Ontology-Based Cloud Manufacturing Framework in Industrialized Construction

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Abstract

Cloud manufacturing is an emerging manufacturing paradigm to enable rapid production for mass customization. Industrialized construction shares a similar production environment with manufacturing products, so it has a great potential to utilize the paradigm. Previous studies never examined cloud manufacturing in the construction context. This work takes the industrial difference into account and proposes a cloud manufacturing framework by ontology modeling. Three ontologies, including ifcOWL, OPW, and OWL-S, are linked to support the design to the manufacturing process of a building project. The framework benefits the design data and manufacturing data integration, and enhances the resource sharing by semantic web service.

Keywords

cloud manufacturing, ontology, design for manufacturing and assembly, BIM

1. Introduction

Cloud manufacturing is a new manufacturing paradigm, driven by the trend of mass customization, globalization, digitalization in the industry 4.0 era. The paradigm is built upon emerging technologies, such as service-oriented architecture (SOA), Internet of Things (IoT), and artificial intelligence (AI) [1]. Similar to cloud computing sharing computing services – servers, storage, databases, software, cloud manufacturing provides on-demand manufacturing services – machines, materials, analytic tools, experimentation, to customers via the Internet, to facilitate the distributed resource utilization and the cross-enterprise collaboration [2]. Although cloud manufacturing has been researched in the context of the manufacturing industry since 2009 [3], there are few studies on adapting the paradigm to the construction industry.

Industrialized construction follows a design-manufacturing-assembly approach to deliver new buildings comprised of kit-of-parts, ranging from linear structural elements (e.g., columns and beams), planar elements (e.g., panels and trusses), to volumetric units (e.g., bathroom pods). The kit-of-parts share a similar production environment with manufacturing products. However, differences also exist in the aspects of product characteristics, supply chain models and supporting hardware and software. For example, one difference is the domain knowledge

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FOMI 2021: 11th International Workshop on Formal Ontologies meet Industry, held at JOWO 2021: Episode VII The Bolzano Summer of Knowledge, September 11–18, 2021, Bolzano, Italy

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used to design a product. Therefore, it requires a novel model to support cloud manufacturing in the construction industry.

Ontology is a formal representation of domain knowledge, supporting knowledge sharing in distributed enterprise organizations. Recently, well-designed ontology-based models are applied to information modeling in cloud manufacturing [4, 5, 6, 7]. However, none of these models is built upon existing construction knowledge. Besides, most models only address the manufacturing concepts without bridging the gap between design and manufacturing. For construction products, building information models (BIM) are widely used on the design stage. BIM is a shared digital representation of a built asset to facilitate design, construction and operation processes. Considering the fact that many design semantics are available in the BIMs, ontology can map this semantic knowledge to the manufacturing domain, aiming at design for manufacturing and assembly (DfMA).

In this paper, we present an ontology-based framework for cloud manufacturing development. The framework is developed based on the off-site production workflow ontology (OPW), which represents offsite construction domain terminology and relationships. The ontology is linked to the ifcOWL ontology to capture design details defined in BIM applications, such as Revit. Next, to transform manufacturing resources and manufacturing capabilities into manufacturing services, which can be used for small-batch customized design, those sources and capabilities are virtualized as web services and managed in a unified way by OWL-S framework [8]. The applications, such as service search and allocation, are built upon the developed ontology.

The rest of the paper is organized as follows: Section 2 introduces the state-of-the-art related to ontology-based cloud manufacturing. Section 3 presents our proposed approach. Section 4 discusses the limitation of the proposed framework. Finally, section 5 concludes our work and introduces the future works.

2. Related Work

In contrast to other sectors, the construction industry is slower in utilizing ontologies in practice and research. Existing ontologies established in the construction industry include: ifcOWL [9], Building Topology Ontology (BTO) [10], and Building Product Ontology (BPO) [11] and Offsite Manufacturing Production Workflow ontology (OPW). The applications of these ontologies are focused on knowledge management, BIM, cost management, quality checking, and safety analysis [12]. Considering that the first three ontologies lack the DfMA concepts for offsite manufacturing [13], we prioritize the OPW ontology for cloud manufacturing development. Therefore, this section firstly reviews the ontologies for DfMA. Then, the operation model of cloud manufacturing is introduced. In the end, how ontology modeling is applied to cloud manufacturing is analyzed.

2.1. Ontologies for DfMA

Design for manufacturing and assembly (DfMA) is first developed for product design, aiming for reducing production time and cost by evaluating manufacturing and assembly performance during design phase. Related work on ontologies for DfMA is still under development. Many researchers developed their own DfMA ontologies for task-specific domains. An et al define a product ontology for wood frame intersections. Based on the ontology, feasible manufacturing operations can be retrieved [14]. Favi et al. use an ontology to formalize the welding knowledge. The appropriate welding methods are derived according to the geometric features [15]. By comparison, Ayinla et al. established a comprehensive off-site production workflow ontology (OPW), which models the production process from material delivery to transportation of products to the site. Our work is built upon the OPW ontology, aiming at providing manufacturing services for customized kit-of-parts.

2.2. Operation Model of Cloud Manufacturing

A cloud manufacturing system consists of main stakeholders, namely service consumers, service providers and service operators [1].

- Consumers submit design files to the cloud manufacturing platform and receive manufacturing quotes and service recommendations from the available manufactures registered on the platform. In the construction industry, service consumers include general contractors, design firms, and individual consumers;
- Providers are able to publish their available manufacturing resources on the cloud platform and receive the design orders assigned by the platform. Service providers are construction companies who own the factories and manufacturing equipment;
- Operators refer to the agents on the cloud manufacturing platform who manage the design orders from the service consumers and manufacturing resource from service providers;

Typical cloud manufacturing services include soft manufacturing resource, hard manufacturing resource, service resource, manufacturing capacities and other resource [4]. This work focuses on hard manufacturing resource, such as machining centers. Due to the fluctuation of the housing market, manufacturers are motivated to increase the resource utilization and avoid resource waste.

2.3. Ontology-based Cloud Manufacturing

The study of ontology in cloud manufacturing is done in two aspects: manufacturing service modeling for service providers [4, 6, 16, 17] and manufacturing task modeling for service consumers [7, 18]. Table 1 summarizes the main concepts in the ontologies. The basic information, including service/task name, type, location., are used for identification. The functional information, including input/output, precondition, are used for task-service matching. The quality of service (QoS), such as cost, time limit, reliability., are decision-making factors for service allocation. The status manifests the load condition and fault condition, which are important for service scheduling and monitoring.

2.4. Cloud Manufacturing System Framework

The development of a cloud manufacturing framework has attracted considerable attention from academia and industry. Many scholars use the multi-layer construction method to establish the system. Ming et al. analyzed the similarities among 66 articles and identified six main

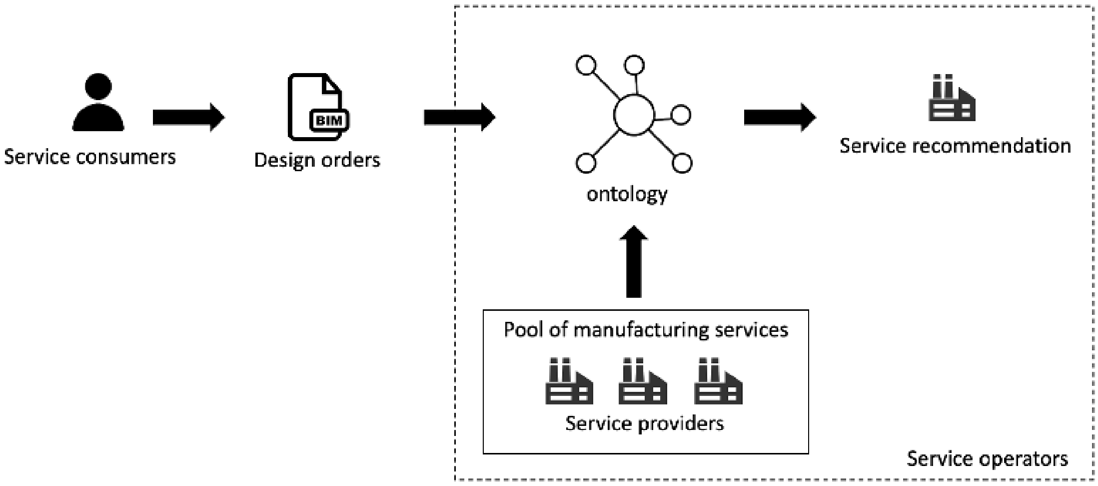


Figure 1: Operation model of cloud manufacturing

Table 1
Main concepts of information model of manufacturing service

Target	Main Concepts
General manufacturing service [4]	Basic info, Functional info, QoS, status, Capacity
General manufacturing service [16]	Resources, Services, Owners, Knowledge, Transaction, Status
Manufacturing equipment [6]	Basic info, Functional info, Process
Manufacturing equipment [17]	Basic info, Functional info, Status, QoS
Manufacturing task [7]	Basic information, Sub-tasks, Relations, Demand, Status
Manufacturing task [18]	Task information, Sub-tasks, Relations

layers, including application layer, resource layer, core service layer, resource virtualization layer, application interface layer, and basic supporting layer [19]. However, they did not explore the role of ontology in the system. The ontology acts as a role of transferring domain knowledge, which is crucial for adapting the framework in the construction industry. In this research, an ontology layer is set on the back end to support the service search and allocation. The interface design, as well as the use of other supporting techniques, is ignored in this research.

3. Proposed Approach

In this section, the framework of cloud manufacturing for industrialized construction is presented. The framework contains three layers: (1) user layer; (2) application layer; (3) ontology layer. The architecture of the proposed framework is illustrated in Figure 2. The user layer reads data input. There are two types of data inputs: design files and manufacturing resource profiles. The data model will be created in the ontology layer and instantiated by the input. Then, Shapes Constraint Language (SHACL) rules are used for data validation. Next, semantic

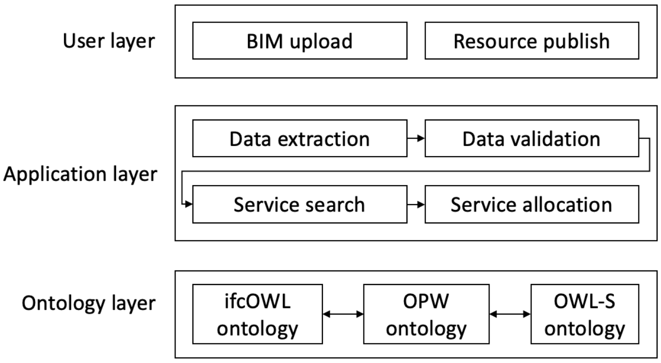


Figure 2: The architecture of ontology-based cloud manufacturing

matching will be performed for service search. In the end, service allocation is implemented to return service recommendations for users.

3.1. User layer

3.1.1. Building Information Model (BIM)

The user input is an industrialized construction project modeled in BIM applications. Revit is a widely used BIM tool for product modeling. 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 and further drives the service search. To achieve interoperability between various BIM applications, Industry Foundation Classes (IFC), a neutral, non-proprietary data model is required. An example of timber panels modeled in Revit is shown in Figure 3.

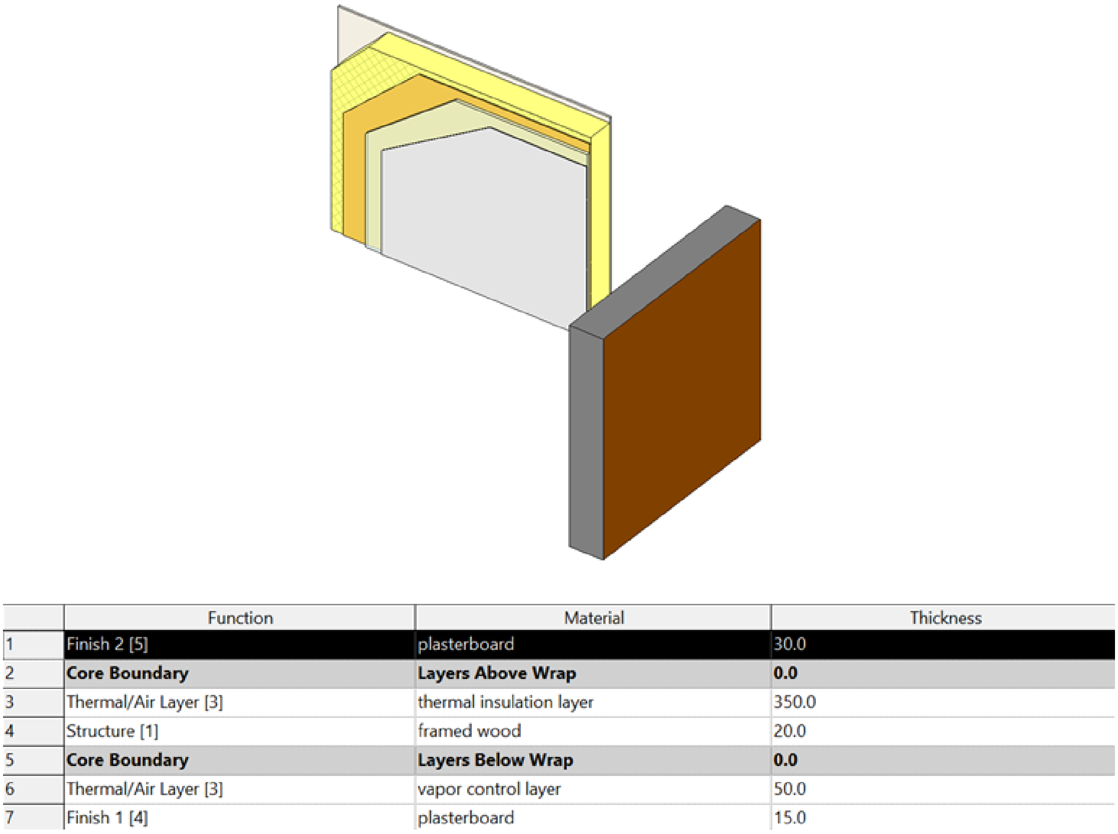
3.1.2. Manufacturing Service Modeling

For industrialized construction, the manufacturing service consists of detailed design development, production, off/on-site assembly, and delivery. The granularity of a manufacturing service is dependent on project itself. A finer granularity can refer to a production activity, such as panel framing. A composite service can fulfill an value-added task. From the previous review, four main categories are used to model a service, namely basic information, functional information, QoS and status. In detail, Table 2 shows some properties for each category. An example of panel assembly service is given in Table 3.

3.2. Ontology Layer

3.2.1. IfcOWL Ontology

Each IFC data model is represented as a schema in the EXPRESS data specification language defined in ISO 10303-11:2004. Since the IfcOWL is automatically generated from the EXPRESS schema using the “IFC-to-RDF" converter [9], it maintains almost the same information as



	Function	Material	Thickness
1	Finish 2 [5]	plasterboard	30.0
2	**Core Boundary**	**Layers Above Wrap**	**0.0**
3	Thermal/Air Layer [3]	thermal insulation layer	350.0
4	Structure [1]	framed wood	20.0
5	**Core Boundary**	**Layers Below Wrap**	**0.0**
6	Thermal/Air Layer [3]	vapor control layer	50.0
7	Finish 1 [4]	plasterboard	15.0

Figure 3: An example of timber panels modeled in Revit

Table 2
Service modeling

Category	Property
Basic info	Service category, Service provider
Functional info	Input, Output, Limitation
Quality of service (QoS)	Unit cost, Production rate
Status	Idle / Running

defined in BIM applications. The ontology contains general concepts of building components, such as “IfcWall", and their properties, such as “IfcRectangleProfileDef" for a rectangular geometry and “IfcMaterial" for building material. Acting as a common knowledge base, IfcOWL is used in the framework to identify ambiguous information defined in BIM.

Table 3
An example of panel assembly service

Category	Material	Cost	Input	Output	Status
Panel assembly	Lumber	\$100/sq	IFC file	Wall	Running

3.2.2. OPW Ontology

Due to the lack of DfMA concepts for industrialized construction, the design information in ifcOWL cannot be directly used for the manufacturing domain. IfcOWL does not contain descriptions on manufacturing resources and production processes. To bridge the design and manufacturing domain, the OPW ontology is aimed to associate the product components with production approaches and required resources. In the OPW ontology, there are eight major classes, including building, product, resources, activity, process type, workstation, production process and factory production method. Besides, some key properties are defined in the ontology, such as “isA", “hasComponentPart", “consumes", “consistOf". The ontology enables practitioners in industrialized construction to formalize the product description and production planning. Take a panel production as an example, OPW specifies the sequential production activities, and required labor, material, equipment and overhead.

3.2.3. OWL-S Ontology

Semantic web service (SWS) technology is used to describe concepts of manufacturing services on the one hand, and relationships to the OPW ontology on the other hand. OWL-S provides a standard specification approach for service definition, execution and monitoring. The description of a service via OWL-S contains four conceptual areas: the process, the service, the profile and the grounding model [8]. In this work, the profile model is mainly used, as it contains a set of concepts and properties relating to a service definition. Specifically, the basic information of a service, such as service name and service provider, can be defined in the profile model as “serviceName” and “contactInformation”. The functional information of a service, including parameters, inputs, outputs, preconditions, and results, can be defined and related to a service class via a set of properties in the model, such as “hasInput” and “hasParameter”.

3.2.4. Ontology Alignment

The three fundamental ontologies mentioned above act as an integral to support the information modeling of cloud manufacturing. First, the ifcOWL supports the preliminary design analysis from the user aspect. Second, the OWL-S describes the manufacturing service from the manufacturer aspect. Finally, the OPW ontology connects the design information to manufacturing information by specifying the product structures and corresponding production processes. The "IfcElement" class in IfcOWL is connected to "BuildingElement" class in OPW, while "ServiceCategory" class in OWL-S is connected to "Production Process" class in OPW. The entire architecture of the ontology for cloud manufacturing is shown in Figure 4.

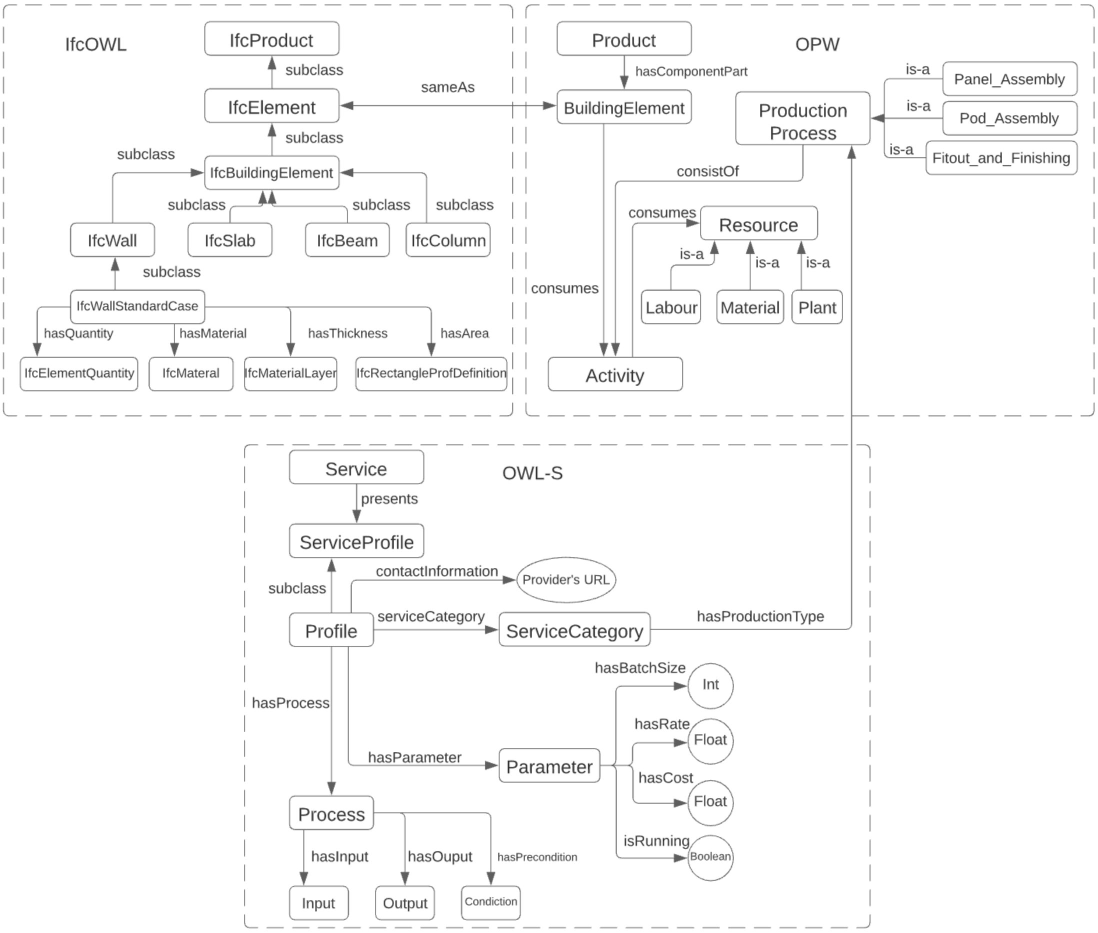


Figure 4: The structure of ontology for cloud manufacturing

3.3. Application Layer

3.3.1. Data Extraction

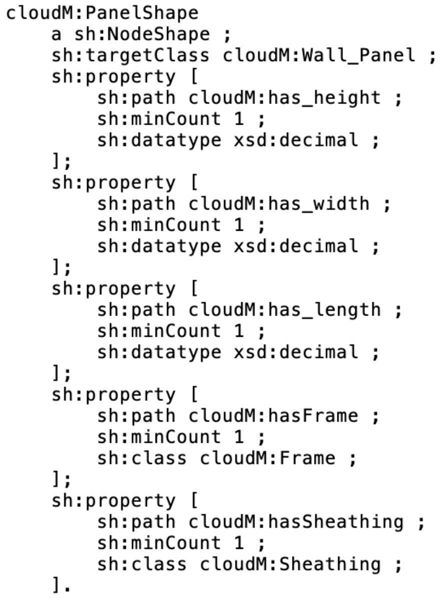
According to IFC standard, the design parameters of a BIM object are defined as IFC entities. To support manufacturing analysis, element types, shapes, dimensions, and materials are of great importance and extracted from the IFC file. Table 4 shows the relationship between the extracted parameters and the IFC entities. The data extraction is done by IfcOpenShell, an open-source software library that helps developers to work with IFC file format.

3.3.2. Data Validation

The Level of Development (LOD) specification, developed by America Institute of Architects (AIA) articulates the characteristics of the BIM models at various stages in the design and construction process. For example, a timber exterior wall at LOD 200 should be modeled as an

Table 4
Relationship between IFC entities and design parameters

IFC entity	Design parameter
ifcMaterial	Building material
ifcMaterialLayer	Layer thickness
ifcRectangleProfileDef	Length, Width
ifcExtrudedAreaSolid	Height



```
cloudM:PanelShape
    a sh:NodeShape ;
    sh:targetClass cloudM:Wall_Panel ;
    sh:property [
        sh:path cloudM:has_height ;
        sh:minCount 1 ;
        sh:datatype xsd:decimal ;
    ];
    sh:property [
        sh:path cloudM:has_width ;
        sh:minCount 1 ;
        sh:datatype xsd:decimal ;
    ];
    sh:property [
        sh:path cloudM:has_length ;
        sh:minCount 1 ;
        sh:datatype xsd:decimal ;
    ];
    sh:property [
        sh:path cloudM:hasFrame ;
        sh:minCount 1 ;
        sh:class cloudM:Frame ;
    ];
    sh:property [
        sh:path cloudM:hasSheathing ;
        sh:minCount 1 ;
        sh:class cloudM:Sheathing ;
    ].
```

Figure 5: An example of SHACL rule for data validation

object with layouts and locations, layers of materials, as well as approximate thickness [20]. The LOD specification is encoded as SHACL rules to check the necessary data entries and required data types from consumers. Figure 5 displays a SHACL rule to check the wall entry with geometric parameters and necessary structures.

3.3.3. Service Search

Once the ontology is instantiated by user inputs representing a product order and various manufacturing resources, service search can be conducted by input/output matching [21]. The matching algorithm consists of three steps: elimination, similarity measurement, and aggregation. In the context of cloud manufacturing, the elimination stage is to narrow down the candidates for matching to the service classes and sub-classes. Additionally, the services which have a running status are also eliminated. Then, the similarity of concepts and properties is measured respectively. For example, material and geometry can be set as comparing factors. In the end, the conceptual similarity and property similarity are aggregated as a weighted average.

3.3.4. Service Allocation

The objective of this step is to select manufacturing services and allocate workloads to them so that the design order can be fulfilled optimally. We model resource allocation as a constrained multi-objective optimization. The manufacturing time and cost are set as objectives of the optimization. Other objectives, such as distance, can also be used. Some assumptions are made in advance: (1) one service can only be assigned to one order at a time. (2) the workloads designated to each service should be multiples of the minimum batch size. (3) all services are available at the initial stage. (4) When an order is assigned to multiple manufacturers, the manufacturing time is calculated as the maximum production time among them.

In detail, the manufacturing time is calculated as:

$$T = max(\frac{Workload_1}{Eff(S_1)}, \frac{Workload_2}{Eff(S_2)}, ..., \frac{Workload_n}{Eff(S_n)}) \tag{1}$$

where $Workload_i$ the workload allocated to service i. $Eff(\cdot)$ returns the productivity rate of the service i. The sum of all workloads should equal the total quantity of the order (Total), shown as below:

$$\sum_{i=1}^{n} Workload_i = Total \tag{2}$$

The manufacturing cost is calculated as:

$$C = \sum_{i=1}^{n} Workload_i \cdot Cost_i \tag{3}$$

where $Cost_i$ is the product unit cost of the service i.

4. Discussion

The proposed framework adapts the cloud manufacturing model in the construction industry. The major differences to the framework in the manufacturing industry lie in two aspects: (1) the domain knowledge is extracted from BIM and mapped to domain ontologies, namely ifcOWL and OPW. (2) the service granularity is the production-line level, which determines the service search and allocation strategy. However, the framework has some limitations:

- There is a lack of real-time resource availability information. The information can be obtained using IOT technology.
- The service-to-task relationship is one-to-one, which is not fit for complex products. A mechanism of service composition is required.
- The service scheduling is lacking in the current framework. Construction products are transported to site and assembled. Therefore, logistics factors, such as transportation, need to be considered in the service scheduling.

5. Conclusion

Similar to the manufacturing industry, the construction market is facing a demand of customization. Clients are eager to participate in the design or manufacturing process. Cloud manufacturing provides clients with on-demand services to their various design requirements. From the manufacturing enterprises perspective, the paradigm enables them to enhance resource utilization by efficient resource sharing and allocation within an enterprise network. However, challenges still exist in many aspects. The main contribution of this work is an ontology-based cloud manufacturing framework for industrialized construction. To model the domain knowledge and manufacturing service, three ontologies, namely ifcOWL, OPW, and OWL-S, are used. The framework is aimed at (1) analyzing the design requirements in BIM, (2) creating a manufacturing service pool, (3) searching competent service by semantic matching, and (4) allocating resources by multi-objective optimization. It is expected that the framework will contribute to cloud manufacturing platform development in future research.

References

[1] Y. Liu, L. Wang, X. V. Wang, X. Xu, L. Zhang, Scheduling in cloud manufacturing: state-of-the-art and research challenges, International Journal of Production Research 57 (2019) 4854–4879.

[2] Y.-K. Lin, C. S. Chong, Fast ga-based project scheduling for computing resources allocation in a cloud manufacturing system, Journal of Intelligent Manufacturing 28 (2017) 1189–1201.

[3] L. Zhang, Y. Luo, F. Tao, B. H. Li, L. Ren, X. Zhang, H. Guo, Y. Cheng, A. Hu, Y. Liu, Cloud manufacturing: a new manufacturing paradigm, Enterprise Information Systems 8 (2014) 167–187.

[4] M. Yuan, K. Deng, W. A. Chaovalitwongse, Manufacturing resource modeling for cloud manufacturing, International Journal of Intelligent Systems 32 (2017) 414–436.

[5] Y. Lu, X. Xu, A semantic web-based framework for service composition in a cloud manufacturing environment, Journal of manufacturing systems 42 (2017) 69–81.

[6] W. Xu, J. Yu, Z. Zhou, Y. Xie, D. T. Pham, C. Ji, Dynamic modeling of manufacturing equipment capability using condition information in cloud manufacturing, Journal of Manufacturing Science and Engineering 137 (2015).

[7] T. Wang, S. Guo, C.-G. Lee, Manufacturing task semantic modeling and description in cloud manufacturing system, The International Journal of Advanced Manufacturing Technology 71 (2014) 2017–2031.

[8] D. Martin, M. Burstein, J. Hobbs, O. Lassila, D. McDermott, S. McIlraith, S. Narayanan, M. Paolucci, B. Parsia, T. Payne, et al., Owl-s: Semantic markup for web services, W3C member submission 22 (2004).

[9] P. Pauwels, W. Terkaj, Express to owl for construction industry: Towards a recommendable and usable ifcowl ontology, Automation in construction 63 (2016) 100–133.

[10] M. H. Rasmussen, M. Lefrançois, G. F. Schneider, P. Pauwels, Bot: The building topology ontology of the w3c linked building data group, Semantic Web (2021) 1–19.

[11] A. Wagner, U. Rüppel, Bpo: the building product ontology for assembled products, in:

Proceedings of the 7th Linked Data in Architecture and Construction workshop (LDAC 2019)', Lisbon, Portugal, 2019, p. 12.

[12] Z. Zhou, Y. M. Goh, L. Shen, Overview and analysis of ontology studies supporting development of the construction industry, Journal of Computing in Civil Engineering 30 (2016) 04016026.

[13] K. Ayinla, E. Vakaj, F. Cheung, A.-R. H. Tawil, A semantic offsite construction digital twin-offsite manufacturing production workflow (opw) ontology, in: Second International Workshop on Semantic Digital Twins, 2021.

[14] S. An, P. Martinez, M. Al-Hussein, R. Ahmad, Bim-based decision support system for automated manufacturability check of wood frame assemblies, Automation in Construction 111 (2020) 103065.

[15] C. Favi, R. Garziera, F. Campi, A rule-based system to promote design for manufacturing and assembly in the development of welded structure: Method and tool proposition, Applied Sciences 11 (2021) 2326.

[16] X. Li, P. Zhuang, C. Yin, A metadata based manufacturing resource ontology modeling in cloud manufacturing systems, Journal of Ambient Intelligence and Humanized Computing 10 (2019) 1039–1047.

[17] N. Liu, X. Li, W. Shen, Multi-granularity resource virtualization and sharing strategies in cloud manufacturing, Journal of Network and Computer Applications 46 (2014) 72–82.

[18] Y. He, Q. L. Zhang, D. C. Hu, Research on ontology-based task modeling in manufacturing grid, in: Applied Mechanics and Materials, volume 63, Trans Tech Publ, 2011, pp. 537–540.

[19] M. K. Lim, W. Xiong, C. Wang, Cloud manufacturing architecture: a critical analysis of its development, characteristics and future agenda to support its adoption, Industrial Management & Data Systems (2021).

[20] J. Bedrick, J. Reinhardt, W. Ikerd, Level of development specification, 2020. URL: https://bimforum.org/lod/.

[21] N. Trokanas, F. Cecelja, T. Raafat, Semantic input/output matching for waste processing in industrial symbiosis, Computers & Chemical Engineering 66 (2014) 259–268.