open Conference Proceedings, vol. 3, http://dx.doi.org/10.52825/ocp.v3i.224.

[27] A. Straßer, F. Riegger, L.D. Hamilton, T. Kränkel, C. Gehlen, M.F. Zaeh, A. Kwade, Selective Paste Intrusion: Integration of reinforcement by WAAM — Concept and current research with special attention to cooling strategies, Constr. Build. Mater. 406 (2023) 133236, http://dx.doi.org/10.1016/J.CONBUILDMAT.2023.133236.

[28] D. Lowke, A. Vandenberg, A. Pierre, A. Thomas, H. Kloft, N. Hack, Injection 3D concrete printing in a carrier liquid - Underlying physics and applications to lightweight space frame structures, Cem. Concr. Compos. 124 (2021) 104169, http://dx.doi.org/10.1016/j.cemconcomp.2021.104169.

[29] T. Wangler, R. Pileggi, S. Gürel, R.J. Flatt, A chemical process engineering look at digital concrete processes: critical step design, inline mixing, and scaleup, Cem. Concr. Res. 155 (2022) 106782, http://dx.doi.org/10.1016/j.cemconres.2022.106782.

[30] M. Krause, J. Otto, A. Bulgakov, D. Sayfeddine, Strategic optimization of 3D concrete printing using the method of conprint3D®, in: ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction, vol. 35, IAARC Publications, 2018, pp. 9–15, http://dx.doi.org/10.22260/ISARC2018/0002.

[31] F. Heidarnezhad, Q. Zhang, Shotcrete based 3D concrete printing: State of art, challenges, and opportunities, Constr. Build. Mater. 323 (2022) 126545, http://dx.doi.org/10.1016/j.conbuildmat.2022.126545.

[32] V. Mechtcherine, A. Michel, M. Liebscher, T. Schmeier, Extrusion-based additive manufacturing with carbon reinforced concrete: Concept and feasibility study, Materials 13, http://dx.doi.org/10.3390/ma13112568.

[33] M. Dahlenburg, C.M. Hechtl, C. Matthäus, J. Fottner, 3D-concrete printing – graded concrete extrusion, in: 2022 3rd International Conference on Computation, Automation and Knowledge Management, ICCAKM, 2022, pp. 1–5, http://dx.doi.org/10.1109/ICCAKM54721.2022.9990494.

[34] K. Dörfler, G. Dielemans, L. Lachmayer, T. Recker, A. Raatz, D. Lowke, M. Gerke, Additive manufacturing using mobile robots: Opportunities and challenges for building construction, Cem. Concr. Res. 158 (2022) 106772, http://dx.doi.org/10.1016/J.CEMCONRES.2022.106772.

[35] R. Mohiuddin, M.C. Policroniades, M. Slepicka, A. Borrmann, Optical process control for extrusion-based additive manufacturing methods in construction, in: ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction, vol. 40, IAARC Publications, 2023, pp. 94–101, http://dx.doi.org/10.22260/ISARC2023/0015.

[36] F. Venturi, R. Taylor, Additive manufacturing in the context of repeatability and reliability, J. Mater. Eng. Perform. 32 (2023) 6589–6609, http://dx.doi.org/10.1007/s11665-023-07897-3.

[37] A. Perrot, A. Pierre, V. Nerella, R. Wolfs, E. Keita, S. Nair, N. Neithalath, N. Roussel, V. Mechtcherine, From analytical methods to numerical simulations: A process engineering toolbox for 3d concrete printing, Cem. Concr. Compos. 122 (2021) 104164, http://dx.doi.org/10.1016/j.cemconcomp.2021.104164.

[38] D. Auer, F. Bos, M. Olabi, O. Fischer, Fiber reinforcement of 3D printed concrete by material extrusion toolpaths aligned to principal stress trajectories, in: Open Conference Proceedings, vol. 3, 2023, pp. 1–15, http://dx.doi.org/10.52825/ocp.v3i.759.

[39] A. Borrmann, M. König, C. Koch, J. Beetz, Building information modeling: Why? What? How? in: Building Information Modeling – Technology Foundations and Industry Practice, Springer, 2018, pp. 1–24, http://dx.doi.org/10.1007/978-3-319-92862-3_1.

[40] A. Paolini, S. Kollmannsberger, E. Rank, Additive manufacturing in construction: A review on processes, applications, and digital planning methods, Addit. Manuf. 30 (2019) 100894, http://dx.doi.org/10.1016/J.ADDMA.2019.100894.

[41] J. Abualdenien, A. Borrmann, A meta-model approach for formal specification and consistent management of multi-LOD building models, Adv. Eng. Inform. 40 (2019) 135–153, http://dx.doi.org/10.1016/j.aei.2019.04.003.

[42] A. Borrmann, J. Beetz, C. Koch, T. Liebich, S. Muhic, Industry foundation classes: A standardized data model for the vendor-neutral exchange of digital building models, in: A. Borrmann, M. König, C. Koch, J. Beetz (Eds.), in: Building Information Modeling - Technology foundations and industry practice, vol. 1, Springer, 2018, pp. 81–126, http://dx.doi.org/10.1007/978-3-319-92862-3_5.

[43] T.B. Allah, W. Anane, I. Iordanova, Robotic additive manufacturing using a visual programming BIM environment, in: R. Gupta, M. Sun, S. Brzev, M.S. Alam, K.T.W. Ng, J. Li, A. El Damatty, C. Lim (Eds.), Proceedings of the Canadian Society of Civil Engineering Annual Conference 2022, Springer International Publishing, Cham, 2023, pp. 605–622, http://dx.doi.org/10.1007/978-3-031-34593-7_37.

[44] S. Krueckemeier, R. Anderl, B. Schleich, File format selection for efficient digital process chains in additive manufacturing, Proc. Des. Soc. 3 (2023) 1875–1884, http://dx.doi.org/10.1017/pds.2023.188.

[45] M. Artus, C. Koch, M. König, Datenmodellierung, Building Information Modeling - Technologische Grundlagen und industrielle Praxis, second ed., Springer Vieweg Wiesbaden, 2021, pp. 53–72, http://dx.doi.org/10.1007/978-3-658-33361-4_3.

[46] S. Lim, R.A. Buswell, P.J. Valentine, D. Piker, S.A. Austin, X.D. Kestelier, Modelling curved-layered printing paths for fabricating large-scale construction components, Addit. Manuf. 12 (2016) 216–230, http://dx.doi.org/10.1016/J.ADDMA.2016.06.004.

[47] L. Chen, X. Yao, P. Xu, S. Moon, G. Bi, Rapid surface defect identification for additive manufacturing with in-situ point cloud processing and machine learning, Virtual Phys. Prototyp. 16, http://dx.doi.org/10.1080/17452759.2020.1832695.

[48] F. Tao, Q. Qi, L. Wang, A. Nee, Digital Twins and Cyber–Physical Systems toward Smart Manufacturing and Industry 4.0: Correlation and Comparison, Engineering 5 (2019) 653–661, http://dx.doi.org/10.1016/j.eng.2019.01.014.

[49] R. Alur, Principles of Cyber–Physical Systems, MIT Press, 2015, http://dx.doi.org/10.5555/2774947.

[50] E. VanDerHorn, S. Mahadevan, Digital twin: generalization, characterization and implementation, Decis. Support Syst. 145 (2021) 113524, http://dx.doi.org/10.1016/j.dss.2021.113524.

[51] J. Duro Royo, Towards Fabrication Information Modeling (FIM): Workflow and Methods for Multi-Scale Trans-Disciplinary Informed Design (Ph.D. thesis), Massachusetts Institute of Technology, 2015, URL http://hdl.handle.net/1721.1/101843.

[52] P. Pauwels, W. Terkaj, EXPRESS to OWL for construction industry: Towards a recommendable and usable ifcOWL ontology, Autom. Constr. 63 (2016) 100–133, http://dx.doi.org/10.1016/j.autcon.2015.12.003.

[53] J. Zhu, P. Wu, X. Lei, IFC-graph for facilitating building information access and query, Autom. Constr. 148 (2023) 104778, http://dx.doi.org/10.1016/j.autcon.2023.104778.

[54] C. Li, F. Petzold, Towards informed design decision support of additive manufacturing in construction-the use of integrated knowledge in BIM-based architectural design, Archit. Plan. J. (APJ) 28 (3) (2023) 7, http://dx.doi.org/10.54729/2789-8547.1202.

[55] R.N. Asl, K.-U. Bletzinger, The implicit bulk-surface filtering method for node-based shape optimization and a comparison of explicit and implicit filtering techniques, Struct. Multidiscip. Optim. 66 (2023) 111, http://dx.doi.org/10.1007/s00158-023-03548-2.

[56] O. Oztoprak, M. Slepicka, A. Aninger, S. Kollmannsberger, E. Rank, A. Borrmann, Linking fabrication information modeling and finite cell method for simulating the behavior of additively manufactured building components, in: EG-ICE Conference, London, United Kingdom, 2023, pp. 1–10, URL https://www.ucl.ac.uk/bartlett/construction/research/virtual-research-centres/institute-digital-innovation-built-environment/30th-eg-ice-1.

[57] M. Slepicka, J. Helou, A. Borrmann, Real-time data exchange (RTDE) robot control integration for fabrication information modeling, Proceedings of the 40th ISARC, 2023, pp. 102–109, http://dx.doi.org/10.22260/ISARC2023/0016.

[58] L. Salameen, A. Estatieh, S. Darbisi, T.A. Tutunji, N.A. Rawashdeh, Interfacing computing platforms for dynamic control and identification of an industrial KUKA robot arm, in: 2020 21st International Conference on Research and Education in Mechatronics, REM, 2020, pp. 1–5, http://dx.doi.org/10.1109/REM49740.2020.9313878.

[59] M. Slepicka, K. Mawas, A. Borrmann, M. Maboudi, M. Gerke, Digital twinning in additive manufacturing - closing the digital-physical-digital loop by automated integration of captured geometric data into fabrication information models, in: Advances in Information Technology in Civil and Building Engineering, Vol. 357, ICCCBE, Springer, Cham, 2022, pp. 459–478, http://dx.doi.org/10.1007/978-3-031-35399-4_34.

[60] S. Espinosa, M. Slepicka, A. Borrmann, Integration of laser profiler feedback into fim for additive manufacturing in construction, in: V. Gonzalez-Moret, J. Zhang, B. García de Soto, I. Brilakis (Eds.), Proceedings of the 41st International Symposium on Automation and Robotics in Construction, International Association for Automation and Robotics in Construction, IAARC, Lille, France, 2024, pp. 89–96, http://dx.doi.org/10.22260/ISARC2024/0013.