Formal knowledge as a basis for BIM-based design decision support in additive manufacturing

Chao Li [1] and Frank Petzold [1]

[1]Chair of Architectural Informatics, Technical University of Munich, Arcisstraße 21, 80333 Munich, Germany

E-Mails: chao1.li@tum.de, petzold@tum.de

Abstract: Emerging Additive Manufacturing in Construction (AMC) technologies provide efficient use of material and multi-function integration for novel architectural design. Coined by the synergy of multi-disciplinary activities incorporating computational design, mechanical engineering, material science, and so forth, AMC has drawn noticeable attention in architecture, engineering, and construction (AEC) industries and remarkable academic efforts. To integrate AM into the well-established Building Information Modeling (BIM) methodology, an essential step is to provide design decision support driven by a formal knowledge base to assist architects and engineers in choosing appropriate AM methods. The purpose of this paper is to introduce the basics of AMC knowledge formalization to support decision-making on appropriate AM methods in the early design stages.

Keywords: BIM, data modeling in construction, design support, AMC

1 Introduction

The construction industry consumes critical amounts of the world's materials and energy while generating construction waste and greenhouse gases that seriously impact the environment. Under the trends of urbanization and population increase, it is urgent to rethink conventional construction approaches to transition towards sustainability in the construction and built world. Recent advancement in AMC has presented advantages, including extended freedom of design, sound mechanical performance, and integration of multiple functions [1][2][3]. To realize AM's capabilities in AEC, Labonnote et al. [4] identified a demanding shift in the architectural design paradigm, a holistic design process incorporating material science and engineering, and more rational designs in compliance with existing regulations. For years, Building Information Modeling (BIM) has been deemed an enabler for digital transformation in the AEC domain. The work of [5] proposes BIM as a methodology for digital planning and data interoperability for AMC. More specifically, based on the object-oriented modeling language of EXPRESS, the Industry Foundation Classes (IFC) data model covers plenty of essential aspects in the construction sector, thus contributing to the data interoperability across heterogenous software from design to construction. Accordingly, the potential of using the IFC schema for fabricating BIM-based design with AM technologies has been demonstrated [6]. Collaborative activities involving different participants, including architects, stakeholders, engineers, etc., can be federated by the common data environment (CDE), information exchange management, and cooperative data management [7].

Although BIM provides a framework for boarding AM technologies in AEC, the challenges raised by Labonnote et al. [4] remain unsolved, primarily due to the missing AMC knowledge and the readily used evaluation tools during the design stages. As such, participating architects and engineers could not answer the questions of: “should AM technologies be applied for current design” and “what are the suitable AM methods for it”. It is known that rational decisions to these questions during early design stages are critical to avoid costly adaptations in the developed design and in-field construction phases. Li and Petzold [8] have proposed a methodology of integrating AM into BIM in the early design stages through decision support of choosing suitable AM methods. On top of that, this paper elaborates on the preliminary procedures to formalize AMC knowledge using OWL 2 DL and SWRL rules, meanwhile proposing a future alignment with the ontological version of IFC to bring AMC knowledge into the BIM model.

2 Background and Related Work

2.1 Overview of AMC

The versatility of AMC methods is mainly reflected in the innovations of processes, materials, and machinery use. Regarding 3D concrete printing (3DCP), Buswell et al. [9] classified the AM processes as particle-bed binding, material extrusion, and material jetting. In addition to concrete, more sustainable construction materials such as earth and wood have also been applied; however, using such materials could require printing of larger components to meet the exact load requirements or restrict the presence environment due to limited durability. Regarding machine systems, particle-bed binding processes generally use gantry systems mounting special-designed nozzles with jetting or spraying mechanisms. In contrast, material extrusion processes often leverage novel machinery solutions for mobility, near-nozzle mixing, and extended degree of freedom (DOF). Using manipulators with high DOF relaxes the slicing orientation from the horizontal and potentially increases geometry freedom of design but imposes complex trajectory planning tasks and careful coordination with feedstock’s fresh state properties. Furthermore, printing processes should be planned on-site or off-site depending on AMC methods’ environmental requirements, machine systems' workspace, and transport regulations. For off-site fabrication, large building components must be manufactured in smaller sizes and milled to the proper profile, then assembled on site. Layer-wise printed building components are inherently weaker in flexural loads. To overcome this deficiency, different reinforcement strategies have been applied in 3DCP to enhance the inter-layer binding of printed components [10]. Another critical research field in AMC is integrating multiple functions with rational inner design to save material and energy consumption and advocating the adoption of AMC for sustainability [11].

2.2 Knowledge Formalization and Semantic Web Technologies

In Artificial Intelligence, formal knowledge representation is a top-down methodology of encoding explicit knowledge in symbolic, machine-interpretable formalisms such as semantic networks, logic, rules, etc. Domain knowledge can then be formalized as ontology, representing experts' understanding of particular professions with cognitive bias. Constituents of an ontological knowledge base formalized with expressive description logic (DL) are, in principle, interdepending concepts (TBox), roles (RBox), and assertions regarding individuals' concepts and role connections (ABox). Accordingly, the World Wide Web Consortium (W3C) has recommended a set of languages for ontology modeling (OWL 2), querying (SPARQL), validation (SHACL), etc. To embody Horn-like rules in the knowledge base, SWRL and nominal schemas are often applied to complement the expressivity limit of OWL 2 while keeping decidability.

The ontology representation of the IFC standard termed ifcOWL is constructed from the translation of EXPRESS expressions using the DL dialect of OWL2 (OWL2 DL). It is in the same status as EXPRESS and XSD schemas of IFC. Pauwels, Zhang, and Lee [12] summarized three expectancies when applying Semantic Web technologies in AEC: *data interoperability*, *linking across domains*, and *logical inference and proofs*. Respectively, collaboration using ABox of ifcOWL-complied knowledge base unsurprisingly enables *data interoperability* through the unified technology stack in terms of serialization, modeling, querying, etc. *Cross-domain data linking* can be triggered by the alignment of domain ontologies and their accessibility in the web environment. *Logical inference and proofs* considerably demand the co-existence of a full-fledged knowledge base and tailored reasoner with proper reasoning capability.

3 BIM-based DDSS for AMC

The gap between BIM-based design and the AMC knowledge base can be bridged by consolidating BIM information retrieval, manufacturing feature extraction, and reasoning of the AMC method's conformity. As illustrated in Figure 1, the fundamental elements of AMC are formalized in modular ontologies and linked at an application level as the AMC knowledge base. The captured AMC knowledge is a triple store by its ABox and the basis of an intelligent agent by its TBox and RBox: when coupled with a dedicated inference engine, new information will be derived regarding existing facts in the knowledge base. The proposed DDSS queries the building components' information from

BIM-based design through a specific API, extracts the geometry and semantic features important to manufacturing processes, accesses the AMC knowledge base, and then makes use of an embedded inference engine to reason material, building space, regional rules and manufacturability conformities w.r.t. different AMC methods. Decisions of appropriate AM method(s) would be supported by visual and textual explanations. Afterwards, the DDSS will enrich both geometric and semantic information of the BIM-based design.

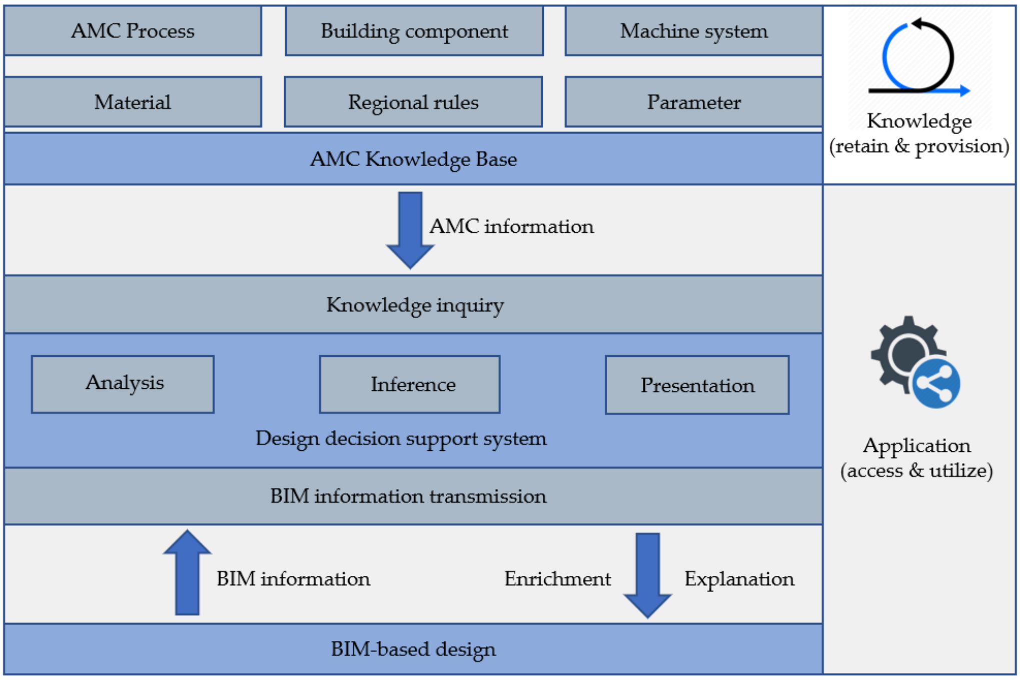


Figure 1: Structure of the DDSS for AMC

4 Formalize AMC Knowledge Base for Design Decision Support

Essential activities for most ontology-development methodologies comprise *specification*, *knowledge acquisition*, *conceptualization*, *formalization*, and *validation* [13][14]. Due to AMC's ever-increasing implementations and complex nature, domain experts‘ knowledge might be incomplete or inaccurately comprehended by ontology engineers during knowledge acquisition. Therefore, it is reasonable to follow the development life cycle of *evolving prototypes* [14]. After each involved activity, if the ontology does satisfy the required evaluation criteria, the previous activity should be repeated to improve the prototype. Furthermore, knowledge acquisition should be performed throughout the whole life cycle to improve the quality of the ontologies. During the course of conceptualization, working on taxonomies of different concepts and grouping them into modules consequently draws an activity of ontology reuse.

4.1 Strategy of Ontology Alignment

In manufacturing, AM techniques have long been deployed. Many studies put efforts into formalizing AM-specific ontologies, especially for manufacturability analysis of designed parts [15]. Due to the distinctive nature of AMC, reuse of these ontologies requires significant adaptions, at least for concept definition and application scenarios. Process type material jetting is defined by ASTM as an "*additive manufacturing process in which droplets of feedstock material are selectively deposited*" and specified by curing or bonding using UV light, chemical reaction, etc. [16]. In the scope of 3DCP, it is informally described as "*where layers are sprayed, using compressed air, one after another*" and is often referred to as the Shotcrete process [17]. Moreover, the semantic information from the BIM model must be provided for meaningful manufacturability assertion, e.g., an overhang feature of 90 degrees has been detected from a wall panel without knowing that this overhang belongs to the opening assigned to a window element, and placement of window frame is one of the integrated tasks for the printing process. It would be falsely stated that no AMC method can print such a wall panel.

As it to the AEC domain, it is unsurprising that existing ontologies rarely embody the AMC-specific knowledge that most practitioners do not yet recognize. The ifcOWL ontology is prioritised due to its remarkable coverage of domain entities, ISO-standard affinity, and potential to facilitate semantic enrichment in a BIM model after decision-making. Admittedly, transcription of EXPRESS to OWL 2 DL for knowledge representation is debatable as EXPRESS is used for information modeling regarding data structure and integrity, while OWL 2 DL is a computational fragment of first-order logic to model human knowledge. Further, the Semantic Web is built upon the open-world-assumption that incompleteness of knowledge is common and permissible. Sanfilippo et al. pointed out that the ifcOWL requires fundamental analysis and further clarifications as a qualifiable domain ontology for practical application [18]. We, therefore, start from a bottom-up and task-driven approach to formalize AMC ontologies and approach to soft reuse and extension of the ifcOWL. As such, it is possible to pertain to both the knowledge embodiment and seamless information flow after decision-making. Knowledge transition from the open-world AMC knowledge base to the closed-world BIM model is out of the scope for this work but would be enabled by a validation process using SHACL.

4.2 AMC Ontology Development

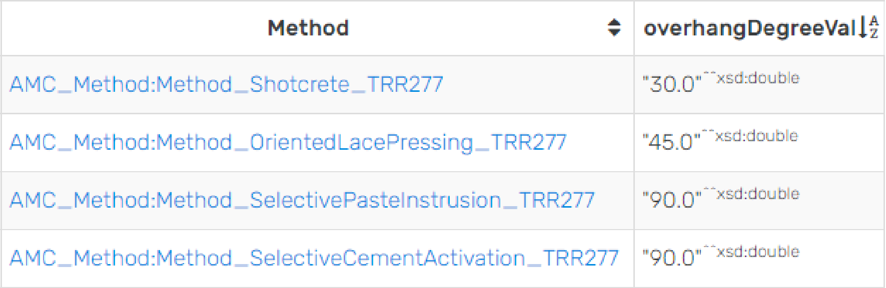
The *specification* process identifies the use of the ontology and its interested domain of discourse. First, we clarify that the AMC ontology is an application-level ontology to choose suitable AM methods. It is not a domain or fundamental ontology consisting of semantically sound definitions of basic terms - in fact, creating computational ontologies for manufacturing processes could require more expressive logic than DL. The ontology should comprise concepts and relationships regarding operational *resources*, *product* categories, descriptive AMC *processes*, etc. A set of competency questions (CQs) should be answered, for instance:

CQ_example: what is the maximum overhang degree printable by each AMC method?

Knowledge acquisition activities, according to Mendonça et al. [13], involve extraction, elicitation, validation and refinement. Based upon it, we first studied AMC-related bibliography to extract technical terms of AMC processes, then drafted an informal questionnaire as the protocol of semi-structured interviews. During interviews, experts in different AMC methods were requested to elaborate and guide the completion of the questionnaire. Experts could also complement and review the critical technical aspects, depending on their subjective willingness to participation. Overall, the filled questionnaire and relevant bibliography become the basis of the conceptualization process. *Conceptualization* phase figures out required concepts for AMC and clarifies their relations. *Process*, *product* and *resource* are indispensable for the entire manufacturing domain; it is, therefore, necessary to classify and relate AMC processes (*process*), building components (*product*), material (resource) and machine systems (*resource*). Further, identified boundary conditions, e.g., manufacturing feature constraints, machine systems' workspace and printed specimens' mechanical properties, should be conceptualized and indicated by corresponding *parameter*s. *Formalization* is meant to transform the concepts and relations in a quasi-formal model. Considering the prior determination of knowledge representation language (OWL2), in this phase, we practically implemented a primary AMC ontology as a basis for upcoming refinement prescribed in the aforementioned *evolving prototype life cycle*. *The validation* phase demonstrates the competency of the ontology regarding CQs raised in the specification process. Due to the limit of length, here we only proof the exemplified CQ in one SPARQL query: as the prefixes' names indicate, *amc_method* refers to the knowledge of AM methods where information about machine systems (*amc_ms*), material (*amc_material*), building components (*buildingcomponent*) and parameters (*amc_parameter*) are aggregated.

Sample query for competency validation

```
SELECT ?Method ?overhangDegreeVal
     WHERE {
     ?Method amc_method:overhangFeatureBoundaryCondition
           [amc_method:upperBoundOverhangFeatureParam
           [amc_parameter:overhangFeatureAngle
           [express:hasDouble ?overhangDegreeVal ]]]. }
```



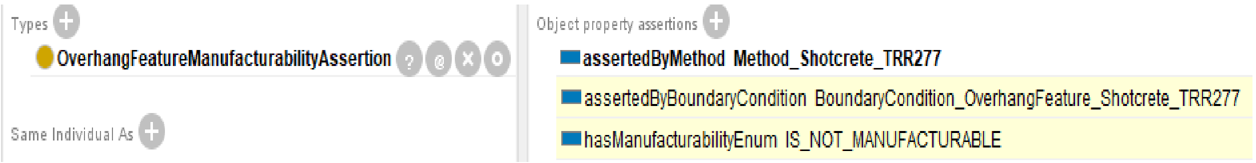
Method	overhangDegreeVal
AMC_Method:Method_Shotcrete_TRR277	"30.0"^^xsd:double
AMC_Method:Method_OrientedLacePressing_TRR277	"45.0"^^xsd:double
AMC_Method:Method_SelectivePasteInstrusion_TRR277	"90.0"^^xsd:double
AMC_Method:Method_SelectiveCementActivation_TRR277	"90.0"^^xsd:double

Figure 2: Query result for the sample CQ. Visualized in GraphDB.

As it to manufacturability assertion, SWRL rules were applied to link manufacturing features' values to corresponding boundary conditions of AMC methods. Through R1, the manufacturing features are able to be determined by methods' boundary conditions. Accordingly, Figure 2 illustrates the inference of an unprintable overhang.

```
greaterThan(?featureValue, ?upperBound),
relatingProcess(?upperBound, ?method),
assertedByMethod(?feature, ?method),
hasManufacturabilityAssertion(?feature, ?assertion) →
hasAssertionEnum(?assertion, IS_NOT_MANUFACTURABLE)
```

R1



OverhangFeatureManufacturabilityAssertion

assertedByMethod Method_Shotcrete_TRR277

assertedByBoundaryCondition BoundaryCondition_OverhangFeature_Shotcrete_TRR277

hasManufacturabilityEnum IS_NOT_MANUFACTURABLE

Figure 3: Overhang feature manufacturability assertion for Shotcrete method

5 Conclusion

This paper briefly introduces the structure of the DDSS and the development life cycle for the AMC knowledge base. As proof of concept, the use of the SWRL rule has been demonstrated to assert the manufacturability of the overhang feature. Alignment with the ifcOWL remains unsolved, but future work would investigate the extension of reused ifcOWL terms within the AMC knowledge base's TBox. Use cases could be ifcProxy for industrial robotics, ifcTaskType for AMC process types, etc. The type-occurrence pattern would be further analyzed for proper description of AMC planning in the overall supply chain.

Acknowledgements

This research was supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – Projektnummer 414265976 – TRR 277 Additive Manufacturing in Construction.

References

[1] “3D Printing.” https://d-shape.com/3d-printing/ (accessed Apr. 03, 2022).

[2] H. Kloft et al., “Influence of process parameters on the interlayer bond strength of concrete elements additive manufactured by Shotcrete 3D Printing (SC3DP),” Cem. Concr. Res., vol. 134, 2020.

[3] C. Gosselin, R. Duballet, P. Roux, N. Gaudillière, J. Dirrenberger, and P. Morel, “Large-scale 3D printing of ultra-high performance concrete - a new processing route for architects and builders,” Mater. Des., vol. 100, pp. 102–109, 2016

[4] N. Labonnote, A. Rønnquist, B. Manum, and P. Rüther, “Additive construction: State-of-the-art, challenges and opportunities,” Autom. Constr., vol. 72, pp. 347–366, 2016

[5] A. Paolini, S. Kollmannsberger, and E. Rank, “Additive manufacturing in construction: A review on processes, applications, and digital planning methods,” Addit. Manuf., vol. 30, no. October, p. 100894, 2019

[6] O. Davtalab, A. Kazemian, and B. Khoshnevis, “Perspectives on a BIM-integrated software platform for robotic construction through Contour Crafting,” Autom. Constr., vol. 89, no. January, pp. 13–23, 2018

[7] Building Information Modeling : Technology Foundations and Industry Practice, edited by André Borrmann, et al., Springer International Publishing AG, 2018

[8] C. Li and F. Petzold, “Integrating Digital Design and Additive Manufacturing Through BIM-Based Digital Support,” Proceedings of the 26th CAADRIA, 2021, vol. 1, pp. 263–270.

[9] R. A. Buswell et al., “A process classification framework for defining and describing Digital Fabrication with Concrete,” Cem. Concr. Res., vol. 134, no. December 2019, 2020

[10] N. Freund, I. Dressler, and D. Lowke, Studying the Bond Properties of Vertical Integrated Short Reinforcement in the Shotcrete 3D Printing Process, vol. 28. Springer International Publishing, 2020.

[11] G. Dielemans, D. Briels, F. Jaugstetter, K. Henke, and K. Dörfler, “Additive Manufacturing of Thermally Enhanced Lightweight Concrete Wall Elements with Closed Cellular Structures,” J. Facade Des. Eng., vol. 9, no. 1, pp. 59–72, 2021

[12] P. Pauwels, S. Zhang, and Y. C. Lee, “Semantic web technologies in AEC industry: A literature overview,” Autom. Constr., vol. 73, pp. 145–165, 2017

[13] F. M. Mendonça, K. C. Coelho, A. Q. Andrade, and M. B. Almeida, “Knowledge acquisition in the construction of ontologies: A case study in the domain of hematology,” CEUR Workshop Proc., vol. 897, pp. 2–6, 2012.

[14] H. S. Pinto and J. P. Martins, “Ontologies: How can They be Built?,” Knowl. Inf. Syst., vol. 6, no. 4, pp. 441–464, 2004

[15] M. Mayerhofer, W. Lepuschitz, T. Hoebert, M. Merdan, M. Schwentenwein, and T. I. Strasser, “Knowledge-Driven Manufacturability Analysis for Additive Manufacturing,” IEEE Open J. Ind. Electron. Soc., vol. 2, no. March, pp. 207–223, 2021

[16] ISO/ASTM, “INTERNATIONAL STANDARD ISO / ASTM 52900 Additive manufacturing — General principles — Terminology,” Int. Organ. Stand., vol. 5, no. I, pp. 1–26, 2015

[17] F. Dietrich, “Development of a Shotcrete 3D-Printing (SC3DP) Technology for Additive Manufacturing of Reinforced Freeform Concrete Structures,” pp. 1–12.

[18] E. M. Sanfilippo, W. Terkaj, and S. Borgo, “Ontological modeling of manufacturing resources,” Appl. Ontol., vol. 16, no. 1, pp. 87–109, 2021