A semantic model for additive manufacturing of concrete structures

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Although recent approaches towards automating construction processes take advantage of additive manufacturing (AM), challenges regarding data modeling of AM of concrete structures have been identified. The challenges confirm that current data models are inadequate for three-dimensional (3D) printing of concrete structures with high geometric precision. As a solution to mitigate this deficiency and optimize data modeling for AM of concrete structures, the research presented in this paper proposes a printing information model (PIM), a semantic model defining AM process, geometry, and material information input parameters together with relationships between the parameters. As will be shown in the paper, the PIM proposed in this study adequately defines all information relevant to AM of concrete structures and has the potential to improve data modeling concepts currently deployed for 3D concrete printing in engineering.

Keywords: Additive manufacturing (AM), printing information model (PIM), 3D concrete printing, semantic modeling, building information modeling (BIM).

1 Introduction

The architecture, engineering, and construction industry faces performance, productivity, and sustainability challenges. Implementing industrial three-dimensional (3D) printing, also referred to as additive manufacturing (AM), is an emerging approach for automating construction processes, corollary to the development of printable concrete (Buswell et al., 2018). The American Society for Testing and Materials defines AM as a process of joining materials to make objects from 3D model data, usually layer upon layer (ASTM, 2012). Generally, AM methods are subdivided into methods based on extrusion, and methods based on selective binding (Nerella et al., 2016). Significant advancements in AM hardware and materials have been achieved to produce concrete structures with adequate structural performance and a certain degree of geometrical precision. In addition, sensing technologies have been matured, enabling sensors recording and analyzing parameters autonomously (Dragos et al., 2018; Smarsly & Law, 2014). Several AM technologies have been developed that use extrusion-based AM methods, which are preferred for large-scale concrete printing, such as contour crafting (CC) and concrete printing (CP). For selective binding-based AM methods, the main exponent is D-shape, which uses cement as binding agent (Lim, et al., 2012).

Data modeling for AM is mainly based on traditional solutions, such as standard tessellation language (STL) and G-code (ISO 6983-1) (Bonnard et al., 2018). Currently, standard
AM data modeling approaches can cause information breaks along the modeling process by decomposing digital models into several data formats to be readable by 3D printers. Current standard file formats, including STL, additive manufacturing format (AMF) and 3D manufacturing format (3MF), may cause redundancy, information loss and inconsistencies, thus requiring new data formats. Furthermore, when considering time-dependent viscous material, such as concrete, material information plays an important role in defining process settings, toolpaths, and computer numerical control (CNC) commands. The current data modeling approaches limit concrete printing to a process with a long trial-and-error learning curve to determine the ideal process settings and printing strategies. The main challenge therefore, is to understand the interaction of AM processes, material, and geometry input parameters to establish optimal information flow.

A new data model is required, enabling smoother information flow without information breaks that describes AM input parameters, adequately allowing real-time monitoring of material properties and adjustments of process parameters. This study aims at formally describing information flow, input parameters, and interactions between input parameters, representing a step necessary for standardizing 3D concrete printing data models for AM in civil engineering. Using a semantic model as a formal basis, an approach based on building information modeling (BIM) is implemented for conceptual validation, inheriting geometry inputs specified in BIM, and incorporating all parameters and parameter interactions required to generate CNC commands. The rest of the paper is organized as follows. The proposed semantic model, the printing information model (PIM), is presented in Section 2, describing parameters and fundamental inter-process dependencies for concrete printing. In Section 3, the validation of the semantic model through a BIM-based approach is presented, using a laboratory-scale 3D concrete printer. The paper concludes with a summary and an outlook on potential future work.

2 A semantic model for additive manufacturing of concrete structures

The semantic model defines all elements of AM of concrete structures, clearly describing how each of the elements interact and associate with each other to systematically represent specifications of 3D concrete printing jobs. In this section, first a concise review of extrusion-based AM of concrete structures is outlined. Reviewing concrete printing with a systematic perspective, AM main elements are identified together with relationships and interactions between the elements. Extrusion-based AM of concrete structures can be divided into two main components: Printing hardware and printing material. For each component, process, material, and geometry input parameters are identified. The semantic model therefore represents the collected information in the form of diagrams. An overview of the main components of AM of concrete structures and the proposed semantic model, i.e. the “printing information model”, is presented in the following subsections.
2.1.1 Main components of additive manufacturing of concrete structures

**Printing hardware**

Most concrete printers have adopted the fused deposition modeling (FDM) printing method, also referred to as “layered extrusion”. In FDM printing, concrete is mixed and pumped into a hose, which is connected to a printing head attached to a motion-controlled printing system. While the concrete is still fluid, it is extruded through a nozzle and starts solidifying by itself in a chemical reaction. Key elements of printing hardware, regarding AM data modeling, are pump system, printhead, and motion-controlled printing system.

The pumping system should be able to transport a concrete mix from the mixing unit to the nozzle, without segregation and bleeding. Pumping is influenced by the viscosity of a concrete mix. For detailed information on relationships regarding the pump system, the interested reader is referred to Bos et al. (2016) and Paul et al. (2018). The printhead consists of several parts, including one or multiple nozzles, allowing the concrete to be printed at a desired location with a desired speed under a desired angle. Printhead speed, nozzle shape and orientation, and height of the printhead above the printing surface are parameters that affect the print quality of the filament layers (e.g. filament dimensions, buildability, and mechanical properties). The motion-controlled printing system processes the CNC commands, and also monitors and adjusts performance using sensor technologies.

**Printing material**

Concrete printing involves concrete as printing material and a reinforcement solution to provide ductility and tensile strength as well as to reduce cracking in printed objects. The concrete composition determines the suitability of a mix with respect to printing processes and properties of the finished object. Slow setting reactions in printed concrete have strong interactions with the applied process parameters and printing strategy (Bos et al., 2016). In addition, the printing strategy affects the way reinforcement can be installed or incorporated. Interactions between concrete material properties and process parameters, together with the print size, are relevant to the way the printing process should be conducted, particularly for stability of objects during printing. The design of objects and printing strategy influences the green and the finished object properties and reinforcement solution (Bos et al., 2016).

Key rheological properties for concrete mixes provide the characteristics necessary for a concrete to be printable. In Paul et al. (2018), the five key rheological properties are discussed in detail besides relationships with process parameters and mechanical properties of fresh concrete (e.g. shear stress, viscosity, and green strength). Printable concrete mixes should be extrudable and buildable, where each layer of filament can retain shape once in place and can adhere to (and carry the load of) subsequent layers.

Concrete mix designs and printing processes affect the desired mechanical properties of a finished AM 3D concrete print object (Buswell et al., 2018; Paul et al., 2018; Bos et al., 2016). There is a direction dependency, where the anisotropy in the material defines the failure of the structure. Detrimental changes in the printing quality of upper layers and interfaces compromise the strength of the concrete, mainly due to hardening and loss of moisture of the concrete mix over time. Consequently, anisotropic proprieties of printing material, layer interval time as well as printing speed and printing strategy significantly influence load-bearing capacity of the printed components.
2.1.2 A printing information model (PIM)

The goal of developing the semantic model is to include all printing information necessary for 3D concrete printing, enabling traceability of the data exchange between elements of the data model. The PIM describes all elements and parameters involved in 3D concrete printing, employing a unified modeling language (UML)-based, object-oriented modeling approach. The elements and parameters are categorized coherently into classes, and the relationships are defined semantically. As part of the PIM, the information flow of digital data from 3D digital models to CNC codes is described. As a result, the PIM represents an understandable and instantiable model for future code applications. For example, the PIM can be implemented in further studies for technology-independent semantic descriptions of buildings using a BIM-based approach, e.g. based on the Industry Foundation Classes (IFC) standard. The IFC have been matured into a formalism to describe building information models not only of buildings or infrastructure, but also sensor systems (Theiler & Smarsly, 2018), wastewater treatment plants (Söbke et al., 2018), cyber-physical systems (Fitz et al., 2019), cognitive buildings (Ibanez et al., 2019), or digital roads (Mirboland & Smarsly, 2019).

The relationships between the different parameters documented in the literature (Bonnard et al., 2018; Bos et al., 2016; Paul et al, 2018), as described earlier, are used as basis for developing the PIM. A UML class diagram is used to describe the structure of the PIM, depicting the inter-process relationships and 3D printing attributes, elements and parameters, which can be instantiated. Figure 1 presents a general overview of the PIM describing the printing information necessary for 3D concrete printing. The PIM comprises three main components, following process, geometry, and material information to be described: Process Information, Geometric Information, and Material Information. The Process Information abstract class includes printing settings data and monitoring data of a concrete extrusion process, and it is further categorized into PumpSystemData, PrintheadData, ToolpathData, FilamentData and ControlData subclasses. The abstract class Geometric Information provides a geometrical description of a 3D digital model, inherited from 3D digital models. The geometry information includes the subclasses Dimension, Point, GeometricObject and ContourLine, resulting in a complete geometrical description. The Material Information abstract class refers to materials implemented in the printing process, such as concrete (ConcreteData) and reinforcement (ReinforcementData). The concrete data includes MaterialSpecifications, MixDesign, and MaterialProperties.

A UML activity diagram is used to describe the information flow in the PIM, depicting the data exchange between 3D printing elements using 3D digital models as input. Figure 2 presents the general information flow. The information flow starts with the information extracted from a 3D digital model and with user-defined parameters (i.e. process parameters). The toolpath is generated combining the user-defined parameters and the geometry representation extracted from the 3D digital model. The toolpath can be modified by changing the user-defined parameters until it fulfills the desired geometrical precision. Once the toolpath is accepted, it is used to generate the CNC code, which incorporates the material properties. Finally, if no modifications are needed, the CNC code is sent to the 3D printer.
Figure 1: PIM class diagram

Figure 2: PIM information flow diagram
3 Conceptual validation for a BIM-based concrete printing

To implement the PIM into a BIM schema, a conceptual validation of the PIM is performed on a laboratory-scale 3D concrete printer. Therefore, BIM-based digital models are taken as geometry input to provide geometry descriptions, which are used later to validate the stated relationships by generating a CNC code. Most BIM tools are capable of exporting models to a neutral file format (e.g. STL, AMF), which can be converted into CNC code. Extrapolating geometry representations and material specifications from IFC files is also possible for a manual extraction of model data. In this study, a manual extraction of model data is used for a conceptual validation test.

A code application is developed in Java for the conceptual validation that instantiates an instance of the PIM for a specific 3D concrete printer. The code application incorporates algorithms for slicing, toolpath definition, and CNC commands generation, and it allows visualization of the generated data. The inputs are user-defined parameters and the extracted model data from a BIM model, while the output is a CNC code readable by the 3D concrete printer. The slicing algorithm solves the plane intersection problem between a cutting plane and the faces of the extracted geometric object, generating contour lines for each layer. The toolpath definition algorithm implements a raster scanning approach to determine the infill of the geometric object for each layer, and defines movements of the printhead using a user-defined printing strategy and filament data for geometric precision. The CNC commands generation algorithm incorporates the process data, i.e. printhead and pump parameters, material properties and the defined toolpath. Variations in the material properties are considered by modifying factors applied to printhead and pump parameters.

The conceptual validation test is performed for an L-shaped small scale concrete wall of 10 cm height and a base of 60×80×20 cm designed using a BIM software application and a 400×300×300 cm laboratory-scale 3D concrete printer, which is capable of extruding concrete filaments up to 20 cm thick. A CNC code is generated, visualizing printing data devised for verification of the printing strategy and geometrical precision. In Figure 3, the results of the conceptual validation test are shown. The slicing algorithm implemented is limited to prisms defined as “Swept Solid” entity in the IFC for generating contour lines. The scanning distance of the toolpath definition algorithm is defined by the thickness of the filament. The CNC code has a start, an ending command block, and printing command blocks that control the manufacturing process.

The parameters and relationships defined in the PIM, together with the digital information flow (Figure 1 and Figure 2) are instantiated in the code application. For example, in the user-defined parameters, the PumpSystemData and NozzleData dependencies on WorkingParameters are defined within the working ranges of the pump pressure. The FilamentData and NozzleData association is stated when the nozzle geometry (i.e. size and shape), together with the user-defined layer height, are used to define the filament properties. The MotionData executes the ToolpathData, extruding the corresponding amount of material with the respective printing speeds and accelerations, which consider the FreshStateProperties using modifying factors. Through the generation of a CNC code as a conceptual validation test, the inter-process relationships provide traceability and a clear understanding of the printing process.
A printing information model has been developed serving as a formal basis to standardize the description of process, geometry, and material information input parameters of AM of concrete structures. A literature review has been conducted and analyzed to determine the main elements, relationships, and associations of process, geometry, and material information input parameters for 3D concrete printing. It has been demonstrated that the PIM sufficiently describes the inter-process relationships between identified elements semantically, resulting in an instantiable model for data modeling. Furthermore, the implementation of a laboratory-scale 3D printer has demonstrated that the PIM adequately defines AM main parameters and fundamental relationships, which can be translated into a CNC code. Further validation is required with respect to inheritance of geometrical information from standardized data models, such as the IFC. In future work, a digital model may be developed that implements the PIM to generate CNC codes from BIM-based models, whose inputs are the parameters for 3D concrete printing, and that can incorporate sensor data for process monitoring and real-time adjustments.

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