Requirements analysis of additive manufacturing for concrete printing – A systematic review

P. Peralta-Abadia and K. Smarsly

Institute of Digital and Autonomous Construction, Hamburg University of Technology, Germany
Email: patricia.peralta.abadia@tuhh.de, kay.smarsly@tuhh.de

Abstract –
The acceptance of concrete printing as a viable construction method is limited because of a lack of expertise and due to the heterogeneous and non-standardized nature of additive manufacturing (AM) data modeling, affecting the reliability and the interoperability of the concrete printing process. To advance standardization of AM data modeling in concrete printing, information exchange requirements must be defined along the digital thread, i.e. the digital workflow that transforms 3D models into printed components. In this paper, a requirements analysis of AM for concrete printing is conducted through a systematic review. The AM process for concrete printing is defined, identifying information exchange requirements. Sources relevant to AM and concrete printing are systematically reviewed, collecting and analyzing attributes of the information exchange requirements for concrete printing. As a result, the requirement analysis serves as basis to standardize the digital thread, in an attempt to advance reliability and interoperability of the concrete printing process.

Keywords –
Additive manufacturing (AM); Concrete printing; Data modeling; Information exchange requirements; Requirement analysis

1 Introduction

In the architecture, engineering, and construction (AEC) industry, research has been conducted to automate construction processes that are based on additive manufacturing (AM). AM allows structures to be built in a layer-by-layer basis, employing computer-controlled processes [1]. Using printable concrete, large-scale building components have been manufactured by deploying concrete-based AM processes, also referred to as concrete printing [2]. In concrete printing, interdependencies of the material and the manufacturing process affect the quality of manufacturing, thus the quality of the printed components. To ensure high-quality concrete components by successfully conducting manufacturing processes, expertise and a common understanding of concrete printing are required [3]. The acceptance of concrete printing as a viable construction method has been limited due to a lack of expertise and understanding and because of the heterogeneous and non-standardized approaches commonly deployed for AM data modeling, for material testing, and for manufacturing, each of which affecting the reliability and interoperability of the concrete printing process. New data modeling approaches proposed for concrete printing, encompassing the digital workflow to transform 3D models into printed components (i.e. digital thread), have to be developed to improve reliability and interoperability. Synergies between conventional AM methods and concrete printing can be exploited to formally describe AM data modeling for concrete printing.

In concrete printing, actors of heterogeneous domains (e.g. design, engineering, material sciences, and machine operation) collaborate along the digital thread to transform the 3D models into printed components, exchanging information to perform concrete printing tasks and subprocesses. Information exchange requirements describe information of a task or subprocess (i.e. a set of tasks) that are exchanged between the actors to enable downstream tasks or subprocesses [4]. However, information exchange requirements along the digital thread have not been clearly defined, causing a loss of semantic information and a lack of interoperability. Concepts of building information modeling may advantageously be used to aid the standardization of the information exchange requirements, preserving semantic information and improving interoperability along the digital thread, while further advancing the acceptance of concrete printing as a viable construction method.

In this paper, a requirements analysis of AM for concrete printing is conducted through a systematic review. Information exchange requirements are defined, following the methodology developed for information delivery manuals known widely used in building information modeling (BIM), which documents processes and describes the corresponding information to be exchanged between the actors [4]. The paper is organized as follows. First, the AM process for concrete printing is defined and the information exchange requirements are identified. Second, sources relevant to AM and concrete printing are systematically reviewed to collect attributes of the information exchange requirements along the digital thread in concrete printing. The information exchange requirements are analyzed, using AM design and optimization as well as AM process planning as illustrative examples. The paper concludes with a summary and an outlook on potential future research.

2 Additive manufacturing process for concrete printing

An extract of the digital workflow for concrete printing, from design to print, is represented as a process map shown in Figure 1. A process can be nested, and it may contain subprocesses. A process (as well as a subprocess) is a set of tasks that are interrelated or that interact with one another, transforming inputs into outputs. The process map shown in Figure 1 is based on [5] and follows the business process modeling notation. Four main actors participating in the workflow are identified: designer, engineer, material scientist, and machine operator. The actors develop specific tasks or subprocesses (differentiated by colors), where the data generated in the tasks or in the subprocesses is exchanged among the actors, following a sequence that translates 3D models into printed objects.

As can be seen from Figure 1, the AM process starts with design concepts, from which design specifications are defined. With the design specifications, geometric models are generated considering manufacturability, and manufacturing hardware is selected. Settings for the manufacturing hardware are defined to design the material (concrete) in an iterative process, until satisfying the design specifications. Once the material is designed, material specifications are generated. Then, the geometric models are sliced and toolpaths are planned according to the process data and the material specifications. Within the subprocess of toolpath planning, simulations of the manufacturing process and of the material are carried out. The subprocess of toolpath planning has AM models as outputs. Then, the AM models are evaluated and, if accepted, the AM models are used as basis to generate machine-readable code (CNC code) that provides the instructions for manufacturing.

Data modeling in concrete printing has synergies with the data modeling approaches used for conventional AM methods, where efforts to standardize basic requirements have been described in [6]. However, considerations regarding the interdependencies of the concrete and the manufacturing process are to be included in the information exchange requirements. A common data model will support interoperability along the digital thread as well as data collection and storage. For the sake of brevity, only the consideration of the material interdependencies in the semantics of AM design and optimization and of AM process planning are reviewed in this paper. In the following section, the requirements of AM for concrete printing are reviewed and analyzed, focusing on AM design and optimization as well as on AM process planning as illustrative examples.

3 Review and analysis of requirements of additive manufacturing for concrete printing

In this section, the systematic review and the analysis of the requirements of AM for concrete printing are presented. Due to the synergies between AM and concrete printing, sources relevant to both areas are systematically reviewed. First, the systematic review of the sources is provided. Then, the requirements analysis according to completeness and interoperability is presented.

3.1 Systematic review

The review methodology comprises three steps, (i) source selection, (ii) data collection, and (iii) data organization. Sources, precisely ***standards***, ***current research*** (i.e. journal papers and conference papers) and ***software applications***, are selected for the review to answer the question "what information is necessary for data modeling of concrete printing?" The papers are indexed in the Web of Science Core Collection, in the Scopus database, or in the American Society of Mechanical Engineers digital collection. An initial search using keywords such as "additive manufacturing", "digital fabrication", or "3D printing" together with "concrete", "ontology", "modeling", "simulation", and/or "digital thread" is carried for the period between 2015 and 2021. Publications with sufficient citations and with documentation of parameters relevant to data modeling in AM and in concrete printing are selected. Additionally, software applications commonly used in AM and concrete printing are selected according to availability of user manuals and implementation in documented studies. A total of 30 sources relevant to AM and concrete printing have been selected: 5 standards, 17 journal papers, 6 conference papers, and 2 software applications. From the sources, attributes of the information exchange are collected and organized in information units. In the following paragraphs, an overview of the systematic review is presented.

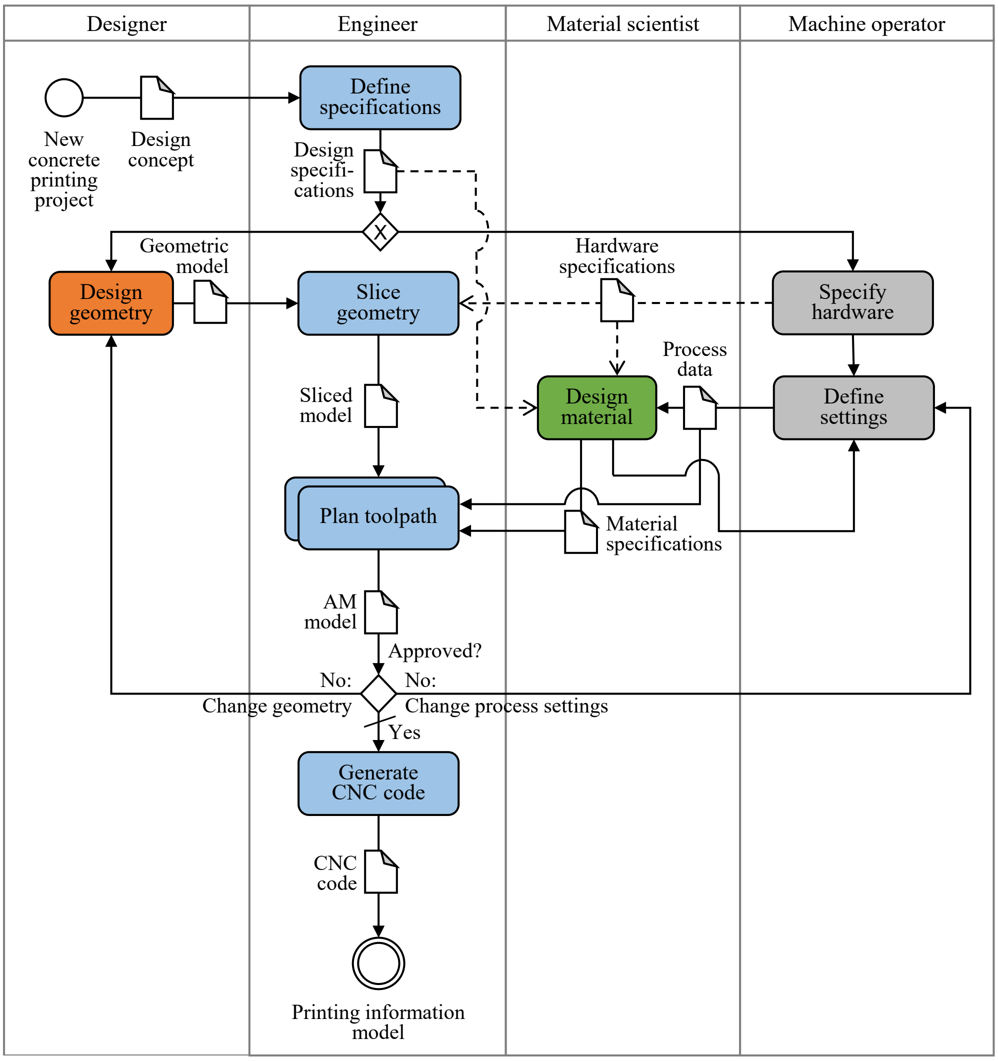

Figure 1. Extract of the process map describing the AM process for concrete printing

Existing ***standards*** for AM define terminology, data formats, and data models are used to exchange information for geometric representation and for hardware control. The standard terminology for AM technologies is defined in the ASTM F2792 standard [1], categorizing AM technologies. There are three main data format standards for geometry representation: standard tessellation language (STL), additive manufacturing format (AMF), and 3D manufacturing format (3MF). The STL format is the de-facto standard in AM. An STL file is an unordered collection of triangles, vertices, and unitary surface normal vectors in binary or ASCII format [7]. AMF is an ASTM/ISO standard (ISO/ASTM 52915), which extends STL to include dimensions, curved facets, recursive subdivision, color, material, constellation descriptions, and metadata. AMF is based on extensible markup language (XML), providing an XML-based schema definition (XSD) for AM technologies [8]. 3MF is an XML-based data format that provides broad model information, such as mesh topology, slices, color, material, and texture, allowing multiple objects to be contained within a single archive [9].

For hardware control, there are two main standards: G-code and the STandard for the Exchange of Product model data compliant Numerical Control (STEP-NC). The ISO 6983 standard [10], also known as G-code, is widely used as a numerical control (NC) programming language. G-code supports hardware control in AM processes, defining motion and action commands in sequential lines [7]. The STEP-NC extends the ISO 10303 standard in ISO 14649 and defines a data model for numerical controllers. STEP-NC provides control structures for the sequence of working steps and associated machine hardware functions specified in the EXPRESS language [11].

In the following paragraphs, ***current research*** in AM and concrete printing, published between 2015 and 2021, is organized according to the research topic. Table 1 presents an overview of the research topics and the related references. Below, a brief overview per research topic is presented.

Relevant to *process and geometry parameters*, the implementation of AM in the AEC industry has been reviewed in [2], while in [3] technical issues in concrete printing have been described. A framework to classify process used in concrete printing has been defined in [12]. Process parameters and the impact on the manufacturing process has been studied in [13]. Strategies to improve the control of the manufacturing process have been proposed by using sensing technologies [14] and by simulating the manufacturing process to optimize process parameters [15]. The interactions between geometry parameters and process parameters, including the manufacturing process, have been studied for concrete printing [3] and for conventional AM methods [16].

Material parameters and the interactions with the manufacturing process have been reviewed in [17]. However, technical issues regarding material parameters are still open points, as discussed in [3]. Research regarding material parameters in concrete printing has been focused mainly on material development [18], on material testing for fresh concrete [19], and on the impact of the manufacturing process on material parameters [20].

Modeling and simulations in AM are used to simulate and optimized the manufacturing process [21], analyze the material [20], and to predict the structural stability of printed components during manufacturing [15]. Numerical modeling and simulations have been used to predict the concrete flow to determine optimal rheological requirements of the concrete [22]. Perrot et al. [23] have discussed the implementation of analytical and numerical tools to assess the concrete printing process as a function of the material properties, the geometry of the components, and the process parameters (e.g. manufacturing hardware settings).

AM-related ontologies are formal descriptions of the field of AM (or subfields), where concepts and relationships are defined. Ontologies contain the current knowledge in AM and can be extended to support future knowledge. The semantics of AM technology have been defined based on STEP-NC [7]. Ontologies have been developed to support manufacturability analysis [24], interoperability for data management [25], and lifecycle data management [26]. Similarly, ontologies have been developed specifically for the digital thread of metal-based AM [5] and for developing BIM-based concrete printing [27].

BIM-related research in AM has been developed to integrate AM into the AEC industry. BIM concepts, providing semantic and geometric information, have been used to digitalize life-cycle information of buildings and infrastructure. Paolini et al. [2] as well as Gradeci et al. [28] have discussed the benefits of coupling AM and BIM for data modeling. Using an open BIM standard, such as the Industry Foundation Classes (IFC), data can be managed and exchanged between software applications used for AM and software applications used in the AEC industry, maintaining semantic and geometric information. Research has been conducted to couple concrete printing and BIM, showing the potential of BIM-based concrete printing, focusing on data retrieval from BIM models [29] and on IFC-based descriptions of process and material parameters [30].

Table 1. Overview of research topics related to AM and concrete printing

Research topic	Qty. of references	References
Process and geometry parameters	18	[2-3, 5, 7, 12-17, 20-21, 24-27, 29-30]
Material parameters	12	[3, 13, 15, 17-23, 27, 30]
Modeling and simulation	5	[19-23]
AM-related ontologies	7	[5, 7, 24-27, 30]
BIM-related research	6	[2, 16, 27-30]

Software applications used to develop concrete printing projects help determine the information generated in tasks along the digital thread (input and output parameters). Functionalities in the AM software applications support *AM design and optimization* as well as *AM process planning*. Software applications for AM design and optimization are usually based on computer-aided designs and enable geometry optimization. Software applications for AM process planning are commonly used for slicing and toolpath planning, creating manufacturing models. Complex AM software applications for AM process planning also support simulations of the manufacturing process where the effect of toolpaths and hardware settings can be evaluated to ensure buildability. The user manuals of common AM software applications, such as *Cura slicer* [31] and *Slic3r* [32], provide insight into the input and output parameters needed for AM design and optimization and AM process planning.

Due to the nature of concrete printing, vendors have developed proprietary solutions for the manufacturing hardware used for concrete printing (i) by modifying existing AM software or (ii) by developing software tools. In the first case, open-source and proprietary software applications for slicing and toolpath planning have been modified to fit specific manufacturing hardware used for concrete printing. In the latter case, computer-aided design software applications have been coupled with programming environments to develop specialized software tools for concrete printing. Moreover, simulation software applications commonly used in the AEC industry have been used to conduct simulations of the manufacturing process and of the material behavior to predict the structural performance of printed components, as shown in [19].

To streamline the digital thread in concrete printing, attributes of the information exchange requirements are collected and organized into information units from standards, current research and software applications. In the following subsection, the requirement analysis relevant to AM design and optimization as well as AM process planning is presented.

3.2 Requirements analysis

From the previous review, the attributes of the information exchange requirements have been collected in the following tables and organized into information units. The attributes are analyzed according to *completeness* (i.e. if an attribute is required or optional) and *interoperability*. The attributes have been discussed with experienced users from the domains of robotics, material science, civil engineering, and mechanical engineering. The experienced users, hence, provide insight in the completeness and interoperability of the attributes via a short survey.

Completeness of the information exchange requirements avoids redundancies and ensures the inclusion of all attributes necessary to manufacture a component. Interoperability is supported when the semantics of the information exchange requirements are preserved when transitioning between actors and tasks. Hence, satisfying completeness and interoperability of the information exchange requirements provides a strong basis for a common understanding between actors, enhancing the reliability of concrete printing. The information exchange requirements are discussed in the following paragraphs, focusing on AM design and optimization as well as on AM process planning for illustration purposes.

In *AM design and optimization*, geometric models are generated from conceptual designs. The main information exchange requirements are design concepts and design specifications (Table 2). The design concepts include the geometry pre-design and information regarding material, print location, structural characteristics, and structural boundary conditions. From the design concepts, design specifications are defined regarding AM process, material requirements, geometric tolerances and geometric requirements. As output, geometrical models (e.g. BIM models) are generated according to design and hardware specifications and can be further be optimized with respect to manufacturability, topology, structural performance, and geometric tolerances. In Table 2, prerequisites of the information exchange requirements for design specifications are highlighted in gray.

Table 2. Information exchange requirements for design specifications

Type of information	Information needed	Rqd.	Opt.
Design concept	The design concept will have been carried out prior to define the basic requirements		
AM process	Requirements for the AM process		
	• AM process type	X	
	• Machine type	X	
	• Reinforcement type		X
Material requirements	Requirements for the materials according to the AM process requirements.		
	• Main material selection (e.g. reinforced high-performance concrete)	X	
	• Support material selection (e.g. plaster)	X	
	• Reinforcement material selection (e.g. carbon fibers)		X
	• Main material minimum strength (e.g. 30 MPa)	X	
Geometric tolerances	Allowed tolerances in the geometric precision of the printed component/structure		
	• Deformation under self-weight	X	
	• Deflection under self-weight	X	
	• Allowed shrinkage	X	
Geometric requirements	Requirements for the geometric details according to the AM process (e.g. machine type) and materials requirements		
	• Maximum overhang angle	X	
	• Minimum feature size	X	

Table 3. Information exchange requirements for process data

Information unit	Attributes	Rqd.	Opt.
Basic requirements	The basic requirements will have been carried out prior to defining the process data		
Hardware specifications	The hardware specifications will have been carried out prior to defining the process data		
Feedback data	Feedback from previous manufacturing processes		
Strategy	Printing strategy for the AM process		
	• Layer-by-layer strategy	X	
	• Layer transition type	X	
	• Infill pattern	X	
	• Infill density	X	
	• Boundary thickness (i.e. number of adjacent filaments)	X	
	• Layer interval time	X	
	• Nozzle height above previous layer		X
Boundary conditions	Boundary conditions of the AM process		
	• Environment temperature	X	
	• Environment humidity	X	
	• Machine boundary conditions (e.g. printing area and flow rate)	X	
Machine parameters	Machine parameters for the AM process		
	• Printing speed	X	
	• Traveling speed (i.e. speed when not extruding)	X	
	• Acceleration	X	
	• Pump pressure	X	

Table 4. Information exchange requirements for material specifications

Information unit	Attributes	Rqd.	Opt.
Hardware specifications	The hardware specifications will have been carried out prior to defining the material specifications		
Process data	The process data will have been carried out prior to defining the material specifications		
Main material design specifications (e.g. Concrete)	Material specifications for the main material to be employed in the AM process. Parameters may vary depending on the material		
	• Concrete type (e.g. C35/45)	X	
	• Design strength	X	
	• Maximum aggregate size requirement	X	
	• Slump requirement	X	
	• Design open time	X	
	• Estimated volume	X	
	• Batching type	X	
	• Pre-process treatment (e.g. contact surface preparation)	X	
	• Post-process treatment (e.g. surface cover and surface uncovered)	X	
Support material design specifications	Material specifications for the support material to be employed in the AM process. Parameters may vary depending on the material	X	
Reinforcement material design specifications	Material specifications for the reinforcement material to be employed in the AM process. Parameters may vary depending on the material	X	

In *AM process planning*, the geometrical models are sliced and the toolpaths are planned. The geometrical models and design specifications, together with hardware specifications, process data and material specifications, provide the basic information necessary for process planning. The effect of the manufacturing process on the material properties and on the behavior of concrete must be considered when defining the material specifications, hence the process data and the material design are adjusted in an iterative process to satisfy the design specifications. As an output, AM models are created containing all the information necessary to generate machine-readable code (CNC code). Table 3 and Table 4 present the information exchange requirements for process data and material specifications, where prerequisites are highlighted in gray.

4 Summary and conclusions

In this study, efforts towards standardizing AM data modeling have been presented, and information exchange requirements in AM have been analyzed in the context of concrete printing. The AM process for concrete printing has been defined, and information exchange requirements have been identified. Attributes within information exchange requirements for concrete printing have been collected and analyzed through a systematic review and discussion with experienced users. In conclusion, the information exchange requirements for concrete printing show synergies with the information exchange requirements of conventional AM methods. In particular for concrete printing, the hardening process of concrete has a non-negligible effect on the process parameters (e.g. manufacturing hardware settings, print strategy) and on planning and control of the manufacturing process. Therefore, the interdependencies of the concrete and the manufacturing process have to be considered along the digital thread when advancing reliability and interoperability of the concrete printing process. For illustration purposes, AM design and optimization and AM process planning have been analyzed in detail, identifying the material-related information exchange requirements necessary for concrete printing.

With the information exchange requirements clearly defined, the digital thread can be described as a formal data model. With the data model, collaboration between actors will be enhanced resulting in a smooth workflow to improve the quality of the manufacturing process and the printed components. There is still a need to develop data models that support the digital thread in concrete printing in compliance with current standards used to digitalize the AEC industry, such as open BIM standards. Through standardization, concrete printing may become a more accepted construction method in the AEC industry. Future research may therefore be conducted to further advance standardization in AM data modeling for concrete printing.

5 Acknowledgments

The authors would like to acknowledge the financial support the German Research Foundation (DFG) through grant SM 281/7-1. Any opinions, findings, conclusions, or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of DFG.

References

[1] ASTM International (2012). ASTM F2792-12 Standard terminology for additive manufacturing technologies. West Conshohocken, PA, United States: ASTM International.

[2] Paolini, A., Kollmannsberger, S. & Rank, E. (2019). Additive manufacturing in construction: A review on processes, applications, and digital planning methods. Additive Manufacturing, 30(2019), 100894.

[3] Buswell, R.A., Leal de Silva, W.R., Jones, S.Z. & Dirrenberger, J. (2018). 3D printing using concrete extrusion: A roadmap for research. Cement and Concrete Research, 112(2018), pp. 37-49.

[4] buildingSmart (2010). Information Delivery Manual: Guide to components and development methods. Accessed on 08/09/2021 from: https://technical.buildingsmart.org/standards/information-delivery-manual/.

[5] Kim, D.B., Witherell, P., Lu, Y. & Feng, S. (2017). Toward a digital thread and data package for metals-additive manufacturing. Smart and Sustainable Manufacturing Systems, 1(1), pp. 75-99.

[6] DIN (2019). DIN SPEC 17071:2019-12 Additive manufacturing - Requirements for quality-assured processes at additive manufacturing centers. Berlin, Germany: Beuth Verlag GmbH.

[7] Bonnard, R., Hascoët, J.-Y., Mognol, P., & Stroud, I. (2018). STEP-NC digital thread for additive manufacturing: data model, implementation and validation. International Journal of Computer Integrated Manufacturing, 31(11), pp. 1141-1160.

[8] ASTM International (2013). ISO/ASTM 52915:2020 Standard specification for additive manufacturing file format (AMF) version 1.2. West Conshohocken, PA, United States: ASTM International.

[9] 3MF Consortium (2018). 3D Manufacturing Format Specification. Accessed on 09/09/2021 from: http://www.3mf.io/.

[10] ISO (2009). ISO 6983-1:2009 Industrial automation systems and integration – Physical device control – Data model for computerized numerical controllers – Part 10: General process data. Geneva, Switzerland: ISO.

[11] ISO (2004). ISO 14649-10:2004 Automation systems and integration – Numerical control of machines - Program format and definitions of address words – Part 1: Data format for positioning, line motion and contouring control systems. Geneva, Switzerland: ISO.

[12] Buswell, R.A., Leal de Silva, W.R., Bos, F.P., Schipper, H.R., Lowke, D., Hack, N., Kloft, H.,

Mechtcherine, V., Wangler, T. & Roussel, N. (2020). A process classification framework for defining and describing digital fabrication with concrete. Cement and Concrete Research, 134(2020), 106068.

[13] Bos, F., Wolfs, R., Ahmed, Z. & Salet, T. (2016). Additive manufacturing of concrete in construction: Potentials and challenges of 3D concrete printing. Virtual and Physical Prototyping, 11(3), pp. 209-225.

[14] Wolfs, R.J.M., Bos, F.P., van Strien, E.C.F. & Salet, T.A.M. (2017). A real-time height measurement and feedback system for 3D concrete printing. In: Proceedings of the 2017 fib Symposium — High Tech Concrete: Where Technology and Engineering Meet, Maastricht, Netherlands, 06/12/2017.

[15] Kruger, J., Cho, S., Zeranka, S., Viljoen, C. & van Zijl, G. (2020). 3D concrete printer parameter optimization for high rate digital construction avoiding plastic collapse. Composites Part B: Engineering, 183(2020), 107660.

[16] Correa, F.R, (2016). Robot-oriented design for production in the context of building information modeling. In: Proceedings of the 33rd International Symposium on Automation and Robotics in Construction, Auburn, AL, USA, 07/18/2016.

[17] Mechtcherine, V., Bos, F.P., Perrot, A., Leal da Silva, W.R., Nerella, V.N., Fataei, S., Wolfs, R.J.M., Sonebi, M. & Roussel, N. (2020). Extrusion-based additive manufacturing with cement-based materials – Production steps, processes, and their underlying physics: A review. Cement and Concrete Research, 132(2020), 106037.

[18] Markin, V., Krause, M., Otto, J., Schröfl, C., & Mechtcherine, V. (2021). 3D-printing with foam concrete: From material design and testing to application and sustainability. Journal of Building Engineering, 43(2021), 102870.

[19] Wolfs, R.J.M., Bos, F.P. & Salet, T.A.M. (2018). Early age mechanical behavior of 3D printed concrete: Numerical modelling and experimental testing. Cement and Concrete Research, 106(2018), pp. 103-116.

[20] Wolfs, R.J.M., Bos, F., & Salet, T. (2019). Hardened properties of 3D printed concrete: The influence of process parameters on interlayer adhesion. Cement and Concrete Research, 119(2019), pp. 132-140.

[21] Vaitová, M., Jendele, L., & Červenka, J. (2020). 3D printing of concrete structures modeled by FEM. Solid State Phenomena, 309(2020), pp. 261-266.

[22] Roussel, N., Spangenberg, J., Wallevik, J. & Wolfs, R. (2020). Numerical simulations of concrete processing: From standard formative casting to additive manufacturing. Cement and Concrete Research, 135(2020), 106075.

[23] Perrot, A., Pierre, A., Nerella, V.N., Wolfs, R.J.M Keita, E., Nair, S.A.O., Neithalath, N., Roussel, N. & Mechtcherine, V. (2021). From analytical methods to numerical simulations: A process engineering toolbox for 3D concrete printing. Cement and Concrete Composites, 122(2021), 104164.

[24] Kim, S., Rosen, D.W., Witherell, P. & Ko, H. (2018). A design for additive manufacturing ontology to support manufacturability analysis. In: Proceedings of the ASME 2018 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Quebec, Canada, 08/26/2018.

[25] Sanfilippo, E. M., Belkadi, F. & Bernard, A. (2019). Ontology-based knowledge representation for additive manufacturing. Computers in Industry, 109(2019), pp. 182-194.

[26] Lu, Y., Choi, S. & Witherell, P. (2015). Towards an integrated data schema design for additive manufacturing: Conceptual modeling. In: Proceedings of the ASME 2015 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Boston, MA, USA, 08/02/2015.

[27] Smarsly, K., Peralta, P., Luckey, D., Heine, S., & Ludwig, H.-M. (2020). BIM-based concrete printing. In: Proceedings of the International ICCCBE and CIB W78 Joint Conference on Computing in Civil and Building Engineering 2020. Sao Paolo, Brazil, 06/02/2020.

[28] Gradeci, K.& Labonnote, N. (2020). On the potential of integrating building information modelling (BIM) for the additive manufacturing (AM) of concrete structures. Construction Innovation, 20(3), pp. 321-343.

[29] Davtalab, O., Kazemian, A. & Khoshnevis, B. (2018). Perspectives on a BIM-integrated software platform for robotic construction through Contour Crafting. Automation in Construction, 89(2018), pp. 13-23.

[30] Peralta-Abadia, P., Heine, S., Ludwig, H.-M. & Smarsly, K. (2020). A BIM-based approach towards additive manufacturing of concrete structure. In: Proceedings of the 27th International Workshop on Intelligent Computing in Engineering (EG-ICE). Berlin, Germany, 07/01/2020.

[31] Chakravorty, D. (2020). Cura tutorial: Master Cura slicer settings. All3DP. Accessed on 09/09/2021 from: https://all3dp.com/1/cura-tutorial-software-slicer-cura-3d/.

[32] Hodgson, G., Ranellucci, A., & Moe, J. (2014). Slic3r manual. Slic3r. Accessed on 09/09/2021 from: https://manual.slic3r.org/.