INTEGRATING DIGITAL DESIGN AND ADDITIVE MANUFACTURING THROUGH BIM-BASED DIGITAL SUPPORT

A decision support system using Semantic Web and Multi-Criteria Decision Making

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Abstract. Additive Manufacturing in Construction (AMC) envisions a possible alternative for predominantly manual construction with various benefits. In addition to the well-known extrusion-based implementations of AMC, other techniques have been developed to meet various visual and functional requirement. However, the application of Additive Manufacturing (AM) into construction projects has to be carefully evaluated, especially during the early phases of architectural design when important decisions are made. From this point, this work devised an AMC-Oriented Design Decision Support System (DDSS) to identify suitable building components which can be manufactured with specific AM methods. In such a DDSS, knowledge base and decision-making strategy are both critical. To this end, principle of leveraging Semantic Web techniques and Multi-Criteria Decision Making (MCDM) methodologies will be addressed. At the current stage of our research, pre-printed building components using concrete material are considered during the decision support process.

Keywords. Additive Manufacturing in Construction; BIM; Design Decision Support System; Multi-Criteria Decision Making; Semantic Web.

1. Introduction

Conventional construction processes are commonly labour-intensive, material-inefficient, time consuming, and in some cases dangerous. As an alternative, the emerging AMC is able to lower material and labour cost, offer faster building rate, and enrich novel shapes (Ghaffar, Corker and Fan, 2018). Among the industrial practices of AMC, extrusion and particle-bed processes are most representative when dealing with concrete materials (Paolini, Kollmannsberger and Rank, 2019). Apart from that, many researchers are investigating further on the underlying AM methods (Lowke et al., 2020) (Kloft et al., 2020). Furthermore, different reinforcement strategies have been proposed

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to improve the mechanical performance of printed elements (Asprone et al., 2018) (Matthäus et al., 2020).

In consequence to versatile industrial practices in AMC, the decision-making of specific AM methods is becoming more complicated, but important. (Sacks et al., 2018, p. 180) illustrates that the early design greatly impacts on the overall functionality, costs and benefits of the building project, thus a preferred design process should put more effort into it. Accordingly, the influences of adopting AMC needs to be analysed in early design phases to minimize expensive changes or corrections of the plan. Nonetheless, inadequate knowledge of AMC by the architects and engineers impedes its consideration during decision-making processes of early-phased design.

It is known that Building Information Modelling (BIM) has significant potential to modernize the conventional AEC business model and brings advantages to the entire range of the building life cycle. Nowadays, it is a de-facto methodology applied in AEC industry (Sacks et al., 2018). Gradeci and Labonnote (2020) state that, although in-depth research studies have been done on both BIM and AM, the integration of BIM into AM is very scarce. They exploited the joint value creation potential of AM and BIM for concrete structures. Among those, the synergy of AM and BIM advantages the design process with greatest potential value. In recent years, BIM-based design decision support draws attention of researchers from various domain. However, it still faces a dilemma as formal description of the underlying knowledge bases receive limited consideration.

We believe that a critical step to advance the AMC is to establish a knowledge-based decision support system which helps architects and engineers determine the feasibility of AM methods given an interoperable building design. So far, research works have hardly covered a comprehensive framework that utilizes decision-making support for the integration of AM into BIM-based design. Within the scope of the collaborative research centre 'Additive Manufacturing in Construction - The Challenge of Large Scale' (TRR 277 2020) funded by 'Deutsche Forschungsgemeinschaft (DFG)', our research unit is dedicated to bridge this gap. As we are in an initial phase of the research period, this paper will propose a preliminary concept of a DDSS and focus on the formalized knowledge base containing capabilities and constraints of AM methods. Based on that, future work will introduce multiple design criteria and explore the potential of combining simulations with such a knowledge base during decision-making processes. To prove our concept, the system will firstly concentrate on the decision-making of concrete printing in scale of individual building components.

2. Related work

2.1. INTEGRATION OF BIM WITH AM SYSTEMS

Several research studies have demonstrated the integration of BIM with AM systems. Among those, Davtalab, Kazemian and Khoshnevis (2018) introduced a comprehensive framework which seamlessly integrates BIM and Contour Crafting. In their study, the named POCSAC software extracted geometry and material information from the BIM design using IFC data schema. Next, the software output an optimized tool path in graphical form. With the architectural and structural requirement specified in building design, a following laboratory test was mandatory to determine proportions of the printing mixture by considering fresh and hardened concrete properties. Finally, G-code was automatically generated for the control of construction robot. In the aforementioned process, the retrieval of material and geometry information from IFC remains implicit. On the other hand, Smarsly et al. (2021) proposed 'Printing Information Modelling' (PIM) as a BIM-based meta-modeling approach to facilitate the concrete printing in terms of data flow from BIM to AM. A PIM model comprises three abstract classes of data which are necessary to describe the AM methods in aspects of process, material and geometry. Smarsly et al. successfully mapped material and geometry information from an IFC formatted design into the PIM, while process parameters have to be fed in manually. The specialized PIM application then generated corresponding CNC code controlling a gantry concrete printer. Both of the practices evidenced the possibility of integrating BIM-based design with AMC, but still faced with a problem between architectural design and the adoption of AM methods, which would be tackled by the proposed DDSS.

2.2. DFAM KNOWLEDGE BASES

Dinar and Rosen (2017) emphasized the importance of AM-specific design guidance system and correspondingly formalized a Design for Additive Manufacturing (DFAM) (Rosen, 2007) knowledge base using Web Ontology Language (OWL). They explained the advantages of choosing ontology over direct use of traditional database in several aspects, mainly: expressiveness to model knowledge, pertinency to tutoring system, and integration to web technology. Similarly, but more in detail, Kim et al. (2019) presented a profound DFAM knowledge base by explicitly structured DFAM knowledge conceptually into three categories: part design (design feature and geometry parameters), manufacturing features and process planning (material and process parameters). In their work, design and manufacturing features were loosely coupled by parameters. Based on that, manufacturability was evaluated by applying design rules on the knowledge base, which is defined using Semantic Query-Enhanced Web Rule Language (SQWRL).

2.3. MCDM METHODOLOGY IN BIM AND AM

Established decision support systems using MCDM have been presented for both AM and BIM. Wang, Zhong and Xu (2018) introduced a posteriori MCDM system for informed decision support to tackle the complexity of choosing a specific AM method. Different from the typical MCDM system, their system allowed users to explore and refine the option space defined by technical, economic and indirect criteria. Such an exploration feature is considered as 'design-by-shopping' (Yannou and Akle, 2017), which is deemed to be helpful in optimizing user's satisfaction of a decision support system. Jalaei, Jrade and Nassiri (2015) applied MCDM approach on a BIM-based design to assist users in selecting sustainable building components. Interestingly, the authors invited a group of attendees to weight the criteria matrix and leveraged Entropy Method to emphasize consensus among different opinions. Afterwards, TOPSIS method was deployed to rank the alternatives for LCC analysis.

3. DDSS Integrating AM into BIM

An overarching goal of the DDSS is to allow a maximum of design freedom by converting resulting design into actually constructible entities. To this end, knowledge needs to be acquired in advance from a number of experts and then formally described for its use in decision support process. DDSS should then apply such a compensating knowledge base to verify feasibility of printing building components selected from a BIM-based design.

3.1. SYSTEM WORKFLOW

In our proposed decision support workflow (see Figure 1), BIM-based design, DDSS and AMC-related knowledge base are organized as in-parallel but interconnecting components. With this manner, knowledge can be maintained without greatly changing the logic behind the DDSS, meanwhile, DDSS is able to provide a close-looped decision support to the architect. Sequentially, five activities are involved:

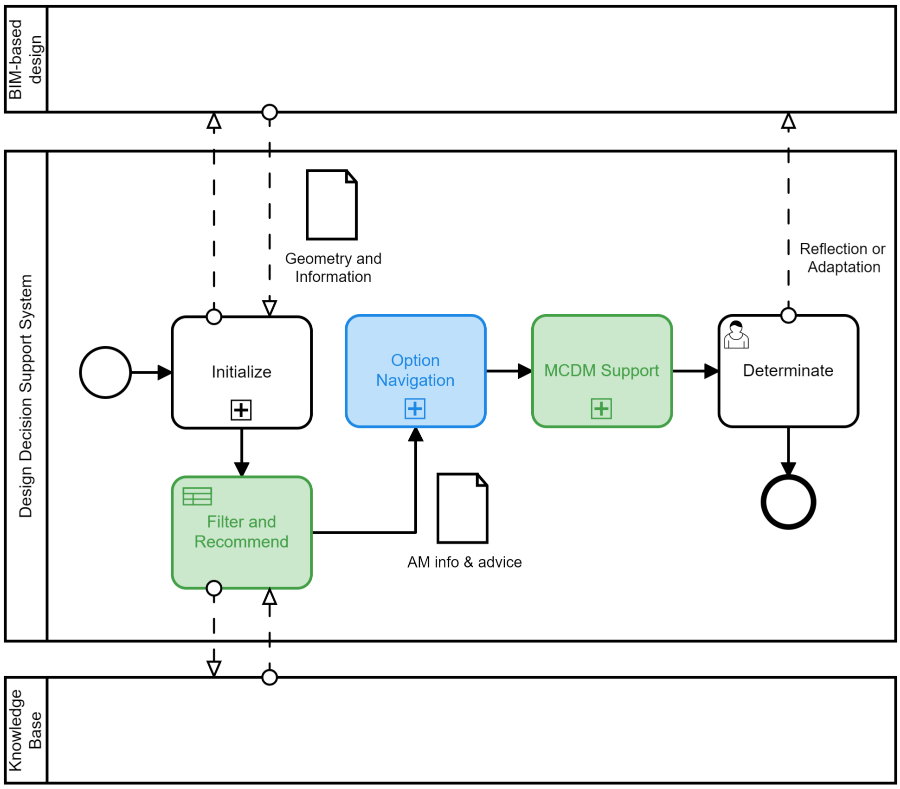

Figure 1. Workflow of DDSS.

1. *Initialize*: It is when an architect chooses working mode, selects building components and sets primary constraints. Correspondingly, the DDSS will read geometry and semantics of selected building components.
2. *Filter and Recommend*: The DDSS builds an option space by reasoning and querying feasible options from the knowledge base. Notably, the generated AM information and recommendation will be kept for use in subsequent decision-making processes. This process is enabled by an embedded inference engine and a specific API for knowledge access.
3. *Option Navigation*: In first instance, this activity asks the architect to pick multiple criteria from an existing list, then computes an optimal set of AM methods to form an option space. Afterwards, the architect is allowed to interactively explore and constrain the option space at will.
4. *MCDM Support*: A posteriori MCDM approach will consider multiple criteria selected by the user for the informed decision support. Ranked alternatives could be generated from this step.
5. *Determinate*: Based on the ranked alternatives and recommendations of design adaptation, the architect now either chooses a feasible AM method or adjusts the design. Once a certain AM method is determined, pre-defined and parameterized object types, hence, "families", will be automatically imported into and configured inside the BIM-based design.

Through this decision-making process, we could foresee the improvement of the Level of Development (LOD) with information obtained from the knowledge base, such as U-value, internal filling method, mechanical strength, etc. Evenmore, upcoming simulation and analysis procedures could also benefit from the given detailed information.

3.2. PRINCIPLE OF KNOWLEDGE FORMALIZATION

Domain-specific knowledge base usually serves as a backbone in a Knowledge-Based System (KBS). Due to the collabrality among various research groups, the knowledge base of proposed DDSS has to be formalized in an extensible, reusable and interoperable manner. Formal Knowledge Representation (KR) methods such as semantic network, frame, production rule and logical representations have their own strengths and limitations, while the paradigm in context of Sematic Web merges both rules and logical representations in form of logic programming and descriptive logic (Patel and Jain, 2018). Concretely, AMC-specific classes, rules and facts can be conceptualized with Web Ontolgoy Language (OWL), defined using Semantic Web Rule Language (SWRL) and queried through Simple Protocol and RDF Query Language (SPARQL). Furthermore, reasoning can be supported by various inference engines which are compatible to the aforementioned languages.

In our research, the specific ontology and design rules of AMC should be conceptualized to build a knowledge base (see Figure 2). The ontology needs to capture a series of information from the following perspectives:

- Method's know-how: The combined use of materials, process parameters and machine systems distinguishes the AM methods from each other. Apparently, characteristics of used material are decisive to the behaviors of printed components. Machine systems' building envelope and mobility directly constrain the scale of the printed components. Process parameters, on one hand, are determined through experiments given specific materials and machine systems. On the other hand, greatly influence the printed component's form and function. Note that an AM method could have multiple candidate materials, machine systems and process parameters.

- Boundary Condition: AM method's boundary conditions indicates the thresholds of method's capabilities (mechanical performance, geometric freedom, etc.) and are often conditioned with AM's proprietary features. For example, the minimum down-sink angle for a printable overhang is captured in AM method's boundary conditions, given by the type of AM method, material, printing path and machine's degree of freedom.
- Design Intention: Building component's material, geometry and function directly reflect the architect's design intentions. Therefore, all decision support activities in the proposed DDSS stem from these aspects. In addition to exterior geometry, the infilling pattern has also been taken into account during construction, as it is closely related to functional performances. Functions such as load-bearing and thermal comfort are in turn described using specific parameters.
- Parameters: Parameters are attributes that represent the above aspects, which can be conceptualized as classes or data properties for individual instances.

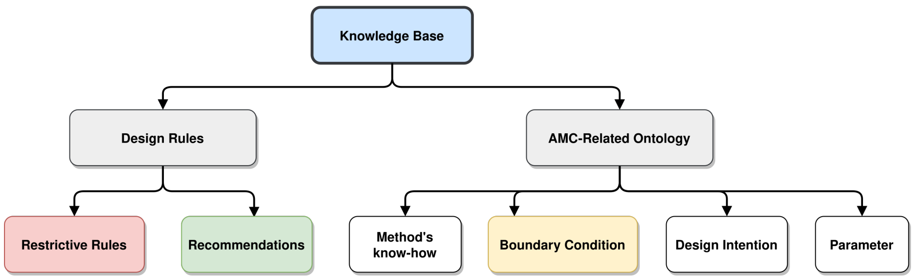

Figure 2. Knowledge Base Structure.

Figure 3 further illustrates the AMC-related ontology by denoting relations among conceptualized classes. Considering the combination of process parameters, material and machine system, experts set AM methods' functional and geometrical boundary conditions, which in turn constrain the evaluated building component. It is worth noting that there could be multiple AM methods that can print a given building component, according to the design rules.

Design rules, on the other hand, provide insights into manufacturability considering constraints in relation to design, process and material (Jee and Witherell, 2017). As far as AMC is concerned, design rules can stipulate various restrictions to apply AM methods, such as manufacturability, transport regulations, building codes requirement, etc. In addition to these restrictive rules, (Kim et al., 2019) utilized design rules for recommendations of overhang support structure and design adaptations. A simple design rule recommending design adaptation, in plain words, may state that: "IF the down-sink angle of the overhang feature is smaller than the corresponding limit in boundary conditions of specific AM method, THEN it is recommended to adjust the overhang to this limit". With the same antecedent, an additional recommendation for support structure can be stated.

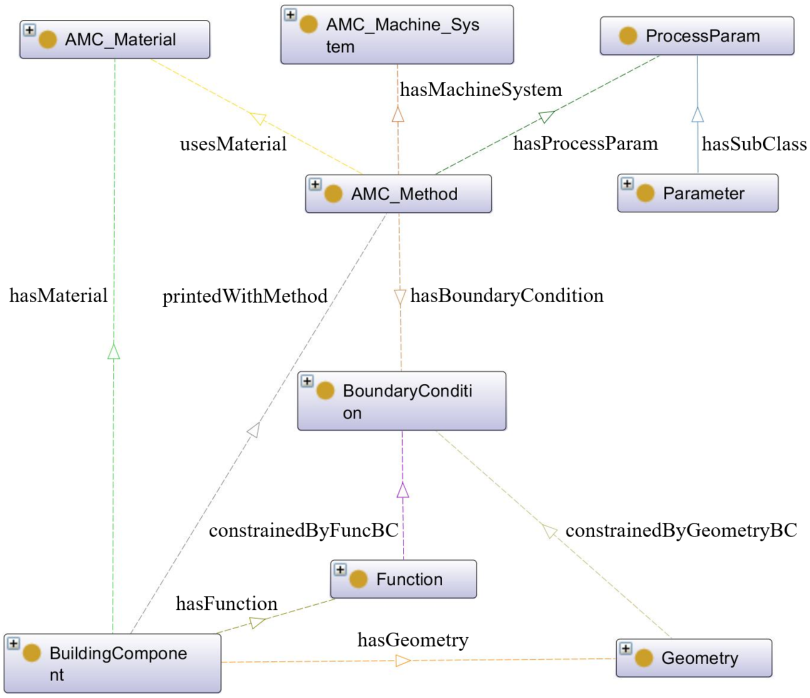

Figure 3. Simplified AMC Ontology (Top Level).

4. Conclusion and future work

This paper proposed an AMC-Oriented decision support system for BIM-based architectural design which aimed at integrating AM methods into BIM using Semantic Web technology and MCDM approach. We had also insight into the knowledge base with respect to its domain ontology and design rules. Since we are in the first phase of a four-year research period, this paper conservatively reveals our research rationality and initial findings. Sequentially, future work will attempt to tackle the difficulties in manufacturability validation and formalize the knowledge base. Afterwards, the knowledge base will be integrated into a BIM authoring system. Multiple decision-making criteria and MCDM approaches will then be studied, adapted and merged into the DDSS workflow. Next, the proposed DDSS will be extended to incorporate simulations processes with assistance of a feedback mechanism.

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