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TOWARDS INFORMED DESIGN DECISION SUPPORT OF ADDITIVE MANUFACTURING IN CONSTRUCTION - THE USE OF INTEGRATED KNOWLEDGE IN BIM-BASED ARCHITECTURAL DESIGN

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Abstract

Additive Manufacturing (AM) technologies have great potential to promote sustainable development in the architecture, engineering, and construction (AEC) domain. But the inherent complexity of AM and lack of domain knowledge hinder decisions about appropriate construction methods. With state-of-the-art Semantic Web technologies, a knowledge base regarding AM technologies can be formalized and integrated into the Building Information Modeling (BIM) methodology. To this end, this paper demonstrates how a Design Decision Support System (DDSS) utilizes formal knowledge to assist architects in choosing the appropriate AM method by assessing the manufacturability of individual building components. By following and refining the essential activities described, we aim to provide architects with informed decision support, thus facilitating the versatile use of AM technologies in the AEC domain.

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ABSTRACT
Additive Manufacturing (AM) technologies have great potential to promote sustainable development in the architecture, engineering, and construction (AEC) domain. But the inherent complexity of AM and lack of domain knowledge hinder decisions about appropriate construction methods. With state-of-the-art Semantic Web technologies, a knowledge base regarding AM technologies can be formalized and integrated into the Building Information Modeling (BIM) methodology. To this end, this paper demonstrates how a Design Decision Support System (DDSS) utilizes formal knowledge to assist architects in choosing the appropriate AM method by assessing the manufacturability of individual building components. By following and refining the essential activities described, we aim to provide architects with informed decision support, thus facilitating the versatile use of AM technologies in the AEC domain.

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ملخص
تتمتع تقنيات التصنيع التجميعى بإمكانات كبيرة لتعزيز التنمية المستدامة في مجال العمارة والهندسة والبناء. ولكن التعقيد المتأصل في التصنيع التجميعى ونقص المعرفة بالمجال يعيقان القرارات المتعلقة بأساليب البناء المناسبة. باستخدام أحدث تقنيات شبكات الانترنت الدلالية، يمكن إضفاء الطابع الرسمي على قاعدة المعرفة المتعلقة بتقنيات التصنيع التجميعى ودمجها في منهجية نمذجة معلومات البناء. وتحقيقًا لهذه الغاية، توضح هذه الورقة البحثية كيف يستخدم نظام دعم قرار التصميم المعرفة المرتبطة بالشكل لمساعدة المعماريين في اختيار طريقة التصنيع التجميعى المناسبة من خلال تقييم قابلية تصنيع مكونات المبنى الفردية. ومن خلال متابعة الأنشطة الأساسية الموضحة وتحسينها، نهدف إلى تزويد المعماريين بدعم قرار مستنير، وبالتالي تسهيل الاستخدام المتنوع لتقنيات التصنيع التجميعى في مجال العمارة والهندسة والبناء.

الكلمات المفتاحية: نمذجة معلومات البناء، نظام دعم القرارات، التصنيع التجميعى فى الإنشاء.

1. INTRODUCTION

Additive Manufacturing (AM) technologies have been increasingly studied to mitigate the environmental impact of the building industry. More sustainable building materials (Liu *et al.*, 2022), material and energy-efficient design (Dielemans *et al.*, 2021), life-cycle analysis from the process control (Kuzmenko *et al.*, 2022), etc., have demonstrated the potential of AM technologies for sustainable development in the AEC domain. The multitude of innovative 3D Concrete Printing (3DCP) methods could be classified as particle-bed binding, material extrusion, and material jetting (Buswell *et al.*, 2020), while each method presents individual strengths and constraints on the printed building components. Considering the practical application of AM technologies in construction, the architects and engineers have to explore feasible AM method(s) in the exponential portfolio of processes, materials, machine systems, applicational contexts, and requirements (Dörfler *et al.*, 2022). It is known that early design stages account for essential decisions for upcoming planning and construction phases, however, a lack of domain knowledge primarily makes the decision-making of AM methods intractable (Zeiler, Savanovic and Quanjel, 2007).

Previous studies have advocated formalizing AM ontologies for design support, mainly addressing the manufacturability problems for particular geometry features (Dinar and Rosen, 2017; Kim *et al.*, 2019). Regarding BIM-based prefabrication and planning, Cao et al. proved that formal knowledge helped to reduce design iterations by proactively validating conformities between product features and manufacturing capabilities (2022).

The achievements of leveraging domain-specific ontologies have led to the effort of integrating a formalized AMC (*About AMC TRR 277 - Additive Manufacturing in Construction*) knowledge base into the BIM methodology for design decision support. Accordingly, Li and Petzold proposed a Design Decision Support System (DDSS) using Semantic Web technologies and Multi-Criteria-Decision-Making (MCDM) methods to assist architects in choosing feasible AM methods for the BIM-based architectural design (2021). As an update, this paper introduced the essential activities evaluating building components' manufacturability, followed by the implementation details of a technical framework. Expanding on this work could provide more comprehensive decision support, thus bringing AMC technology to the forefront of novel architectural design.

2. BACKGROUND

2.1. Explicit Knowledge and Semantic Web Technologies

In order to identify suitable formalization techniques for the AMC knowledge base, we first study the data-information-knowledge-wisdom (DIKW) hierarchy and disambiguate different terms of knowledge. According to Rowley (2007), data is unprocessed input that needs to be structured and formatted to be part of the information, whereas knowledge derives from the synthesis of information and can be put to productive use. Wisdom is built upon accumulated knowledge with the exclusive capability of visioning foresight even in new situations or problems. Polanyi further distinguished knowledge as tacit or explicit (2009). While tacit knowledge remains subjective in peoples' ability, values, experience, etc., explicit knowledge can be objectively articulated and codified. Using machine learning techniques such as Convolutional Neural Networks (CNN) and Case-Based Reasoning (CBR), tacit knowledge can be captured and served in specialties such as architectural design and medicine (Roith, Langenhan and Petzold, 2017; Alzubaidi *et al.*, 2021). Knowledge representation (KR) techniques, on the other hand, are able to encode knowledge in formalisms such as semantic networks, production rules, and monotonic or non-monotonic logic (Russell and Norvig, 2016). With KR techniques, explicit domain knowledge can be formalized as domain-specific knowledge bases consisting of logic-based ontology and rules. As to the expressive description logic (DL), the ontology is further anatomized as terminologies (TBox), roles (RBox), and assertions (ABox) (Rudolph, 2011).

Semantic Web technology provides a standard set of languages for building knowledge bases. World Wide Web Consortium (W3C) has recommended the Web Ontology Language (*OWL - Semantic Web Standards*), SPARQL query language (*SPARQL 1.1*), SHACL (*Shapes Constraint Language (SHACL)*) for ontology-making, query, and validation. Additionally, SWRL (*SWRL: A Semantic Web Rule Language Combining OWL and RuleML*) and nominal schemas are often applied to strengthen the expressivity of OWL in rule-making (Krisnadhi, Maier and Hitzler, 2011). Notably, a distinguishing feature of the Semantic Web technology is the Open-World Assumption (OWA) – one cannot state false for the sake of missing knowledge as it might be found somewhere else, as opposed to the Closed-World Assumption (CWA) for database-like information systems or logic programming adopting the presumption of Negation-as-Failure (NAF) (Rudolph, 2011).

2.2. Impacts of AM Methods on Architectural Design Space

The entanglement and interaction of material, machinery, and process account for AM methods' varying capabilities and constraints for architectural design. Apparently, materials used for printing and their properties in a hardened state should comply with design intent and regulations. Further, as to extrusion-based AM methods, fresh material's properties such as buildability and open time, are critical to a collapse-free print as well as sufficient layer-wise bonding strengths that influence mechanical performances of the building component. Therefore, cycle time derived from toolpath and printing speed should be coherent to extruded material's fresh state properties. In this sense, building components' dimensions are constrained by fresh state properties, planned toolpath, and printing speed.

Dörfler *et al.* (2022) illustrated that the architectural design space was constrained by the Crane system from WASP (*Stampante 3D per case*). Indeed, the workspace of a machine system envelopes the printed components at their largest scale. Without extra operations, such as repositioning and reorientation of the machine system, the geometry of printed components must be confined to the workspace. Moreover, slicing or printing directions also impact the design space: functional workspaces of an articulated robot with 6 degrees of freedom (DOF) is a proper subset of its maximum workspace (Gudla, 2012). Consequently, many processes that deploy 6-DOF articulated robots but only print vertically are mechanically subject to additional geometric constraints. Knowing constraints of such a kind in the early design stages could reduce the time-consuming iterations from design to construction.

Many AM processes have promised greater design freedom in geometry (Paolini, Kollmannsberger and Rank, 2019). Nonetheless, careful considerations are required to ensure manufacturability. Particle-bed methods can print complex overhanging structures; however, they cannot realize a closed volume with any internal cavity (Lowke *et al.*, 2018). Conversely, the maximum degrees of overhang for extrusion-based methods are usually determined by concrete's fresh state as well as planning of the print path, whereas cavities are less problematic (Carneau *et al.*, 2020). In order to seize the opportunities brought by AM technologies and reduce time-demanding design iterations, it is worth formalizing AM processes' geometric boundary conditions and making them accessible during the early stages of architectural design.

3. DESIGN DECISION SUPPORT SYSTEM FOR AMC

3.1. Concept

The design decision support system, or DDSS, aims to assist architects and engineers in choosing appropriate AM method(s) for BIM-based architectural design. It addresses the decision-making problem by integrating the AMC knowledge into the BIM methodology, by which multiple design criteria can be evaluated to make sound decisions (Fig.1).

The AMC knowledge includes, but is not restricted to, process workflow, machine system, material, quantitative description of geometry freedom and function, as well as information about the assembly. The availability of such knowledge is enabled by *knowledge formalization*. Baumeister et al. (2009) pointed out a formalization continuum from unstructured images to logic and rule - the latter constitute an AMC knowledge base in the context of this DDSS. By demand, this knowledge base could be accessible to relevant BIM practitioners through specific SPARQL queries.

Such a DDSS is able to assess the manufacturability for a BIM-based architectural design, and a different attitude, when compared to other works, e.g., from Cao *et al.* (2022), has been held for interactive and informative decision support. Non-manufacturable geometry features, e.g., overhangs that exceed the upper bound of individual AM methods, are visualized in the BIM model as a reference for design adaptations. The MCDM algorithms would adaptively compute the ranking of applicable AM methods based on architects' preferences. Furthermore, the system is built on a closed-loop information flow. After each decision on the appropriate AM method, the relevant information is applied to the BIM model for semantic and geometry enrichment.

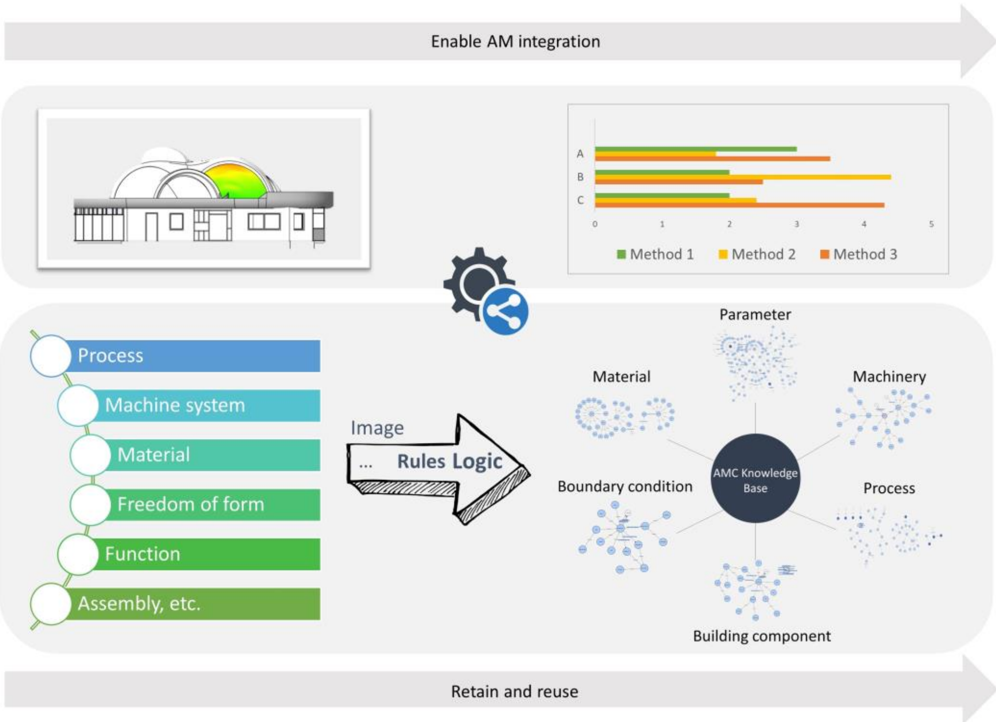

Fig.1: Schematic of Design Decision Support System

3.2. Overview of AMC Knowledge Base

As an integral part of the knowledge base, the AMC ontology is formalized through the processes of specification, knowledge acquisition, conceptualization, formalization, and validation (Pinto and Martins, 2004). The module dependency and concept hierarchy of the current AMC knowledge base are shown in Fig.2.

The module dependency on the left illustrates four tiers of imports from the *Parameter* module to the AMC knowledge base. The *Parameter* module arranges concepts that are used to describe different aspects of an object subjectively. These concepts are defined based on perspective or use cases rather than realism. This module consists of process parameters, e.g., layer height, water jet pressure, etc., manufacturing-feature parameters for overhang and bounding box, and material parameters ranging from mass density to mechanical strength, to name just a few. Importing this module as a backbone, properties of the material and machine systems and quantized in the second tier. Next, the *AMC Method* module incorporates the second tier for descriptions in the process-resource pattern, and *Designed Building Component* module solely imports the *Material* to reflect the design intent. All the modules are finally integrated to form the AMC ontology.

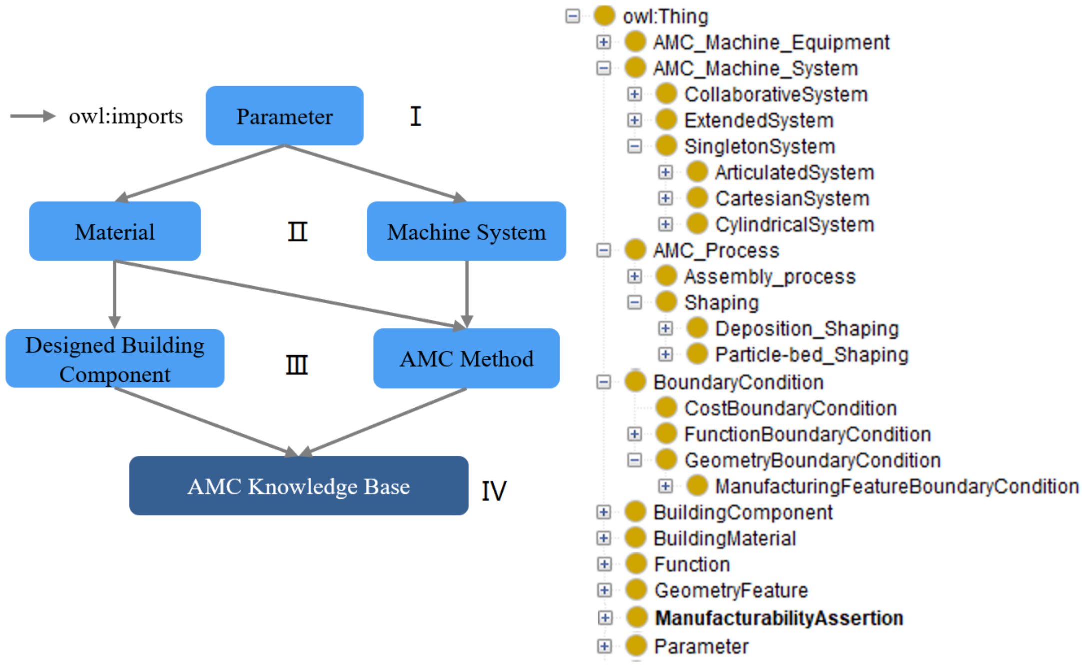

Fig.2: Dependency and Class Overview of AMC Knowledge Base

On top of the aggregated, application-level AMC ontology, restrictive design rules are made regarding the geometry, material, and functional conformities of the designed building components. As shown in the class hierarchy on the right, we formalized different boundary conditions for AM methods in terms of cost, function, geometry, etc. The designed building components will be connected to these boundary conditions through SWRL rules (see Section 3.3.3). By comparing extracted information from the BIM model against these boundary conditions, manufacturability can be asserted via the *ManufacturabilityAssertion* entity. This way, conformities of specific AM methods are attributed to individual features from the design perspective.

3.3. Activities for Manufacturability Assessment

To determine the building component's manufacturability regarding a given AM method, a list of essential activities in the DDSS has been identified: *1) extraction, 2) statement of facts, 3) reasoning, and 4) feedback.* The *extraction* activity provides semantics as well as quantized manufacturing features, which are translated into an ad-hoc data schema bridging the BIM authoring tool and the DDSS integrating a local copy of the AMC knowledge base. After that, facts are stated upon this knowledge base, followed by the *reasoning* process of AM methods' conformities. Last but not least, the deduced facts about conformities are presented on the DDSS and can be selectively visualized in the BIM environment.

3.3.1. Extraction

A BIM model embodies both geometry and semantic information. In the scope of this work, the building component's manufacturing features, material, and function information need to be retrieved or computed for further analysis. In both closed and open BIM environments, access to material and functional information via dedicated application programming interfaces (APIs) for proprietary and IFC (Industry Foundation Classes) models is relatively straightforward. Manufacturing feature extraction from geometry, however, is a synthetic problem of modeling techniques, geometry representations, algorithms in computational geometry, etc.

Even more, process and machinery parameters are also input to the precise calculation of manufacturing features. For instance, the calculation of overhang degree has to consider layer height, nozzle size, and printing direction. A comprehensive study of manufacturing feature recognition is beyond the scope of this work. In the previous stage of our research, we opted to fast and trivial approximations of two manufacturing features: overhang and Oriented Bounding Box (OBB).

During the approximation of the overhang degree, we disregarded the process and machinery parameters and defined the overhang degree as a *down-sink angle per face*. From this, the solid model is triangulated into meshes and then evaluated for the overhang degrees based on individual normal directions of these faces. To track the manufacturability of these overhangs, each can be assigned a unique identifier and visualized according to their deviations from the maximum overhang value.

As to the OBB feature, the entity provided in the IFC data schema essentially represents the Axis Aligned Bounding Box (AABB), which does not necessarily fit the building component tightly (*IfcBoundingBox*) tightly, thus possibly leading to manufacturability misjudgments about dimensions. Considering the structural functions and inherent mechanical anisotropy for many AM processes, in actual cases, the prefabricated building components are rarely re-oriented from the build-up direction during assembly. To this, the OBB feature can be computed efficiently: first, all vertices of the triangulated solid are projected on the horizontal plane; afterward, the minimum-area enclosing rectangle is derived using the algorithm of *Rotating Calipers* (Toussaint, 2014); at last, such a 2D rectangle is erected to the vertical extent of the building component. By demand of the actual 3D OBB feature, one could refer to a variety of methods reviewed by Chang *et al.* (2011).

3.3.2. Statement of Facts

Facts, or assertions relating to individuals constitute the ABox of the AMC knowledge base. The original AMC knowledge base, however, does not hold assertions for individual building components. Thinking on the frequent geometry adaptations during early design stages, neither should the knowledge base expand after each manufacturability assessment. In other words, extracted information from the BIM model should be updated in the knowledge base during assertion activity, accessed during reasoning activity, and removed after the feedback activity. These Create, Read, Update and Delete (CRUD) operations are enabled by open access APIs, e.g., OWL API (*OWLAPI - Semantic Web Standards*).

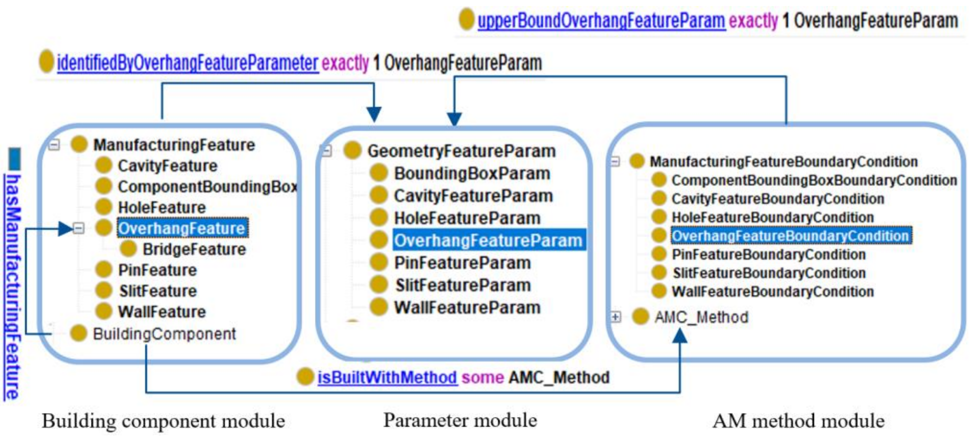

Fig.3: Classes and Object Properties for Manufacturability

There are three groups of assertions in OWL 2: class and individual assertion, object property assertion, and data property assertion (*OWL 2 Web*

Ontology Language). See in Fig.3, each building component has some manufacturing features which are identified by corresponding parameters via a specific object property; further, these parameters are constrained by AM methods' boundary conditions. In each assessment, individuals for *OverhangFeature* and *OverhangFeatureParam* classes need to be created and specified (class assertion); afterward, the object property of *hasManufacturingFeature and identifiedByOverhangFeatureParameter* should associate the two newly created individuals (object property assertion). Although not shown in the figure, related data properties should assign numeric values to *OverhangFeatureParam* as well (data property assertion). Similar procedures apply to the material and function information.

3.3.3. Reasoning

Reasoning is an integrated part of Knowledge Representation and Reasoning (KR & R) to infer implicit knowledge from an explicitly defined knowledge base. To foster a practical and full-fledged decision support system, we have ported a reasoner for manufacturability inference and future explanation functionalities.

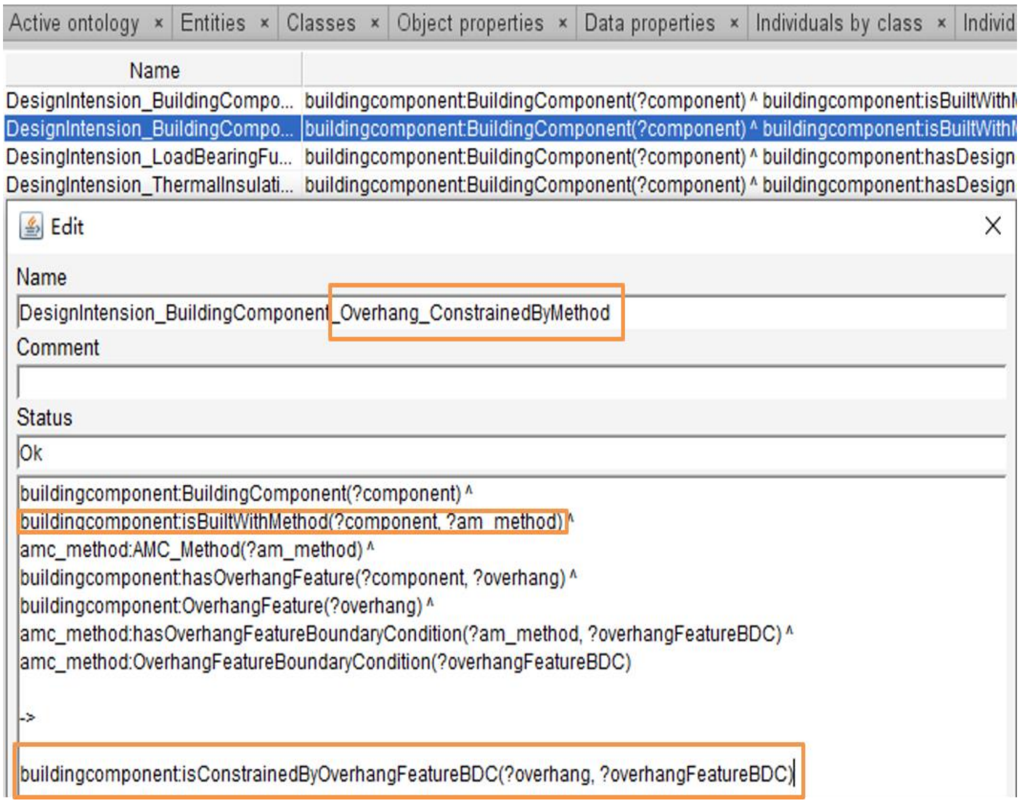

Fig.4: SWRL Rule to Apply Boundary Condition on Building Components

Khamparia and Pandey (2017) provided a comprehensive analysis of a variety of DL reasoners from multiple perspectives. On this basis, we adopted *Pellet* (*Pellet - Semantic Web Standards*) as the reasoner used by DDSS, considering technical aspects such as the expected DL expressivity (SROIQ(D)), rule-making language (SWRL) support, reasonable response time, justification capability, etc., as well as non-technical ones including availability and licensing.

On top of the updated geometry and semantic information from previous activities, the *Pellet* reasoner will apply the declared SWRL rules to relate AM methods to the building component and deduce manufacturability assertions accordingly. A designed building component is not direct output from any conceptualized AM processes; still, it can be virtually constrained and evaluated: Fig.4 demonstrates an SWRL rule that connects the overhang boundary condition of

AM methods to the evaluated building component(s). Once a building component is associated with a specific AM method through the *isBuiltWithMethod* object property, the *Pellet* reasoner will be triggered, to first apply AM method's intrinsic boundary conditions on the building component, then deduce the manufacturability through numeric or type comparisons.

3.2.4. Feedback

In this activity, the DDSS should present textural and visual feedback for informed design adaptations. Inconformity between design and AM methods will be represented to both architects and domain experts during the iterative processes of architectural design. Notably, in the current stage of our research, the system only aims to facilitate rational design for AM rather than automating the design processes. To frame the design development with multiple actors, Zahedi and Petzold (2019) proposed BIM-based, minimized communication protocol and visualization tools.

As a proof-of-concept, this paper demonstrates how the manufacturability is presented on the DDSS portal and fed visually back to the BIM authoring system so that architects can reference for design adaptations.

4. TECHNICAL FRAMEWORK AND USE CASE

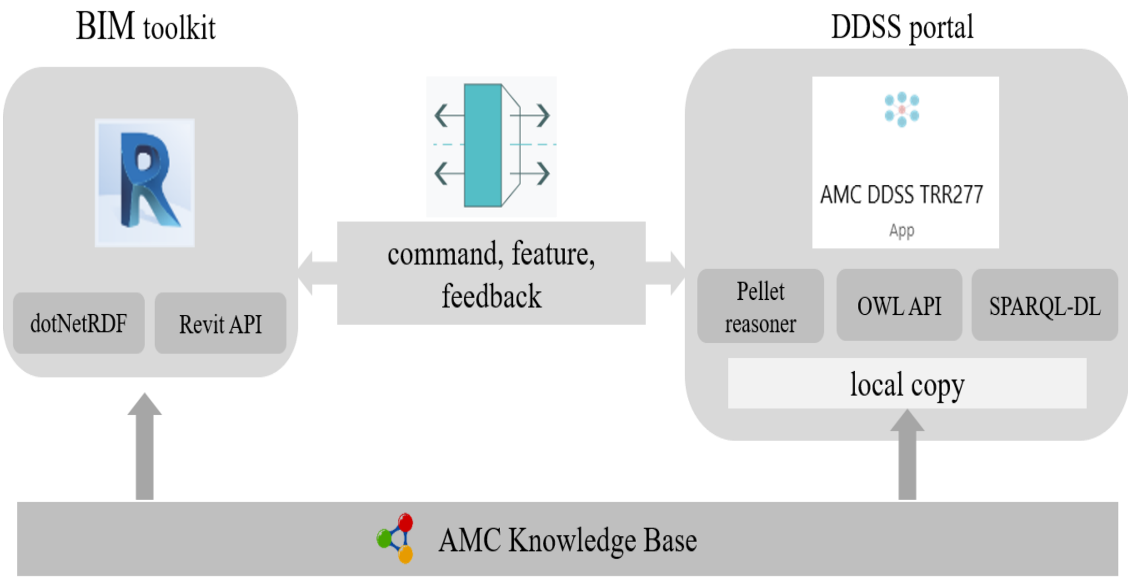

Fig.5: Technical Framework of DDSS

Fig.5 illustrates the framework of DDSS from a technical view. Basically, two functional parts - DDSS portal and BIM toolkit, are separated to deal with prescribed activities while the formalized AMC knowledge base keeps intact as a shared knowledge pool. A local copy of the knowledge base must be streamed and stored in the DDSS portal for facts assertion and reasoning activities, while the BIM toolkit is responsible for feature extraction and visualization.

To meet scalability, the DDSS portal is built as standalone software while communicating with the BIM toolkit. More in detail, the DDSS portal has ported the necessary libraries, including Pellet reasoner (*Pellet - Semantic Web Standards*), OWL API (*OWLAPI - Semantic Web Standards*), SPARQL-DL (*SPARQL-DL - Semantic Web Standards*), etc., and is deployed as an application on the Universal Windows Platform (UWP). In addition to Revit API, BIM toolkit also integrates dotNetRDF (*DotNetRDF - Semantic Web Standards*) to retrieve parameters for feature extraction (see Section 3.3.1). The communications between the DDSS portal and BIM toolkit are enabled by remote procedure calls (*gRPC*).

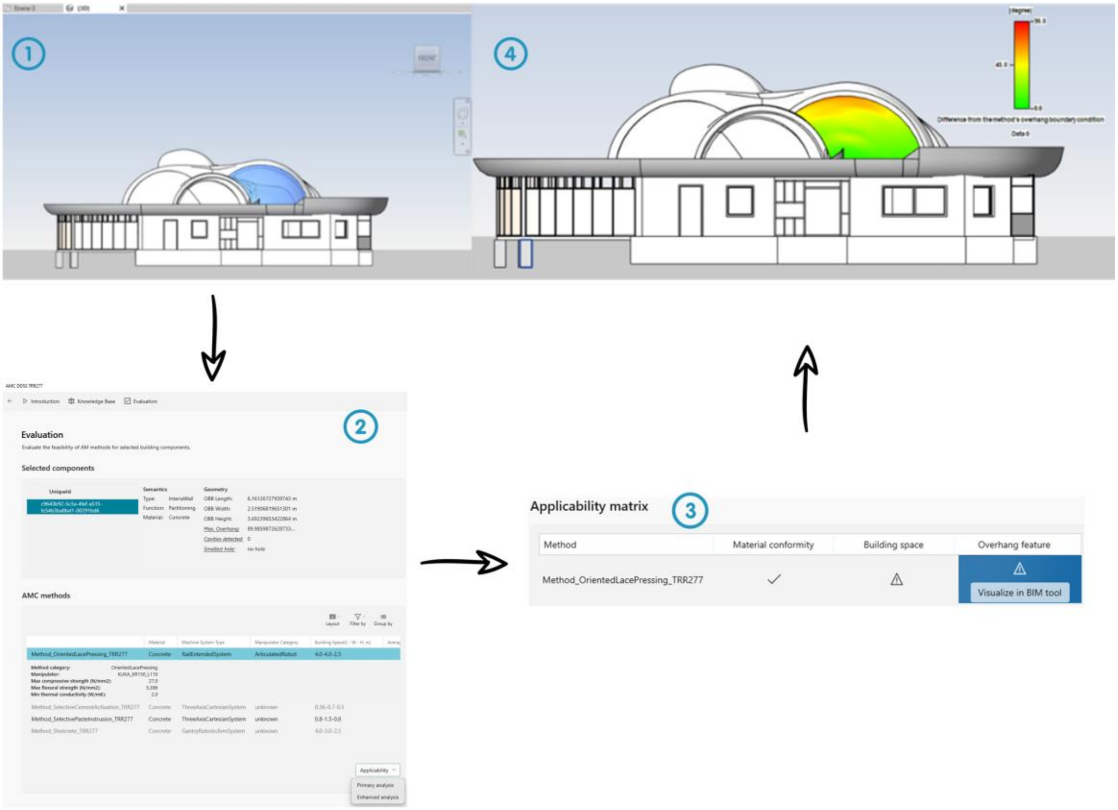

Fig.6: Building Component Manufacturability Evaluation

For BIM-based architectural design, a use case is defined as follows: an architect is about to complete the preliminary design, corresponding to the Level of Development 200 (LOD 200). At this point, the architect would like to be informed of appropriate AM methods for further analysis about cost, performance, etc. Current design may be adapted, provided that quantitative or qualitative opportunities are given.

As illustrated in *Fig.6*, the first step in this workflow is to select building components in the BIM authoring tool (Revit); afterward, material information and manufacturing features are retrieved and computed by the BIM toolkit, then transferred to and illustrated on the DDSS portal. The DDSS portal, meanwhile, provides a structured view of AM method's information, including material, maximum workspace, mechanical strength, etc. By choosing and evaluating a specific AM method, more features such as overhang are computed and asserted into the localized AMC knowledge base. Accordingly, the building component's manufacturability is inferred and presented on the portal. Last but not least, visual representation of manufacturability is triggered and overlaid in the BIM model. Till now, the manufacturability of the building component is evaluated and visualized according to boundary conditions of specific AM method, and the architects are informed of visual references for design adaptation.

5. DISCUSSION

It is worth noting that although we focused on formalizing, refining and utilizing the formal knowledge in the current stage, there is no doubt that the organization of different participants and heterogeneous digital resources contributes to better decision support in the long term. This has been discussed both in both AEC domain and other industries (Carrillo and Anumba, 2002) (Fakhar Manesh *et al.*, 2021).

Regarding the ontology structures shown in Fig.2, one might question why the AM method module (named as *AMC Method)* does not import the building component module (*Designed Building Component)* as product in the prevailing resource-process-product pattern followed by other ontologies (Cao, Zanni-Merk and Reich, 2019). We defense from two aspects: first, till now, BIM-based design is not yet able to embrace the fabrication information from different AM methods. In this regard, we look forward to filling this gap through the fabrication information model which is now under research (Slepicka, Vilgertshofer and Borrmann, 2021); second, as mentioned in Section 2.2., architectural design space is influenced by many intra- and inter-process uncertainties in both time and spatial regions. Without aligning to one of the so-called upper ontologies it would be inefficient and error-prone to enhance the current knowledge base to a more comprehensive level (Ocker, Paredis and Vogel-Heuser, 2019). Currently, such an alignment is still under work.

6. CONCLUSION

This paper introduces the concept of the DDSS that utilizes formal AMC knowledge to foster a manufacturing-aware architectural design. In particular, it depicts the holistic workflow for manufacturability evaluation from feature extraction to visualization. We believe that this work will be the foundation of future extensions, including MCDM approaches, simulation tools and feedback mechanism on a communication basis.

We are aware that formal knowledge is only capable to embody explicit rather than tacit knowledge which is pervasive during the design stages. In the future, we will envision a knowledge management system that integrates different knowledge types and heterogeneous digital resources to greatly improve the design decision support for AM technologies, thus promoting sustainable development in the AEC domain.

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