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Ontology-based manufacturability analysis automation for industrialized construction

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ABSTRACT

The current digital fabrication workflow requires many iterations between design and manufacturing. Automated manufacturability analysis can reduce the number of iterations at the design stage. However, existing approaches that leverage design for manufacturing and assembly (DfMA) do not consider detailed product features and production capabilities. To address this limitation, this paper utilizes an ontology-based approach to connect design and manufacturing knowledge. The developed manufacturability analysis system (MAS) involves semantic reasoning to analyze manufacturability by combining feature-based modelling, production capability modelling and manufacturing rules. The system was tested on a timber panelized project to demonstrate complex manufacturability analysis capability. The testing proves that the system could provide real-time feedback to the designers, leading to fewer design iterations. Thus, the paper is a first step towards automated fabrication-aware design and the results from the study lay the foundation for future research on connecting knowledge for interdisciplinary rule checking

1. Introduction

The construction sector could potentially save $20 billion in cost and 50% in time annually through the adoption of industrialized construction [1]. A crucial factor for achieving this goal is to leverage digital fabrication for industrialized construction. Digital fabrication combines digital design and advanced manufacturing technologies in a design-to-fabrication workflow [2]. Although the breadth of application for digital fabrication in architecture and construction is wide, in this paper digital fabrication refers to the following process with three steps. First, computational design software such as building information modelling (BIM) is used to design and analyze the building performance. Then, a domain-specific computer-aided manufacturing (CAM) application will interpret the geometry modelled using the design software into machining features and generate instructions of manufacturing processes. Finally, these instructions are converted into operation code (G-code or M-code) to support computer numerical control (CNC) machinery [3].

Today, this digital fabrication workflow requires many iterations between the design and manufacturing stages. However, the use of a manufacturability analysis during the first stage can allow the evaluation of various manufacturing aspects during the design stage and consequently reduce the time and cost of final products. In the context of information integration between design and manufacturing, manufacturability analysis can be defined as "Evaluating the manufacturability of a proposed design involves determining whether or not it is manufacturable with a given set of manufacturing operations, and, if it is, finding the associated manufacturing efficiency. [4]". Traditionally, design and manufacturing activities take place sequentially with many iterations between designers and manufacturers when the design does not match the fabrication capabilities of suppliers. These iterations often result in higher costs and longer time for project delivery.

The existing approach to minimize this iteration is to apply design for manufacturing and assembly guidelines (DfMA) [5,6]. However, the guidelines neither support a real-time evaluation in the BIM environment nor detailed analysis by considering the capabilities of available production systems. Prior studies have investigated frameworks [3,7,8] for implementing BIM in the design to fabrication workflow and tested it using case studies [8–10]. However, the information exchange between BIM and production systems still involves many time-consuming and subjective manual processes which rely heavily on experts' experience and knowledge [11].

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Some knowledge-based applications have been applied to address this limitation. For example, An et al. analyzed and compared the outputs of commercial software for design-to-manufacturing workflows of timber construction (such as AGACAD, Vertex DB, WoodStud_Frame, etc) [11]. These commercial solutions focus on transferring information automatically to production systems of specific vendors. However, they lack the flexibility to analyze manufacturability for all available production facilities and machinery [11]. This problem arises primarily due to three reasons. Firstly, BIM-based design does not utilize feature-based modelling, which is the foundation for Computer-aided Design/Computer-aided manufacturing/Computer-aided production planning (CAD/CAM/CAPP) integration in mechanical engineering [12–14]. In the construction domain, previous works apply geometry computation to detect manufacturing features from the design model [11,15]. However, these are limited to a few features and are not representative of industrialized construction. Secondly, there is a lack of knowledge modelling on capabilities of production systems for Industrialized construction. Thirdly, manufacturers have trouble formulating the feedback regarding manufacturability in such a way that designers can better comprehend it.

This paper proposes that these three problems could be resolved through an ontology-based approach to automate the manufacturability analysis. An ontology is "a specification of a representational vocabulary for a shared domain of discourse — definitions of classes, relations, functions, and other objects [16]." Ontologies have been used to semantically enrich existing design stage BIM models to perform additional tasks such as constructability check [17], safety check [18], energy performance assessment [19]. They are useful for this work because ontologies have proved to achieve effective integration between interdisciplinary knowledge bases such as design knowledge and manufacturing knowledge required for the manufacturability analysis. Therefore, the aim of this research is to demonstrate if the use of ontology technology can help reduce manual involvement in validating design conditions against manufacturing constraints using semantic modelling. For example, from the designers' perspective, an ontology-based manufacturability analysis system (MAS) may provide clear and timely design assessment and recommend modifications to product design according to the available production capabilities. Also, from the manufacturers' perspective, the system could evaluate the associated production efficiency, such as production time and resource consumption for the design order.

The research question in this paper is: *How can we integrate product features and production capability from multiple manufacturers to enable automated manufacturability analysis for product design to reduce design iterations?* To address this question, this paper is structured as follows. In Section 2, we review the current literature on feature-based modelling, production system modelling and manufacturability analysis. We give specific attention to how existing research uses ontologies for modelling features and production systems, and the limitations of these existing design and manufacturing ontologies. In Section 3, we describe the research method used to develop a manufacturability analysis system (MAS) and its knowledge base. Then in Section 4, we describe the development of MAS which includes 1) the knowledge base: the design and manufacturing ontologies as well as the rulesets and 2) the rule checking system for manufacturability analysis. The MAS described in Section 4 is tested using a panelized timber project as a case in Section 5. The findings from this paper are discussed in Section 6 and the conclusions are presented in Section 7.

2. Summary of Departure

This section reviews three main topics related to this work, including feature-based modelling, production system modelling and manufacturability analysis.

2.1. Feature-based modelling

Feature-based modelling was introduced for geometry representation and reasoning in computer-aided design (CAD) utilities [20]. Geometric models of a product, such as faces, loops, edges, surfaces, curves, and points, do not suffice for advanced evaluation of design, such as manufacturability evaluation [21]. For this purpose, features are developed as high-level abstractions of geometry or high-level information defining a set of characteristics [22]. The features are associated with a certain phase of product development and serve the stakeholders of that phase [21]. In mechanical engineering, features are associated with machines and operations during the manufacturing process. The feature model can be used for cost estimation [23], evaluation for manufacturability [24] and creation of production planning [25].

2.1.1. Feature-based modelling in AEC industry

Design information in the construction sector was represented historically as two-dimensional drawings initially on paper and then as CAD. 2D representation still plays an essential role today, describing the geometry of a building product with dots, lines, and curves, along with textual descriptions to give context. Building Information Models emerged as the next generation models for representing information regarding different stages of a built environment asset with a three-dimensional representation of the asset and associated information related to the function of the model. Early researchers define BIM objects as features as the objects contain richer information than geometric models [21,26,27]. Design stage BIM focused on representing design information alone. These models were further enriched for construction by adding process information such as cost, resources and time [28]. However, functional semantic information stored in design models are not sufficient for manufacturing and assembly [29] and could not be used for manufacturability assessment.

Although there are no sufficient explicit details for manufacturability analysis, there are implicit details in design stage BIM from which further details could be inferred to support cost estimation, evaluation of manufacturability and production planning. Table 1 summarizes the examples of building product features as well as the applied circumstances. A common strategy is taken above for feature classification, namely component features and intersection features [23]. For multi-feature analysis, a complementary category, macro features, is defined as pre-specified combinations of the above two types of features [30]. An alternative classification strategy takes more generic information into account and groups features into form features, physical features, context features, procedural features, and life-cycle features [21].

In the construction domain, there exist three approaches to obtain

Table 1
Building product, features and associated application.

Product	Features	Application
Drywall	Openings, wall turns, wall-beam intersections [23]	Construction cost estimation
Timber frame	Stud-to-stud connections, stud-to-plate connections [29]	Evaluation for manufacturability
Light-gauge steel frame	Stud-to-track connection [15]	Evaluation for manufacturability
Precast concrete	Connections, reinforcement and form stripping and lifting inserts [31]	Construction cost estimation
Interior walls and concrete columns	Component similarity (w.r.t wall type, wall height, column connection) [30]	Construction cost estimation
Steel frame	Profiles, flanges, holes, grooves [32]	Evaluation for manufacturability
Wood cabinet	Profiles, holes, slots, grooves [3]	Production planning

those feature information, (1) collection from user requirements [33], (2) extraction from BIM or IFC files [3,26,30], (3) reasoning by computational geometry [15]. In most cases, the design files do not contain sufficient connection details. As a result, intersection features need to be identified by reasoning, while the component features can be retrieved by the first two approaches. More approaches for feature recognition can be found in the manufacturing industry [34].

2.1.2. Ontologies for modelling features

An ontology approach has been studied to model features. Napal et al. proposed an ontology of construction-specific design features [26]. The ontology parses IFC entities into component features and intersection features. Component features can be derived from IfcBuildingElements, such as IfcWall, and related properties, such as locations and shapes can be derived from IfcLocalPlacement and IfcProductDefinitionShape respectively. Then, an advanced query from a construction practitioner's viewpoints can be formulated. In this approach, users without knowing the underlying BIM data can enhance BIM utilization for construction management tasks. However, the intersection features are not well addressed in this study, because IFC-based BIM does not provide a mechanism to filter for specific types of intersections. Liu, et al. solved this problem [35]. They detect wall-to-wall connections by computing geometric information of faces, edges and points. Using the richer vocabularies, they built a product ontology for cost estimation in the light-frame building industry. To analyze how design features affect construction method selection, productivity and cost performance, Staub-French and Napal introduced the component similarity as a novel feature class [30]. They formalized five types of attributes in the ontology, namely component class, component properties, geometric property variation, direction and component variation to characterize the component similarity.

The above ontologies provide a conceptual foundation for describing design features in the construction domain. However, the developed ontologies do not capture the characteristics of industrialized buildings. Industrialized construction can be classified according to the types of prefabricated elements, component materials, geometry and sector of work for a product [36]. The existing ontologies for traditional construction focus more on the geometry and location correlated to site activities [26,35], but neglect product typologies and compositions, which have a close relationship to off-site production. As the manufacturability analysis aims to match designed products to appropriate digital fabrication workflows, it is necessary to extend the ontologies to capture production-related features.

2.2. Production system modelling

Industrialized construction demonstrates many similar characteristics as the manufacturing industry. One of the core characteristics is to apply off-site production systems for building products development. Production systems can be viewed as "realizing necessary value-adding processing operations through an organized sharing of the (human and technical) resources available [37]". Gibb described four generic production systems for multifamily residential projects, including component manufacture and subassembly, non-volumetric preassembly, volumetric preassembly and modular building [38]. Jonsson and Rudberg classified the four systems in two dimensions: product characteristics and process characteristics [39].

2.2.1. Capability of production systems

The capability or capacity of a production system is a description of what it is able to produce, and can be determined by manufacturing resources. Ståhl defined tooling, workpiece material, manufacturing process, and personnel [40] as manufacturing resources in industrialized construction. The categorization is general enough but does not manifest the capacity of each type of resource. In the Computer-Aided Manufacturing (CAM) domain, the capability is defined in three contexts, process capability, machine capability and shop capability [41,42]. Built upon that, a fourth dimension, supplier capability, can be added to specify the expertise of the supplier who runs a physical facility, such as product focus, years of experience and quality assurance standards [43]. The capability of a production system for industrialized construction can be formalized by a similar approach.

2.2.2. Ontology works on production systems

The construction industry contains a variety of manufacturing resources and lacks a common data schema for information description and sharing. Here, we focus on examining the existing ontology application in the digital construction domain. The *E*-COGNOS platform firstly presents an ontology for knowledge management in the construction domain [44–46]. The ontology describes that "a group of Actors uses a set of Resources to produce a set of Products following certain Processes within a work environment (Related Domains) and according to certain conditions (Technical Topics) [45]". El-Gohary and El-Diraby developed an IC-PRO-Ontology for the infrastructure and construction domain. The ontology defines attributes of construction processes in terms of functional, performance, temporal, control, dependency, effect, locational and cost perspectives, and constraints of the processes [47]. Yuan et al. created a suite of ontologies for the digital construction domain (DiCon). The ontology supports the integration of construction workflows from various information and communication technologies (ICT), such as BIMs (Building information models), ERP (enterprise resource planning), and SCM (supply chain management) [48]. Ayinla et al. established a comprehensive off-site production workflow ontology (OPW), which models the production process from material delivery, production and assembly to transportation of products to the site [49]. The OPW ontology associates the product components with production processes and required resources. Järvenpää et al. developed an ontology to represent manufacturing capabilities, called MaRCO [50]. However, as MaRCO is designed under the mechanical engineering background, the classification of production systems for industrialized construction is not included.

Although the above ontologies have been developed for the construction sector, they do not yet support some of the key processes found in industrialized construction. Firstly, ontologies such as *E*-COGNOS and IC-PRO-Onto only provide a theoretical framework rather than a formalized information model. It helps the new ontology development but is not directly applicable in similar problems. Secondly, Ontologies such as DiCon, are only intended to capture high-level concepts within a broad scope, which is not sufficient for complex domain tasks, such as manufacturability analysis. Those tasks usually need detailed manufacturing taxonomy and entities, such as manufacturing capability, for semantic reasoning. Thirdly, the implementation of the above ontologies is only validated under certain scenarios given by original authors. The applicability and challenges for an extension have been less studied.

2.3. Manufacturability analysis

To achieve high-quality products and avoid time-consuming design iterations, manufacturability analysis has to be taken into account at the design stage. Manufacturability analysis can be defined as "Evaluating the manufacturability of a proposed design involves determining whether or not it is manufacturable with a given set of manufacturing operations, and, if it is, finding the associated manufacturing efficiency. [4]". For industrialized construction, manufacturability analysis is closely related to DfMA (design for manufacturing and assembly) with the same goal. A list of DfMA guidelines can be found in [51–53]. Many studies have investigated the process of using the guidelines in construction projects. However, there are only a few quantitative applications of DfMA [54,55]. To support quantitative evaluation, Gbadamosi et al. proposed a list of DfMA variables that need to be rated by practitioners [55]. Yuan et al. added a manufacturing simulation into the design process, but the simulation criteria are not provided in their study [56]. Thompson et al. suggested a set of key performance indicators (KPIs) to measure the product manufacturability, but the KPIs are either too generic, such as increased quality requirements, or lacking a computational approach, such as parts compliant with capability list [57]. Other quantitative studies to achieve a higher degree of manufacturability are mainly by reducing the number of parts, so as to reduce the corresponding assembly time [52,58]. Another major limitation for DfMA-based analysis is that manufacturing capabilities are not taken into account. In short, developed DfMA guidelines and variables are not sufficient nor formalized to perform manufacturability analysis of the design of industrialized products.

To overcome the limitations of DfMA-based analysis, other approaches have been proposed in the manufacturing industry, including neural network (NN), fuzzy logic (FL), agent-based system (ABS), rule-based system (RBS). According to a literature survey on different approaches for developing MAS [59], RBS is the most popular approach, which use IF-THEN clauses with logic combinations to represent manufacturing rules, such as processes/materials constraints and properties for fabrications of specific designs. In the construction domain, a rule-based system using ontological methods has been widely studied in previous research [60,61]. Hu et al. defined a set of inference rules using semantic web rule language (SWRL) to identify indirect links of building energy performance. Jiang, Shi and Wang built an automated code compliance checking platform using SWRL [61]. Soman, Molina-Solana and Whyte modelled scheduling constraints in Shape Constraint Language (SHACL) to support look-ahead planning [60]. However, few studies consider combining design features and production capabilities together to define rules for manufacturability analysis. A crucial reason is that the assessment of manufacturability requires silo-like information from designers, manufacturers and suppliers.

To summarize the above, there is an opportunity to use an ontology-based approach to build upon and connect two previous areas of work: feature-based modelling [26,30,35] and production system modelling [49,50], in order to create a manufacturability analysis for digital fabrication in industrialized construction. A review of existing works shows that some developed concepts, relationships, and taxonomies can be reused, while new ones will need to be created. From those previous studies, some research gaps can be identified. First, the existing design ontologies do not define detailed feature classes for industrialized construction. Second, few classes on production systems' capability were created in the manufacturing ontology. As a result, the existing DfMA methods cannot provide quantitative manufacturability analysis. Third, rule-based manufacturability analysis has not been studied in the construction domain and few studies consider how to formalize and retrieve rules. Therefore, this study focuses on integrating the design features and production capabilities by ontology to model and formalize the rules that are crucial for manufacturability analysis for industrialized construction.

3. Methodology

In the field of construction engineering and management, there is a tradition to develop technologies that support decision-making [62–64]. Researchers have applied a design science research methodology, following six steps: 1) identification of the problem, 2) definition of the objectives of the solution, 3) development of the solution, 4) demonstration of the solution, 5) evaluation of a prototype, and 6) communication of the results [65–68]. First, problem identification is performed through a review of existing literature (Section 2). Then, the methodology of solution development is defined on the basis of the identified problem and the knowledge of what is possible and feasible (Section 3). Following the objective definition, a prototype of a manufacturability analysis system was developed to address the problem (Section 4). This prototype was then evaluated via an illustrative case (Section 5). Conclusions from this research, its implications and the directions for future research are presented (Sections 6 & 7).

3.1. Manufacturability analysis system development

A Manufacturing Analysis Systems (MAS) is constructed via a three-step, unidirectional flowchart methodology that includes data input mechanism, engines for manufacturability aspects analysis and reasoning and outputs reporting [59,69]. Fig. 1 shows the flowchart of MAS construction. The data input mechanism contains obtaining data from CAD models, using user-system interactions and collection of manufacturing information, with the aim to feed design and manufacturing information into the system. The next step is to analyze the input gathered for manufacturability assessment to determine the level of difficulty or cost to manufacturing the design. The assessment is built upon a domain-specific knowledge base which stores ontologies, data and rules. This is the most important step in MAS as it determines the scope and accuracy of the manufacturability outputs. The final step is to generate the outputs and assist designers in considering manufacturing aspects during the design phase. The typical outputs are redesign suggestions; selection of processes and materials; process sequencing setups; estimation of production costs and times; process planning setups.

3.1.1. Knowledge base development

For the manufacturability analysis component, we build a domain-specific knowledge base that describes design and manufacturing concepts relevant to industrialized construction. The knowledge base is formed by three distinct parts: Terminological Box (TBox) which contains ontologies of the domain of interest by defining classes and properties, Assertion Box (ABox) which represents instance-level information associated with TBox's ontologies, and Rule Box (RBox) which infers implicit links among instances [70].

However, as the above review shows (Section 2.1 & 2.2), the existing works on both design ontology and manufacturing ontology are limited for manufacturability analysis. To extend the ontology, we first review some ontology development frameworks, such as the Grüninger and Fox approach [71], the Uschold and Gruninger approach [72], "simple knowledge engineering methodology" (SKEM) [73], and NeOn methodology [74]. In this research, we applied NeOn methodology. NeOn is a scenario-based methodology that supports different aspects of the ontology development process, as well as the reuse and evaluation of networked ontologies. It defines a set of nine scenarios for building ontologies and ontology networks. For each scenario, processes and activities are prescribed.

In this paper, we follow a "Five phase Waterfall Model", an ontology network life cycle model [74]. We made this choice as our ontology suite contains a design ontology and a manufacturing ontology, where the former relies more on the non-ontological resources and the latter relies more on the ontological resources. For design ontology, we chose scenario 1: from specification to implementation and scenario 2: reusing and re-engineering non-ontological resources of the Neon methodology. For manufacturing ontology, we chose Scenario 1 and Scenario 5: reusing and merging ontological resources of the NeOn methodology.

The "Five phase Waterfall Model" is shown in Fig. 2 and the main purposes are illustrated as follows:

(1) Initiation phase. In this phase, an ontology requirement specification document (ORSD), which specifies the purpose and scope of the ontology should be identified, its level of formality, its intended uses and end-users and what specific requirements the ontology should fulfil are, mainly in the form of competency questions (CQs). In this study, the competency questions are elicited and discussed in workshops between ontology developers and domain experts, including designers, manufacturers and software developers in the construction industry. By combining

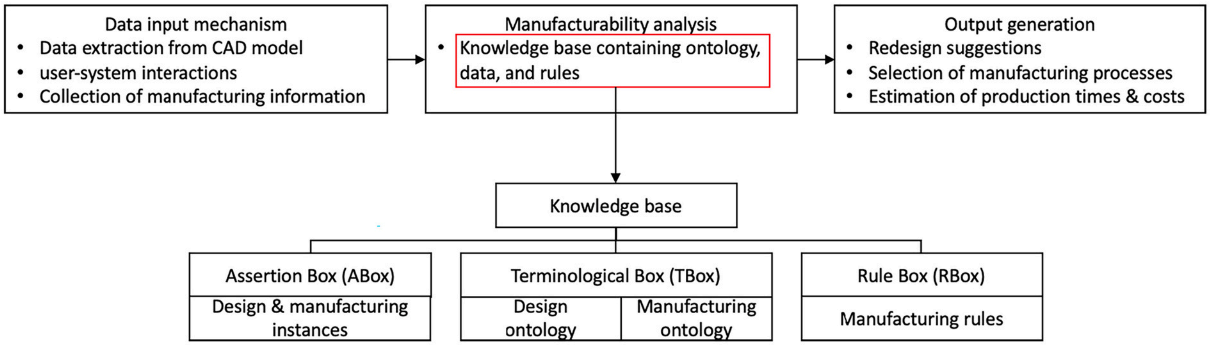

Fig. 1. Basic methodology of MAS development

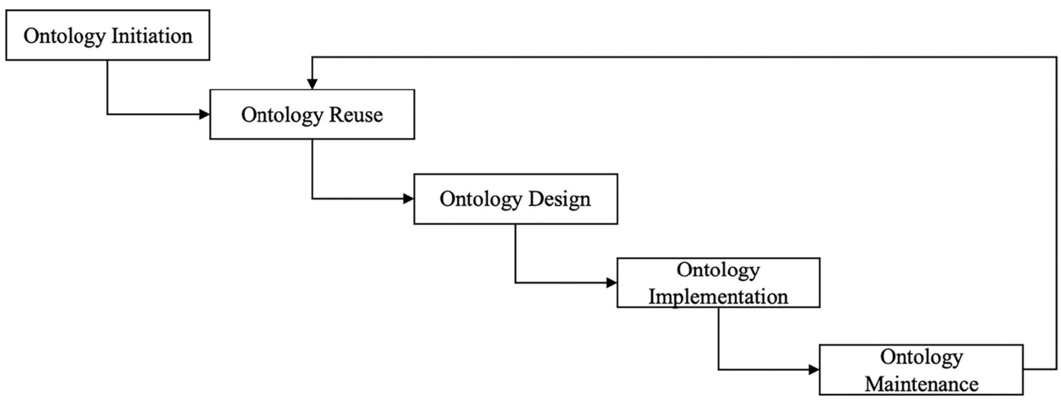

Fig. 2. Five-Phase Waterfall Model.

intended purposes and domain knowledge, the ontology developers defined a set of CQs.

(2) Reuse phase. The main purpose of the reuse phase is to obtain one or more resources, either non-ontological or ontological, to be reused in the ontology network being developed. The defined nine scenarios in NeOn methodology will be applied in this phase.
(3) Design phase and implementation phase. The design phase and implementation phase are normally performed together when ontology development tools (e.g. Protégé) are used. The output is an ontology implemented in RDFS, OWL or other languages that can be used by semantic applications.
(4) Maintenance phase. During the use of the ontology network, if errors or missing knowledge are detected, the ontology development team should go back to the reuse phase and generate a new version for the ontology network.

To provide design recommendations based on manufacturing capabilities, a rule base is developed. The rules consist of two parts: a) client and design requirements, and b) production capabilities. The former is derived from contracts and design documents, while the latter is derived from manufacturers' experience, production handbooks, and machine brochures. The rules are embedded in the MAS to be used as a guide for assessing the manufacturability of the design. In this study, four types of manufacturing constraints are conceptualized as an example.

The rules are coded in SHACL (shapes constraint language). SHACL is a World Wide Web Consortium (W3C) specification for validating graph-based data against a set of conditions. SHACL rules contain two components: data graph and shape graph. A data graph is an RDF graph that contains data to be validated and a shapes graph that specifies which nodes in the data graph are validated. A shapes graph has two types of constraints for target declarations, node shapes and property shapes. Node shapes declare constraints directly on nodes and property shapes declare constraints on the property that is associated with the node through a path. The targets can be classes, specific nodes, the subject of property and the object of property [75]. Compared with SWRL, SHACL covers data validation (in a "closed world") similar to traditional schema languages and can also be used for general purpose rule-based inferencing [76].

4. Manufacturability Analysis System for industrialized construction (MAS-IC)

In this section, we illustrate the development of a manufacturability analysis system for industrialized construction (MAS-IC). The development is composed of five key steps: 1. data input mechanism, 2. design ontology modelling, 3. manufacturing ontology modelling, 4. ontology mapping and 5. rule base modelling.

4.1. Data input mechanism

The user input is an industrialized construction project modelled in BIM design authoring applications. Unlike other CAD software used in the manufacturing industry, it incorporates domain concepts and relationships, such as element types, materials and geometries. The project information, classified in the model, supports the manufacturing analysis. To achieve interoperability between various BIM applications, Industry Foundation Classes (IFC), a neutral, non-proprietary data model is required. According to the IFC standard, the design parameters of a BIM object are defined as IFC entities. To support manufacturing analysis, element types, shapes, dimensions, and materials are of great importance and extracted from the IFC file. The data extraction is done by IfcOpenShell [77], an open-source software library that helps developers to work with the IFC file format.

4.2. Design ontology

The design ontology is developed by combining Scenario 1 and Scenario 2 of the NeOn methodology. The reused non-ontological resources are classification schemes from previous studies [26,36]. The specific activities for carrying out the ontology development for Scenario 2 are non-ontological resource reuse and re-engineering.

4.2.1. Ontology initiation

The design ontology is aimed at modelling product designs of industrialized construction that directly and indirectly influences manufacturability. The scope of the ontology will cover the digital fabrication of typical industrialized building systems, including their major components and properties. The site-built parts and furnishes are not included. The end-users of the ontology are industrialized building designers, manufacturers and software engineers in the construction domain. The functional requirements are determined in the form of competency questions (CQs) shown in Table 2.

4.2.2. Non-ontological resource re-use

The feature classification model developed by Napal et al. [26] will be reused (Fig. 3). The classes and properties are built on top of the IFC entities, so as to be compatible with existing BIM tools. The two major classes are the Component class and the Intersection class. The Intersection class is further classified into the Penetration class, the Opening class and the Component Intersection class. The Component class will be re-engineered to match the industrialized building systems (IBS). According to the classification of industrialized building systems, the industrialized systems can be classified in terms of the types of prefabricated elements, component materials, geometry and subsector of work for a product [36]. The classification schema generalizes the common features of the IBS and can be used to re-engineer the component class.

4.2.3. Non-ontological resource re-engineering

A re-engineering process is used to transform the non-ontological resource into an ontology. The major goal in this step is to create representations for the above basic classes at the different levels of abstraction. The typology of prefabricated elements includes frames, panels and volumetric modules. Each typology can be classified by functions. For instance, panels can be categorized into wall panels, roof panels, and floor panels. The material includes structural materials, finishing materials and insulation materials. For example, structural materials consist of timber, steel, and precast concrete. The geometry includes shapes, such as rectangles, triangles, circles, used for the architectural design and associated dimensions. To support matching with a manufacturing service, a performance category is added. The performance includes fire rating, acoustic rating, thermal performance (U-value) and load-bearing capacity. Finally, a conceptual model is generated from defined concepts. It will be used as input for the ontology design.

Table 2
List of core CQs for the design ontology.

Competency questions	Reasons
1. What is the type of the building component?	To identify the building components
2. What is the quantity of the building component?	To evaluate the production duration
3. What are the materials of the building component?	To identify the needed materials
4. What are the dimensions of the building component?	To evaluate the machine's capabilities
5. What are the performances of the building component?	To support the detailed designs

4.2.4. Ontology design

The hierarchy is developed using a "top-down" approach. The feature class is classified into the Component class and the Intersection class. The Intersection class is classified into the Penetration class, the Opening class and the Component Intersection class. The Component module is re-engineered using the industrialized construction feature taxonomy. The component class is linked to the "Typology" class, "Material" class, "Geometry" class and "Performance" class via the object properties "hasType", "hasMaterial", "hasGeoemtry" and "hasPerformance" respectively. As described above, those classes can be further classified into more detailed subclasses, shown in Fig. 4.

4.2.5. Ontology implementation

A formal model of the ontology is built via protégé, a popular ontology editor for scholars and ontology engineers. The data from a design team is populated in the ontology. The data silos usually include (1) architectural BIM data; (2) Excel spreadsheets containing performance information for building elements; (3) client-manufacturer contract. These data need to be extracted semi-automatically (e.g., using the IFC format for BIM) and mapped to the ontology.

4.3. Manufacturing ontology

The manufacturing ontology is developed by combining Scenario 1 and Scenario 5 of the NeOn methodology. The reused ontological resources are OPW ontology and MaRCO ontology [49,50]. The specific activities for carrying out the ontology development for Scenario 5 are ontology aligning and ontology merging.

4.3.1. Ontology initiation

A design needs to go through a series of production services, consuming resources and producing waste. The manufacturing ontology aims to model the capability of the services that have constraints or requirements on the design. The scope of the ontology will cover the material supply, production, assembly and transportation processes. The on-site construction activities are not included. The end-users of the ontology are manufacturers and software engineers in the construction domain. The functional requirements are determined in the form of competency questions (CQs) shown in Table 3.

4.3.2. Ontology reuse

The OPW ontology developed by Ayinla et al. [49] and the MaRCO ontology developed by Järvenpää et al. [50] are reused. The OPW ontology defines eight major classes to formalize off-site production process knowledge. The OSMFactoryProductionMethod class is used to classify production systems for different building types. The Production Process class consists of the WorkStation class and the WorkStation consists of the Activity class proceeded. The Process Type specifies the sequence of the production workflow. The Resource class defines all consumed resources, including materials, subcontractors, direct labors, equipment and overhead, during the production process. The Product class refers to the final product from a production line and the Building class refers to the final product shipped to the site. The MaRCO ontology contains four major classes to describe production capabilities. The Capability class is classified into the Simple Capability class and the Combined Capability class, where the latter is the combination of two or more (simple or combined) capabilities. The Capability Parameter Class describes the characteristics of a capability, which are given in machine catalogues.

4.3.3. Ontology aligning and merging

The basic hierarchy is the same as the OPW ontology. To link the MaRCO ontology to the OPW ontology, the property "hasCapability" is used. The capability is abstracted into five levels, namely process level, station level, machine level, supplier level and labor level. Hence, the Capability class is linked to the Production Process class, WorkStation

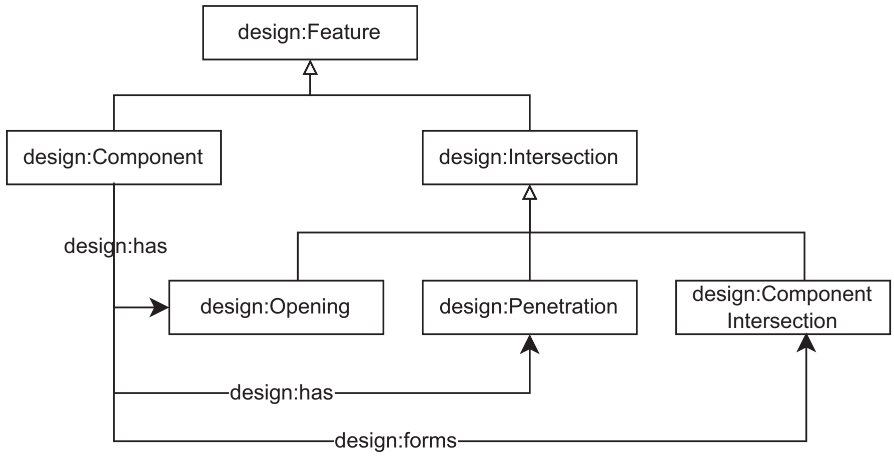

Fig. 3. Feature classification model modified from Napal et al. [26]

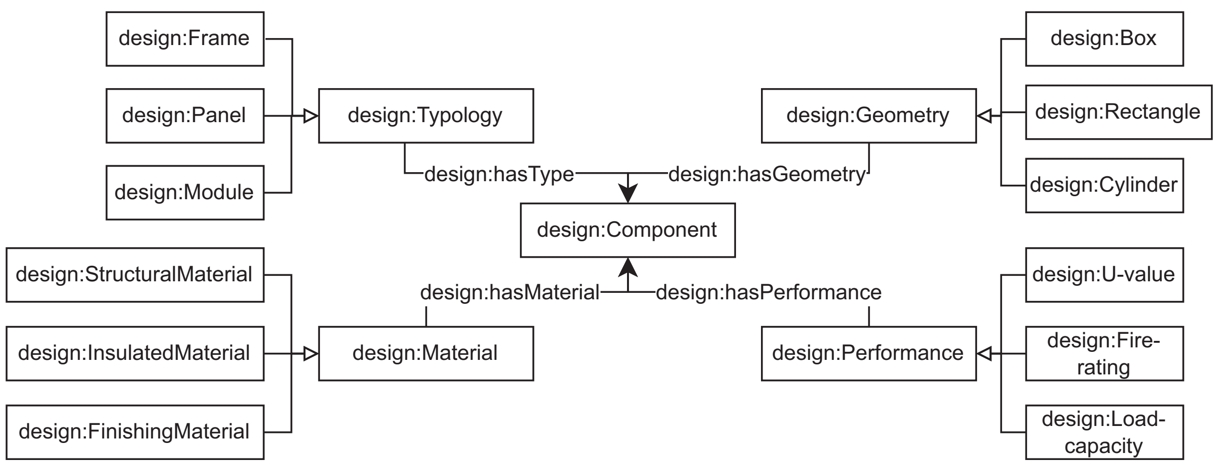

Fig. 4. Re-engineered Component module.

Table 3
List of core CQs for the manufacturing ontology.

Competency questions	Reasons
6. What capability does the production process have?	To specify the available inventory
7. What capability does the workstation have?	To specify the production rates
8. What capability does the equipment have?	To specify the technical limitations
9. What capability does the subcontractor have?	To specify the outsourced product details
10. What capability does the labor have?	To specify the workers' required skillfulness

class, equipment class, subcontractor class and labor class respectively. A similar categorization is applied in the manufacturing service description language (MSDL), an upper ontology for the digital manufacturing market [78]. The difference is that the labor level capability is extended from MSDL, as the manufacturing process in the construction domain relies more on labor skills than other manufacturing industries. The merged ontology is shown in Fig. 5.

4.3.4. Ontology implementation

Protégé is used again to model the ontology. The datasets for the manufacturing ontology include: (1) inventory information from the manufacturer MRP (material requirements planning) system; (2) manufacturing details from a product catalog; (3) operation information from a manufacturing ERP (enterprise resource planning) system. The data from the MRP system and ERP system can be exported in a tabular form.

4.4. Design and manufacturing ontology mapping

To build the knowledge base for manufacturability analysis, the design ontology needs to be mapped to the manufacturing ontology. Two mapping mechanisms are used. Firstly, the Component class in the design ontology is connected to the Product class in the manufacturing ontology via the "sameAs" property. Secondly, the object properties "producedBy" is used to connect classes in the design ontology and the manufacturing ontology, to represent the design-production relationship (Fig. 6). Considering the reconfigurable workstations and multi-functional equipment, the design-production relationship might be varied product by product. Hence, it is set manually here. For example, a multi-"functional bridge" instance can be used to produce a "timber panel" feature and produce an "opening" feature.

4.5. Rule base

The rule base stores expert knowledge for manufacturability analysis based on design and manufacturing knowledge. Designers can get feedback from collaborated manufacturers during the design phase. From the designer perspective, it ensures that the design complies with

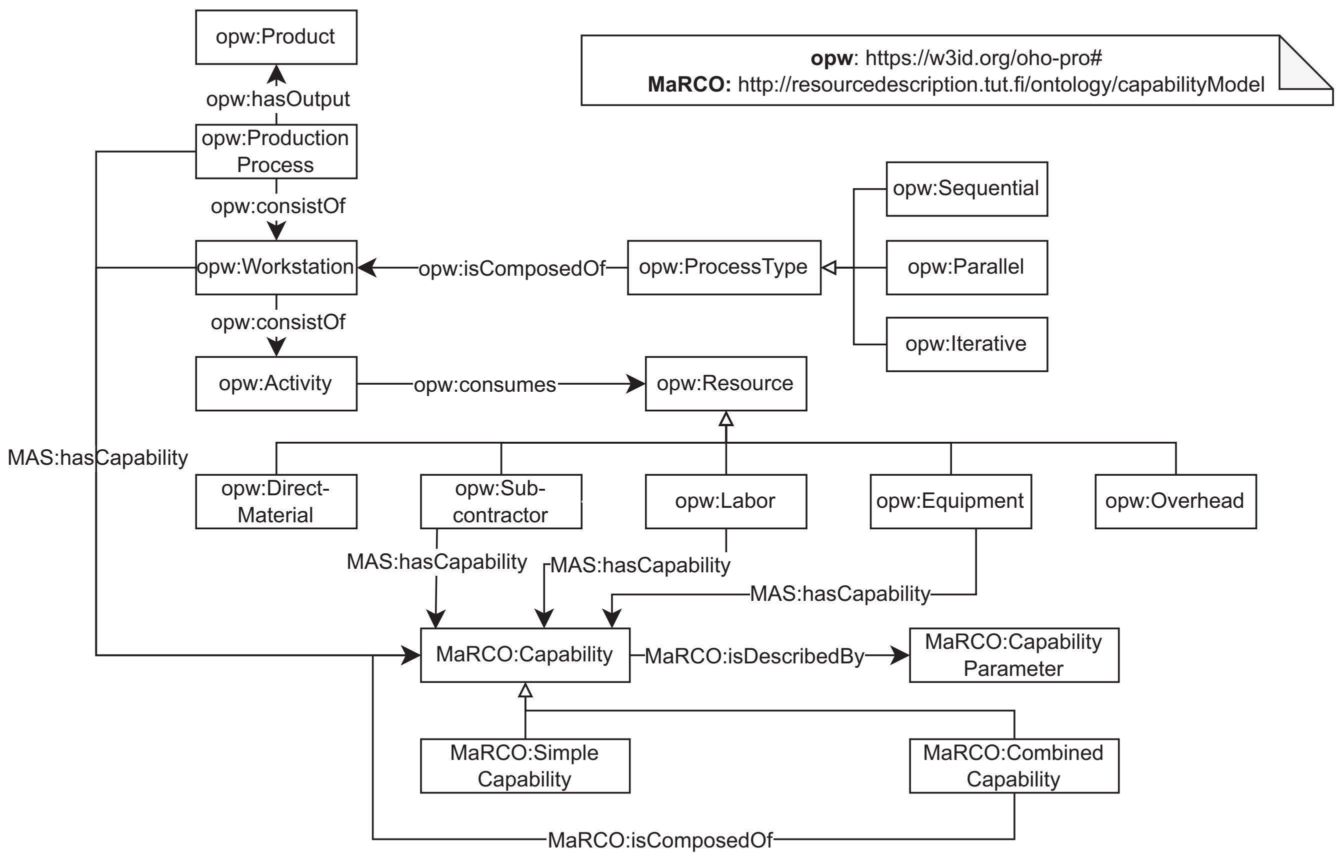

Fig. 5. Manufacturing ontology.

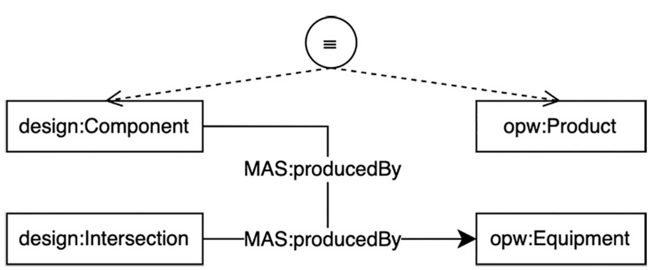

Fig. 6. Mappings between the design ontology and the manufacturing ontology

the rules can be manufactured without errors and economically with the available production systems. From the manufacturer perspective, the rules assist the production planning and the quality check. In this research, we collect rules from contracts, design documents, manufacturers' experience, production handbooks, and machine brochures. The rules include size constraints, lead time constraints, resource constraints and assembly constraints. The design freedom is defined within the technical capability of the available facilities at the parameter level through the constraints. The parameter values can be different project by project, so as to accommodate various project settings. This section describes how these rules are defined and modelled conceptually. The detailed examples of those constraints are in Section 5.

Size constraints indicate a range within which the geometrical features of the product can be manufactured by the chosen equipment. The constraints are modelled in four steps:

1. The value of the dimension of the specified component is accessed by querying the ShapeAndSizeDefinition class, which is associated with the focus product via "hasGeometry".
2. The manufacturing equipment is set for the production of the component via the "producedBy" property.
3. The range of the allowable size is gathered from the chosen equipment capability by querying the Capability Parameter.
4. For each pair of the values, namely the designed dimension and the allowable dimension, the shape operator "sh:lessThanOrEquals" is applied, and a validation result is returned.

Lead time constraints stipulate the production time based on the selected production facilities, which should meet the requirement of the delivery, namely lead time. The constraints are modelled in five steps:

1. The total amount of the selected building elements is retrieved by querying the component class.
2. The process is set for the element production via the "producedBy" property.
3. The production capacity is obtained from the Capability Parameter.
4. The estimated production duration is calculated.

Table 4
Design related information.

Panel	Structural Material	Finishing Material	BoxShape	length (mm)	height (mm)	thickness (mm)	quantity	fire-resistance time (hour)	lead time (days)
wall01	CLT-wood	shingle	box01	6400	2522	150	30	2	2

Table 5
Manufacturing related information.

Activity	Equipment	height min (mm)	height max (mm)	length min (mm)	length max (mm)	cycle time (hr/panel)	work hours (hr/day)	material waste index	connection index	available inventory (m^3)
Panel machining	bridge	1200	3800	6000	12,000	0.5	6	1.15	0.35	100

5. For each pair of the values, namely the production time and the user-required lead time, the shape operator above is applied and a validation result is returned.

Resource constraints measure whether the consumed resources for producing the building elements is less than the resources available in storage. Then, the time for material purchase can be saved. The constraints are modelled in four steps:

1. The total amount of the selected building elements, quantified in volume, area, or mass, is retrieved by querying the component class. The component class can be specified by its features, such as the type.
2. The amount of material in the manufacturer's storage is obtained by querying the direct material class.
3. The material used for producing the elements is accessed from the capability of the workstation class. Then, the total amount of the material consumed is calculated by adding the material waste.
4. For each pair of the values, namely the consumed resources and the available resources, the shape constraint operator above is applied and a validation result is returned.

Assembly constraints check whether the manufacturer-specified production details, such as connection types, satisfy the design requirements. The constraints are modelled in four steps:

1. The performance index correlated to the designed component is extracted.
2. The detailing index is queried from the component intersection class.
3. The achieved performance by the selected detailing type is calculated based on empirical knowledge.
4. For each pair of the values, namely the designed performance and the achieved performance, the shape operator above is applied and a validation result is returned.

4.6. Validation

Once the ontology and rules are developed, the validation is done by a task-based CQ-answering approach. The approach is done in three steps [48]: first, to access how the ontology could be used to solve certain tasks based on the designed purpose; second, to answer the competency questions using practical data for instance information of the ontology; third, to illustrate the application scenario by triggering the rule sets. Based on the procedures, we conducted a task-based validation in the following section.

5. Testing MAS for timber panelized project

An industrialized construction project using panelized timber (IC-PT) is used as a test case to evaluate the proposed MAS. The project consists of prefabricated timber panels, that are combined in various configurations to create mass-customized buildings. Each panel is engineered to suit the building profile on the selected site, the layout of the apartment on the floor plan, the material type of façade. While the product concept is standardized, the individual panel configuration can vary from the dimensions, materials, opening types and joint detailing. The design companies need to incorporate timber panels in their design with an aim to produce cost-efficient and ecological living spaces. This requires streamlining and digitalizing the design and planning processes of their construction projects. Since the company does not own a production hall themselves, they rely on feedback about the manufacturability of the kit-of-parts components from the manufacturers. However, manufacturing analysis is often time-consuming and based on an employee's experience. Further, the manufacturers tend to have trouble formulating their feedback. These problems make this project an ideal test case for evaluating the MAS framework proposed in this study. The

```
mas:SizeShape
a sh:NodeShape ;
sh:targetClass design:Component ;
sh:severity sh:Warning ;
sh:sparql [
a sh:SPARQLConstraint ;
sh:message "the size of the element {?length} exceeds
the allowable range {?min_length} - {?max_length}" ;
sh:select """
SELECT DISTINCT $this ?length ?max_length ?min_length
WHERE {
$this design:hasType ?panel .
$this design:hasGeometry ?shape .
$shape design:length ?length .
$this mas:producedBy ?machine .
?machine marco:length_max ?max_length .
?machine marco:length_min ?min_length .
FILTER (?length > ?max_length || ?length < ?min_length) .
}""";
] .
```

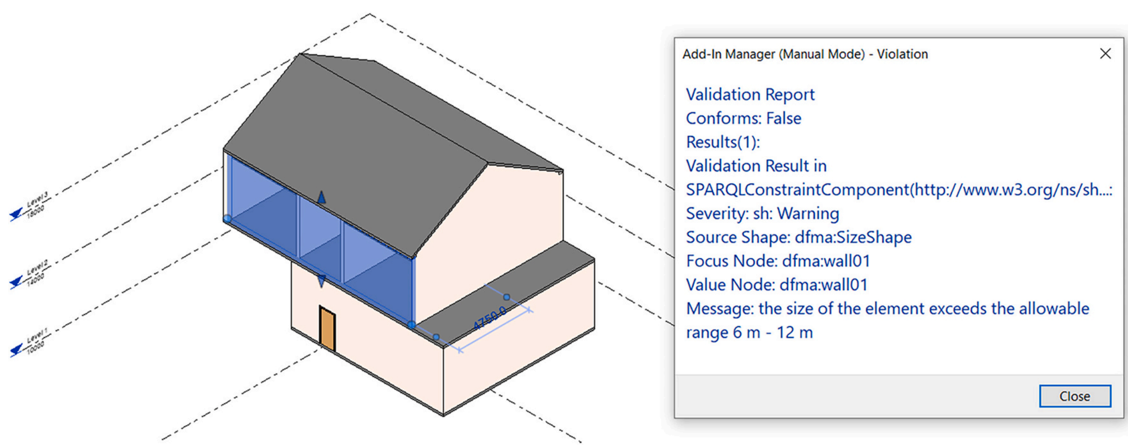

Fig. 7. SHACL size constraint and validation result

application of the proposed MAS will help in automating the manufacturability analysis and provide feedback within a short time.

This section describes the evaluation of MAS in the panelized timber industrial construction project. It consists of three steps. They are 1) Preparation of design and manufacturing related information (Section 5.1), 2) Assessment results of manufacturability analysis (Section 5.2) and 3) Technical framework (Section 5.3).

5.1. Preparation of design and manufacturing related information

This section introduces the data sets that need to be extracted from heterogeneous sources for manufacturability analysis. These include

- Geometry and material description of the building elements from design stage BIM: e.g. length and finishing material types;
- Performance information for building elements from Excel spreadsheets: e.g. fire resistance time, and bill of materials (BOMs);
- Inventory information from manufacturer's MRP systems; e.g. Material availability inventory;
- 2D detailing information from shop drawings in PDF format; e.g. as the connection index;
- Operation information from manufacturer's ERP systems; e.g. the capability of equipment, such as maximum length, and the production cycle time; and
- Contractual relations from the client – manufacturer contract: e.g. lead time requirement.

An example of data set from the design and the manufacturing system is described in Table 4 and Table 5.

5.2. Assessment results of manufacturability analysis

This section describes and gives examples of how constraints used in manufacturability checks are modelled using SHACL.

5.2.1. Size constraints

This constraint checks that the size of designed panels is manufacturable by the factory equipment. Here, we have a sh:NodeShape that targets all instances under the class Component. In the sh:sparql part, we select panel components and query the value of the length of each panel, and the minimum and maximum manufacturing length of the equipment. Finally, we use FILTER operator to return results that the length of the designed panels exceeds the length limitation of the equipment. By a similar approach, we can check the height and the width of the elements. (shown in Fig. 7) Through this example, we evaluate the ontology capability to answer the competency questions 1, 4 and 8.

5.2.2. Lead time constraints

This constraint checks that the production time for the design order meets the clients' lead time requirement. The sh:NodeShape targets at the class Panel. In the sh:sparql part, the quantity of the panels, the lead time are extracted from the panel class, while the cycle time for a single panel and the working hours of the process are queried from the workstation class. Next, the production time is calculated as the quantity

```
mas:LeadtimeShape
a sh:NodeShape ;
sh:targetClass design:Panel ;
sh:property [
sh:severity sh:Warning ;
sh:sparql [
a sh:SPARQLConstraint ;
sh:message "the production time exceeds the lead time target" ;
sh:select """
SELECT  $this ?production_time ?lead_time
WHERE {
$this design:quantity ?quantity .
$this design:lead_time ?lead_time .
$this mas:producedBy ?station .
?station mas:cycle_time ?time .
?station mas:working_hour ?working .
BIND (?quantity * ?time/?working AS ?production_time) .
FILTER(?production_time>=?lead_time) .
}"""];
] .
```

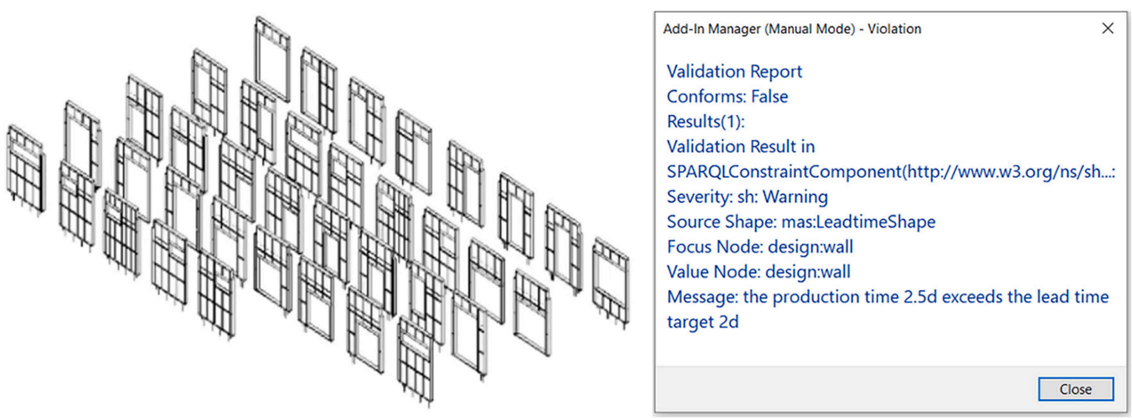

Fig. 8. SHACL lead time constraint and validation result

of the panels multiple the cycle time and divide the factory's daily working hours. Finally, we use FILTER operator to return results that the production time exceeds the lead time. (shown in Fig. 8) Through this example, we evaluate the ontology capability to answer competency questions 2 and 7.

5.2.3. *Resource constraints*

This constraint checks that the material inventory available is sufficient for the design order. Here, we have a sh:NodeShape that targets the Panel class. In the sh:sparql part, the amount of the available material is queried from the production process. The consumed material is calculated by multiplying the volume of the element with the quantity with the waste index, where the waste index is an estimation of the total material used by considering a certain proportion of material as waste. Finally, we use FILTER operator to return results that the consumed material is more than the available material. (shown in Fig. 9) Through this example, we evaluate the ontology capability to answer competency questions 3 and 6.

5.2.4. *Assembly constraints*

This constraint checks that the connection type between panels specified by the manufacturer satisfies the fire resistance requirement. The sh:NodeShape targets at the Component class. In the sh:sparql part, the panels are first selected and the thickness of the panel, the fire resistance time, as well as the connection index of the connection type are retrieved respectively. Next, the achieved fire resistance is calculated using the methodology from the CLT handbook, where the fire resistance time equals the panel thickness (in inch) dividing the nominal charring rate (1.5 in./h) and multiplying the connection index. Finally, we use FILTER operator to return results that the achieved fire duration is shorter than the designed performance. (shown in Fig. 10) Through this example, we evaluate the ontology capability to answer competency questions 1 and 5.

5.3. *Technical framework of MAS*

The overall architecture for implementing MAS in a timber panelized Industrial Construction project is shown in Fig. 11. The MAS is designed as a python client application residing in the designer's application suite which accesses the design from both designer and manufacturer. Due to the fragmented nature of construction projects, the design data is stored in one server and the manufacturing data in another. To simulate the same, the design data are stored in Autodesk Object Storage Service (OSS) [79] whereas the manufacturing files are stored in Amazon Simple Storage Service (AWS S3) [80] in this test case. Autodesk OSS is a cloud storage solution that allows the design team to organize and share any

```
mas:ResourceShape
a sh:NodeShape ;
sh:targetClass design:Panel ;
sh:severity sh:Warning ;
sh:sparql [
a sh:SPARQLConstraint ;
sh:message "the inventory is not sufficient" ;
sh:select """
SELECT $this ?available_material ?consumed_material
WHERE {
$this design:quantity ?quantity .
$this design:hasGeometry ?shape .
?shape design:length ?length .
?shape design:height ?height .
?shape design:thickness ?thickness .
?this mas:producedBy ?factory .
?factory mas:inventory ?available_material .
BIND(?height*?length*?thickness*?quantity*1.15 AS ?consumed_material).
FILTER (?consumed_material >= ?available_material) .
}"""];
] .
```

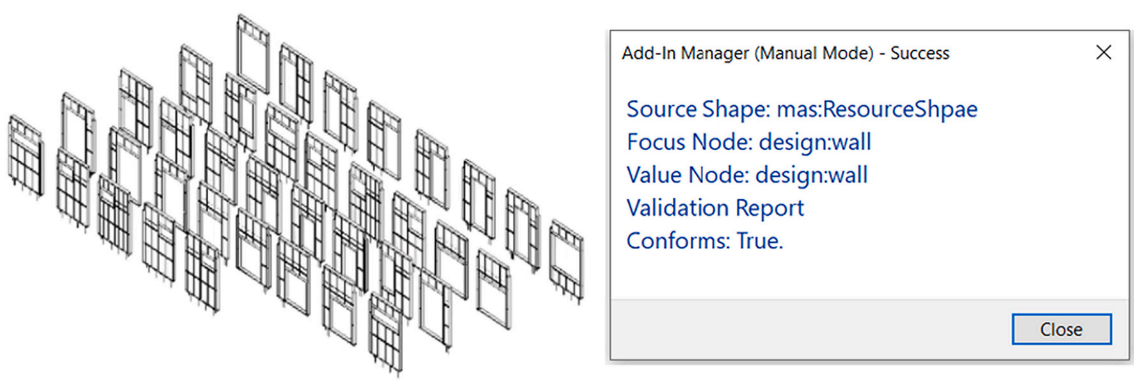

Fig. 9. SHACL resource constraint and validation result

type of design or model data. The stored data can be extracted using Data Management APIs. AWS S3 is a cloud object storage with industry-leading scalability, data availability, security, and performance. The data on S3 can be retrieved via Boto3 [81], a Python SDK for AWS.

For the client application, the developed ontology (Section 4) is first loaded into the backend of the application via Owlready 2.0 [82], a package for manipulating ontologies in Python. The ontology contains the rulesets for enabling the manufacturability checks (further explained in Section 5.3). Then, design and manufacturing data are converted to RDF triples by RDFLib [83], and inserted into the loaded ontology using the "WITH <ontology IRI> INSERT …" syntax in SPARQL. Once ontology, design data and manufacturer data are loaded into the client application, it is ready for the manufacturability check as the ontology connects design and manufacturer information. For the manufacturability check using SHACL, a python module "pySHACL" [84] is applied. to validate the RDF graphs (ontology+ design data+ manufacturer data) against defined SHACL rules. Once the manufacturability-check is complete, the validation results "True/False", together with the manufacturing feedback are returned as outputs back to the user using the SHACL property "sh:message".

6. Discussion

In the construction industry, the designers are often not aware of the potential manufacturing constraints and may create a design that is either costly or non-manufacturable [85]. The current industry structure is loosely-coupled to allow for craft worker interpretation of design intent [86]. However, the use of more precise fabrication methods for industrialized construction requires changes in the relationship between design and production. Therefore, information integration is the first step towards design for manufacturing.

This research tries to provide a solution using ontology. According to the well-classified domain knowledge given by Ayinla [36], the developed design ontology can be a unified representation of the industrialized construction with related entities and relations. On the other hand, the manufacturing ontology models a flexible and reconfigurable production system with its capability at different granularities (process, workstation, equipment, subcontractor, and labor). The mapping between the design ontology and the manufacturing ontology correlates the customized design with the available production capabilities. Built upon that, the detailed manufacturing constraints can be formulated and brought about at the design stage, so as to support designers decision-making and avoid inefficient feedback loop between designers and manufacturers.

In the traditional design to manufacturing workflow, designers initially provide manufacturers with documentation of design intent, which seldom can be used for fabrication. The manufacturers next provide feedback to the designers informing them of certain manufacturing constraints to improve the manufacturability of the design, and such iterations continue until a consensus of a final fabrication-ready design is reached. However, using the proposed MAS described in Section 5, this unnecessary feedback loop could be eliminated. For example, if the design is non-manufacturable due to a size constraint, the MAS would provide real-time feedback to the designers,

```
mas:AssemblyShape
a sh:NodeShape ;
sh:targetClass design:Component ;
sh:severity sh:Warning ;
sh:sparql [
a sh:SPARQLConstraint ;
sh:message "the design performance is not
satisfied by the engineered detailing" ;
sh:select """
SELECT  $this ?fire_duration ?achieved
WHERE {
$this design:hasType ?panel .
$this design:hasGeometry ?shape .
?shape design:thickness ?thickness .
$this design:fire_resistance_time ?fire_duration .
?this design:forms design:connection .
?connection design:connection_index ?index .
BIND (?thickness*0.04/1.5*?index AS ?achieved) .
FILTER (?fire_duration >= ?achieved) .
}""";
] .
```

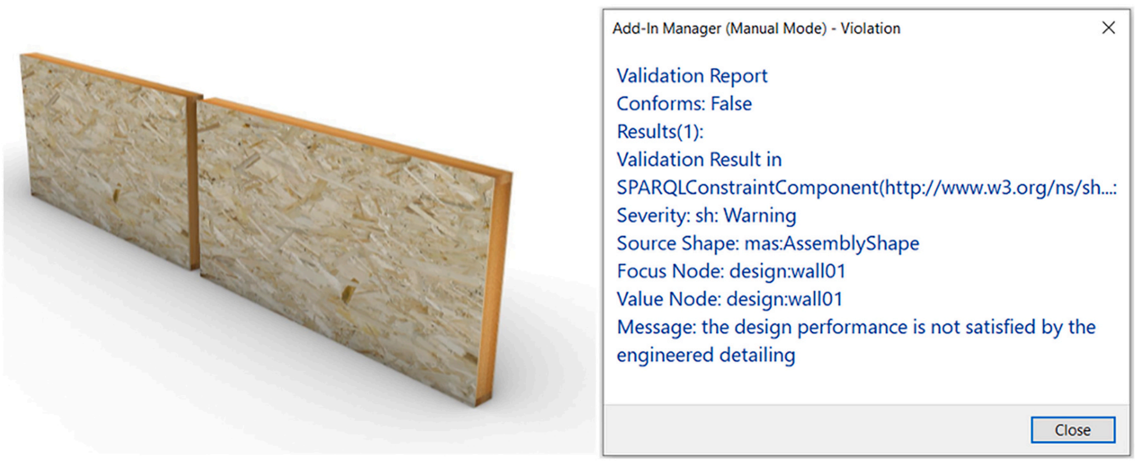

Fig. 10. SHACL assembly constraint and validation result

as shown in Section 5.2.1. Similarly, if the design consumes the material resource that exceeds the manufacturers' capability, the MAS system would provide real-time feedback to the designers using the constraint defined in Section 5.2.3, leading them to change the design. The results shown in Section 5 demonstrate how the developed MAS reduces the number of design iterations.

The research presented is an important first step towards automated fabrication-aware design. Although the MAS demonstrates effective automated checking of manufacturability issues, future steps by academic researchers and practitioners are needed to implement in industrialized construction practice. First, designers should provide digital deliverables in which product information is accessible. IFC files that are the most common deliverables nowadays require a high level of knowledge about the IFC hierarchy and about data mapping mechanisms [87]. Other simple and human-readable formats, such as JSON, can be studied to support the data exchange process for AEC. Second, manufacturers should generalize implicit knowledge from handbooks, catalogues, experiences and brochures. Unlike design, there are no off-the-shelf regulations to support a manufacturability check. Previous studies on DfMA provides a list of guidelines that can support manufacturing rules generation [17]. In this study, four types of general rules are created as an example. Further study on manufacturing rules at different granularities (process, workstation, equipment, subcontractor, and labor) is important for a more comprehensive manufacturability analysis.

The proposed manufacturability analysis system has some limitations. First, we only evaluate the ontology with the test case during the rule validation process. The use of case-based evaluation is twofold, to assess how the ontology can be applied to check the manufacturability of the design in an industrialized context and to demonstrate the capability in integrating segmented data sources. However, due to the narrow scope of the test case, a more comprehensive evaluation approach is needed. This can be done by criteria-based evaluation, expert workshops and answering competency questions [88]. Second, this study defines the boundary conditions for the manufacturability check in terms of the material resource, the product size, the engineering specification, and the production time. Other types of boundary conditions might be included, such as cost and logistic factors. For example, the weight index is crucial for the transportation and crane loading process. For solving this problem, the generic categories captured by the developed ontology can be extended with domain concepts and properties.

Other limitations are more common and widely mentioned in ontology-based research [48,89]. The solution for those limitations might need advanced information technology and intensive industrial collaboration. Firstly, the process of data conversion from design file to ontology is semi-automated. Although data can be extracted from IFC

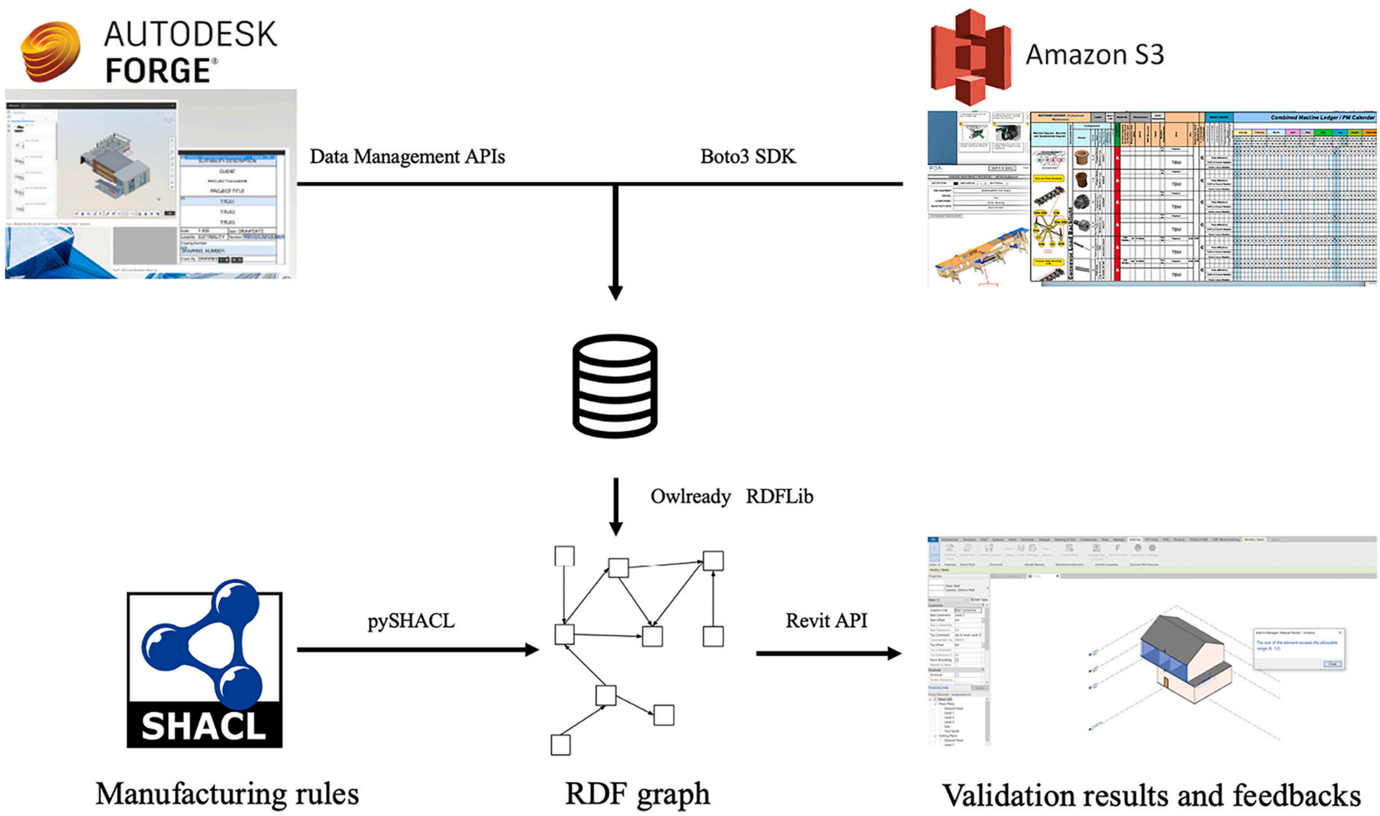

Fig. 11. Technical framework of MAS.

file automatically, the mapping process is still done manually, as the software does not support the ontology. Secondly, manual development of the ontology, and associated rules based on existing hierarchy and models is applied in this study. Creating such a domain ontology is time-consuming and error-prone. However, there are no reliable methods to automatically convert unstructured text to formal ontologies and rules. Recent studies on ICTs, such as machine learning, natural language processing (NLP) and text mining can provide possible solutions. Thirdly, the test case does not cover all defined concepts and rules of the knowledge base. The reason is that the design data is collected from a specific design project and the manufacturing data is restricted within the available production systems of the studied firm. From the literature review, the ontology considers a broader scope of design features and manufacturing techniques, which can support a more comprehensive manufacturability analysis.

7. Conclusions

The study proposes a design and manufacturing ontology network for industrialized construction to facilitate manufacturability analysis. The ontology is able to integrate product features from design files and production capabilities from manufacturer's systems. The manufacturing rules are retrieved from contracts, design documents, manufacturers' experience, production handbooks, and machine brochures and coded in SHACL. Finally, by validating a design against the manufacturing rules, the developed MAS prototype is able to assess whether the design is manufacturable or not. If it is possible to manufacture, the prototype also evaluates the production efficiency, such as production time and resource consumption. As a result, the system could reduce unnecessary feedback loops between designers and manufacturers and enable savings for cost and time.

This paper contributes to the emerging research trajectory on three aspects. Firstly, both design and manufacturing ontology are extended within the digital construction context. The design ontology is enriched with common features categorized for industrialized building systems. The manufacturing ontology is supplemented with a capability model to support complex domain tasks, such as manufacturability analysis. Secondly, the ontology network can be used as a formal knowledge reference to integrate heterogeneous information from designers and manufacturers. The information exchange can be well formulated in the semantic query language. Thirdly, built upon the ontology network, the rule base provides a set of constraints that can be used to support the manufacturing check at the parameter level. The check can be triggered simultaneously in the design software to offer real-time feedback. It is an important improvement upon the DfMA guideline-based design towards an automated fabrication-aware design.

The research presented in this paper is the first step. To exploit the full potential of the manufacturability analysis, further research is needed to extend it. Researchers working on DFMA can use this work as a basis to encode the DFMA guidelines into constraints and evaluate the design quantitatively. Researchers working on digital fabrication can extend the ontology to model the capabilities of the robotic workflow and detect the violations related to processes, equipment, and labor. Researchers working on integrated project delivery can extend the rule base to cater to the constraints from other suppliers and on-site crews and test its effectiveness in reducing the design rework and production wastes. Research working on CAD/BIM can extend the technical framework of MAS to integrate ERP and MRP systems. Such future research can build upon this work and take the next step towards automated fabrication-aware design.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

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