Ontology-based Product Configuration for Modular Buildings

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Abstract –

To support mass customization for industrialized construction, researchers and industry have adopted product configuration strategies. Based on the theory of modularization, pre-defined module libraries can be configured into feasible construction projects. However, the digital representation of configuration knowledge is understudied. Current Building Information Modeling (BIM) product modeling does not enable automatic generation and reasoning of configuration solutions for new products. This study proposes an ontology-based strategy to configure modular buildings. The proposed BIM-to-ontology workflow collects and formalizes configuration constraints. In particular, we elaborate on how those constraints can be modeled within the ontology in a modular building case. The ontology maintains the product hierarchy needed for product assembly. Such ontology development can support the rapid development of new products with customized variations. The paper identifies the limitations of the current product modeling approach. The proposed ontology can act as a foundation for BIM-based product platform development and increase the use of mass customization for industrialized construction.

Keywords –

Product configuration; ontology; BIM; Modular buildings

1 Introduction

Although mass production increases production efficiency and product quality, it lacks design flexibility and customization [1]. Increased design flexibility can be achieved through the configuration of standard components and variant components (i.e. modules) via a platform-based strategy [2]. To support the product configuration, a flexible product model is required [3,4]. It should not only describe the product composition in terms of the assemblies, sub-assemblies and parts, but also satisfy configuration reasoning and inference. However, few scholars uncover how product modeling could support the configuration of industrialized construction, especially modular buildings. For example, software vendors often embed a product structure in configuration applications, i.e. component trees and feature models. The structure has no functionalities to specify how a correct product could be configured from the available parts and assemblies. In many industrialized construction settings, the configuration is done manually based on document-based design handbook. The project practitioners need to familiar with the rules and abide by them. Considering the nature of low digitalization and fragmentation of construction information management, the procedure is difficult to implement. There is significant potential risk of rework and changes during the project.

To fix this problem, the authors propose an ontology-based structure to represent the configuration knowledge for modular buildings. The results facilitate the reuse of the configuration knowledge and lay a foundation for technical platform development. The paper is organized as follows. In the next section, strategies for product modeling in the manufacturing industry and the construction industry are first reviewed. Then, the ontology modeling approach is explained. Built upon that, an ontology-based product modeling is adapted to the modular building settings. In the end, a modular building case is used to illustrate how the configuration semantics could be modeled via ontology.

2 Literature Review

2.1 Product Modeling Strategies

Due to trends of product complexity and global manufacturing, the unified product model is becoming increasingly important throughout the product lifecycle. A unified model that supports the integration and transformation of different model views can improve industrial competitive advantage [5].

In the manufacturing industry, bill-of-material (BOM) is the most widely used approach in modelling a product structure. It uses a tree structure to represent the product hierarchy. However, it is not efficient to enable derivative product modelling with an increasing number of variants

[6]. An alternative approach is the Generic bill-of-material (GBOM). GBOM attempts to fix the variants of the product configuration by inheritance. The parameters of primary generic products are passed through the levels of GBOM and inherited by lower level of generic subassembly products [7]. However, GBOM is only able to model a product with a predefined set of components. It cannot support engineer-to-order variants, which are designed according to special customer requirements.

Two approaches – Adaptive generic product structure (AGPS) and product variant master (PVM) –have been developed to solve limitations of engineered-to-order products by categorizing the base models, reused variants and new components [8] [9]. Two types of syntaxes, including "part-of" and "kind-of" are used to model the structures of aggregation and specialization respectively. Rules are set to restrict the variant selection and property determination. The PVM depicts properties, functions and structure of a product at the engineering view and production view, similar to the engineering bill of material (E-BOM) and manufacturing bill of material (M-BOM).

2.2 Product Modeling for Modular Buildings

Unlike products in the manufacturing industry and projects in traditional site-built construction projects, industrialized construction product platforms combine both product-level information and project-level information [10,11]. The hierarchy between components is more important in industrialized construction systems[10,12], compared with site-built construction.

Several researchers have adapted or proposed product modeling structures for use in industrialized construction. Hvam and Thuesen used Product Variant Master (PVM) to represent a product part view [13]. Ramaji et al proposed a Product Architecture Model (PAM) to capture the product information of modular buildings [14]. Both strategies build upon a hierarchical structure [15,16], where modules are defined at different levels of complexity. First, the overall product architecture uses a hierarchical determination for sub-assemblies and parts. Then, the variations of each assembly and part are decided as a set of interchangeable components, which share similar features and functionalities. Finally, the components and related attributes are categorized based on the level of details. The benefits of the hierarchical structure include ensuring easy connection to the information management systems (e.g. ERP and PLM) [17,18], maintaining consistency with the construction classification system (e.g. Uniclass and Omniclass) [19], and providing customization at different hierarchical levels of products [20].

2.3 Current Product Modeling using BIM

Product modeling in the construction industry is implemented in existing BIM applications. Firstly, the architects have a rough design concept of a certain type of modular construction, such as volumetric modular structures. A general building outline can be created as mass models, including facility layout, building shape and direction, floor plan, etc. Secondly, the conceptual design is developed with architectural modules. The modules are categorized by product hierarchy [21]. For example, these modules can contain standalone units (e.g. smaller room pods), components (e.g. level, floor, wall, ceiling components), and/or subcomponents (e.g. pillars, beams, framing studs). Thirdly, the engineering team receives analytical models to conduct structural and mechanical analysis. The generated component-level BIM is validated and optimized in terms of material use and geometric dimensions. This feedback information is incorporated into the BIM with updated parameters. Finally, a detailed design is conducted by production teams to split the components into subcomponents [22].

Due to BIM's low compatibility with the production systems, the subcomponents are usually modeled within the third-party application, such as HSBCAD. The industry foundation classes (IFC) and a documented information exchange manual (IFD) are used to support the information exchange between model views. Beetz et al. developed ifcOWL and a mechanism to transform IFC specification from EXPRESS to OWL [23], which improves knowledge extraction [24], integration [25] and reasoning [26] from BIM. However, a product hierarchy which reflects the product composition is usually not represented in the exported IFC file.

3 Research Approach

3.1 Ontology Modeling

Ontology is widely applied in many industries for domain knowledge management. Due to its formal representation, ontology facilitates the knowledge capture, reuse and integration [27]. The construction of ontology for product configuration has been studied as early as the 1990s [4]. It is applied to manufacturing products, such as Personal Computers (PC) [28], manufacturing machines [29], and automotive [30]. The formal procedures to build an ontology follow five steps [31]: 1. identifying the purpose and scope of ontology; 2. reviewing existing ontologies, taxonomies, or other sources; 3. Enumerating main classes and build corresponding class hierarchy; 4. constructing an ontology in an ontology editor tool (e.g. Protégé); 5. ontology validation. The construction and validation steps are illustrated via an illustrative example in Section

3.1.1 Define Scope and Purpose

This research looks specifically at floor plan configuration. The proposed ontology is built to represent both the building structure / composition and constraints in a well-defined formal semantics to validate a customized configuration. The information involved in the configuration process includes customer requirements and design regulations. Customer requirements specify the acceptable combinations of spatial modules or variations of compositional building elements in the final floorplan design [15]. The design regulations, such as the horizontal stability, can be encoded to validate the customized floorplans.

The intended users of the ontology are customers without sufficient design knowledge. The ontology is maintained by professionals with the means to develop new spatial modules and building elements for their product platforms.

3.1.2 Reuse Existing Ontologies

Building Information Modeling (BIM) applications contain taxonomies and content libraries, which can be extracted to enable ontology construction. Generally, a BIM project contains system families and loadable families. The former one is embedded in the project template with default structures, while the latter is created independently and loaded into projects. Because most BIM libraries do not contain well-defined components for industrialized construction, design teams for modular construction usually need to create customized ones. The customized BIM modules can be reused in different project settings. In this study, a MEP-integrated volumetric unit is defined as the first level hierarchy under the project. Each unit is modeled as sub-project, which can be further linked to the main project. The main project and linked models are stored separately to facilitate the reuse of linked models. The components of volumetric units, such as walls, floors and ceilings are the second level of product hierarchy, which is modeled in the linked project.

To extract the BIM data of the module as well as their components, Revit API is used in this study. First, the volumetric units can be filtered under the category of “RvtLinks”. The “RvtLinks” is a built-in category used to represent linked models in the main project file. Then, the linked document is located. The component granularity is extracted from linked document through the “FilteredElementCollector”, which provides access to obtain a collection of elements by category.

3.1.3 Build Class Hierarchy

The extracted BIM data, including BIM families, instances and parameters, should be mapped to the ontology structure. The structure of an ontology is constructed as a tree structure of classes, to represent the hierarchy of the modular buildings. The object properties are used to assert relationships between classes. The attributes of each class are modeled as data properties. The mapping relationships are illustrated as BIM family to Ontology class, BIM instance to Ontology individual, BIM parameter to Ontology data property. In addition, some inexplicit relationships in BIM, such as the hosted relationship between opening families (e.g. windows and doors) and wall families, can be mapped to the object properties. The extracted objects are collected as key-value pairs in the C# dictionary, where the keys are unique “ElementId” used to maintain the one-on-one relationship between BIM and ontology, and the values are attributes of elements. The Python module “Owlready” [32] is used to write the BIM data into the ontology.

The above concepts of an ontology contain the basic taxonomy for a configuration problem. However, they are usually not enough to describe complex semantics. These semantics, including the constraints over the product structure, are useful to reason the correctness of a configured solution. The typical constraints for configuration include composition, compatibility, dependency and cardinality [33]. Composition rules define which components are mandatory or optional in the product architecture. The product architecture can be built as a tree structure. A component can be either a root node, an intermediate node or a leaf node. Once a non-leaf component is selected, the direct child component can be automatically added to the product. Compatibility rules define which components cannot exist simultaneously in the product. If a component with a compatibility rule is selected, the system will exclude certain components from the option lists. Dependency rules define which components must belong together in a product. If a component with a dependency rule is selected, the system will add its mated components to the product. Cardinality rules define the required or limited number of components under certain circumstances. The product structure can only represent the existence of a components. A component with a cardinality rule need to be assigned the quantity occurring in the product and checked against its validity.

4 Implementation

To demonstrate the ontology usage, a multi-story modular residential project from a European construction company is used as an illustrative example. The project consists of prefabricated, highly standardized volumetric units that are combined under a set of restrictions to create apartment buildings. Each module is fully designed for certain functionalities. While the product concept is standardized, the individual configuration can vary from the building profile on the selected site, the layout of the apartment on the floor plan, the material type of façade, the roof types and the balcony types. The project-specific configuration is supported by a library of 3D models in Autodesk Revit that define all relevant design regulations. The BIM content library can be linked to the proposed ontology following the process mentioned above. Then, the project can be configured with the BIM library and reasoned for correctness. Figure 1 shows the classes and object properties in the configuration model.

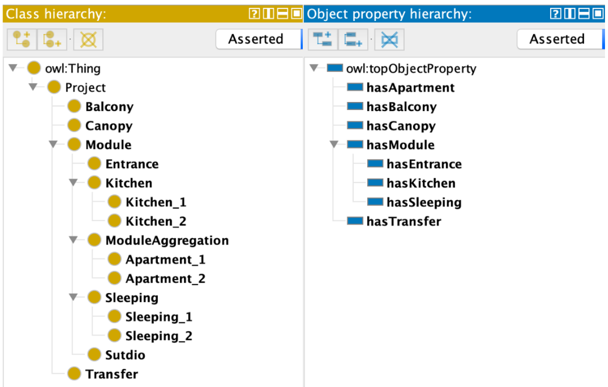

Figure 1. Class hierarchy and object property hierarchy of the modular building

4.1 Composition constraint

"An Apartment_2 is composed of 1) one entrance module; 2) one kitchen module; 3) one sleeping module." The definition of the class "Apartment_2" in Protégé is shown in Figure 2. The "Entrance", "Sleeping", and "Kitchen" are disjointed classes. The "hasEntrance", "hasSleeping" and "hasKitchen" are object properties which map from the apartment class to the corresponding module class. "Exactly" keyword is used to restrict the existence of a certain class.

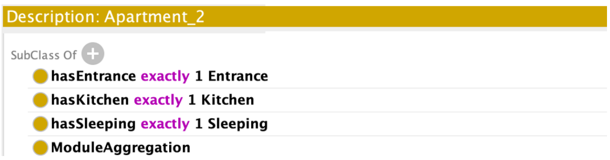

Figure 2. Composition constraint to define a three-module apartment

4.2 Cardinality constraint

"A two-story modular project is developed for wind loads in terrain type 1, which requires at least five modules in width per floor." The constraint is encoded in SWRL and SQWRL (Semantic Query Enhanced Web Rule Language) as shown in Figure 3. SQWRL support collection operators that provide the grouping and aggregation functionalities. In this scenario, each type of modules, including "Sleeping", "Kitchen" and "Entrance", are grouped and added. Then, the total number of selected modules is compared with the required number of modules based on the design requirements.

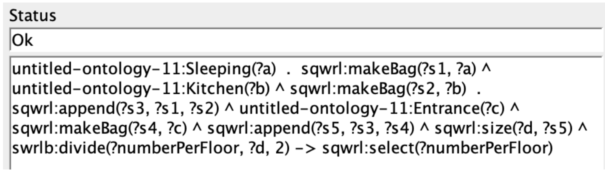

Figure 3. Cardinality constraint to check the required number of spatial modules

4.3 Compatibility constraint

"The Kitchen modules should not be selected to configure a studio apartment". The constraint is defined as a SWRL (Semantic Web Rule Language) as shown in Figure 4 via the SWRLTab of Protégé. The constraint is a conjunction of four positive atoms. The "Project (?x)" and "Kitchen (?m)" represent the instance of project (x) and kitchen (m) respectively, while the "onlyStudio(?x, true)" represents that the project only contains studios. Finally, when the kitchen module (m) is added to the project (x), the "hasModule (?x, ?m)" will be generated automatically. As the consequence of the rule is void, the checker returns an error, representing the event at the left side of arrow cannot occur.

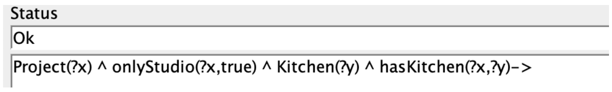

Figure 4. Compatibility constraint to limit the module selection

4.4 Dependency constraint

"If a user specifies an apartment with balcony, the matched canopy will exist in the same configuration." Similar to compatibility constraint, the constraint is defined in the SWRL as shown in Figure 5. For the specified apartment, if a balcony with width equals 1.5 meters is required in the sleeping room. The rule will automatically add the matched canopy and set its width same as the balcony.

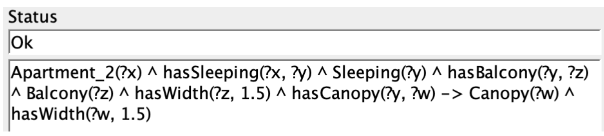

Figure 5. Dependency constraint to select mated

components

5 Discussion

The proposed ontology-based product modeling is a novel approach to represent design information for modular buildings. It is aimed at achieving mass customization by linking customer requirements and design regulations with a predefined module library. The research is built upon the product modularization. With a module library, the various configuration can be achieved. Compared with the PVM and PAM approaches, this ontology-based approach is capable to represent more complex product structures and semantics. Furthermore, the proposed ontology can be well-connected to BIM tools through ifcOWL to avoid reconstruction of taxonomies.

6 Conclusion

Mass customization has been strongly emphasized in the construction industry, especially the industrialized construction. Product configuration is an idea borrowed from the manufacturing industry to achieve mass customization. Similar to the automotive industry, modular buildings can be configured with different categories of modules, such as volumetric units and panels. Compared with the traditional design process, the key benefits of configuration are the fast derivation of product variety to satisfy customer's needs, and the reuse of digital BIM contents to improve design efficiency and product quality. However, the existing product modeling only deals with the categorical classification of product composition, without considering a configurable product structure.

To support the digital representation of configuration knowledge, this research proposes an ontology-based modeling approach. First, it illustrates how configuration tasks can be implemented in a BIM environment via a BIM-to-ontology workflow. Second, the paper focus on how product hierarchical structure and semantical constraints can be modeled in an ontology. A modular building project is used as a case study to explain it in detail. Ultimately, this lays the foundation for the technical configuration platform development.

The research has some limitations. First, the configured product is limited at the floor plan. A wider scope of building products, such as MEP systems, should be included in the configuration process. This might require a better understanding of customer requirements on the building performance. Second, the complex semantics of product configuration has to be manually added into the ontology. Previous scholars have identified that building such large-scale ontology requires domain knowledge, which will take time and considerable resources [34]. Future research direction might be the automatic construction of multi-domain ontology with natural language processing.

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