A BIM-based approach towards additive manufacturing of concrete structures

Patricia Peralta Abadia*, Sebastian Heine, Horst-Michael Ludwig, and Kay Smarsly
Bauhaus University Weimar, Germany
patricia.peralta.abadia@uni-weimar.de

Abstract. Additive manufacturing (AM) of concrete structures, a technology to automate the architecture, engineering, and construction industry, has been gaining relevance over the past decade. Current data models employed for AM of concrete structures have been evolving slower than AM technologies, most of which relying on solutions that are not suitable for concrete. Current data models insufficiently support complex inter-process relationships within concrete printing. Taking advantage of building information modeling (BIM), a semantic modeling approach, referred as “printing information modeling” (PIM), is proposed in this paper. The PIM model describes the parameters necessary to execute concrete printing jobs, taking into account processes, material, and geometry information. From the results achieved in this study, it is concluded that integrating PIM into BIM models has the potential to provide complete information models advancing AM of concrete structures.

1. Introduction

Additive manufacturing (AM) of concrete structures, also known as concrete printing, allows producing structures and structural components without using formwork, while reducing manufacturing costs, material costs, and waste (Buswell et al., 2007). Concrete components are manufactured from 3D models by computer-controlled processes in a layer-by-layer basis by extruding and precisely placing concrete. In contrast with fix materials such as polymers or metals, using concrete as printing material implies a strong dependency of the material properties on printing processes and strategies, due to the slow chemical reaction hardening the concrete (Bos et al., 2016). However, current data models employed for AM of concrete structures are derived in the same way as conventional AM, not taking into account the unique conditions specific to concrete printing.

Data modeling for AM is mainly based on traditional solutions, such as standard tessellation language (STL) for geometric representation and G-code (ISO 6983-1) for hardware control (Bonnard et al., 2018). The digital thread from 3D models to printed components is composed of five steps, where data is decomposed into several data formats:

i. design of 3D models as computer-aided design (CAD) models,
ii. conversion of 3D models to STL file format,
iii. generation of computer-aided manufacturing (CAM) models or build files and slicing,
iv. generation of G-code files, and
v. building and post-processing of components.

Information breaks along the digital thread, together with the limitations of the different formats used, cause redundancy, information loss, and inconsistencies, as shown by Lu et al. (2015) and Bonnard et al. (2018). Current data models for AM are insufficient to additively manufacture concrete structures and/or components with adequate structural performance and with geometric precision. Changes in the fresh material properties of concrete and problems with manufacturing processes during printing have a negative effect on the AM process and may diminish the performance of the printed components (Buswell et al., 2018). The inconsistency and unreliability in concrete printing, mainly related to unaccounted inter-
process relationships between process, material and geometry, hampers the robustness of the technology. Expertise is required in the AM processes and in material science, from setting ideal process parameters to the preparation and formulation of printable concrete. Geometry and material design, process planning, and process monitoring in concrete printing jobs should go hand-by-hand, allowing traceability along the digital thread. In these respects, deficiencies regarding AM data modeling for concrete structures, such as a lack of knowledge of the relationships between AM parameters and information breaks occurring between 3D models and printing processes, limit the concrete printing process to a long trial-and-error learning curve, as also noted by Salet et al. (2017).

In AM of concrete structures, the material behavior of printable concrete, as a function of time, plays an important role in defining process settings, toolpaths, and computer numerical control (CNC) commands in G-code or CNC code. A new data model containing the main information regarding processes, material, and geometry is required to allow standardization of additive manufacturing in civil engineering. Therefore, the main challenge is to formally describe the relationships of AM processes, material, and geometry parameters to enhance the digital thread currently employed for concrete printing. A new AM data model that takes advantage of building information modeling (BIM) may support the standardization of AM in the architecture, engineering, and construction (AEC) industry. A widely used standardized open BIM exchange format in the AEC industry are the Industry Foundation Classes (IFC). However, a formal description of AM processes using IFC has not yet been reported.

To compensate for the deficiencies and to enhance AM data modeling for concrete structures, a semantic model to be integrated with BIM has been developed in this paper. The semantic modeling approach, referred to as “printing information modeling” (PIM), formally defines the parameters necessary to execute concrete printing jobs regarding processes, material, and geometry. By integrating PIM into BIM, i.e. onto the IFC schema, data generated in the AM digital thread can be stored without losing semantic information. The remainder of the paper is organized as follows. First, a background of joining BIM with AM is presented. Second, the semantic modeling approach is described, presenting the PIM model for AM of concrete structures. Third, the integration of the PIM model with BIM is proposed, where the PIM model is mapped onto the IFC schema to provide a comprehensive information model for additive manufacturing. Fourth, the integration is validated by a case study with an IFC model containing printing information, including slicing and toolpath generation. Finally, the paper concludes with a summary and an outlook on potential future research.

2. Background

BIM is a semantic modeling approach to digitally represent buildings and infrastructure, from planning and design phases to construction and facility management phases (Lu et al., 2015). BIM contains information regarding geometry, material, lifecycle, and compliance checking. The IFC describe basic information of buildings and infrastructure, and may be extended to support domain-specific information (Theiler & Smarsly, 2018). Several extensions have broadened the IFC schema to support point clouds (Krijnen & Beetz, 2017), sensor systems (Theiler & Smarsly, 2018), and cyber-physical systems (Fitz et al., 2019). In the manufacturing domain, an initiative has been started in 2016 to integrate BIM and prefabrication processes, known as IFC4precast. The initiative IFC4precast is currently under development to align precast CAD systems, manufacturing execution systems, and production planning systems (buildingSMART, 2020).
The idea of joining BIM and AM for construction as a digital planning method has been studied by Teizer et al. (2015) and Paolini et al. (2019). In a review, Gradeci et al. (2019) have identified promising potential for integrating BIM and AM, where standardization and documentation of life-cycle data will accelerate the acceptance of AM in the AEC industry. Studies that provide proof of concept for integrating BIM and AM have been developed, using BIM data as input for small-scale study cases (Ding et al., 2014; Correa, 2016; Davtalab et al., 2018). The BIM models, stored in IFC files, are used to transfer the data from BIM software applications to process planning software applications. In Ding et al. (2014), BIM models are manually sliced and data, such as geometry representations, material types and colors, are extracted from the IFC files to generate CNC code. Correa (2016) has developed a computer-aided design system for robot-oriented design of BIM models. The geometry data is extracted from the IFC files and processed according to constraints and limitations of 3D printers, such as printing size and resolution, using proxy elements. Davtalab et al. (2018) proposes to customize BIM models using user-defined property sets for additional material parameters and proxy elements to describe printers. The data is extracted from the IFC files of the customized BIM models and processed for process planning. However, using proxy elements and user-defined property sets to customize BIM models may cause a loss of semantic information (Theiler & Smarsly, 2018).

Formal descriptions of the information necessary for AM of concrete structures are required to preserve the semantic information generated during design and manufacturing. Formal descriptions are represented in the form of semantic models. Recently, semantic models have been developed for conventional AM, focusing on the AM product lifecycle (Lu et al., 2015) and to describe AM technology and operation based on the ISO 14649 standard (Bonnard et al., 2018). Semantic models for conventional AM cannot properly describe the interdependencies within concrete printing. Therefore, a semantic model that describes AM of concrete structures, which can be integrated with BIM, is needed. In the following section, a semantic modeling approach to describe the interdependencies within concrete printing is presented.

3. Printing information modeling

The PIM model defines all parameters relevant to AM of concrete structures for systematically representing specifications of concrete printing jobs. Classes are defined to group the main parameters describing processes, material, and geometry. The relationships between the parameters documented in literature are used as basis for developing the PIM model (Bos et al., 2016; Bonnard et al., 2018; Paul et al., 2018; Salet et al., 2017; Buswell et al., 2018). The PIM model is shown in Figure 1 as a unified modeling language class diagram, describing the printing information required for concrete printing jobs. In this section, elements of the PIM model are printed in *italics* when describing the semantic model.

The PIM model comprises three main abstract classes, `ProcessInformation`, `MaterialInformation`, and `GeometryInformation`. The process information is categorized into subclasses describing printing settings for the pump system and the printhead (`PumpSystemData` and `PrintheadData`), filament properties (`FilamentData`), printing strategy and toolpaths (`ToolpathData`), and monitoring data (`ControlData`). The material information includes subclasses to describe reinforcement (`ReinforcementData`) and concrete (`ConcreteData`). The geometry information may be inherited from BIM models, which incorporate geometry information by nature, and it is categorized into subclasses describing dimension definition (`Dimension`), point definition (`Point`), and geometric object definition (`GeometricObject`) as well as contour lines data (`ContourLine`) as a result of slicing. A
A detailed description of the semantic model is presented in Smarsly et al. (2020). In Figure 1, the gray-colored elements are used to illustrate the IFC mapping of the semantic model in the following sections.

![Figure 1: Extract of the PIM model.](image)

### 4. IFC-based printing information modeling

A BIM approach towards concrete printing that aligns the PIM model and the IFC schema for IFC-based printing information modeling is presented in this section. Geometry parameters and material parameters that describe specifications required for AM are already specified in common BIM models compliant to the IFC schema (Smarsly et al., 2020). In this study, by mapping all parameters and parameter relationships defined in the PIM model onto the IFC schema, a comprehensive BIM model describing the AM digital thread is achieved. The BIM model is used later to generate commands that control concrete printers as CNC code. Hence, a BIM-based file format for 3D printing integrates the digital thread in a single file, from slicing to CNC code generation.

The PIM model is mapped onto the current IFC version “IFC 4 – Addendum 2”, or “IFC4” for short (buildingSMART, 2017). IFC schema elements (e.g. IFC entities and property sets) and core concepts that can be reused are identified based on the description presented in Borrmann et al. (2015) and on the documentation of IFC4. Aligning the PIM model with the IFC schema reduces the need to define new IFC entities and property sets, ensuring the maintainability of the IFC schema. In this section, when describing the mapping, elements of the IFC schema are printed in *italics* and elements of the PIM model are printed in **bold italics**. In the following paragraphs, a description of the mapping of the abstract classes `ProcessInformation`, `MaterialInformation`, and `GeometryInformation` onto the IFC schema is presented.
The *ProcessInformation* describes specific information required for additive manufacturing. Therefore, a domain-specific schema extension must be integrated into IFC’s domain layer. In Table 1, the mapping for the subclasses of the abstract class *ProcessInformation* is summarized. In the table, it is noted if new subentities, enumeration constants, or property sets are needed.

**Table 1: Mapping of the subclasses of the abstract class ProcessInformation onto the IFC schema.**

<table>
<thead>
<tr>
<th>PIM class</th>
<th>IFC entity</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>PumpSystemData</td>
<td>IfcDistributionSystem</td>
<td>Describes the pump system as a network to distribute concrete as an operational type. The mixer is described as an <em>IfcTank</em> holding a source port, the pump is described as an <em>IfcPump</em>, and the hose is described as an <em>IfcPipeSegment</em>. All entities are connected through the concept of port nesting. The sink port of the distribution system is the nozzle in the printhead.</td>
</tr>
<tr>
<td>PrintheadData</td>
<td>IfcTransportElement</td>
<td>Describes an element that moves horizontally in the XY plane and vertically in the Z axis, and that transports concrete. It is related to an actuator (<em>MotionData</em>) and a terminal (<em>NozzleData</em>). A new enumeration constant of <em>IfcTransportElementEnum</em> is required to describe movement in XYZ axes.</td>
</tr>
<tr>
<td>MotionData</td>
<td>IfcActuator</td>
<td>Controls the motion of the printhead converting input signals into a motion output.</td>
</tr>
<tr>
<td>NozzleData</td>
<td>IfcFlowTerminal†</td>
<td>Describes the basic shape and dimensions of the nozzle. A new subentity for <em>IfcFlowTerminal</em> is required to describe a nozzle.</td>
</tr>
<tr>
<td>FilamentData</td>
<td>IfcBuildingElementPart</td>
<td>The printed element is an assembly of filament layers. Similar to the approach used for precast elements, each filament layer is described as an <em>IfcBuildingElementPart</em>. A new enumeration constant of <em>IfcBuildingElementPartTypeEnum</em> is required.</td>
</tr>
<tr>
<td>ToolpathData</td>
<td>IfcLinearPositioningElement†</td>
<td>Describes the toolpath with a curve, similar to an alignment. Properties to define attributes of the toolpath, such as direction, change of velocity (in curves) and print pattern, must be defined.</td>
</tr>
<tr>
<td>ControlData</td>
<td>IfcMonitor</td>
<td>The IFC schema extension <em>IfcMonitor</em> proposed by Theiler et al. (2018) can be applied to monitor and control the printing process.</td>
</tr>
</tbody>
</table>

† New subentities, enumeration constants, or property sets are required.

The *MaterialInformation* is aligned with the *IfcMaterialResource* schema in IFC’s resource layer. The materials are associated to the *IfcElements* with the relationship *IfcRelAssociatesMaterial*, and property sets are used to define material properties. In the case of *ConcreteData*, existing property sets, such as *Pset_MaterialConcrete*, may be used to describe one or a set of *MaterialSpecification*. In a similar manner, *Pset_MaterialCommon* and *Pset_MaterialMechanical* may be used to describe one or a set of *HardenStateProperty*. New property sets need to be created to describe the subclasses *MixDesign*, *FreshStateProperties*, and *WorkingProperty*. 
The **GeometryInformation**, as mentioned earlier, may be inherited from BIM models, i.e. entities and property sets that exist in the IFC schema, to describe dimensions, points, and geometric objects. Instances of **GeometricObject** are defined in the IfcProductExtension in IFC’s core layer, aligned with subentities of the entity **IfcElement**, and their geometry may be defined with **IfcShapeRepresentation** or **IfcTopologyRepresentation**. In the case of building elements, such as walls and columns, instances of **GeometricObject** are defined in the schema IfcSharedBldgelements in IFC’s interoperability layer. The subclass **ContourLine** describes the 2D geometric representation of the layers resulting from slicing the geometric objects. In this case, the sliced geometric objects may be defined either with the layers being instances of **IfcElement** connected to each other by the relationship **IfcRelConnectsElements** or with the layers being instances of **IfcElementComponent** (i.e. **IfcBuildingElementPart**) aggregated to form an **IfcElement** or an **IfcElementAssembly**. An example of the aggregated relationships can be seen in the example of **IfcWallElementedCase** (buildingSMART, 2017) and in the progress reports of the initiative IFC4precast (buildingSMART, 2020). In the following section, a case study is presented to validate the mapping described herein.

5. **Case study**

A case study is devised to validate the IFC-based printing information modeling approach for AM of concrete structures and to test the feasibility of the proposed mapping. A test structure is modeled for concrete printing, from slicing to generating a toolpath. The classes **ContourLine**, **FilamentData**, **ToolpathData**, and **FreshStateProperty** of the PIM model are described using IFC entities. In this section, the elements of the IFC schema are printed in italics.

The test structure of one story height is modeled using an IFC-compliant BIM software application. The test structure, shown in Figure 2, is composed of five walls (**IfcWallStandardCase**) of 2000 mm height, 150 mm thickness, and different lengths. The test structure is sliced into layers of 40 mm height. For each wall, every layer is described as an **IfcWallStandardCase** connected to each other layer using the relationship **IfcRelConnectsElements**. The layers are associated to data regarding filament, toolpath, and fresh material properties of the printable concrete, which requires new subentities, enumeration constants, and property sets. The new IFC elements and the associations with the layers are shown in the object typing diagram given in Figure 3. The filament data is described with an **IfcBuildingElementPart** (with a user-defined enumeration constant), the toolpath data is described with an **IfcLinearPositioningElement**, and the fresh state property for green strength is described with an **IfcPropertyListValue** added to the **IfcMaterial** for concrete.

As a result of the case study, an IFC-based printing information model is obtained, describing data regarding contour line, filament, toolpath, and fresh state material properties of the printable concrete. Each layer has a layer height of 40 mm, and the contour line information is described by the geometry representation of each layer. The filament has a thickness of 150 mm and a height of 40 mm, equal to the dimensions of each layer.
In the sliced model, each layer is represented as an *IfcSweptAreaSolid*, defined by a profile and an extrusion height. The profile describes the contour line of the layer, and the extrusion height describes the layer height. As shown in Figure 2, each wall is sliced into layers independently. Each layer has filament data, toolpath data, and the fresh material property “green strength”. The geometry of the filament depends on the shape and dimensions of the nozzle (here 150 mm × 40 mm) and the composition of the concrete. By visualizing the filament data during the planning process, the tradeoff between printer resolution and geometric precision is addressed in case of the wall thickness being different from the filament thickness or in case of detailing. When the thickness of the wall and the filament are the same, the toolpath is defined by the centerline of the layer. The toolpath is later used to define the list of coordinates for the CNC code. It must be noted that for more complex layouts, fresh material properties, such as green strength, may affect the toolpath definition. In this case study, the green strength is described with a list since it is a function of time, i.e. it increases with time. Knowing the behavior of the green strength allows to accordingly modify the toolpath, improving the quality of the printed structure.
6. Summary and conclusions

A semantic modeling approach that takes advantage of BIM, referred to as “printing information modeling”, has been developed, serving as a tool to define a new data model that provides a formal basis for standardizing additive manufacturing in civil engineering. The PIM model has been integrated into BIM by mapping its components onto the IFC schema. A case study has been devised to validate the mapping obtaining a comprehensive information model for AM of concrete structures. It has been demonstrated that the PIM model can be integrated with BIM to store the information necessary for data modeling of AM of concrete structures, showing potential of using IFC-compliant BIM models as sole formal basis for AM of concrete structures. Implementing the IFC-based PIM approach, besides advancing standardization in the AEC industry, allows collaboration between disciplines to integrate building services into the manufacturing process. However, the approach has only been tested with structures that have simple layouts, where toolpaths can be easily determined. In future work, the integration of AM into BIM documented in this paper may be improved by adding algorithms for toolpath optimizations and CNC code generation, known as “algorithmic BIM”. Further studies are required to accurately describe the relationships between process information and material information in the IFC schema. Last, but not least, the integration of the PIM model into BIM may be formalized by an IFC schema extension.

Acknowledgments

The authors would like to acknowledge the financial support the German Research Foundation (DFG) through grant SM 281/7-1. Parts of this research have been conducted in the “Structural Health Monitoring Laboratory”, sponsored by the European Union through the European Fund for Regional Development (EFRD) and the Thuringian Ministry for Economic Affairs, Science and Digital Society (TMWWGD) under grant 2016 FGI 0009. Any opinions, findings, conclusions, or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of DFG, EFRD, or TMWWGD.

References


