Ontology-Based Knowledge Modeling for Frame Assemblies Manufacturing

S. An[a], P. Martinez[a], R. Ahmad[b], and M. Al-Hussein[a]

[a] Department of Civil and Environmental Engineering, University of Alberta, Canada.
[b] Laboratory of Intelligent Manufacturing, Design and Automation (LIMDA), Department of Mechanical Engineering, University of Alberta, Canada.
E-mail: san3@ualberta.ca, pablo1@ualberta.ca, rafiq.ahmad@ualberta.ca, malhussein@ualberta.ca

Abstract –

As modular construction becomes popular, an increasing number of products are prefabricated in an offsite construction environment. While improving the productivity and efficiency of construction-oriented production, it also raises the complexity of process planning. Although the specifications of a product are fully defined by Building Information Models (BIM), no information is provided on how construction products are manufactured and assembled. This paper proposes an ontology-based approach aimed to link construction-oriented product assemblies and manufacturing resources using manufacturing operations. By identifying intersections of connecting members of a product assembly, feasible manufacturing methods and resources are determined based on expert knowledge and machine configurations. The proposed approach is validated using a wood frame assembly.

Keywords –

Building information modeling; Ontology modeling; Offsite construction; Construction automation; Construction manufacturing

1 Introduction

Modular and panelized construction have been promoted and recognized globally as advanced construction techniques for commercial and high-rise residential buildings in the last decade. Thus, an increasing number of buildings are manufactured using off-site construction methods: first, wall panels are prefabricated in an indoor facility; then, shipped on-site for installation. Offsite construction is becoming increasingly popular as it improves productivity of the construction process, reduces material waste, and yields better quality products [1, 2]. With the growing interest in modular construction, industrial automated machines have been developed to satisfy such needs. A prototype was designed at the University of Alberta for automatic light-gauge steel framing [3].

In industry, the current practice of introducing new construction products to an existing or new facility consists of the following procedures: (1) a 3D model of the desired product assembly is generated using the Building Information Model (BIM) specifications; (2) then, it is analyzed by product engineers to determine the manufacturing process (or processes) required and to select the appropriate machines necessary to accomplish such tasks; (3) the machinery is finally analyzed for installation in the indoor facility (i.e., layout design, safety requirements).

The vision of the 4th industrial revolution describes the realization of smart factories, where a higher flexibility and adaptability of production systems is achieved [4]. The challenge arises when deciding if a new assembly can be manufactured in the existing production line or if one or more machines must be commissioned to make a new product assembly. Although BIM models provide information on what the final product assembly would be, it does not offer the benefit of hindsight as to how it is manufactured and assembled. Such challenges are often overcome by engineering experience. As a result, no link between machinery, manufacturing processes and construction product assemblies in the knowledge domain exists. To shorten the decision-making effort in determining machine eligibility, a relationship between product assemblies, manufacturing procedures, and machines needs to be established.

The objective of this study is to create knowledge models that represent components of a manufacturing domain with a special focus on the manufacturing of product assemblies. An ontology-based model is proposed to communicate between three knowledge domains: the 3D BIM model of a desired product assembly, its necessary manufacturing steps, and the key attributes of the machines used for manufacturing. A wood frame assembly is used as a case study.

2 Related Work

Relating product information to the manufacturing domain exists in the machining industry. Computer Aided Process Planning (CAPP) is the use of computer technology to aid in the process planning of a product in manufacturing [5]. CAPP is used to interpret product design data by recognizing features on a part and translating them into manufacturing operation instructions [6]. CAPP has been proven to be successful in providing process planning to manufacture a designed part. The challenges of using CAPP in manufacturing construction-oriented products arise due to the complexity of the products, which usually involves assembling individual parts.

Extracting information from BIM models is the first step involved in fabricating and inspecting the quality of construction-oriented products. Malik et al. successfully extracted product specifications from BIM models and generated safe tool-paths for moving carriages in an automated framing machine [7]. Martinez et al. proposed a vision-based system for pre-inspection of steel frame manufacturing. The proposed approach provides real-time inspection of steel frame assemblies by comparing real frame assembly with manufacturing information from the BIM model [8].

In typical manufacturing processes, knowledge modeling has successfully enabled decision making systems to be defined for such purposes [9]. However, a link between construction-oriented products and construction machinery is yet to be properly defined. Gruber defined ontology as "an explicit and formal specification of a conceptualization" [10]. Ontology is used for various reasons. First, ontologies offer interoperability of information from various knowledge domains; second, ontologies support consistency checking and reasoning; third, concepts used in product and manufacturing domains can be represented by defining classes and properties of the ontology in an intuitive way [11]. A proposal named MASON (MAnufacturing's Semantics ONtology), proposed by Lemaignan et al., created a common semantic net in the manufacturing environment using ontologies for general purposes [12]. This approach successfully related product specifications (entities) and manufacturing related resources using operations. MASON sets the foundation to link construction-oriented products to the manufacturing environment.

Ontologies have been proven useful in extracting information from BIM for practical use. Zhang et al. proposed an ontology-based model to relate on-site construction safety management with job hazards of construction activities. By linking tasks, methods, and the job hazards involved in construction activities, the developed automated system provides a significantly more efficient and formalized job hazard analysis [13]. Liu et al. proposed an ontology-based semantic approach that successfully extracts construction-oriented quantity take-off information. Using this approach, construction practitioners can readily obtain and visualize the relevant information from complex BIM models [11].

3 Methodology

By integrating the work proposed by Lemaignan et al. and Liu et al., this paper proposes an ontology-based semantic approach to relate construction-oriented product assemblies to machineries in a production line that is responsible for manufacturing the products. Extending the methodologies proposed by Liu et al. by using a MASON-based approach to the manufacturing

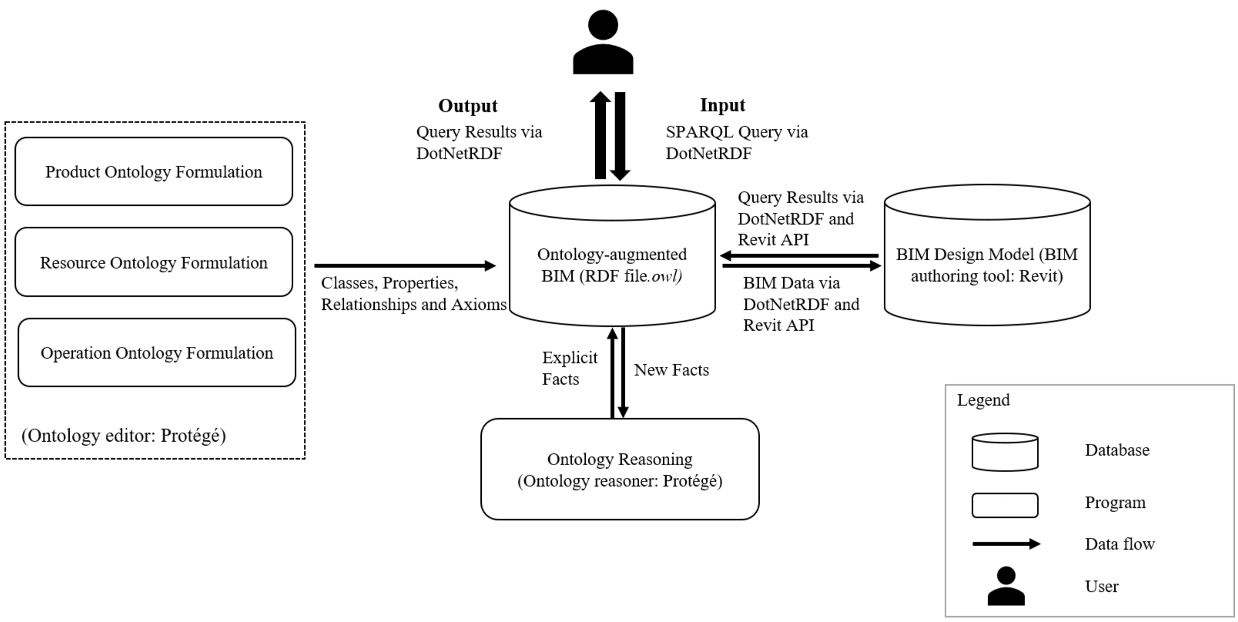

Figure 1. System architecture

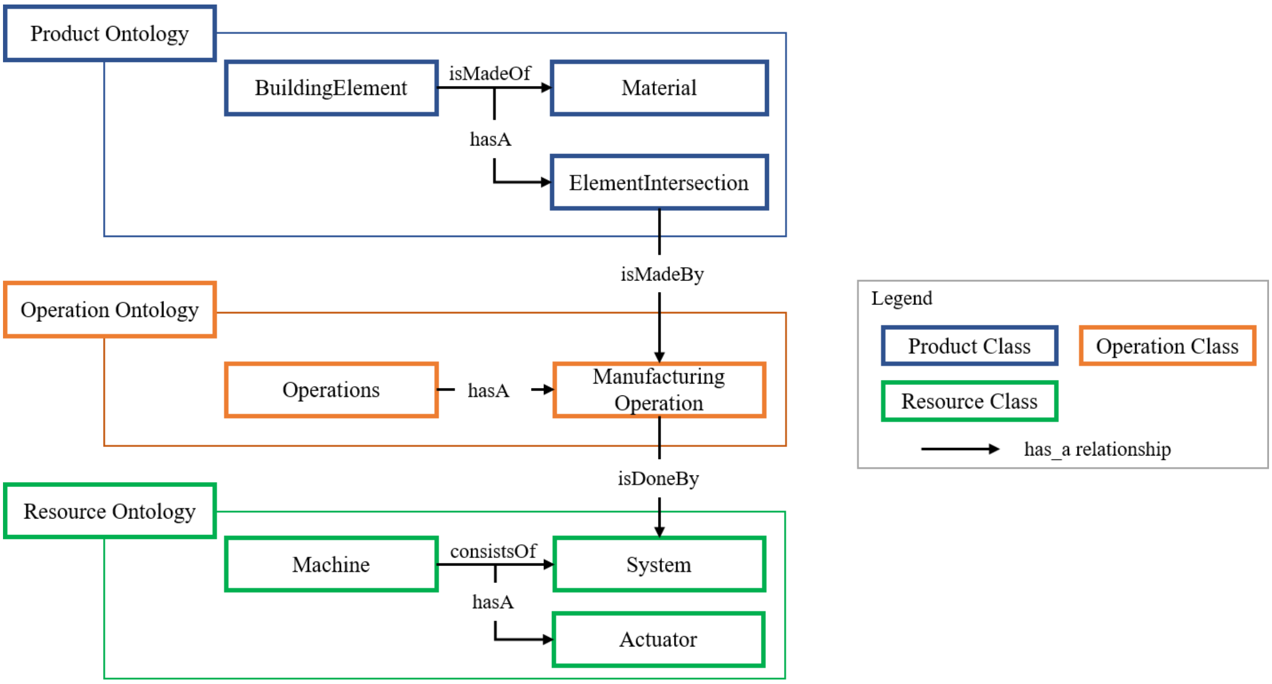

Figure 2. Product, operation and resource ontology models

domain, the proposed system architecture is shown in Figure 1. Three knowledge domains (manufacturing resource, operation, and product) need to be incorporated to build the ontology-augmented BIM model. Each knowledge model is simplified in Figure 2. Protégé, an open source ontology editor and reasoner, was used to build the ontology model using the following steps: (1) Entity class is created to specify construction-oriented products; (2) Resource class is used to describe manufacturing machineries to be used to fabricate and assemble the products; (3) Operation class is then built to relate entities and resources. Once the knowledge domains are constructed, machine eligibilities can be determined.

Using the approach proposed in MASON, classes will be used to define the product, operations and manufacturing domains. Attributes of classes are specified using "Data properties". The relationship between classes are captured using "Object properties". Instances of classes are modeled using "Individuals" [12].

3.1 Product Ontology Formulation

First, the class *Product* containing information from BIM is modeled. BIMs are digital representations of physical and functional characteristics of a facility and contain all the physical information related to a product [14]. In terms of the construction of a building element using machines, the following information will be used to allocate manufacturing resources: material, dimension, and intersection between elements. All machines have limitations as to the material to be processed and the dimension of a product. Since a product assembly is typically made using multiple basic elements, intersections of these elements also place constraints on how the product assembly may be constructed. An intersection is defined as the interface between any two or more members to be connected. Since an intersection is dominantly affected by the product material, each intersection is specific to each type of product. For wood frames, intersections are identified based on 3 criteria: (1) single or double plates/studs; (2) either it is at a corner (LConnection) or inside the frame (TConnection); (3) horizontal or vertical. Six intersections are identified using the above criteria and are denoted by specific notations:

Table 1. Intersections in wood frames

Intersection Type	Notation
Stud_Plate_LConnection	SP_L
Stud_Plate_TConnectionVertical	SP_TV
Stud_Plate_TConnectionHorizontal	SP_TH
Stud_DoublePlate_LConnection	SDP_L
Stud_Stud_Connection	SS
Stud_DoublePlate_TConnectionHorizontal	SDP_TH
Stud_DoublePlate_TConnectionVertical	SDP_TV

Since manufacturing processes depend on the material and the intersections of each product assembly, they must be defined in the ontology model. As an example, Figure 3 shows the class hierarchy of wood element intersections.

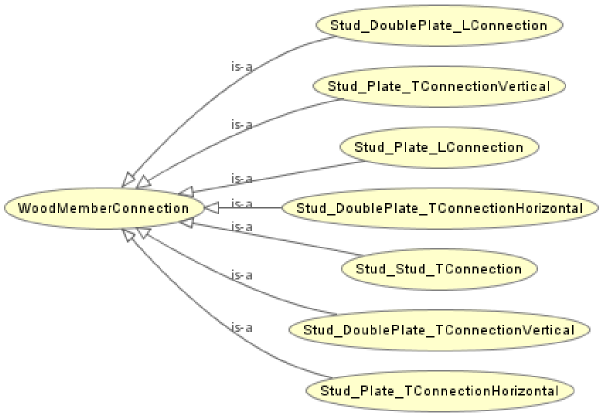

Figure 3. WoodMemberConnection class hierarchy

3.2 Resource Ontology Formulation

Similar to the product model, the resource ontology is also modeled. Although resources consist of multiple categories, only machine resources need to be considered as far as machine eligibility is concerned. A construction manufacturing machine consists of several systems that carry out manufacturing operations. For example, a nailing system in a wood framing machine can shoot nails into the wood frame to create a permanent connection. In this model, the class *Resource* that consists of subclasses *Machine* and *Actuator* are created. Under the class *Machine*, several sub-classes of various machines are created. Systems of certain machines are specified under each *Machine* sub-class. The *Machine* resource ontology model is shown in Figure 4.

Figure 4. Resource ontology model

3.3 Operation Ontology Formulation

As mentioned before, the BIM model does not include information pertaining to how a product assembly is fabricated. Therefore, manufacturing operations need to be analyzed to form a relationship between product entities and machine resources. Since a product assembly is typically made of several members, intersections of these members require certain manufacturing method(s) to secure these elements. In addition to joining materials, some locations also require the addition and/or removal of materials. These locations, along with intersections, are defined in the BIM model and categorized into classes of connections defined in the *Product* model. Each category of intersection requires specific manufacturing method(s). Therefore, based on the type of connections identified, the manufacturing operation is determined.

In the *Operation* ontology model, the class *ManufacturingOperation* is created to identify feasible product assembly construction methods. By establishing relationship "isMadeBy" between the class *Product* and *ManufacturingOperation*, the system now has clear knowledge about how a product assembly can be constructed. The ontology model of *Operation* is shown in Figure 5.

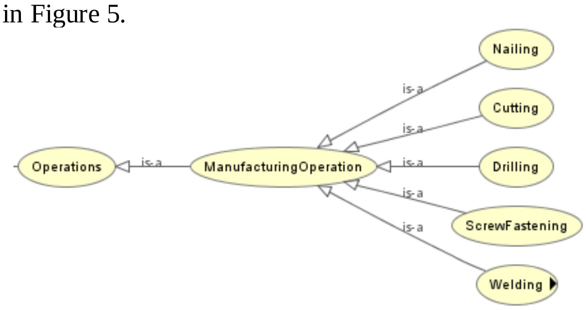

Figure 5. Operation class hierarchy

4 Results and Discussion

In this section, the proposed methodology is validated with a wood framing wall. The advantages and limitations of using ontology models to relate product, manufacturing resources, and operation are also discussed.

4.1 Case Study

A wood frame is to be modelled and studied. The panel is 20 ft (approximately 6 m) long and 10 ft (approximately 3 m) high and is made of 2x6 (38 mm x 150 mm) wood timbers of various length. The frame contains a window and a door component. Note that a single plate is used for the footer and double plates are used for the header. The frame is shown in Figure 6 below.

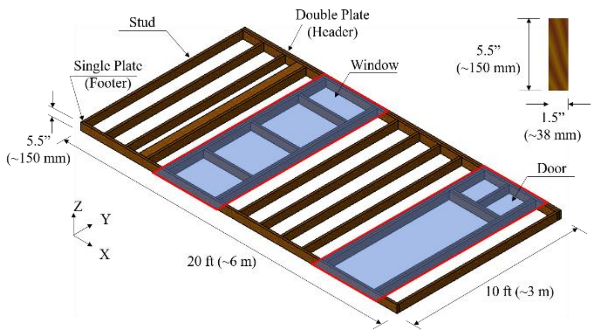

Figure 6. 3D representation of the wood frame case study

First, using the given information, material and dimensions are identified. Next, the possible types of intersections are recognized: stud-to-stud intersections and stud-to-plate intersections. Plates are wood members along the x-axis and studs are the rest of the members. As shown in the product ontology model, all the possible intersections of product assembly of wood framing wall are modeled as sub-properties under the object property "isMadeBy". Since it is a group of properties of the element intersection which requires manufacturing operations, the domain of "isMadeBy" is *ElementIntersection* and the ranges are within *ManufacturingOperations*. This relationship is represented in Figure 7.

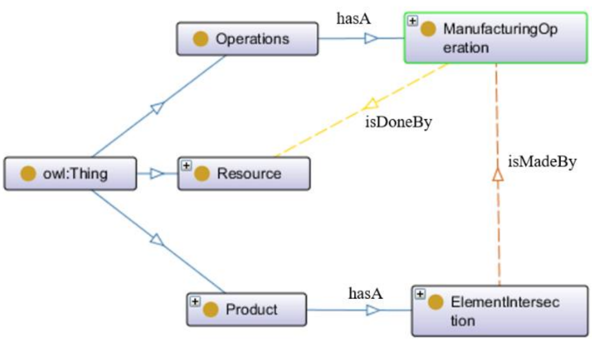

Figure 7. Class wood member intersections

For this wood frame, all types of intersections are identified and matched to the ontology model. These types of intersections are annotated in Figure 8 and are tabulated in Table 2. Note that an integer that follows the letters in the Identifier column represent a specific instance of corresponding wood members.

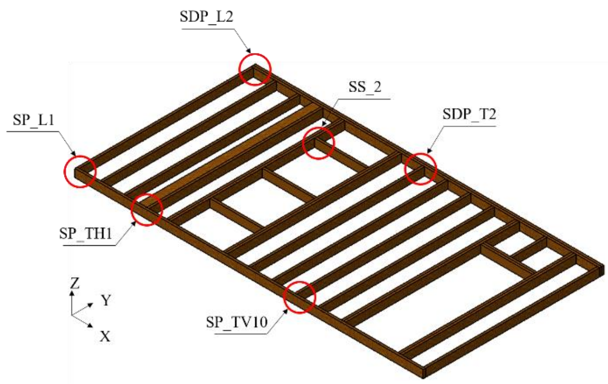

Figure 8. Intersections identified from provided wood frame

Table 2. Connections in wood frame panel

Intersection Type	Identifier
Stud_Plate_LConnection	SP_L1
Stud_Plate_TConnectionVertical	SP_TV10
Stud_Plate_TConnectionHorizontal	SP_TH1
Stud_DoublePlate_LConnection	SDP_L2
Stud_Stud	SS2
Stud_DoublePlate_TConnection	SDP_T2

To represent knowledge of the manufacturing machine domain, resource ontology is modeled for further analysis. As an example, the Wood Framing Machine Prototype (WFMP) built at the University of Alberta is used for this case study. It is a semi-automated framing machine designed to build wood frames. The prototype consists of four independent systems: cutting, dragging, drilling, and nailing. These systems are modeled in Protégé as shown below in Figure 9. Note that WFMP has not equipped with decision-support system to this point. The knowledge of the machine, however, will lead to development of decision-support system in the future.

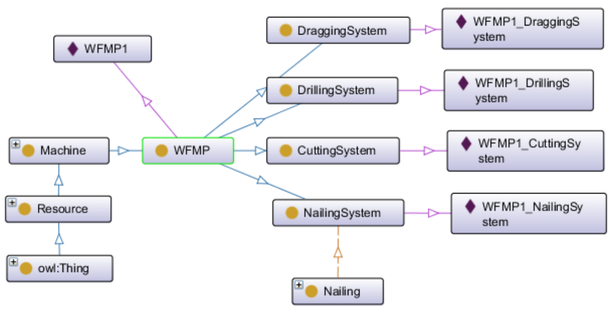

Figure 9. Systems of the WFMP

After knowing element intersections and systems of the machine, the relationship among product assemblies and machine domains can be established by analyzing the manufacturing operations needed to make such product assemblies. Based on expert knowledge, wood members with intersections presented in Table 2 should be joined using screw fastening or nailing. In the ontology model, this knowledge is embedded in the object property "isMadeBy": the domain consists of element intersections and the ranges contain feasible operations. As an example, a sub-property "SDP_LConnection" of "isMadeBy" is defined in Figure 10.

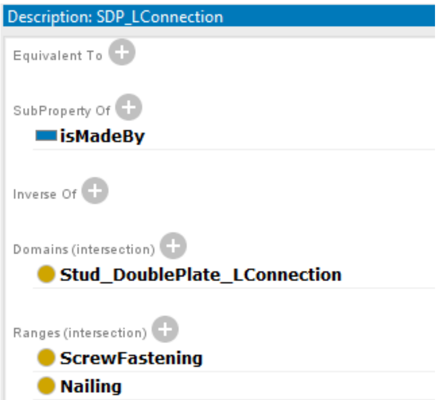

Figure 10. Object properties of SP_LConnection

Analyzing all the intersections in the wood frame, only screw fastening and nailing operations are feasible options for creating permanent connections. Since nailing is more popular for connecting wood timbers in North America, the only manufacturing process required for building this panel is the nailing operation. This result agrees with current industry practice for framing a wood panel.

4.2 Discussion

As shown in the case study, ontology models can not only represent knowledge of construction-oriented product assemblies and machine resources in detail, but also form a relationship between these knowledge domains. Using the product assembly information such as material, dimension, and intersections exported from The BIM model, appropriate manufacturing operations are suggested by the knowledge model. This requires building ontology models for both the product to be built and assembled, and the potential machines to be used to make such product.

A number of advantages are observed after having the knowledge model. First, a machine's capacity fabricate certain construction-oriented products can be determined by analyzing the manufacturing processes required to complete the product assembly. Second, if one machine cannot fulfill the manufacturing requirement, a well-defined model will suggest the appropriate manufacturing activities, such as a combination of machines, to fabricate the product. In addition, the ontology model built in the case study can easily be expanded to a related field. For example, machine logic, actuators, and sensors can be modeled and integrated to the existing model. As a result, a data exchange will be initiated between physical systems such as product assemblies and machines, which will accelerate product fabrication and simplify the modifications to existing production lines if needed.

However, certain limitations are also observed. Building knowledge models is extremely time consuming. A machine cannot decide or suggest manufacturing activities without sufficient knowledge from all relevant knowledge domains. In fact, ontology formulations need to cover all manufacturing resources in a production line. It is common that a product assembly is made by a series of activities and it is not feasible for a single machine to have all the functionalities required. The sequence by which a product assembly is made must be determined in addition to the specific manufacturing operations required. Therefore, future work is needed to address:

1. A more detailed ontology formulation that includes machines of the entire production line and encompasses material cost and manufacturing time estimation;
2. The sequence by which a product must be assembled (process planning of manufacturing processes);
3. The machine-product interaction within a production line has yet been defined.

5 Conclusion

Since the BIM model does not provide information regarding how products are to be fabricated, ontology models are used to bridge the knowledge gap. By building knowledge models for product, operation and machine, the relationship between product and machine is formed. Using expert knowledge, the required manufacturing operations are determined by identifying the intersections in a product assembly.

Once the manufacturing system is equipped with knowledge, it is possible to determine if a machine can manufacture a certain product, even though this is not the main focus of this study. Future more, it can further suggest additional manufacturing activities needed to complete the product in the case where one machine can only fulfill part of the fabrication requirements. In this case, combinations of machines need to be used to make the product. In future work, the proposed approach can be extended to all the machines in a factory to address this issue.

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