A BIM-based Ontology Method for Knowledge Representation in Light Gauge Steel Panel Assembly

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Abstract –

Off-site construction offers significant potential to improve productivity and quality in the Architecture, Engineering, and Construction (AEC) industry; however, the practical adoption of Design for Manufacturing and Assembly (DfMA) remains limited due to the lack of explicit integration between product-focused Building Information Modeling (BIM) data and construction process knowledge. While BIM provides detailed geometric representations, assembly logic and process-related information are not explicitly expressed.

This paper proposes a BIM-based ontology framework for semantic knowledge representation in Light Gauge Steel (LGS) panel assembly. A BIM model is developed and exported to Industry Foundation Classes (IFC) format. Relevant component and geometric attributes are selectively extracted using IfcOpenShell and mapped to ontology individuals implemented in a semantic web-based ontology editor that supports formal knowledge modeling and reasoning. Product components and their connection relationships are explicitly modeled, and a connection-based reasoning approach is adopted to infer assembly operations, enabling a clearer linkage between BIM-derived product information and DfMA-oriented process knowledge.

Keywords –

BIM; Ontology; DfMA; Off-Site Construction; Light Gauge Steel

1 Introduction

1.1 Off-Site Construction

Off-Site Construction (OSC) refers to the manufacturing prefabricated building components in a factory or controlled facility, where elements are produced off-site under controlled conditions and then transported to the construction site for final assembly [1]. OSC has gained notable attention for its ability to address several limitations of traditional on-site construction. Major advantages include alleviating skilled labor shortages, shortening project timelines and reducing cost fluctuations, decreasing construction waste, employing environmentally friendly methods, and enhancing quality through controlled factory environments [2]. Although OSC offers several benefits, its adoption presents several challenges. Wuni and Shen [3] identified key obstacles in implementing OSC through literature reviews and categorized them into eight groups, including technical barriers related to design information management and constructability.

1.2 Role of Building Information Modeling (BIM)

Building Information Modeling (BIM) is defined in ISO 19650-1:2018 as the use of a shared digital representation of a built asset to facilitate design, construction and operation processes to form a reliable basis for decisions [4]. In practice, BIM acts as a digital model that supports planning, design, construction, and operation across the entire project lifecycle [5]. Consequently, BIM has proven to enhance decision-making in the architecture, engineering, and construction (AEC) industry by improving work efficiency, reducing modeling rework, and minimizing the repeated collection of building data for different analytical uses.

However, implementing BIM in construction practice still presents several limitations. In particular, extracting construction quantities and procedures from BIM design models requires specialized technical expertise and dedicated tools. This limitation arises because product and process information are typically structured using different schemas and classification systems: BIM product information is commonly represented using the Industry Foundation Classes (IFC) schema, whereas construction process information is usually organized according to material- and method-based classification systems employed in construction planning and management. BIM models represented using the IFC schema describe buildings as assemblies of parametric objects with associated properties, while construction process models are structured as collections of activities organized by these classification systems [6]. This misalignment hampers the direct use of BIM data represented in IFC format for construction planning and execution, emphasizing the need to improve interoperability and integration between product and process information.

1.3 Ontologies for Knowledge Representation

Ontology is a formal approach to knowledge modeling that explicitly defines domain concepts and their relationships. An ontological model consists of classes, properties, and relationships [6][7]. In an ontology, classes represent domain concepts, properties describe their features, and relationships indicate connections among different concepts, enabling a clear and intuitive representation of complex information.

Ontologies enable custom, user-defined relationships among classes. They also allow for the explicit definition of semantic features such as symmetry, transitivity, and inversion of relationships. Based on formal logic, ontologies support automated reasoning and inference, which helps derive new knowledge and identify inconsistencies without requiring all information to be explicitly modeled [7]. Although BIM data represented in IFC can include custom property sets and attributes to describe information structures, the IFC schema itself does not provide ontology-level semantics, such as axioms and logical relationships that enable reasoning. Consequently, IFC can describe data and its structure but cannot infer new knowledge from existing relationships, whereas ontology-based representations can. This capability reduces the amount of data that must be extracted from BIM, as additional information can be inferred from existing data, and it enhances semantic interoperability by providing a shared conceptual framework through which BIM and construction-related information can be consistently integrated.

Ontology-based approaches have been successfully applied in construction to support construction-oriented quantity take-off [5], IFC-based cost modeling [8], automated verification of quality control specifications for off-site manufactured components [9], and formal representation of space and task-related constraints to enhance lean construction planning and execution control in steel fabrication projects [10]. These applications demonstrate the capacity of ontologies to structure domain knowledge and improve interoperability in BIM-driven workflows.

Beyond the construction domain, ontologies have been widely adopted to model complex cyber-physical and intelligent systems, including smart homes, smart farms, smart factories, and other Industry 4.0 environments. In these contexts, ontologies are often combined with machine learning and deep learning techniques to address interoperability challenges, support system monitoring and control, enable digital twin representations, and optimize design and operational parameters for improved performance and reduce cost [11]. This capability is particularly relevant for off-site construction, where design information, manufacturing constraints, and assembly knowledge must be systematically linked to support informed decision-making.

1.4 Design for Manufacturing and Assembly (DfMA)

Design for Manufacturing and Assembly (DfMA) is a structured design approach that incorporates manufacturing and assembly considerations early in the design process to enhance constructability, productivity, and overall project performance. In off-site construction, DfMA plays a vital role by facilitating the design of prefabricated components optimized for factory production and efficient on-site assembly [12]. Past research shows that DfMA helps reduce construction time, cut material waste, improve quality control, and boost coordination between design and construction teams [7][12]. These advantages are especially important for prefabricated systems like Light Gauge Steel (LGS) panel assemblies, where manufacturing efficiency and assembly sequencing directly influence project results.

However, the practical application of DfMA is limited by the absence of a structured and explicit way to represent manufacturability and constructability knowledge during the design process. DfMA-focused decision-making needs detailed information about component geometry, connection types, assembly logic, and construction procedures. Although BIM provides a detailed, product-centered view of building components, it does not explicitly include construction processes or assembly information needed to support DfMA-based analysis fully [6]. Several researchers have highlighted the importance of supplementing BIM with knowledge-based approaches to facilitate the integration of product and process information for prefabricated construction [6][7]. Ontology-based modeling has been recognized as an effective way to formally represent construction knowledge, establish relationships between components and processes, and enable semantic reasoning to support advanced analysis and automation [7].

In this context, this paper proposes a BIM-based ontology framework for the semantic representation of product and process knowledge in Light Gauge Steel (LGS) panel assembly. The proposed framework acts as a crucial step toward enabling DfMA-oriented analysis by connecting BIM-derived product information with construction process knowledge.

2 Related Work

Ontology-based approaches are increasingly used in the AEC industry to improve the semantic representation and use of BIM data for construction-related applications. Current studies show that ontologies can support decision-making, automate validation tasks, and enhance information sharing across different stages of the construction process, as well as exploring the use of ontologies to support Design for Manufacturing and Assembly (DfMA) in prefabricated construction. Qi and Costin introduced a BIM and ontology-based DfMA framework to help verify manufacturability and constructability requirements for prefabricated components [7]. Their work focused on representing stakeholders' needs and constraints with an ontology to enable automated checking and feedback during the design phase. This highlights the role of ontology in formalizing DfMA knowledge and improving design validation for prefabrication. Ontology-based methods have also been applied to construction-focused quantity take-off (QTO). Liu et al. created a semantic approach that combines BIM and ontology to support QTO in the light-frame building industry [5]. Their work shows how ontology can connect BIM product models with construction process information, allowing for accurate quantity extraction through semantic queries. Additionally, ontologies have been used to extend IFC-based representations for cost-related applications. Isatto proposed an IFC ontology to support process-based cost modeling, emphasizing the semantic representation of construction processes and their costs [8]. This work demonstrates the potential of IFC-based ontologies to improve interoperability and enable analysis linking product, process, and cost information.

More recently, ontology-based decision support systems have been developed to assess manufacturability in prefabricated framing systems. An et al. [13] presented a BIM-based decision support system for automated manufacturability checking of wood frame assemblies. Their system integrates BIM data input, geometric feature detection, ontology formulation, and machine eligibility determination to evaluate whether a given frame assembly can be manufactured using specific machinery. This study represents an important step toward linking BIM-derived product information with manufacturing constraints and operational feasibility.

Despite these advances, existing ontology-based approaches in the AEC industry generally focus on specific applications or isolated aspects of the construction process. While Qi and Costin [7] emphasize DfMA requirement validation, Liu et al. [5] concentrate on construction QTO, Isatto [8] addresses cost modeling, and An et al. [13] focus on manufacturability assessment for wood frame systems, these studies tend to treat product, process, and operational knowledge separately. Furthermore, limited attention has been given to explicitly linking BIM-based product geometry, component-level connection types, and the corresponding fabrication or assembly operations required for prefabricated systems. There remains a need for an integrated ontology framework that connects BIM-based product information with DfMA-oriented process knowledge, particularly for Light Gauge Steel (LGS) panel assemblies. This paper addresses this gap by proposing a BIM-based ontology framework that represents LGS components and their connections and associates them with fabrication and assembly operations, establishing a semantic foundation for knowledge representation and reasoning in prefabricated LGS construction.

3 Methodology

3.1 Overall Approach

The proposed framework creates a structured process for integrating BIM with ontology-based knowledge representation to support the semantic modeling of LGS panel assembly. It is an essential step toward DfMA-oriented analysis by systematically linking product information from BIM models with process-related construction knowledge.

The workflow starts with developing a BIM model of an LGS wall panel using Autodesk Revit. This BIM model serves as the main source of digital product information, including structural components like studs, tracks, and fasteners, along with their parametric and geometric properties. Simultaneously, a domain-specific ontology is defined using Protégé to represent relevant product and process knowledge, such as component classifications, geometric attributes, connection types, and assembly operations.

Next, the BIM model is exported from Revit to the IFC format to enable open and standardized data exchange. The IFC file is validated with BIMVision to check schema compliance and ensure accurate representation of building elements. IFC acts as an intermediary schema to facilitate interoperability and automated access to BIM data across various software platforms [2].

Relevant BIM attributes are then extracted from the IFC file using a Python-based workflow with IfcOpenShell. This tool allows computational access to IFC entities and their properties, enabling the extraction of attributes necessary for manufacturability and constructability, such as component identifiers, classifications, and geometric data [13]. The extracted information is organized to support subsequent semantic mapping and reasoning.

After data extraction, the BIM information is mapped to ontology individuals and properties. Each LGS element becomes an individual in the ontology within Protégé, linked to relevant classes and data properties, resulting in an ontology-enhanced BIM that explicitly captures product semantics.

Connections between components are modeled explicitly in the ontology and used as a basis for linking product elements with construction processes [13]. In this approach, connections rather than component types are used to associate assembly operations. By formally representing these connection relationships within the ontology, the proposed framework builds upon the geometric and relational information available in the IFC schema and extends it with semantic constructs that enable process inference. While IFC can represent component geometry and basic relationships, it does not natively support the logical rules required to derive construction operations from connection types. The ontology, therefore, introduces a semantic layer that enhances the expressive capability of IFC to support the DfMA-oriented assembly use case presented in this study.

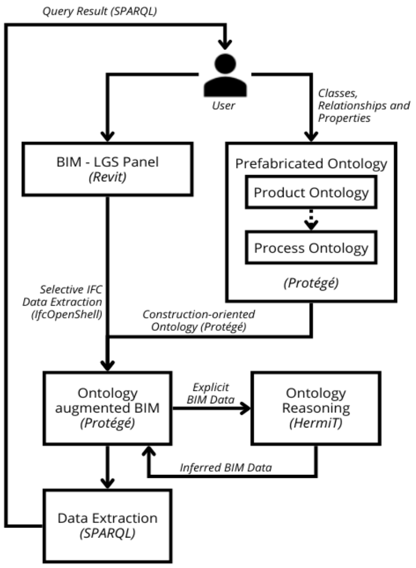

Figure 1. Overview of proposed methodology

Ontology-based reasoning is performed using the HermiT reasoner to ensure logical consistency and to infer implicit knowledge from formally defined class restrictions and object property relationships. Assembly operations are inferred through predefined axioms that associate specific connection types with corresponding construction activities; when the required semantic conditions are satisfied, individuals are automatically classified into the appropriate operation classes. This reasoning process enriches the ontology by generating product–process relationships that are not explicitly represented in the original BIM model. HermiT was selected due to its reliable support for OWL-based classification and instance reasoning, as well as its stable integration with the ontology development environment used in this study.

Finally, the populated and reasoned ontology facilitates semantic querying using the SPARQL Protocol and RDF Query Language to retrieve both explicit and inferred information related to LGS panel assembly. The query results support validation and analysis of product-process relationships and provide a structured semantic representation that can enable future developments in automated assembly planning and BIM-ontology interoperability.

3.2 Ontology Development

The ontology development process adopted in this paper follows established methodologies reported in the literature [12]. The major steps are summarized as follows:

1. <u>Determine the purpose and scope of the ontology.</u>

The purpose of the proposed ontology is to support BIM-based information modeling for DfMA-oriented fabrication. The scope of the ontology includes all information related to light-gauge steel panel components and their associated fabrication and assembly processes.

2. <u>Review existing ontology.</u>

The ontology for manufacturability and constructability of prefabricated components proposed by Qi et al. [12] is used as a reference to extract and structure product-related information from the BIM model. The shared ontology is adapted and simplified to focus on the relevant concepts needed for light gauge steel panel components. Additionally, the ontology-based knowledge modeling approach for frame assemblies proposed by An et al. [13] is reviewed to help guide the representation of relationships between product and process knowledge.

3. <u>Enumerate main classes and build the corresponding class hierarchy.</u>

Product-related knowledge is broken down from the product level to geometry and connection types, while process-related knowledge is shown through operation classes.

4. <u>Construct a machine-readable ontology.</u>

The ontology is implemented using the Protégé platform, where classes, properties, and relationships are formally defined.

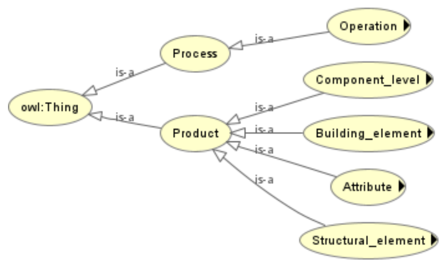

Figure 2. Core ontology classes

3.2.1 Product Ontology

The product ontology describes the physical components and attributes of an LGS panel assembly. Structural elements such as studs, tracks, joists, noggings, and fasteners are modeled as subclasses of a general Structural_element class. Each component is represented as an ontology individual derived from BIM data and linked to relevant geometric and identification attributes. Geometric details, including length, height, width, thickness, and cross-sectional area, are represented through data properties and populated with values extracted from the BIM model.

In addition, component relationships are explicitly modeled through connection types (e.g., perpendicular, lateral, angled), allowing the representation of assembly logic between elements. This structured representation enables product information to be interpreted beyond purely geometric descriptions and establishes a semantic foundation for linking product and process knowledge.

It is important to note that the product ontology presented in this study represents the first iteration of the proposed framework. Further refinement and extension of the ontology structure are planned through expert feedback, validation exercises, and additional case studies to improve coverage, consistency, and applicability to broader prefabricated construction scenarios.

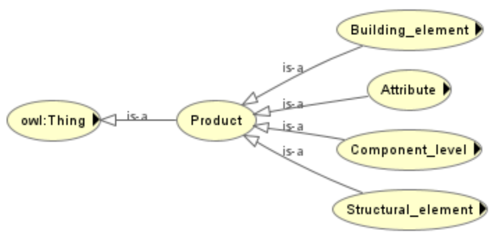

Figure 3. Product class hierarchy.

3.2.2 Process Ontology

The process ontology describes construction and assembly operations related to LGS panel fabrication and installation. Assembly procedures are modeled as subclasses of a general Operation class, representing actions such as positioning, aligning, and screwing.

The proposed framework adopts a connection-based modeling strategy in which assembly operations are inferred from the type of connection established between components, rather than being directly assigned to component categories. Connection types are explicitly represented in the ontology and semantically linked to corresponding fabrication or assembly operations through predefined relationships and logical restrictions.

By structuring process assignment around connection semantics, the framework enables a more precise representation of product–process relationships derived from BIM data. This approach supports DfMA-oriented reasoning by translating geometric and relational information into construction-relevant operations through formal semantic rules.

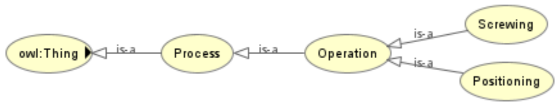

Figure 4. Process class hierarchy.

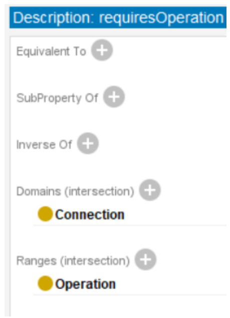

Figure 5. Object Property requiresOperation.

3.3 BIM to Ontology Mapping

The BIM-to-ontology mapping establishes a semantic link between the BIM design model and the ontology-based knowledge representation, following the ontology-driven mapping approach proposed by An et al. [13]. The LGS panel developed in Autodesk Revit is exported to Industry Foundation Classes (IFC) format as an intermediate schema for interoperable exchange. Rather than mapping the full IFC schema, only BIM attributes relevant to prefabrication and assembly are selectively extracted, consistent with the strategy in [13].

IfcOpenShell is employed to parse the IFC file and retrieve component-level data, including identifiers and geometric properties of LGS elements. The product data extraction process is based on IFC entities and property sets that represent structural components and their geometric information. Structural members are primarily retrieved from entities such as *IfcMember*, while geometric representations are accessed through shape information associated with the IFC product representation and processed using ifcopenshell.geom. Element placement and orientation are derived from local placement information, and element attributes are accessed through property sets using IfcOpenShell utilities such as ifcopenshell.util.element.get_psets, including BaseQuantities and Identity Data, which provide dimensional and identification information. The overall implementation is carried out through the following steps:

1. Product data extraction:

A Python-based script automatically extracts element identifiers (GlobalId), semantic roles, and dimensional attributes from IFC entities and property sets using IfcOpenShell.

2. Connection detection and classification:

Geometric information derived from the IFC model is used to automatically detect potential connections between structural members using a tolerance-based proximity (AABB) method. Each detected interaction is classified into a predefined connection type (e.g., Perpendicular, Lateral, Angled) based on geometric overlap and angular relationships.

3. Ontology instantiation:

The extracted elements and classified connections are automatically transformed into RDF triples. Each component is instantiated as an ontology individual and linked to predefined classes and data properties, while connection instances are created to explicitly relate connected elements and assign their corresponding connection types. Connections between components are explicitly represented in the ontology and used to link product elements with construction operations defined in the process ontology. This connection-based mapping separates process definitions from specific component types, allowing flexible reasoning over assembly operations. Through this mapping process, BIM data are converted into structured semantic knowledge, forming the basis for ontology-based reasoning and querying in subsequent stages.

4 Validation and Results: A Case Study

A Light Gauge Steel (LGS) wall panel is selected as the case study to demonstrate the applicability of the proposed BIM-based ontology framework. The panel represents a typical prefabricated wall assembly composed of studs, tracks, and fasteners commonly used in off-site construction.

The LGS panel is modeled in Autodesk Revit using parametric definitions for its structural components. The BIM model captures geometric dimensions, spatial configuration, and connection arrangements relevant to panel fabrication and assembly. The model is exported to IFC format and processed through the proposed BIM-to-ontology mapping pipeline. Figure 6 presents the three-dimensional representation of the LGS panel used in this study.

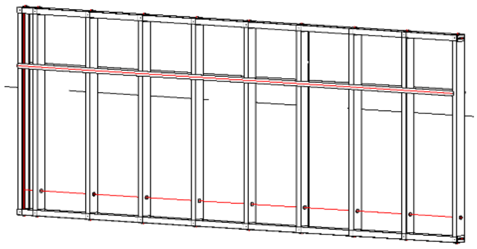

Figure 6. LGS panel case study

Through the mapping process, BIM-derived product information is transformed into a semantically structured ontology populated with both product and process knowledge. A total of 144 structural elements were extracted from the IFC model and mapped directly into ontology individuals. Each element corresponds to one ontology individual and is enriched with geometric and identification attributes derived from IFC property sets. Among these, a subset of primary structural members was considered for connection detection, including 10 studs, 2 tracks, and 2 straps. For the purpose of connection detection and process inference, only load-bearing members (i.e., studs and tracks) were used, while secondary elements such as straps were excluded from the connection detection stage.

By formalizing these relationships, the framework establishes an explicit and machine-interpretable link between product geometry and construction processes. This connection-based semantic modeling enables BIM-derived product information to be systematically translated into DfMA-oriented assembly knowledge, thereby supporting more integrated and construction-aware decision-making.

The ontology is evaluated using four validation metrics adapted from prior ontology-based studies [14]: competency, consistency, completeness, and clarity. The adopted evaluation structure is summarized in Table 1.

Table 1. Validation metrics and approaches implemented

Metrics	Approach	Tool
Competency	Competency questions	Case study + SPARQL queries
Consistency	Automated consistency checking	HermiT and Pellet reasoners
Completeness	SPARQL query	SPARQL query engine
Clarity	Structural modeling review	OOPS! (Ontology Pitfall Scanner)

4.1 Competency

Three competency questions were defined based on the purpose and scope of supporting BIM-based modeling for DfMA-oriented LGS fabrication:

1. Can the ontology retrieve geometric and identification attributes of LGS components extracted from BIM?
2. Can the ontology explicitly represent and classify connection relationships between structural elements?
3. Can the ontology infer appropriate assembly operations based on identified connection types?

The proposed ontology successfully answered all three questions. The developed ontology includes 30 classes, 6 object properties, and 22 data properties. Through the BIM-to-ontology mapping process, 144 structural component instances were automatically generated from the IFC model. Geometric attributes (e.g., length, thickness, positional data) were successfully assigned to each individual. The AABB-based geometric detection identified 20 connection instances, which were classified into predefined connection types (e.g., Crossing, Perpendicular, Lateral, Angled, Double_Angled).

To validate inference capability (Competency Question 3), the SPARQL query in Figure 7 was executed.

```
SELECT ?conn ?elem1 ?elem2 ?ctypeClass ?operationClass
WHERE {
  ?conn rdf:type bim:Connection .
  ?conn bim:connectsElement ?elem1 .
  ?conn bim:connectsElement ?elem2 .
  ?conn bim:hasConnectionType ?ctypeInd .

  ?ctypeInd rdf:type ?ctypeClass .

  # Read the class restriction:  ctypeClass ⊑ requiresOperation some OperationClass
  ?ctypeClass rdfs:subClassOf ?restr .
  ?restr owl:onProperty bim:requiresOperation .
  ?restr owl:someValuesFrom ?operationClass .
}
```

Figure 7. SPARQL query for validation

The query successfully retrieved connection instances, associated elements, classified connection types, and inferred assembly operations. A total of 20 operation instances were inferred automatically through ontology reasoning without manually assigning operations to specific component categories. These results confirm that assembly operations are derived semantically from connection relationships rather than explicitly encoded within the BIM model.

4.2 Consistency

Logical consistency and classification were verified using both the HermiT and Pellet reasoners. Automated reasoning confirmed the validity of class hierarchies, object property restrictions, and inference rules linking connection types to operations. The ontology was processed in 0.388 seconds using HermiT (v1.4.3.456) and 0.411 seconds using Pellet, demonstrating computational feasibility for the case study scale. No logical inconsistencies were detected.

4.3 Completeness

Completeness was evaluated through SPARQL-based query testing against the defined competency questions. Queries successfully retrieved:

- All structural component individuals and their geometric attributes.
- All detected connection instances and their classified types.
- All inferred assembly operations associated with each connection type.

The successful retrieval of expected results demonstrates that the ontology sufficiently covers the defined product and process scope.

4.4 Clarity

Clarity was evaluated through structural inspection of class hierarchies, object property definitions, and naming conventions. The ontology maintains a clear separation between product, connection, and process concepts while preserving semantic coherence. Additionally, the ontology was analyzed using the OOPS! (Ontology Pitfall Scanner) tool. The evaluation reported no critical errors and only minor warnings, indicating acceptable modeling quality for this first implementation.

4.5 Interpretation

The case study confirms that the proposed framework establishes an explicit, machine-interpretable link between product geometry and construction processes. By associating assembly operations with connection types rather than component categories, the framework addresses the research problem of integrating product-oriented BIM data with process-oriented DfMA knowledge. Although this implementation represents the first iteration of the framework, the validation results demonstrate its feasibility, logical soundness, and reasoning capability. Future work will focus on incorporating expert feedback, expanding case studies, and enhancing automation of connection recognition to further strengthen the ontology model.

5 Conclusion and Future Work

This paper introduced a BIM-based ontology framework for semantic knowledge representation in LGS panel assembly. The proposed approach combines

BIM-derived product data with ontology-based process knowledge to support DfMA-oriented analysis in off-site construction. Using IFC-based data extraction, ontology modeling, and reasoning, the framework allows for structured representation and inference of assembly-related information. The case study demonstrated the feasibility of mapping BIM elements to ontology individuals, enriching them with geometric attributes, and associating construction operations through a connection-based reasoning approach. The results confirm that the proposed framework can bridge the gap between product-centric BIM models and process-oriented construction knowledge.

Future work will focus on extending the proposed ontology framework to incorporate formal constraint modeling beyond product–process relationships. Ontology-based approaches have demonstrated strong potential for representing quality control requirements, manufacturing constraints, regulatory specifications, and task-level planning rules within BIM-driven workflows. Building on this direction, future developments of the framework will investigate the integration of design standards, regulatory requirements, and task-level constraints into the ontology, enabling automated compliance checking and enhanced decision support during LGS panel design and assembly planning. This extension will further strengthen the ontology as a knowledge base for DfMA-oriented optimization and constraint-aware design in prefabricated construction.

Acknowledgments

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