A design support system to determine the machine eligibility for manufacturing frame assemblies

by

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Abstract

As offsite construction is trending, an increasing number of construction products are fabricated in a controlled factory environment. By using automated machinery, the productivity and accuracy of construction-oriented products have been improved. However, as BIM models do not provide manufacturing information, the planning of manufacturing processes for construction-oriented products are manual, time consuming, and relying heavily on the knowledge of manufacturing engineers. To achieve automated process planning, the planning system must be able to decide machine capabilities given the BIM models, specifications of machinery, and manufacturing rules defined by domain experts. This research develops a decision-support system that automatically determines a machine's eligibility of manufacturing the light frame assemblies using the given specifications. First, common manufacturing features of frame assemblies and manufacturing rules are formulated using ontologies. Second, the geometries of the manufacturing features are determined using techniques of computational geometry. Furthermore, manufacturing locations are determined using previously formulated manufacturing rules. Lastly, whether or not a frame defined by the BIM is manufacturable using a given machine is determined by checking if the manufacturing features are within the effective range of the machine. The developed system is tested on wood and steel frame assemblies using semi-automated framing machines. It is proven that the system accurately determines manufacturing features and the machine eligibility.

Preface

This paper-based thesis is an original work by Shi An. Two journal papers and one conference paper related to this thesis have been submitted or published and are listed below. As such the thesis is presented following the paper-based thesis guideline.

1. **An, S.**, Martinez, P., Ahmad, R., and Al-Hussein, M. (2019). "Ontology-based knowledge modeling for frame assemblies manufacturing." *Proceedings, 2019 International Symposium on Automation and Robotics in Construction*, Banff, AB, Canada, May 21–24, 2019.

2. **An, S.**, Martinez, P., Al-Hussein, M., and Ahmad, R. "Development of BIM-based machine eligibility decision support system for 2D wood frame assemblies manufacturing." *Automation in Construction.* (under review)

3. **An, S.**, Martinez, P., Al-Hussein, M., and Ahmad, R. "Development of BIM-based machine eligibility decision support system for steel frame assemblies manufacturing." *Automation in Construction.* (under preparation)

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Abbreviations

BIM Building Information Modeling.

CAD Computer-Aided Design.

CAM Computer-Aided Manufacturing.

CAPP Computer-Aided Process Planning.

LGS Light Gauge Steel.

MEDS Machine Eligibility Determination System.

MPDA Mating Plane Determination Algorithm.

OSC Offsite Construction.

PLC Programmable Logic Controller.

RCA Ray Casting Algorithm.

ROE Region of Effect.

SFMP Steel Framing Machine Prototype.

WFMP Wood Framing Machine Prototype.

Chapter 1

Introduction

1.1 Background

Canada has experienced continuous growth in residential house construction during the past decade [1]. To support the growing demand, offsite construction methods have become increasingly popular [2]. In offsite construction, building components such as wood and steel-structured frame assemblies are prefabricated in a controlled factory environment and then delivered to the job site to be installed [2]. Wood frame assemblies are more commonly used for residential houses whereas steel frame assemblies are preferred in mid-rise buildings. Due to the controlled manufacturing environment, offsite construction has the potential to increase productivity, quality, and the deliverability of the products [3]. By applying offsite construction technologies, 30 - 50% of total construction time can be saved [4]. The controlled factory environment allows the use of automation that may further increase the productivity of machines that manufacture frame assemblies.

To improve the cost-effectiveness and reduce the production time of construction projects, substantial research efforts haves been dedicated to building information modeling (BIM) and offsite construction (OSC) [5]. However, the in-depth integration of BIM and OSC is falling behind. As an example, the information exchange between BIM enabled design and automated manufacturing has yet to be initiated [6]. The restriction of information exchange prevents the manufacturing system from freely communicating with its components (such as machines). In information technology or system engineering, "interoperability" is defined as a characteristic of a system to work with other systems in either implementation or access without any restrictions [7, 8].

In the context of industry 4.0, the data exchange is the most important feature of a cyber-physical system [9]. The lack of transparency in information exchange results in delayed interoperability of the manufacturing system. As the global market becomes increasingly competitive, the ability to mass customize products are needed as standardized products are less in demand [10]. This further increases the need for interoperability of manufacturing systems in order to be able to promptly respond to market changes. For this reason, this thesis is intended to improve the interoperability of the manufacturing system designed to fabricate frame assemblies.

1.2 Motivations

While BIM-OSC integration is still under development in the construction industry, the integration of product design models and manufacturing resources have attracted drastic amount of interest by those involved in the machining of mechanical parts. Computer-aided process planning (CAPP) facilitates information exchange and bridges the gap between computer-aided design (CAD) and computer-aided manufacturing (CAM). The main task of CAPP is to send detailed manufacturing instructions to the manufacturing machines. Over decades of development, various branches of CAPP have evolved. Among all the categories, feature-based technologies have been a central topic for CAPP [11]. In the feature-based approach, the geometrical and topological features of the part are examined and converted to manufacturing instructions [11, 12].

Several challenges are encountered in the process towards achieving automated process planning using CAPP technologies. First, the BIM models of frame assemblies do not provide manufacturing information. Furthermore, geometric features in frame assemblies are formed differently from that of mechanical part. In machining, the geometric features are usually where the material is to be removed. Whereas in manufacturing frame assemblies, the features represent intersections where joining processes are needed. This makes implementing CAPP technologies into construction manufacturing extremely difficult. Moreover, frame assemblies manufacturing is experienced-based, and no manufacturing rules are formally defined. In addition, based on a review of the literature, it can be concluded that no system exists currently to determine if a frame assembly can be fabricated given its BIM model and the machine specifications. As a result, process planning of frame assemblies manufacturing is manual, time consuming, experience-based, and extremely sensitive to product changes. As the global market becomes increasingly competitive, customized products are in demand compared to standardized products [10]. The information interoperability of the manufacturing system must be improved to satisfy this requirement.

In summary, a BIM-based, automated process planning system is in demand for frame assemblies manufacturing. To achieve this long-term objective, the first step is to develop a BIM-based, automated machine eligibility determination system for frame assemblies manufacturing.

1.3 Research Objectives

The objectives of this thesis are outlined as follows:

1. Develop knowledge models that represent experience gained from practice with respect to manufacturing frame assemblies. By defining the relationships between classes of different objects, manufacturing rules are to be formulated;

2. Develop an automated decision support system that determines whether a particular machine has the eligibility of manufacturing 2D wood frame assemblies using the given BIM models and knowledge gained from practice;

3. Extend the applicability of the decision support system to consider 3D geometric features of frame assemblies.

1.4 System Architecture

To achieve the aforementioned objectives, the overarching framework and general methodologies are outlined below.

1.4.1 System framework

In frame assemblies manufacturing, building elements are assembled and connected. In general, manufacturing operations are needed at the locations where building elements intersect. Given the geometric descriptions of intersections, feasible manufacturing operations can be determined based on the manufacturing rules. If a machine has the appropriate systems to carry out the required manufacturing operations, it can be concluded that the machine is capable of fabricating the frame assembly, and is therefore selected for manufacturing the frame. The system that determines the machine eligibility is named "Machine Eligibility Determination System" and is abbreviated as "MEDS".

The system architecture of this research is presented in Figure 1.1.

1.4.2 Knowledge modeling for frame assemblies manufacturing

In Chapter 2, intersections of frame assemblies and related manufacturing operations are formulated using ontology as product and operation formulation, respectively. Ontology is chosen to define and integrate different systems and formulate manufacturing rules. As such, any component related to frame assemblies manufacturing activities can be integrated and accessed freely. As a result, the interoperability of the system is improved. The intersections are geometrically defined and categorized. To determine the relationship between geometric features and feasible manufacturing op-

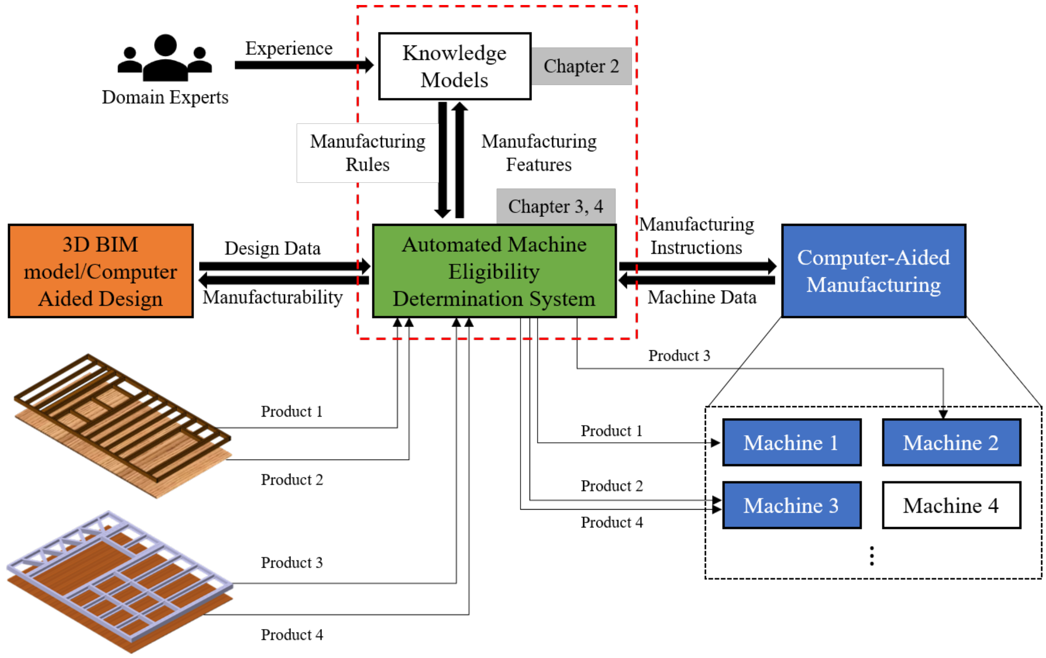


Figure 1.1: System architecture of the research project.

erations, manufacturing rules are formulated by specifying class relationships between product and operation formulations. As such, feasible manufacturing operations can be queried given the mathematical description of intersections. This approach is used in Chapter 3 and Chapter 4.

1.4.3 MEDS: wood frame assemblies manufacturing

In Chapter 3, the general framework (i.e., MEDS) for determining machine eligibility suitable for wood frame manufacturing is presented. Intersections in a frame assembly vary depending on the building elements used to construct the frame. For a wood frame, the intersection between two wood elements is the contact area referred as the "mating plane". The mating planes are geometrically detected and categorized based on the product ontology formulation. Using the previously formulated manufacturing rules, the feasible manufacturing operations and manufacturing locations are determined. By comparing the manufacturing locations to the manufacturing range of an appropriate machine, the machine's eligibility with respect to manufacturing the frame assembly are determined. The MEDS is validated using two wood frames with different complexities on the wood framing machine developed at University of Alberta. The results show that the system accurately determines if a user-selected machine can manufacture a construction product (i.e., wood frame assemblies) pre-designed using a BIM software.

1.4.4 MEDS: steel frame assemblies manufacturing

In Chapter 4, MEDS is generalized to encompass 3D features of frame assemblies (such as ones in steel frame assemblies). In the case of a steel frame, one steel element is inserted into the other at the connection point. Consequently, the intersection between two steel elements is represented by the volume. Using the techniques of computational geometry, the input steel frame elements are processed and the intersection volumes are detected. Manufacturing locations are then extracted based on the intersection volumes. Using the framework outlined in Section 1.4.3, these manufacturing locations are compared to the region that an appropriate system/machine can perform operation in. As such, machine eligibility may be determined. The extended MEDS framework is validated using a steel frame on the steel framing machine also developed at University of Alberta.

1.5 Thesis Outline

The remainder of this paper-based thesis is organized as follows. Chapter 2 presents ontology formulations of product, operation and machinery that represent knowledge gained from experience. Chapter 3 describes the overall framework for developing the automated decision support system based on building information model (BIM) that determines the manufacturability of 2D wood frame assemblies. Chapter 4 generalizes the system from 2D to 3D space using techniques of computational geometry. Chapter 5 summarizes the advantages and limitations of the developed system and lays out a blueprint for future directions of automated process planning in frame assemblies manufacturing.

Chapter 2

Ontology-Based Knowledge Modeling for Frame Assemblies Manufacturing[1]

2.1 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 [4, 13]. 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 [14].

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 man-

[1] A version of the content of this chapter was published in *36th International Symposium on Automation and Robotics in Construction*, Banff, AB, Canada.

ufacturing 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 [15]. 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.

2.2 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 [16]. CAPP is used to interpret product design data by recognizing features on a part and translating them into manufacturing operation instructions [12]. 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 [17]. 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 [18].

In typical manufacturing processes, knowledge modeling has successfully enabled decision making systems to be defined for such purposes [19]. 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" [20]. 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 [21]. 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 [22]. 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 [23]. 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 [21].

2.3 Methodologies

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 domain, the proposed system architecture is shown in Figure 2.1. Three knowledge domains (manufacturing resource,

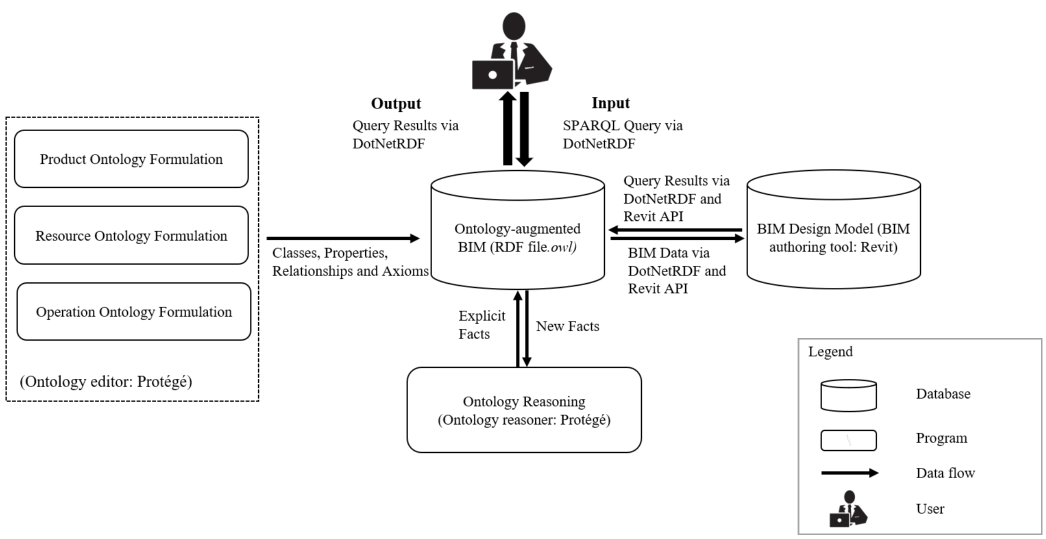


Figure 2.1: System architecture.

operation, and product) need to be incorporated to build the ontology-augmented BIM model. Each knowledge model is simplified in Figure 2.2. 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 machinery to be used to fabri-

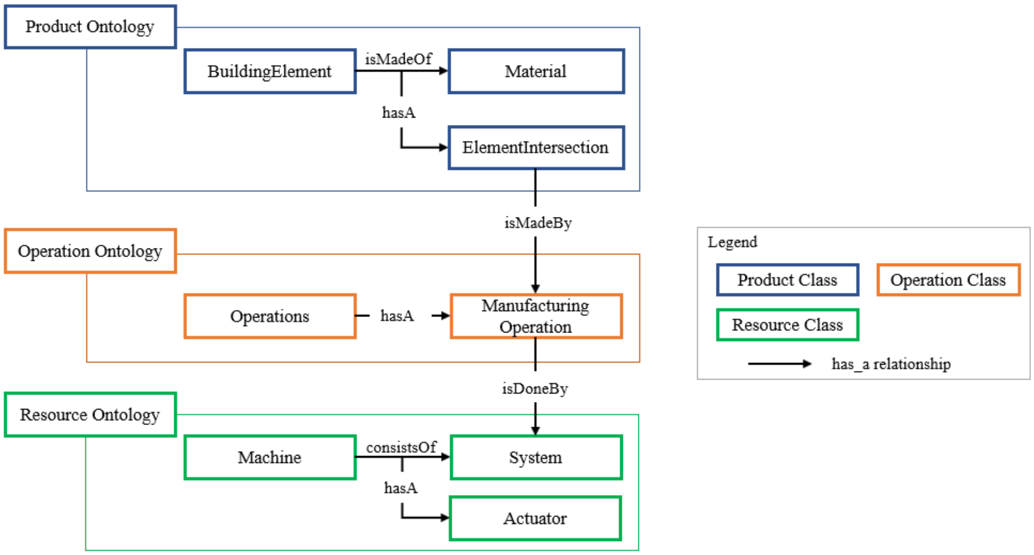


Figure 2.2: Product, Operation and Resource ontology models.

cate and assemble the products; (3) Operation class is then built to relate entities and resources. Once the knowledge domains are constructed, machine eligibility 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" [22].

2.3.1 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 [24]. 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 2.1: Intersections in wood frames

Intersection	**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

The above intersections are mathematically defined based on the criteria. As an example, "SP_TV" connection is shown below: Mathematically, the intersection "SP_-

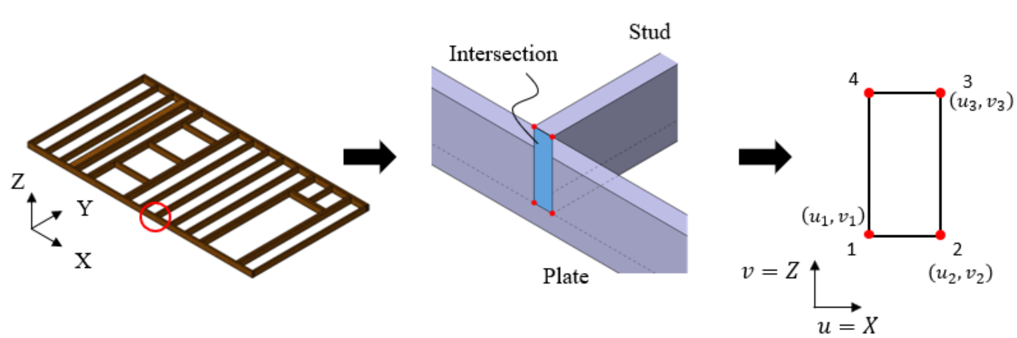


Figure 2.3: "SP_TV" connection.

TV" is defined as follows:

$$(E_1 \in \text{stud} \land E_2 \in \text{plate}) \land (v_3 - v_2 \geq u_2 - u_1) \land (u_1 \neq 0 \land u_2 \neq u_{max}) \tag{2.1}$$

Detailed mathematical definitions of intersections are listed in Appendix A. 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 2.4 shows the class hierarchy of wood element intersections.

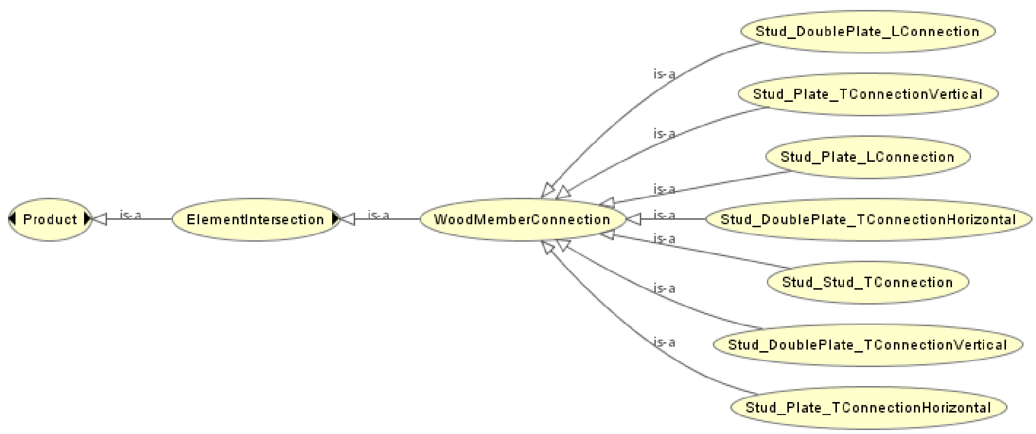


Figure 2.4: *WoodMemberConnection* class hierarchy.

Intersections in steel frame assemblies are categorized in a similar approach. The formulation of steel intersections varies since the intersections are 3D volume instead of 2D mating planes.

2.3.2 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 2.5.

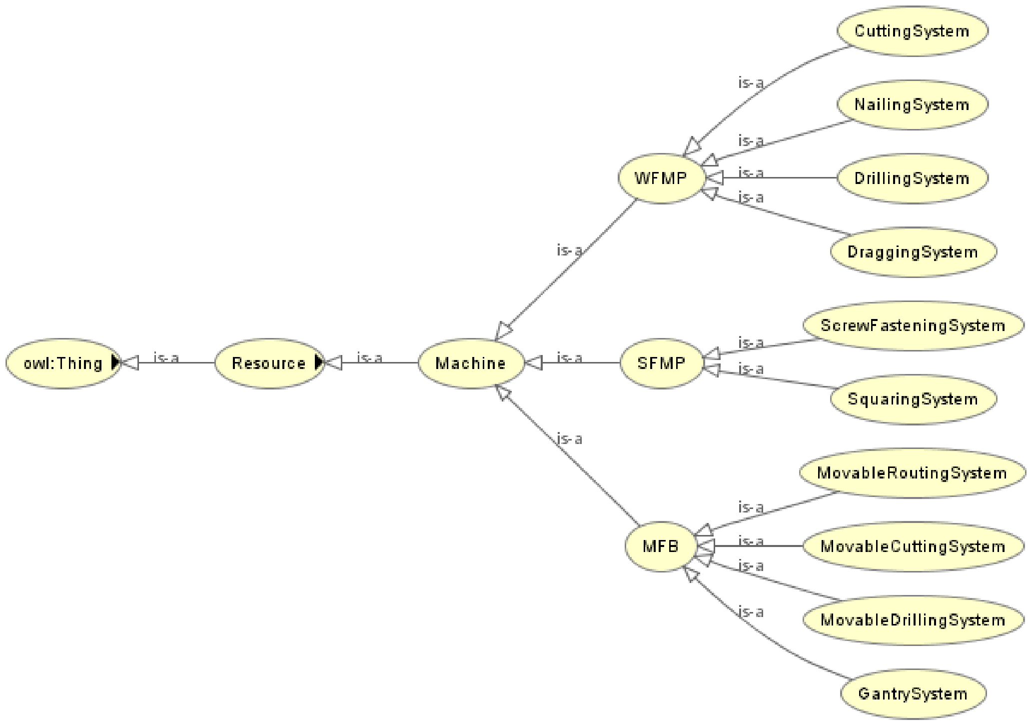


Figure 2.5: Resource ontology formulation.

2.3.3 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 2.6.

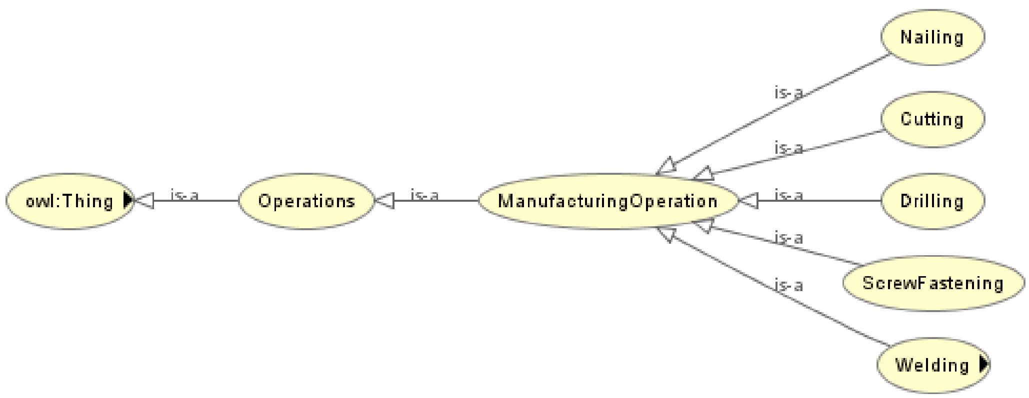


Figure 2.6: Operation ontology formulation.

2.4 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.

2.4.1 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 2.7 below. First, using the given information , material

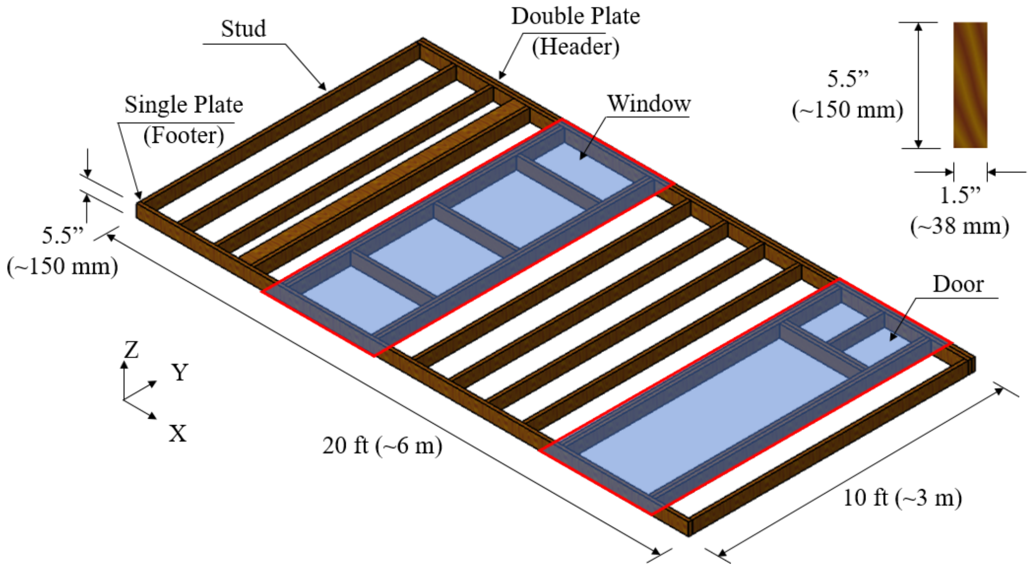


Figure 2.7: 3D representation of the wood frame used in case study.

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 2.8. For this wood frame, all types of intersections are identified and matched to the ontology formulation. These types of intersections are annotated in Figure 2.9 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.

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

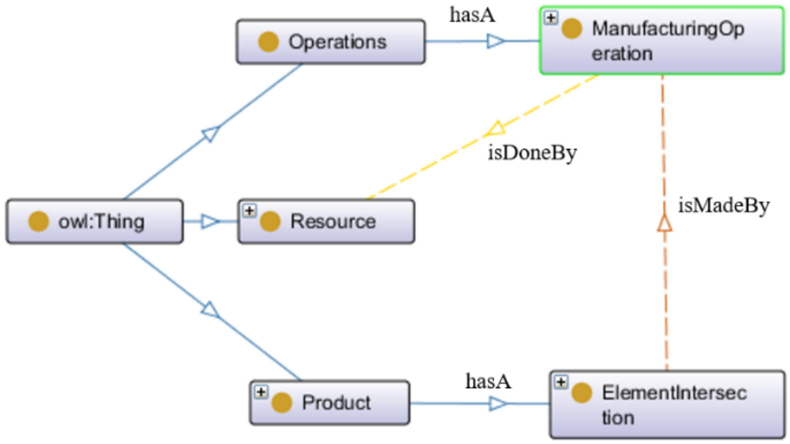


Figure 2.8: Class wood member intersections.

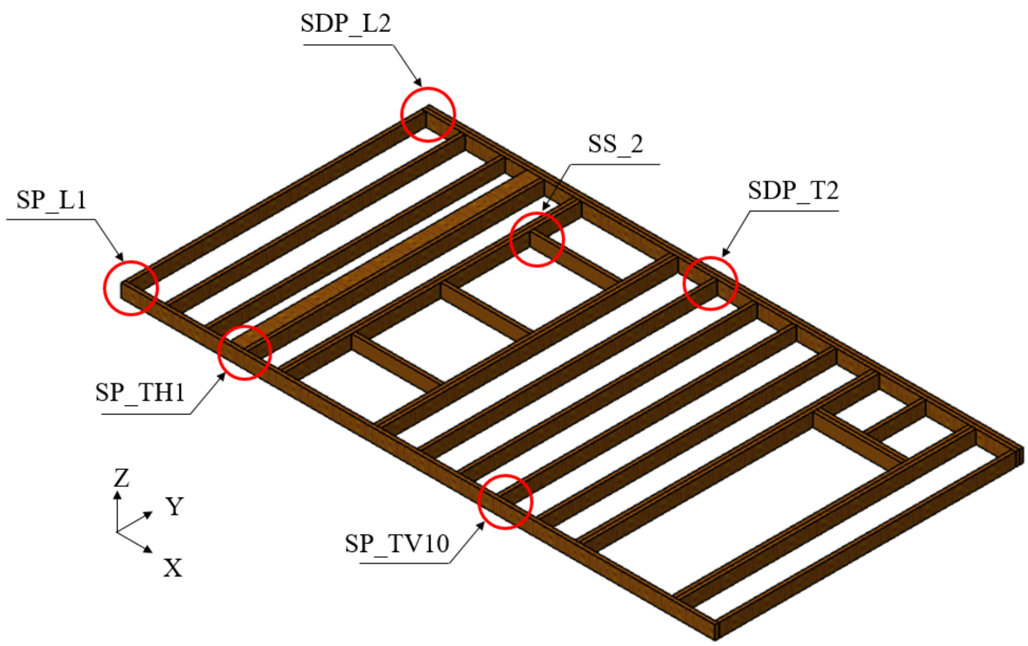


Figure 2.9: Intersections identified from provided wood frame.

consists of four independent systems: cutting, dragging, drilling, and nailing. These systems are modeled in Protégé as shown below in Figure 2.10. 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. After knowing element intersections and systems of the machine, the relationship among product assemblies and machine domains can be established by analyzing the

Table 2.2: Connections in wood frame panel

Intersection	**Notation**
Stud_Plate_LConnection	SP_L1
Stud_Plate_-TConnectionVertical	SP_TV10
Stud_Plate_-TConnectionHorizontal	SP_TH1
Stud_DoublePlate_-LConnection	SDP_L2
Stud_Stud_Connection	SS2
Stud_DoublePlate_-TConnectionVertical	SDP_TV2

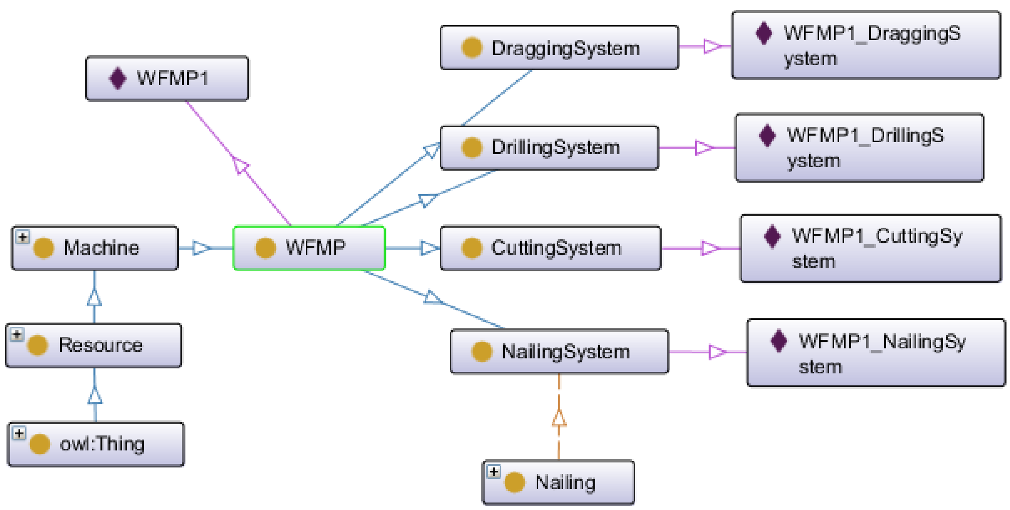


Figure 2.10: Systems of the WFMP.

manufacturing operations needed to make such product assemblies. Based on expert knowledge, wood members with intersections presented in Table 2.2 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. Analyzing all the intersections in the wood frame, only screw fastening and nailing operations are feasible options for

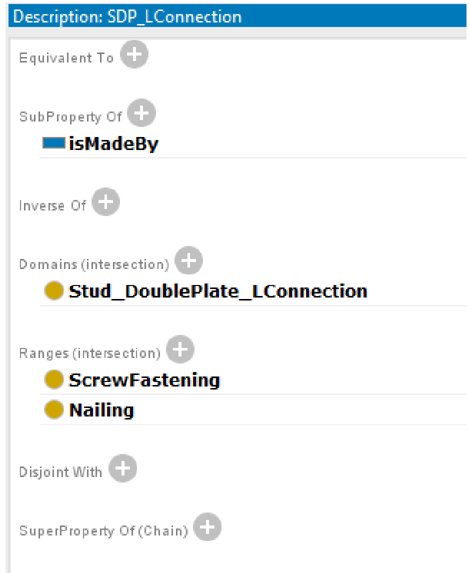


Figure 2.11: Object Properties of SP_LConnection.

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.

2.4.2 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.

2.5 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.

Although the developed ontology formulation can determine manufacturing operations based on the intersections, it does not extract the intersection information from the BIM models of frame assemblies. To achieve automated process planning, detection of intersections must be carried out automatically. In the next chapter, an automated machine capabilities determination system will be presented that not only automatically detects the intersections in 2D wood frame assemblies, also determines if a machine can perform required manufacturing operations.

Chapter 3

Machine eligibility decision support system: 2D wood frame assemblies manufacturing[1]

In Chapter 2, an ontology model is presented to obtain feasible manufacturing operations given the intersections of a frame assembly. While the intersections are mathematically defined, the ontology model does not extract these intersections from the BIM model. This paper proposes a BIM-based framework for automating the evaluation of machine eligibility for the manufacturing of construction-oriented products. By identifying intersections of the building elements of the product, feasible manufacturing operations are determined and manufacturing locations are calculated. These locations are then compared to the manufacturing capabilities of the machine. The proposed approach is validated using two wood frame assemblies. The results show that the system accurately determines whether a user-selected machine can manufacture a construction product pre-designed using BIM software.

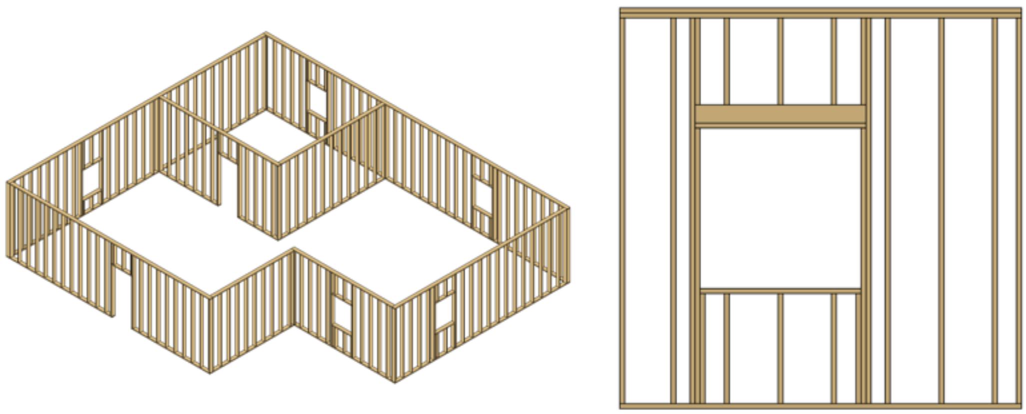
[1]The content of this chapter was submitted to *Automation in Construction*, at the time of submission of this thesis.

3.1 Introduction

3.1.1 Background

Recent technological advancements in offsite construction has resulted in frame panels becoming increasingly popular in North America. Traditionally, frames are constructed manually on-site and assembled on-site. These frame construction processes are labour intensive, time consuming, prone to error, weather dependent, and lack precision. Using offsite construction methods, wall frames are prefabricated in a factory environment and shipped to the construction site. Due to the controlled factory environment, offsite construction dramatically increases the productivity, quality, and deliverability of the products [3]. Through the use of industrial automated machines in the framing processes, the productivity of frame assembling increases greatly. An example of wood partial wood frame residential house along with a typical wood frame is shown in Figure 3.1. The house structure shown in Figure 3.1 (a) consists of multiple modular frames as shown in Figure 3.1 (b). Each wood frame consists rectangular lumber with various lengths. Before framing the wood panel as shown in Figure 3.1 (b), timbers are first cut to length based on the manufacturing drawing. Then the building elements are placed in the correct locations based on the drawing. Finally, the intersections between the elements are secured using nailing or screw fastening operation.

To produce frame assemblies, panel structures must be fully described. The detailed specifications of frame assemblies, such as overall dimensions and composed components, is commonly given by the building information model (BIM). According to the National Institute of Building Sciences, BIM is "a digital representation of physical and functional characteristics of a facility" [24]. While BIM provides detailed specifications of construction-oriented products, the integration of BIM with manufacturing systems is still under development [5]. As an example, quantity take-off for construction oriented light-frame buildings may be automatically obtained from



(a) (b)

Figure 3.1: (a) BIM model of a partial residential house, and (b) typical wood frame used for residential building construction.

BIM information [21]. Similarly, the machinery, time and expenditure required to fabricate a construction-oriented product could be described in the BIM model and, therefore, would be instantly obtained in the early stage of design. This approach would ease the process planning for construction product manufacturing, which is an important step in optimizing the sequence of operations "where one-of-a-kind products or the same product are made infrequently" [25]. Wood panels, considering the limited diversity in the options given by designers, are one-of-a-kind products in most cases.

Presently, the lack of integration between manufacturing and BIM is overcome by expert knowledge and experience in different domains; however, this approach can be time consuming, subjective, and relies heavily on the knowledge of the experts. In addition, this lack of integration creates a barrier that inhibits information exchange between product designers and manufacturers and adds to the cost to produce a product due to increased communication overhead. Consequently, an automated, cost-effective and real-time decision-support system is in demand in offsite construction facilities that specialize in panelized construction.

Frame assemblies are complex products because of their diverse structural compositions and heterogeneous materials. As a result, the manufacturing activities required to make such products are also complex and the interactions between the products and manufacturing systems present many challenges. Due to the complex nature of these domains, it is unrealistic to develop, initially, a system that accounts for every aspect of the BIM-manufacturing relationship. As a first step, this paper aims to integrate BIM and manufacturing systems by developing an automated decision-support system for the manufacturing of wood-frame assemblies. Since wood frames are composed of 2D manufacturing features, a 2D framework is chosen to be developed.

3.1.2 Related Work

Offsite construction provides an efficient, productive, safe, and less labour intensive construction environment thanks to controlled factory environment [26]. Implementation of BIM for offsite construction further enhances the productivity and quality of construction-oriented products in the manufacturing stage. Malik *et al.* extracted product information from the BIM model and generated near-optimized tool paths for automated light-gauge steel framing [17]. Martinez *et al.* proposed a vision-based real-time inspection system for steel frame manufacturing. The proposed framework successfully improves the accuracy of the steel framed panel by comparing the real and the nominal geometries obtained from the BIM model and providing automatically generated instructions to the operator [18]. Although intensive research has been conducted on BIM and offsite construction, integration between the two fields is still under development [5]. The information required from the BIM model to enable offsite construction is yet not fully available, namely the manufacturing instructions for the construction products are still not linked within the BIM environment [27]. The existing approach in the manufacturing of construction products is a sequential process that includes an incredible amount of manual work; the overall process is presented in Figure 3.2. All the necessary 2D manufacturing drawings are created based on the BIM model and manual process planning must be completed before manufacturing. This one-way process has no instant feedback mechanisms, i.e. any necessary changes required in the manufacturing stage will need to be manually communicated to the design personnel. Several disadvantages are observed in the existing approach: 1) both the creation and interpretation of 2D drawings are time consuming and error-prone; 2) manufacturing engineers must be familiar with both the products and the manufacturing resources to perform proper process planning; 3) manufacturability of frame assemblies is not transparent due to the bottleneck in the flow of information; and 4) the manufacturing system is extremely sensitive to product changes as updates to the process planning are required for even minor changes applied to the products. As the global market becomes increasingly competitive, mass customization of products, including the frame assemblies, is in demand compared to standardized ones [10]. Mass customization requires information transparency and decentralized decision making of manufacturing systems [28].

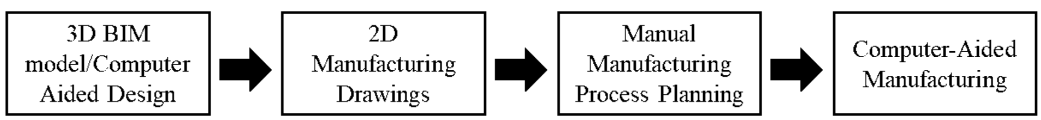


Figure 3.2: Current BIM-based frame assemblies manufacturing.

In manufacturing, computer-aided process planning (CAPP) is the use of computer technology to assist the process planning for the manufacturing of a part or a product [25]. CAPP is a crucial activity to bridge and integrate Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM). It converts various requirements (such as functional and mechanical requirements) of a product into manufacturing instructions [29]. As a critical intermediate step, CAPP has attracted an increasing amount of research interest in the past few decades [11]. As reviewed by Xu *et al.*, feature-based technology, among various categories in CAPP research, has been a major topic for CAD/CAM integrations as well as for CAPP systems [11]. In feature-based approaches, topological and geometrical features of a part are interpreted and are translated into manufacturing operations. While CAPP has been developed to provide detailed manufacturing instructions of a mechanical part, limitations are encountered when applying CAPP to construction-oriented products. In contrast to sophisticated geometries of mechanical parts, the geometries of the parts of frame assemblies are primitive. For example, the building elements of wood frames are rectangular prisms. Challenges arise when assembling these building elements into frames. Manufacturing operations are rarely needed for individual parts, instead, securing all the different elements of the frame in the correct location, orientation and sequence is required. Consequently, planning of the manufacturing processes is needed for construction-oriented products.

Robust process planning is built using the knowledge of domain experts [11, 19]. Knowledge-based systems are also needed as construction engineering is heavily governed by experience. Ontology, as defined by Gruber, is "an explicit and formal specification of a conceptualization" [20]. As reviewed by An *et al.*, ontologies can be used for knowledge modeling because: 1) they offer interoperability of knowledge from different domains; and 2) they support consistency checking [27]. Jardim-Goncalves *et al.* proposed the knowledge framework "funStep" using ontologies to improve the interoperability of manufacturing systems [30]. Lemaignan *et al.* proposed the framework MASON (MAnufacturing's Semantics ONtology) to manage the knowledge in manufacturing environment using ontologies [22]. In construction, specifically, ontologies have been proven useful in extracting information from BIM for practical use. Zhang *et al.* extracted BIM information of construction materials and related job hazards involved in construction activities using ontology formulation [23]. By modeling tasks, methods, and the job hazards involved in construction activities using ontology, the developed system provides automated job hazard analysis, which significantly improves the efficiency of project management tasks [23]. Liu *et al.* proposed an ontology-based semantic approach that extracts quantity take-off information of construction-related activities [21]. Using the proposed framework, construction practitioners can readily obtain and visualize the materials needed for construction activities [21]. Recently, and following the ontological model MASON, a knowledge model was built by An *et al.* that effectively determines manufacturing operations based on BIM model of construction-oriented products [27].

To summarize, using BIM as the source of information with current expert knowledge organized using ontologies, a system is needed to automatically determine the machine capabilities for manufacturing 2D wood frame assemblies and to facilitate process planning in offsite construction. The remainder of this paper is organized as follows: Section 3.2 illustrates the proposed system framework in detail; Section 3.3 presents the experimental setup used for validation of the proposed methodology; Section 3.4 presents the simulation results; Section 3.5 discusses the implications of the results and the limitations of the proposed framework; and, finally, Section 3.6 concludes by presenting tangible results and discusses the future directions of the proposed system.

3.2 System Framework: Machine Eligibility Determination System (MEDS)

The system presented aims to determine if any wood frame assembly can be manufactured by a machine using the product information pre-generated in the building information model (BIM) and the given machine specifications. The proposed system is presented in Figure 3.3, where the architecture can be divided into four modules: 1) BIM data input; 2) mating plane detection algorithm; 3) ontology formulation; and 4) machine eligibility determination. The proposed framework is developed and implemented using Python programming language. Python is chosen for the following reasons: 1) Python is an open environment that allows rapid programming, 2) allows the user to quickly read, process and modify data, and 3) has graphical libraries that allow complex simulation and visualization.

In the proposed framework, the four modules are applied sequentially. First, the BIM data input module involves retrieving the relevant geometric information of the

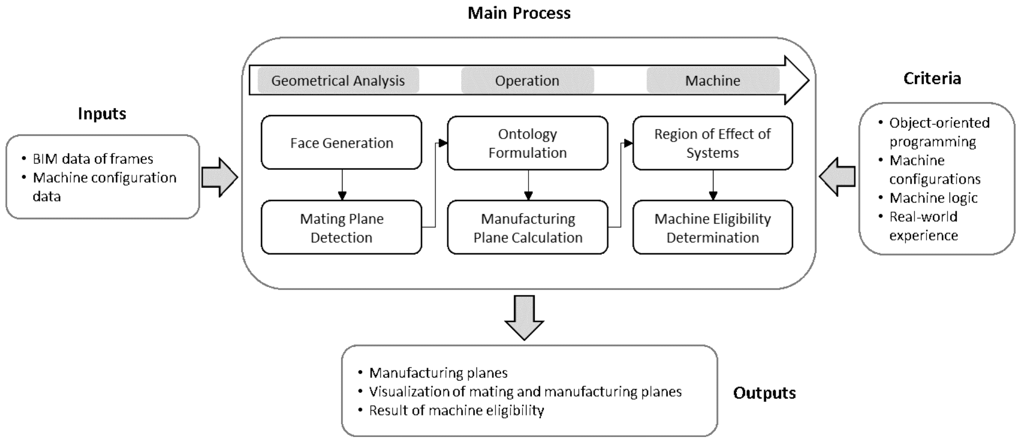


Figure 3.3: MEDS system framework overview.

modelled construction-related product from a pre-designed 3D BIM model software, such as Autodesk Revit. The input required for geometry interpretation are the coordinates of each building element (such as studs and plates). The completion of this stage generates coordinates of points that define the planes of all building elements and the unit normal of each plane. A wood frame is re-constructed in simulation environment based on BIM data.

Once planes and their directions are known, these data are fed into the second module named mating plane detection algorithm (MPDA). Mating planes refer to areas where building elements are in contact with each other. While mating planes are directly related to any frame product manufacturing operations, they are currently not available in the BIM model. After running MPDA on the generated wood frame, all the mating planes are detected and generated.

The mating planes are then mapped to predefined formulations stored in the ontology model. Ontology stores the knowledge that construction personnel have gained throughout their experiences. It takes the types of mating planes and determines the feasible operations required to fabricate such frame assemblies.

Having determined the manufacturing operations, systems that can carry out such operations are determined. A machine that possesses such systems will be then selected. The machine eligibility determination module is responsible for determining if a particular machine can perform the required manufacturing operations. Upon completion of this stage, the user of the proposed framework will have a clear understanding as to which manufacturing operations the selected machine may apply to the designed wood frame.

The subsections that follow will provide details about the proposed system framework.

3.2.1 BIM Data Input

BIM models provide a thorough set of information about the designed construction product. The 3D geometry of a construction-oriented product, for example, is an important subset of BIM. In Autodesk Revit, each component of the model is referred to as a building element. A building element is a 3D geometry model that is part of the building. Examples of building elements include walls, windows, doors, and roofs *etc.* [31]. Figure 3.3 shows the BIM model of a residential house and a randomly selected wood frame from the presented residential house.

Initially, for any wood panel, detailed geometrical data are required to deeply understand the manufacturing process that would be required to fabricate it. As investigated by Liu *et al.*, 'Element ID', element 'MaterialSet' and 'LocationPoint' coordinates can be extracted from every building element [21]. The relevant information adapted from the proposed Revit API unified modeling language (UML) diagram is shown in Figure 3.4 [21]. Using these location points from the BIM model, the geometry of each building element of the panel, such as faces, can be reconstructed in simulation environment. As only a very small fraction of the information that BIM can provide is useful for the purpose of this study, the relevant building element location points are downloaded into a Python-based simulated environment to downsize the computational power required, although programming the proposed software in the Revit application programming interface (API) environment should ultimately be done. The pseudo code to generate all the faces of each element is as follows.

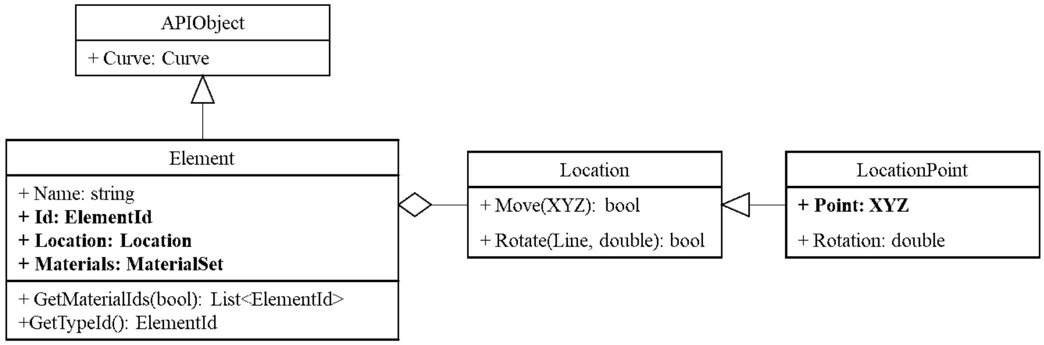


Figure 3.4: UML diagram of Autodesk Revit building elements [21].

1. Get all the unique identifiers (such as 'P01' for plate) from the BIM model. This provides the total quantity of building elements.
2. Select one identifier and filter the data using this identifier. The output should be 8 rows of data as there are 8 points in a building element.
3. Select one row and get the coordinate $P_1 = (x_1, y_1, z_1)$.
4. Select the rest of the points with the same x-coordinate (x_1). This should output the coordinates of 4 points which define one face F_1 of the element.
5. Repeat step 4 with y and z-coordinate (y_1 and z_1, respectively). This will give us 2 additional planes F_2 and F_3.
6. Select diagonal point P_2 with respect to P_1.
7. Repeat steps 4 and 5 with P_2. This should give us 3 mutually perpendicular planes F_4, F_5, and F_6.
8. Repeat steps 2 to 7 for the rest of building elements.

After generation of faces, the generated faces of each element are arranged as follows:

$$[identifier, material, \begin{bmatrix} F_1 & F_2 & F_3 & F_4 & F_5 & F_6 \end{bmatrix}^T]$$

$$F_i = \begin{bmatrix} P_{i1} & P_{i2} & P_{i3} & P_{i4} \end{bmatrix}^T \quad i = 1, ..., 6$$

$$P_{ij} = (x_{ij}, y_{ij}, z_{ij}) \quad j = 1, ..., 4$$

where F_i is the ith face of a building element, P_{ij} is the jth point of face i, and (x_{ij}, y_{ij}, z_{ij}) is the 3D coordinate of point P_{ij}. Once all the faces of each building element are identified, the coordinates of points are ordered counter clockwise. This is required for successive tasks, such as constructing two local mutually perpendicular vectors in one face.

3.2.2 Mating Plane Detection Algorithm (MPDA)

Since construction-oriented product manufacturing involves assembling building elements, the assembly of building elements needs to be permanently connected. A mating plane is defined as the common area of two building elements in contact with each other. Mating planes of a product are where hard connections happen. For the proposed system to decide whether a machine can manufacture a product by securing the connections, the system first needs to know the locations of all the mating planes. Automatic detection of the mating planes is therefore needed for each product. Mating plane detection algorithm (MPDA) consists of two parts: plane intersection detection and mating plane determination. Plane intersection detection is used to find out if two planes have the potential to intersect. Mating plane determination is used to calculate the exact location of each mating plane. Note that MPDA only applies to mating planes that are in parallel to xy plane, yz plane or xz plane.

Plane Intersection Detection

Let A and B be two planes of two different building elements. If they intersect, knowing their direction and the distance between them is needed. The direction of each face is represented by a unit normal vector, $\vec{u}$, and is calculated using Equation (3.1):

$$\vec{u} = \frac{\vec{a} \times \vec{b}}{\left|\vec{a} \times \vec{b}\right|} \tag{3.1}$$

where $\vec{a}$ and $\vec{b}$ are two non-parallel vectors in the face constructed using the points that define the face as shown in Figure 3.5. The distance between A and B, d_{AB}, is calculated using Equation (3.2):

$$d_{AB} = \vec{v} \cdot \vec{u} \tag{3.2}$$

where $\vec{v}$ is a vector formed by connecting 2 points, one from each plane, as shown in Figure 3.5.

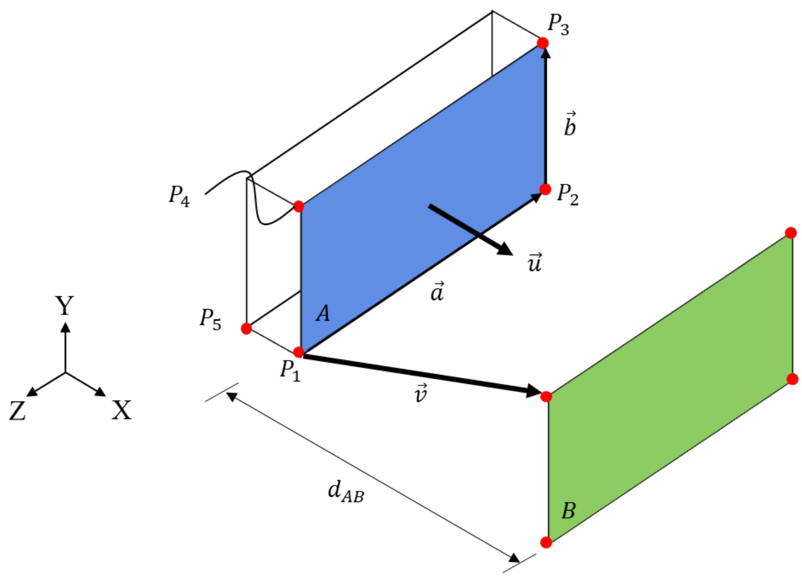


Figure 3.5: Graphical representation of plane intersection detection.

For any two intersecting planes A and B of two different building elements, the conditions in Equation (3.3) and Equation (3.4) must be satisfied. Equation (3.3) forces planes A and B to be parallel to each other and in opposite direction, and Equation (3.4) ensures that the distance between both faces, A and B, is zero. Equation (3.3) and Equation (3.4) are shown below:

$$\vec{u}_A \cdot \vec{u}_B = -1 \tag{3.3}$$

$$d_{AB} = 0 \tag{3.4}$$

Note that Equation (3.3) and Equation (3.4) are necessary but not sufficient to guarantee an intersection between planes A and B. The following section calculates the potential overlap between planes A and B.

Mating Plane Determination

Once two planes A and B from different building elements satisfy Equation (3.3) and Equation (3.4), possible relationships could be established: 1) containment, 2) partial intersection, 3) full intersection and 4) no intersection. These relationships are illustrated in Figure 3.6. For the intersection between planes A and B to generate a mating plane, Equation (3.5) must be satisfied:

$$A \cap B \neq \phi \tag{3.5}$$

To validate each intersection generated by every pair of planes within a product,

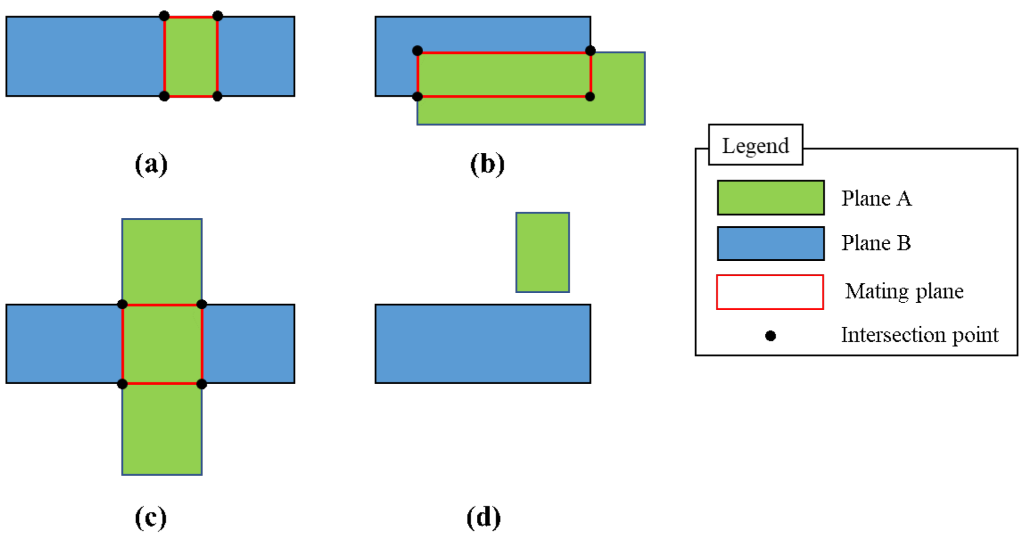


Figure 3.6: Potential relationships between any two faces: (a) containment, (b) partial intersection, (c) full intersection and (d) no intersection.

several sequential steps are required. As stated in Section 3.2.1, points in every plane are ordered counter clockwise. A local coordinate system of each plane is generated by constructing two mutually perpendicular vectors using three successive points in that plane using Equation (3.6) and Equation (3.7):

$$\vec{u}_A = \vec{n}_{A,12} \quad \vec{v}_A = \vec{n}_{A,23} \quad \vec{u}_B = \vec{n}_{B,12} \quad \vec{v}_B = \vec{n}_{B,23} \tag{3.6}$$

$$\vec{n}_{X,ij} = \frac{P_j - P_i}{|P_j - P_i|} = \frac{(x_j - x_i, y_j - y_i, z_j - z_i)}{\sqrt{(x_j - x_i)^2 + (y_j - y_i)^2 + (z_j - z_i)^2}} \tag{3.7}$$

where $\vec{u}_A$ and $\vec{v}_A$ are mutually perpendicular and form a local coordinate system S_A of plane A, and $\vec{u}_B$ and $\vec{v}_B$ are mutually perpendicular and form a local coordinate system S_B of plane B. Let S_A be the reference coordinate system. Three possible relationships exist between S_A and S_B: a) S_B is parallel to and in the same direction as S_A, b) S_B is parallel to but in the direction opposite to that of S_A, b) S_B is perpendicular to S_A counter-clockwise, and d) S_B is perpendicular to S_A clockwise. These relationships are depicted in Figure 3.7. To find the boundaries of a potential mating plane, both coordinate systems, S_A and S_B, must be aligned in the same direction as in case (a). The goal is to have S_A and S_B parallel and in the same

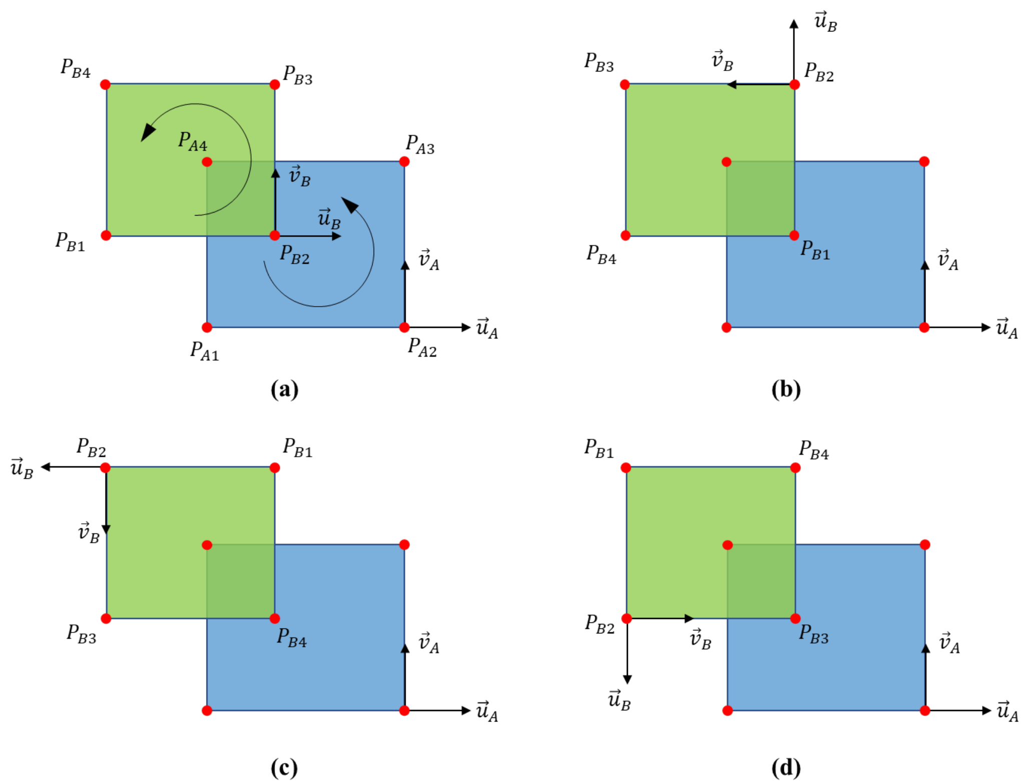


Figure 3.7: (a) S_B and S_A are parallel and in the same direction, (b) S_B is 90° counter-clockwise from S_A, (c) S_B and S_A are parallel and in the opposite direction, and (d) S_B is 270° counter-clockwise from S_A.

direction (case (a)). Therefore, for all the other mentioned relationships between S_A

and S_B, points in plane B need to be re-ordered using Equation (3.8):

$$\begin{bmatrix} P_{B1}^* & P_{B2}^* & P_{B3}^* & P_{B4}^* \end{bmatrix}^T = \begin{cases} \begin{bmatrix} P_{B4} & P_{B1} & P_{B2} & P_{B3} \end{bmatrix}^T & case(b) \\ \begin{bmatrix} P_{B3} & P_{B4} & P_{B1} & P_{B2} \end{bmatrix}^T & case(c) \\ \begin{bmatrix} P_{B2} & P_{B3} & P_{B4} & P_{B1} \end{bmatrix}^T & case(d) \end{cases} \tag{3.8}$$

Once boundaries of planes A and B are found, the points that define the construction lines of the boundaries of their intersecting area can be calculated using Equation (3.9):

$$\begin{aligned} \text{Left:} \quad L_I &= \begin{cases} P_{B1}^* & if \quad (P_{B1}^* - P_{A1}) \cdot \vec{u}_A \geq 0 \\ P_{A1} & if \quad (P_{B1}^* - P_{A1}) \cdot \vec{u}_A < 0 \end{cases} \\ \text{Right:} \quad R_I &= \begin{cases} P_{B2}^* & if \quad (P_{B2}^* - P_{A2}) \cdot \vec{u}_A \geq 0 \\ P_{A2} & if \quad (P_{B2}^* - P_{A2}) \cdot \vec{u}_A < 0 \end{cases} \\ \text{Top:} \quad T_I &= \begin{cases} P_{A3} & if \quad (P_{B3}^* - P_{A3}) \cdot \vec{v}_A \geq 0 \\ P_{B3}^* & if \quad (P_{B3}^* - P_{A3}) \cdot \vec{v}_A < 0 \end{cases} \\ \text{Bottom:} \quad B_I &= \begin{cases} P_{B2}^* & if \quad (P_{B2}^* - P_{A2}) \cdot \vec{v}_A \geq 0 \\ P_{A3} & if \quad (P_{B2}^* - P_{A2}) \cdot \vec{v}_A < 0 \end{cases} \end{aligned} \tag{3.9}$$

The construction lines generated using Equation (3.9) are shown in Figure 3.8 (b). Intersecting points must satisfy Equation (3.10):

$$\begin{aligned} P_1 &= L_I + ((B_I - L_I) \cdot \vec{v}_A) * \vec{v}_A \\ P_2 &= R_I + ((B_I - R_I) \cdot \vec{v}_A) * \vec{v}_A \\ P_3 &= L_I + ((T_I - L_I) \cdot \vec{v}_A) * \vec{v}_A \\ P_4 &= R_I + ((T_I - R_I) \cdot \vec{v}_A) * \vec{v}_A \end{aligned} \tag{3.10}$$

where P_1, P_2, P_3, P_4 are vertices of the potential mating plane (as shown in Figure 3.8 (c)) and '*' is element-to-element multiplication.

Note that points may still be generated even if there is no intersecting area as shown in Figure 3.6 (d). Therefore, it is necessary to verify that these points are in both planes A and B. Using the unit normal determined using Equation (3.1), coordinates of relevant directions ξ and η are checked. As the wood frame elements are forcibly aligned with an orthogonal frame due to its inherent geometry and to simplify the

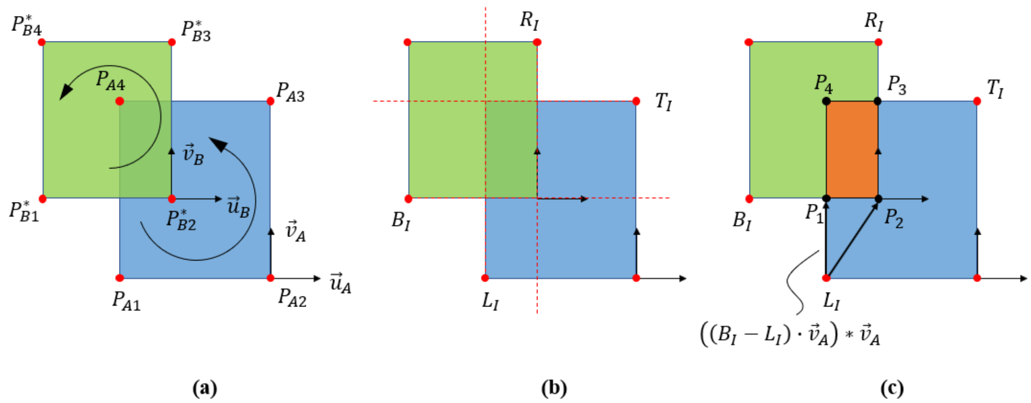


Figure 3.8: Determination of intersecting area: (a) re-ordering points in plane B, (b) construction lines of the mating plane for planes A and B, and (c) mating plane of planes A and B.

following equations, only coordinates within the xy, yz or xz planes will be checked. The containment relationship between the points P_i obtained from Equation (3.10) and plane A, and plane B, are checked using Equation (3.11):

$$\forall P_i \in A \wedge \forall P_i \in B, \quad i = 1, 2, 3, 4 \tag{3.11}$$

If Equation (3.11) is satisfied, it can be concluded that the mating plane exists between planes A and B. As a result, Equation (3.5) is satisfied. To summarize the process, Figure 3.9 shows the flowchart to determining all the mating planes of all the building elements contained in a BIM model.

Even if the MPDA criteria are satisfied, exceptions are made in the cases where 1) double-plate or double-stud is encountered, or 2) two side-by-side parallel studs with different dimensions are detected. Double-plate is formed when two identical plates are placed next to each other. Similarly, double-stud refers to two identical studs that are in contact with each other. While it is required to secure the connection between double-plate/double-stud, common practice is to treat the two elements as one and secure the combined element with the other elements it is in contact with. Therefore, if a double-plate is detected in MPDA, the possible mating plane between the two plates is ignored, and both plates are merged into one plate. In the case where two parallel studs that are side-by-side with different dimensions are detected, the mating

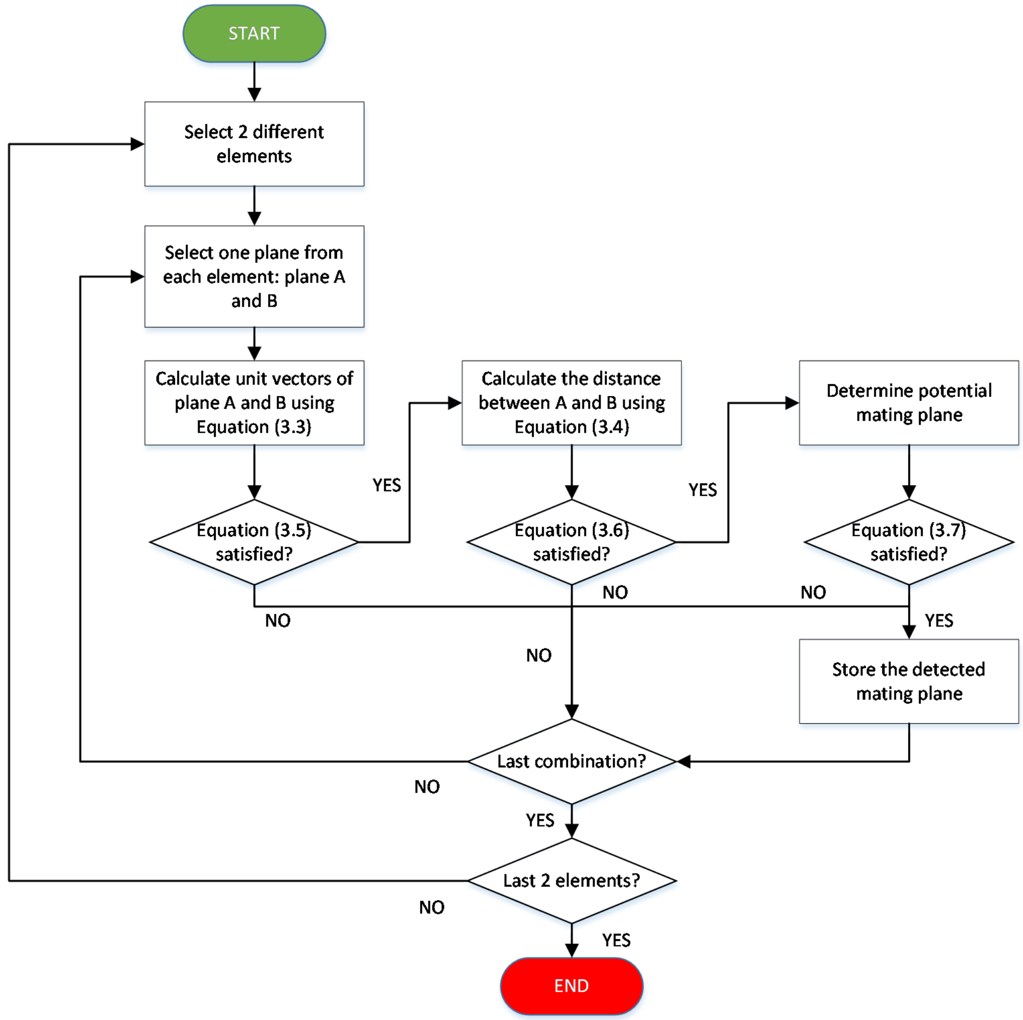


Figure 3.9: Intersection plane detection flowchart.

plane between the studs is ignored. Similarly, in the case of a double-plate/double-stud connection, it is not required to secure the two studs as they will be connected to other building elements. The two studs, however, are not merged due to the previous assumption that every building element is a rectangular prism.

3.2.3 Manufacturing Rules

In the knowledge model proposed by An *et al.*, product, operation and resource ontologies are formulated in Protégé (an open source ontology editor) [27]. Extending this proposed approach, mating planes determined in Section 3.2.2 are formulated and categorized as shown in Figure 3.10 (a). In the lowest level of class hierarchy shown in Figure 3.10 (a), the naming rules are as follows: 1) the first two letters represent two building elements involved in the connection, and 2) the integer in the third place refers to the number of the building element represented by the second letter. For example, the class 'SP2' represents a single stud and a double-plate connection. Typical components in a wood frame and the respective symbols are shown in Figure 3.10 (b).

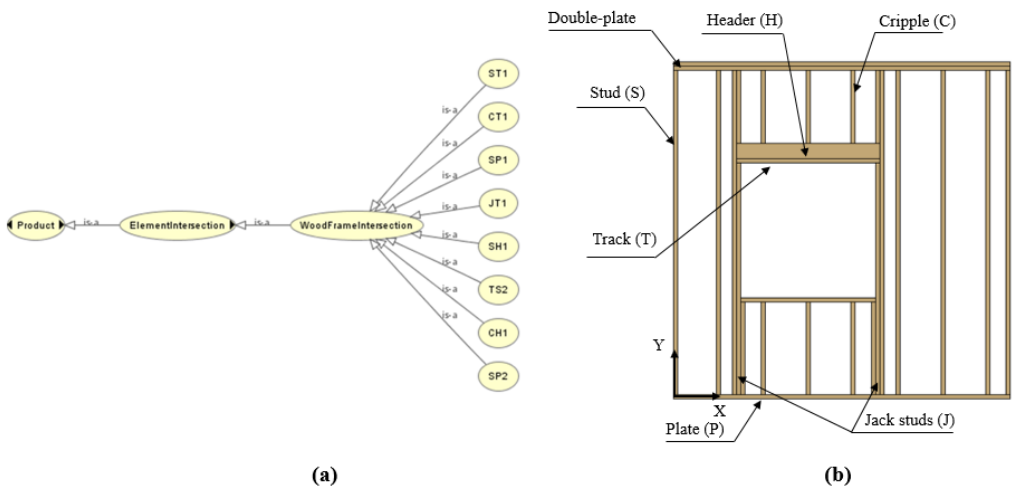


Figure 3.10: (a) Product ontology formulation of mating planes (wood frame intersections), and (b) building elements in a wood frame.

Based on the mating plane definitions, feasible manufacturing operations can be determined using the manufacturing rules defined in the ontology model. As proposed by An *et al.*, feasible manufacturing operations for the wood frame shown in Figure 3.10 (b) are nailing and screw fastening operations [27]. Nailing operation is popular for securing wood framing members due to the relative speed of the operation. The manufacturing operation is, therefore, manually overruled to be the nailing operation.

3.2.4 Manufacturing Plane Determination

Once the mating planes are detected using MPDA, they will be matched to the ontology formulation to determine the possible type of operations that are required to secure the connection. A manufacturing plane is the region where any manufacturing operation occurs. The locations of all the manufacturing planes are needed to simulate where the selected manufacturing operation will occur. The manufacturing plane is not only determined by the type of manufacturing operation, but also by the connection type. For example, a welding operation most likely would happen at the location of the mating plane whereas a nailing operation would take place at the most outer surface of the building element that the mating plane can be projected onto. In this study, nailing operations are applied to secure the wood frame elements. For a typical SP1 (single-stud-single-plate) connection, the manufacturing plane is calculated using Equation (3.12):

$$P_j = P_i + (x_m, y_m, z_m) * \vec{n}, \quad i, j = 1, 2, 3, 4 \tag{3.12}$$

where P_j is a point that defines the manufacturing plane, P_i refers to a point in the mating plane, $\vec{n}$ is the normal vector of mating plane, and x_m, y_m, z_m are the dimensions of the manufacturing part in x, y and z direction respectively. Figure 3.11 shows the procedure followed to generate a manufacturing plane from a mating plane.

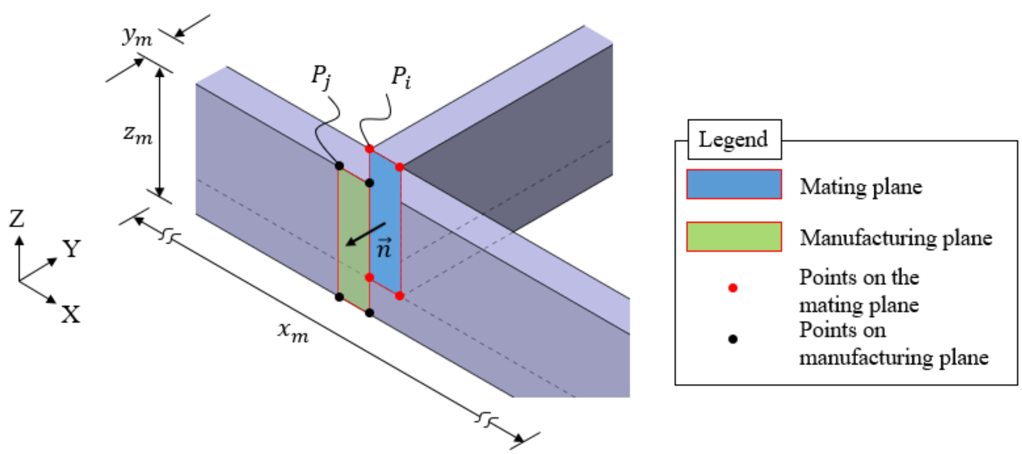


Figure 3.11: Mating plane and manufacturing plane.

In addition to the offset required based on the particular manufacturing operation, some types of connections also influence the location of the manufacturing plane. Based on the ontology formulation, SP2 connections occur when studs are connected to a double-plate, commonly two identical plates next to each other. As stated in Section 3.2.2, mating planes generated between two plates are ignored and both are merged into one plate. To prevent false projections of manufacturing planes, they are calculated based on the merged plate. This procedure is illustrated in Figure 3.12.

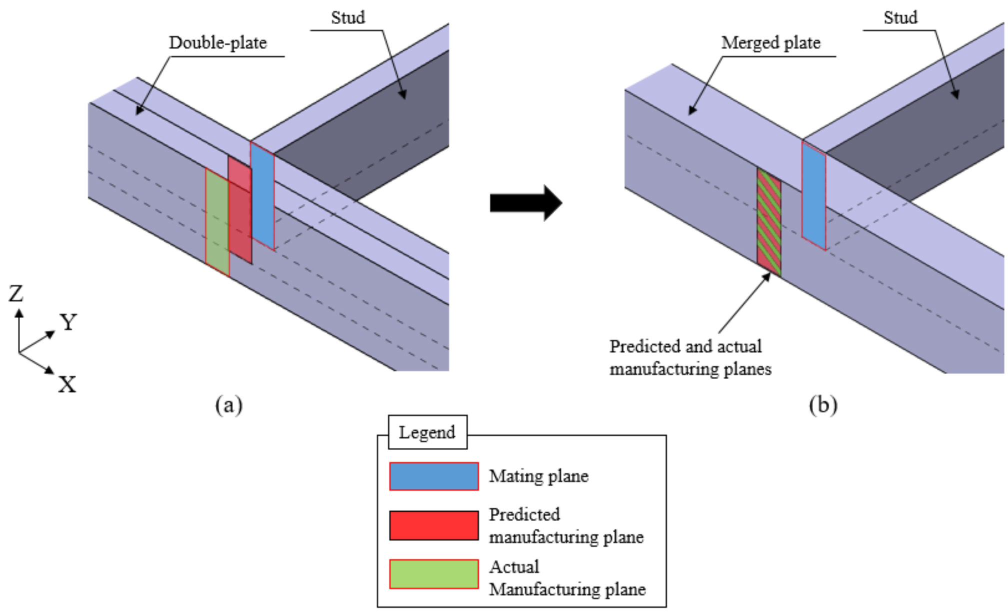


Figure 3.12: Mating plane and manufacturing plane.

The procedure is different when two parallel studs with different dimensions are encountered as the studs cannot be merged into a rectangular prism, such as king studs and jack studs located on doors. If any generated manufacturing plane is in contact with two building elements, it is relocated further to the outer surface of the building element.

3.2.5 Region of Effect of 2D Systems

Manufacturing operations are carried out by machine systems. The region in which a system can perform manufacturing activities is defined as the Region of Effect (ROE). Several factors can affect the ROE of a system and can be summarized into two categories: machine configurations and machine logic. Machine configurations are dictated by the physical infrastructure of the system. Once a machine is installed, physical parameters such as range of motion and work direction are fixed and cannot be changed unless important changes to the machine are made, such as upgrade of the actuators. Machine logic, however, dictates how the machine should operate. Although machine logic can be a limiting factor of the ROE of a system, changes to the machine logic are much easier to make. In addition, machine logic is subject to how the machine is set up and the limitations of the hardware. As a result, machine configurations control the ROE of a system and machine logic is ignored in this study.

The ROE of a 2D system that is subject to linear motion is limited by the range of motion of the actuator that drives the system. Linear motion can be achieved by directly using a linear actuator or converting a rotary motion driven by a rotary actuator to a linear motion. The range of motion of the system can be determined using a similar approach. To determine the range of motion of a actuator i, we need: 1) the coordinates of each mounting position, (x_{i0}, y_{i0}, z_{i0}); 2) the direction cosine of each linear actuator, $\vec{n}_i$; 3) the starting location of each actuator, (x_{i1}, y_{i1}, z_{i1}); and 4) the stroke of each actuator, L_i. The mounting position is needed to locate where the actuator is, while the direction cosine represents the orientation of the actuator in the reference frame. The direction cosine is defined by Equation (3.13):

$$\vec{n}_i = (cos\phi_i, cos\theta_i, cos\psi_i) \tag{3.13}$$

where ϕ_i, θ_i and ψ_i represent the rotation angles about the x, y and z axis, respectively. In this study, the linear actuators are aligned with x, y or z axes only. The starting location of each actuator is obtained from its specifications and is determined using Equation (3.14).

$$(x_{i1}, y_{i1}, z_{i1}) = (x_{i0}, y_{i0}, z_{i0}) + D_i \cdot \vec{n}_i \tag{3.14}$$

The end position of each actuator is calculated by adding the stroke of each actuator to the start position as shown in Equation (3.15):

$$\begin{aligned}(x_{i2}, y_{i2}, z_{i2}) &= (x_{i1}, y_{i1}, z_{i1}) + L_i \cdot \vec{n}_i \\ &= (x_{i0}, y_{i0}, z_{i0}) + (L_i + D_i) \cdot \vec{n}_i\end{aligned} \tag{3.15}$$

The above characteristic parameters of the linear actuators are represented in Figure 3.14. For a system S subjected to linear motion that is driven by a linear actuator

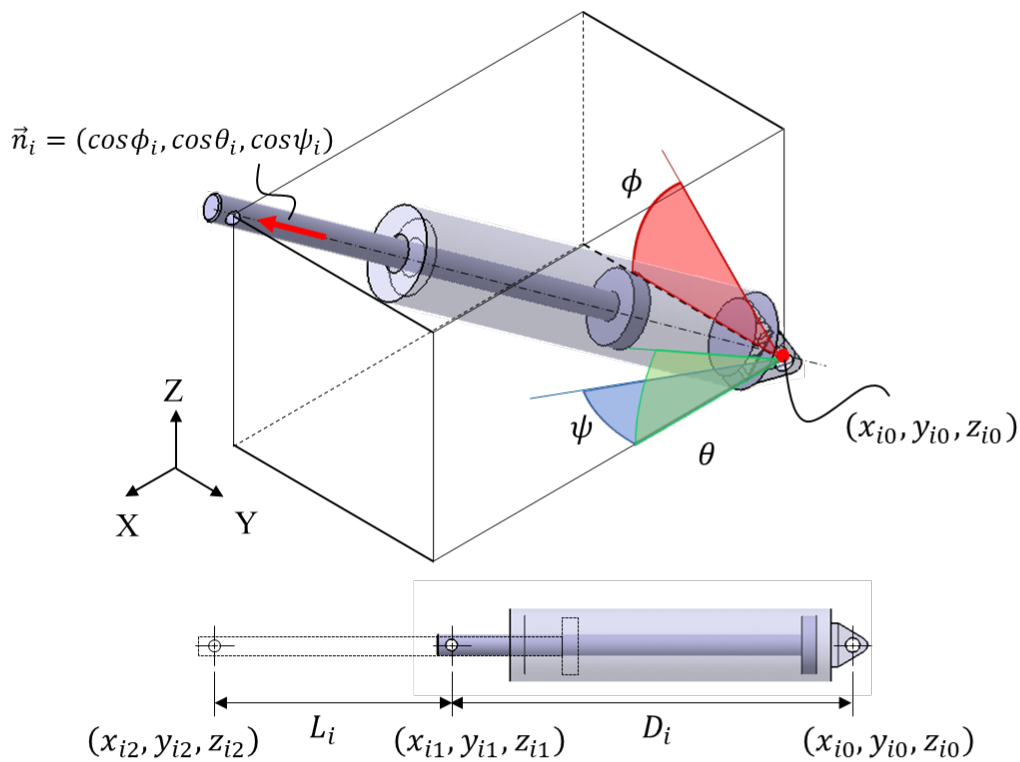


Figure 3.13: Range of motion of a linear actuator.

i, the ROE of the system S is a line segment defined by two points. This is given by Equation (3.16):

$$ROE_S = \begin{bmatrix} x_{i1} & y_{i1} & z_{i1} \\ x_{i2} & y_{i2} & z_{i2} \end{bmatrix} = \begin{bmatrix} R_{i1} \\ R_{i2} \end{bmatrix} \tag{3.16}$$

Note that all the ROE coordinates are aligned with the frame coordinates. If the system S is collaborating with the system driven by linear actuator j that can move in the direction perpendicular to that of S, the ROE of system S is a rectangle defined by four points which are formulated by Equation (3.17):

$$ROE_S = \begin{bmatrix} R_{i1} \\ R_{i2} \\ R_{i1} + R_{j2} - R_{j1} \\ R_{i2} + R_{j2} - R_{j1} \end{bmatrix} \tag{3.17}$$

Similarly, if the system S is collaborating with the third system driven by linear actuator k that can move perpendicular to both actuators i and j, the ROE of system S is a rectangular prism defined by eight points which are represented by Equation (3.18):

$$ROE_S = \begin{bmatrix} R_{i1} \\ R_{i2} \\ R_{i1} + R_{j2} - R_{j1} \\ R_{i2} + R_{j2} - R_{j1} \\ R_{i1} + R_{k2} - R_{k1} \\ R_{i2} + R_{k2} - R_{k1} \\ R_{i1} + R_{j2} - R_{j1} + R_{k2} - R_{k1} \\ R_{i2} + R_{j2} - R_{j1} + R_{k2} - R_{k1} \end{bmatrix} \tag{3.18}$$

3.2.6 Machine Eligibility Determination

Machines that can perform the required manufacturing operations are determined by: 1) determining if the machine contains a system that can perform the required manufacturing operation suggested by ontology formulation, 2) comparing the generated manufacturing planes with the ROEs of all available systems, and 3) comparing the directions of each manufacturing plane with the system tool directions. Equation (3.19) describes a system ROE, A_{ROE}, that contains a manufacturing plane, A_{mfg}:

$$\forall P \in A_{mfg} \subset A_{AOE} \tag{3.19}$$

where P refers to any point inside the manufacturing plane A_{mfg}. The direction of the manufacturing plane must be opposite to the direction of the tool used for the manufacturing activity required as formulated in Equation (3.20):

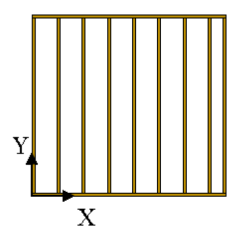
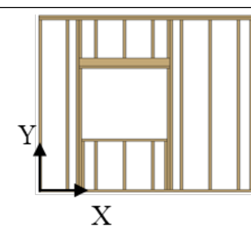
$$\vec{n}_{mfg} \cdot \vec{n}_{tool} = -1 \tag{3.20}$$

where $\vec{n}_{mfg}$ and $\vec{n}_{tool}$ represent the unit vectors of the manufacturing plane and tool, respectively.

3.3 Experimental Setup and Case Studies

Two wood frames are studied to validate the proposed framework: one simple wood panel with only vertical studs and a more complex panel with a window component. Both panels are built in the 3D modeling software Revit using FrameX, a Revit add-on developed at the University of Alberta, Canada [32]. Relevant specifications of wood panels obtained from BIM are presented in Table 3.1.

Table 3.1: Summary of relevant panel specifications.

Panel Design	**Panel 1**	**Panel 2**
Shop Drawing		
Frame Dimensions (mm)	$X = 3048$, $Y = 2438.4$, $Z = 139.7$	$X = 3048$, $Y = 3048$, $Z = 139.7$
Connection Type(s)	SP1	SP2, CH1, SH1, ST1, JT1, TS2, CT1, SP1

The wood framing machine prototype (WFMP), as shown in Figure 3.14, is used as the manufacturing resource for the purpose of this study. The WFMP is a semi-automated wood framing machine designed and built by the Modular Construction Group at the University of Alberta, Canada. The purposes of the machine are to increase the productivity and the accuracy of wood framing process. A recipe file

Table 3.2: Summary of WFMP machine specifications.

System	Work Direction	Work Range (mm)	Collaborative Systems	Tool Direction
Nailing System (Left)	Z	0 – 150	Dragging System	$(0, 1, 0)$
Nailing System (Right)	Z	0 – 150	Dragging System, Table Movement	$(0, -1, 0)$
Dragging System	X	0 – 3200	-	-
Table Movement	Y	2438 – 3658	-	-
Cutting System (Left)	Z	0 – 150	Dragging System	$(0, 0, 1)$
Cutting System (Right)	Z	0 – 150	Dragging System, Table Movement	$(0, 0, 1)$
Drilling System	Y	0 – 100	Dragging System	$(0, 1, 0)$

containing all the manufacturing instructions is first imported into the programmable logic controller (PLC). An operator then places the top and bottom plates and the first stud into place. The machine will secure the first stud by nailing both plates to the stud. Once nailing is finished, the dragging system will grab the frame and drag it to the next operating location defined in the recipe file. The above processes are repeated until the frame is finished. It has been proved that the WFMP produces fast and accurate wood frame assemblies which are critical in residential buildings. Relevant machine specifications of the WFMP used in this study are summarized in Table 2.

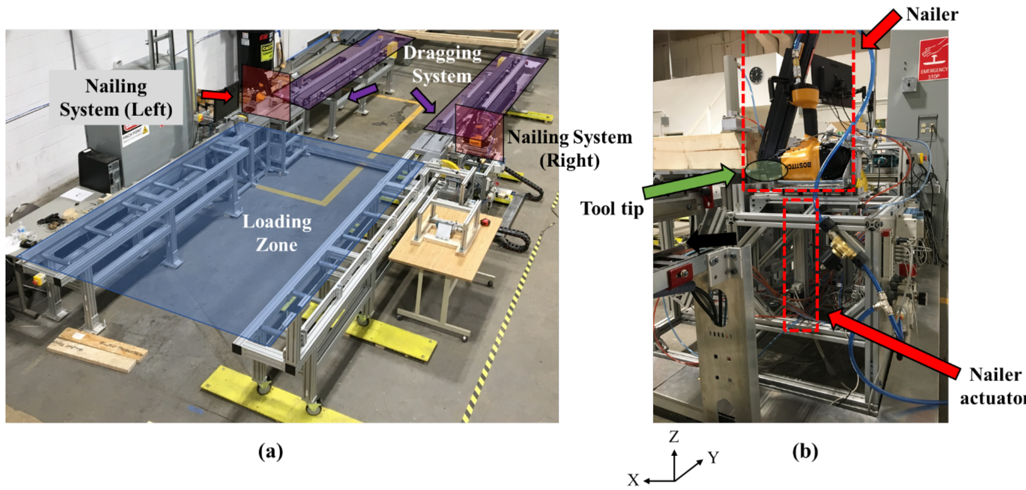


Figure 3.14: (a) Systems of Wood Framing Machine Prototype, and (b) details of nailing system.

3.4 Results

The previously mentioned wood frame panels are studied to validate the proposed framework. The detected mating planes are inspected visually to compare with the automatically generated mating planes of the actual products. The generated manufacturing planes are then compared to knowledge obtained from based on common practice. The predicted machine eligibility of the WFMP is compared with knowledge from theheld by the design personnel of who work with that machine.

3.4.1 Case Study 1

The expected mating planes for Panel 1 are the cutting faces of all the studs as they are in contact with the plates. Based on expert knowledge, nailing operations are the most feasible manufacturing operations to secure the building elements in Panel 1. As a result, all the manufacturing planes of Panel 1 are expected to be parallel to the mating planes and on the outside surface of both plates. Figure 3.15 (a) shows Panel 1 with all the automatically generated mating planes and Figure 3.15 (b) additionally shows the location of all the manufacturing planes detected by MEDS. It can be observed from Figure 3.15 that locations and geometry of both mating planes and manufacturing planes are as expected.

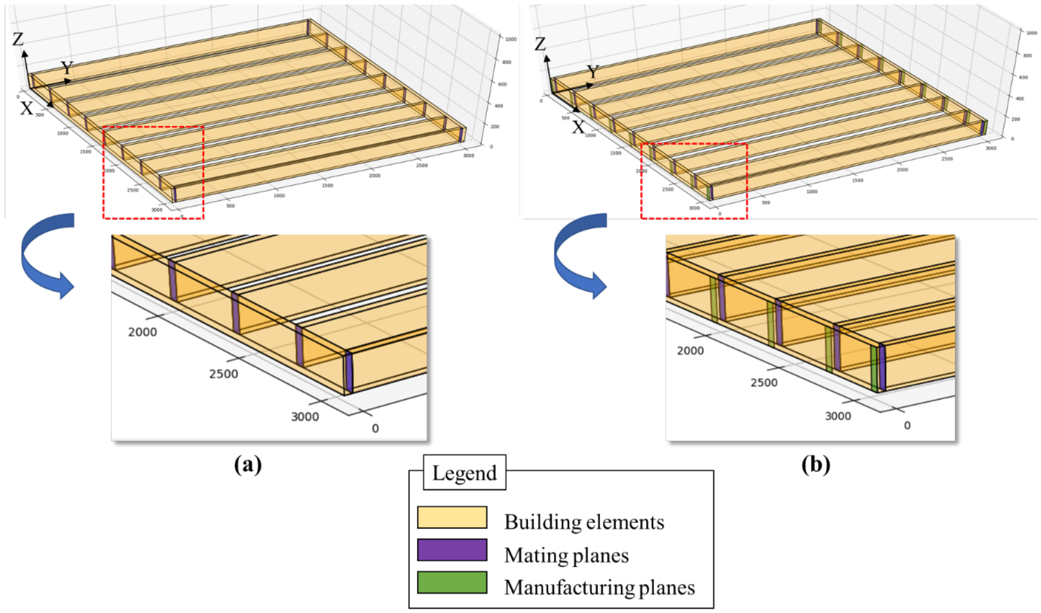


Figure 3.15: Wood frame with (a) mating planes, and (b) mating planes and manufacturing planes.

Figure 3.16 shows the predicted manufacturing planes of Panel 1 and the ROE of the nailing systems of the WFMP. All the manufacturing planes are on the outside of the top and bottom plates. Manufacturing planes on the bottom plate (left XZ plane) are covered by the ROE of the left-hand side nailing system. Manufacturing planes on the top plate (right XZ plane) are included in the ROE of right-hand side system. Since all the manufacturing planes are included in the system ROEs Equation (3.19) is satisfied. In addition, manufacturing planes and tool directions are summarized in Table 3.3. It can be clearly shown in the table that Equation (3.20) is satisfied. As a result, the WFMP is fully capable of manufacturing Panel 1 using its nailing systems.

3.4.2 Case Study 2

Figure 3.17 shows the mating planes of Panel 2 detected by MEDS. As shown in the figure, Panel 2 comes with various types of mating planes because of the double-plate and window structure. Expected and detected types and quantities of mating planes

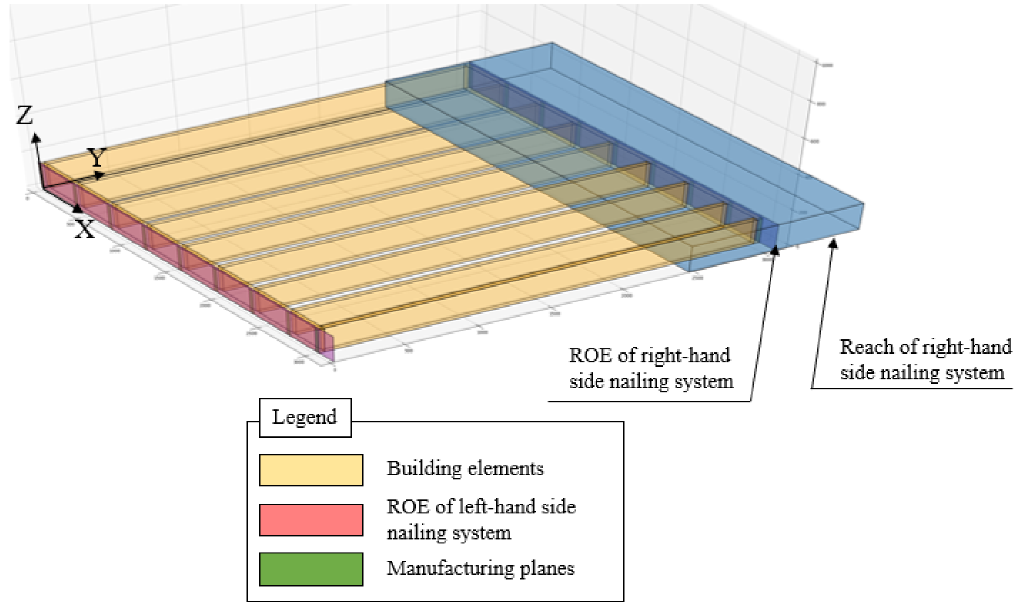


Figure 3.16: Manufacturing planes of Panel 1 and ROEs of nailing systems.

Table 3.3: Manufacturing planes of Panel 1 and tool direction

Intersection Type	**Manufacturing Plane direction,** $\vec{n}_{mfg}$	**Tool Direction** $\vec{n}_{tool}$	$\vec{n}_{mfg} \cdot \vec{n}_{tool}$
SP1	$(0, -1, 0)$	$(0, 1, 0)$	-1
SP2	$(0, 1, 0)$	$(0, -1, 0)$	-1

are listed in Table 3.3. It can be shown in the table that the detected mating planes match the expected mating planes.

Figure 3.18 represents detected mating planes and predicted manufacturing planes of Panel 2. The location of all the manufacturing planes are as expected. For SP1 connections shown in Figure 3.18 (b), manufacturing planes are projected onto the outer surface of the plate as before. For JT1 connections shown in Figure 3.18 (a), manufacturing planes are not projected between the studs. Instead, they are relocated to the most outer surface of respective building elements due to manufacturing plane correction, as stated in Section 3.2.4. Figure 3.18 (c) represents the manufacturing planes of double-plate connections. As expected, manufacturing planes are found on

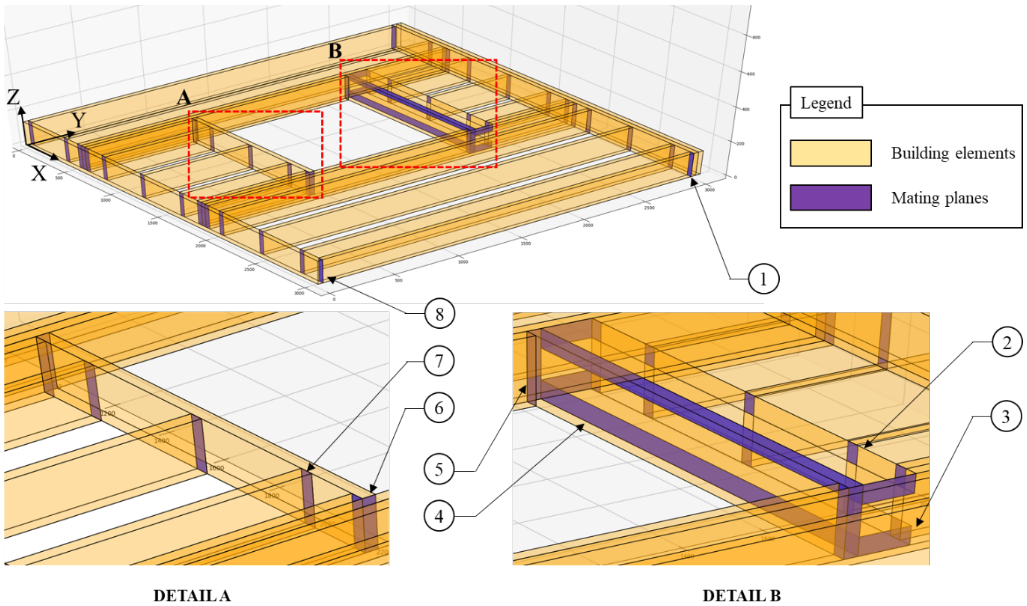


Figure 3.17: Mating planes of Panel 2.

the outer surface of the plate due to the merging of double-plate as illustrated in Section 3.2.2. In summary, all of the manufacturing planes calculated using MEDS are as expected.

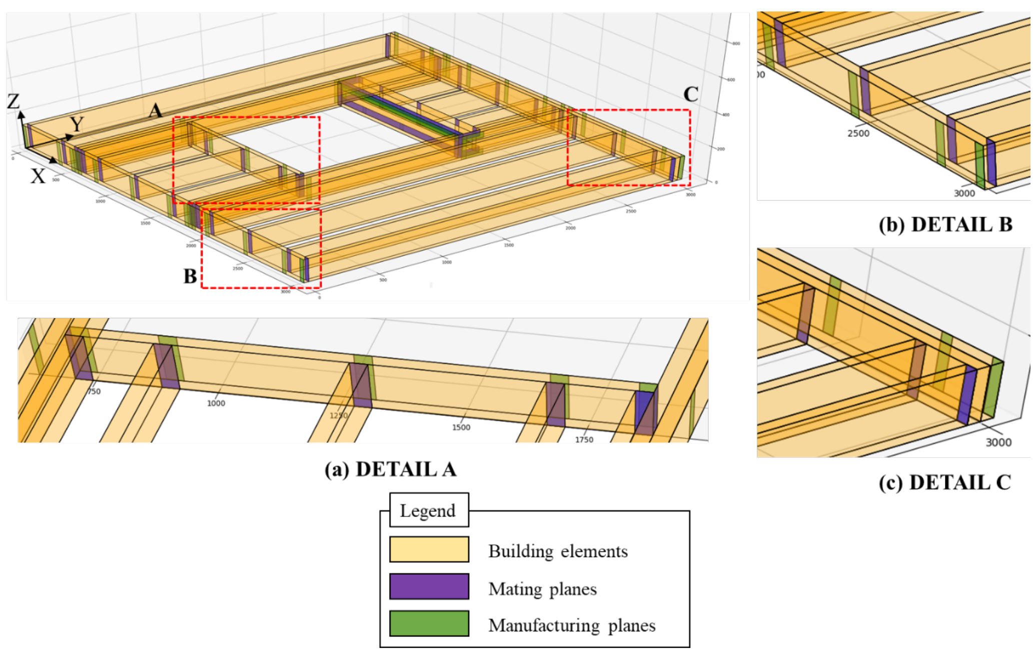


Figure 3.18: Mating planes and manufacturing planes of Panel 2. (a) JT1 connections, (b) SP1 connections, and (c) SP2 connections.

Figure 3.19 shows the manufacturing planes and ROE of nailing systems of the WFMP. The manufacturing operation required to fabricate Panel 2 is nailing operation based on ontology formulation, therefore, nailing systems are therefore required to perform nailing operations. As shown in Figure 3.16 and Figure 3.19, the ROE of left- and right-hand side nailing systems are identical. However, only manufacturing planes on the bottom and top plates are covered in the ROE. Manufacturing planes in the window component are outside the nailing system ROE. That is, only manufacturing planes on the top and bottom plates satisfy Equation (3.19) and Equation (3.20) and can be fabricated using WFMP nailing systems. Additional effort is required to fully manufacture Panel 2, which is consistent with the current use of the WFMP in the manufacturing procedure of such panels where window components are pre-assembled.

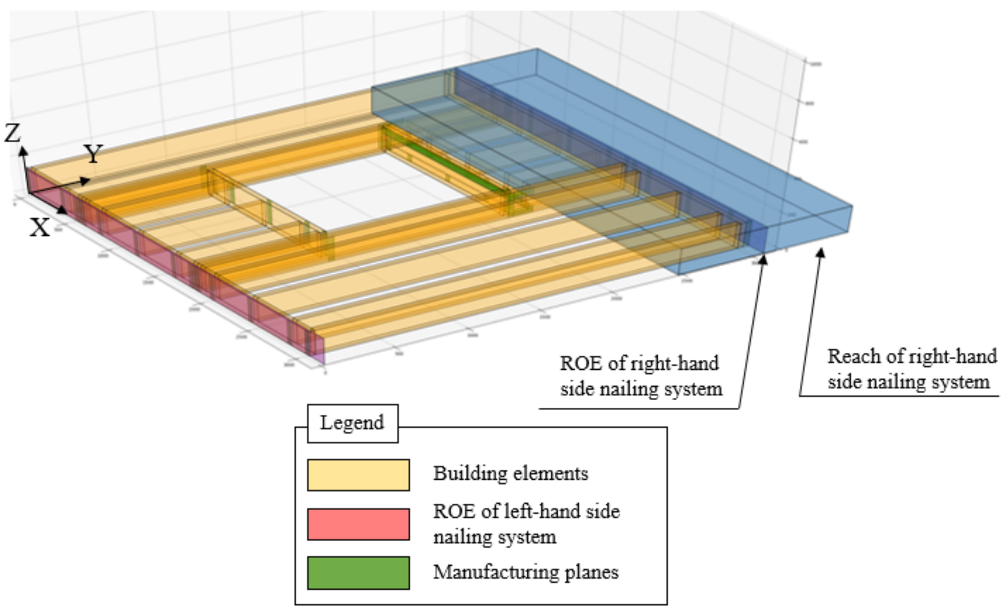


Figure 3.19: Manufacturing planes of Panel 2 and ROE of nailing systems.

3.5 Discussions and Limitations

As shown in the case studies investigated in Section 3.4, the proposed framework (MEDS) detects mating planes and calculates manufacturing planes of wood frames accurately. In addition, it allows the software to decide whether the machine can perform the required manufacturing operations or not. Certain limitations are encountered while testing MEDS on various scenarios. The first limitation arises from the geometry of the building elements. The current state of MEDS only interprets building elements that are rectangular prisms that align with x, y and z axes. However, various forms of building elements are frequently encountered in construction environment. For example, a wood frame roof consists of trapezoidal prism-shaped elements. At the current stage, the system is unable to generate the points of every face as it is assumed that all the faces of an element are aligned with the xy, yz or xz planes. Furthermore, for the same reason, further development is required for MEDS to interpret rectangular prisms that are oriented in a 3-dimensional space for the same reason either. Limitations also occur in cases of header-to-cripple nailing

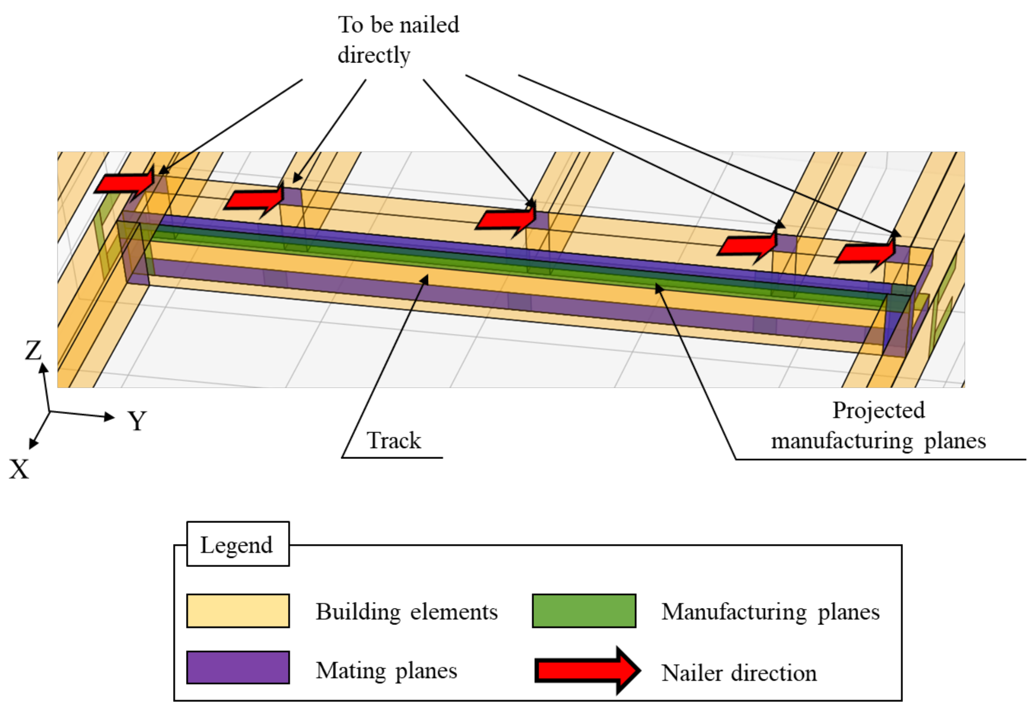


Figure 3.20: Header-to-cripple nailing operations.

operations. From Figure 3.20 one can observe that the manufacturing planes of CH1 connection are projected to the correct location, i.e., the most outer surface of the track. In practice, however, it is difficult to find nails that are more than 6-inches (approximately 150 mm) long to secure such connections. The appropriate operation is to place the nailer at an angle to secure the header and cripple directly. At the current stage, MEDS does not consider the limitations of the current manufacturing systems related to the tools, i.e. the length of the nails'.

The proposed system is additionally limited by the ROEs of the systems. As discussed in Section 3.2.5, current state of ROE formulation only applies to systems that are subject to translational motions, since most construction-oriented manufacturing operations can be achieved by only using linear motions. While rotary actuators are beyond the scope of this study, rotations in 3-dimensional space are constantly employed in manufacturing activities as robot manipulators are getting more popular and are starting to be used in offsite construction facilities. Furthermore, tool orientations are currently assumed constant, which does not accurately reflect any robotic environment.

3.6 Conclusions

As automated manufacturing of construction-oriented products is trending, process planning is in demand to reduce error and increase the productivity of manufacturing activities. As a prerequisite, the proposed BIM-based framework is intended to determine the machine capabilities prior to process planning. The Machine Eligibility Determination System (MEDS) first generates the mating planes of the product by analyzing its geometry. Second, feasible manufacturing operations are determined using expert knowledge formulated in an ontology model. In addition, manufacturing planes are calculated and are compared to region of effect (ROE) of systems of the machine. Finally, a decision as to whether a machine can carry out the required manufacturing operations is made. The proposed framework is validated using two wood framing panels with different complexities and a wood-framing machine prototype. It is proven that the MEDS can decide which connections the machine can perform.

The system MEDS is limited to 2D wood frame assemblies that align with coordinate system. Such limitation prevents the system to be applied to frame assemblies that involve 3D geometric features, such as ones in steel frames. In steel frames, intersections between building elements are 3D volumes. An upgrade is therefore needed to account for 3D features in frame assemblies, and building elements oriented in 3-dimensional space. In the next chapter, an upgraded system that accounts for 3D geometric features in frame assemblies will be presented with a strong orientation to steel frame assemblies manufacturing.

Chapter 4

Machine eligibility decision support system: 3D steel frame assemblies manufacturing[1]

In Chapter 3, an automated system is presented to determine machine eligibility for manufacturing wood frame assemblies. Even though machine eligibility can be automatically evaluated for 2D wood frames, many construction-oriented products, such as steel frames, have features that have not been accounted for yet. This chapter extends the framework presented in Chapter 3 to consider 3D geometric features. The upgraded system detects intersection regions (3D) in a frame assembly and calculates areas that require manufacturing operations. This objective is accomplished with the use of classic techniques commonly used in computational geometry. The proposed framework is tested using a steel frame with common features in the machine environment. The result proves that the proposed approach accurately determines the manufacturing locations of the frame assembly.

[1] The content of this chapter was under preparation to be submitted to *Automation in Construction*, at the time of submission of this thesis.

4.1 Introduction

4.1.1 Background

Recent technological advancement has made off-site construction increasingly popular in North America. In off-site construction, frame assemblies such as walls, floors, and roofs are prefabricated, shipped to the construction locations, and assembled on site. In contrast with traditional construction methods, where materials are shipped to the job site and constructed element-by-element, in off-site construction, fabrication of building elements takes place in a factory environment. Due to the controlled factory environment, frame assemblies can be fabricated using industrial automated machines, which dramatically increases the productivity, quality, and the deliverability of the products [3].

For frame assemblies fabricated using automated framing machines, the current manufacturing process follows a sequence of operations. First, a 2D manufacturing drawing is drafted based on the building information model (BIM), which is “a digital representation of physical and functional characteristics of a facility” [24].Next, process planning engineers will then decide if the existing machines in the factory can fabricate that product based on the 2D drawings, and also determine which operations will be performed manually by operators and which ones will be automated. If possible, the drawings will be passed to the operator of the selected machines. The operator will interpret the drawings, prepare the materials and proceed with the manufacture of the frame assemblies. Currently, process planning for frame assemblies manufacturing relies heavily on the experience of various domain experts, which is an approach that has been found to be time consuming and error prone. Furthermore, the restriction of information exchange prevents the manufacturing system from freely communicating with its components (such as machines). which implicitly imposes communication overhead to the manufacturing company. Consequently, the off-site construction industry requires automating the process planning of frame assemblies manufacturing in industrial environments.

Integration of BIM into off-site construction processes greatly improves the productivity of manufacturing construction-oriented products. For example, quantity take-off information for constructing light-frame buildings can now be automatically obtained from BIM models [21]. Machine eligibility can also be automatically determined based on BIM models for wood-frame assemblies [33]. A similar approach is needed for steel frame assemblies. However, steel frame assemblies have 3D geometric features as shown in Figure 4.1. Therefore, the previously developed system needs to be extended to incorporate 3D features.

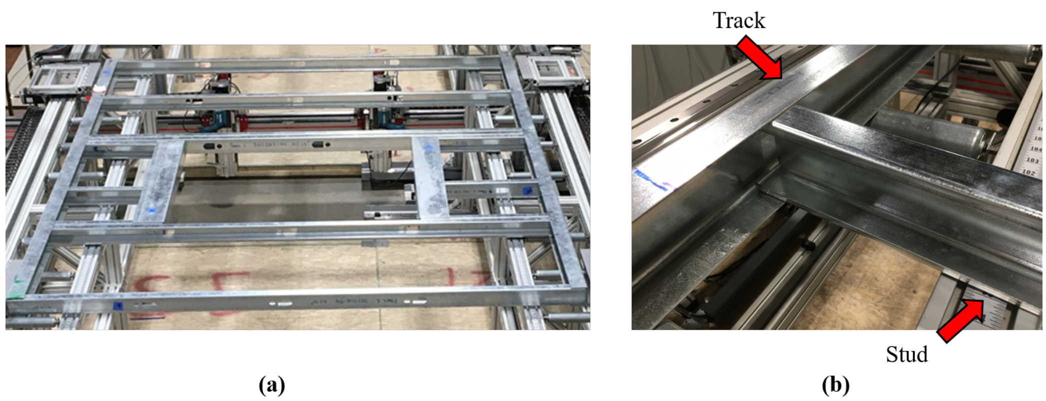


Figure 4.1: (a) Typical steel frame with a door component, and (b) detailed view of a typical intersection. Note that the stud goes inside the track forming 3D intersection.

Achieving automated process planning is a challenge that requires constant development from different knowledge domains, such as knowledge of the products, manufacturing systems and project planning. This paper aims to extend the existing machine eligibility determination system proposed by An *et al.* to account for frame assemblies that have 3D geometrical features [33].

4.1.2 Related Work

The implementation of BIM in the manufacturing domain has been proven to enhance the productivity and quality of prefabricated construction-oriented products. Malik *et al.* successfully shortened the manufacturing time by optimizing the tool paths of automated framing machines using the product information extracted from the BIM model [17]. Quality inspection is also important in the manufacturing industry. Martinez *et al.* proposed a real-time, vision-based system that inspects steel frame assemblies in a pre-manufacturing state. The proposed system compares the real frame with the BIM model of the frame, identifies any misplacement of the frame elements, and corrects the frame elements if needed [18]. Manrique *et al.* proposed a framework that automated the generation of shop drawings using a parametric model that is incorporated in the BIM model [32]. The proposed framework was proven to be effective and accurate in generating 2D drawings that were used for manufacturing frame assemblies. Automated generation of shop drawings improves the productivity of the building designers. Based on the abovementioned research, it can be concluded that although an increasing effort has been dedicated to BIM and OSC separately throughout recent years, more attention is needed to integrate BIM and OSC [5]. Currently, in the manufacturing of construction-oriented products, the process planning is still carried out manually. As the global market becomes increasingly competitive, agile manufacturing is in demand because it can quickly respond to changes in customer requirements [29]. Since manual process planning is time consuming, inefficient when responding to changes, and relies heavily on experience, an automated process planning system is needed. One of the roadblocks to achieving automated process planning is that BIM models of construction-oriented products do not provide manufacturing information. Similar to BIM models, computer-aided design (CAD) models, which are digital representations of mechanical parts, do not provide manufacturing information. To link the manufactured parts and manufacturing machines, computer aided process planning (CAPP) has been in development since Neibel first presented the idea of developing process planning using computer technologies in 1965 [34]. CAPP uses computer technology to assist the process planning of manufacturing a part [25] by converting various product requirements (such as functional, mechanical and aesthetic) into detailed manufacturing instructions for the corresponding machinery [29]. CAPP has attracted a large amount of research interest and has been developed based on different approaches [11]. Feature-based and knowledge-based approaches have been developed intensively. In a feature-based approach, geometrical and topological features of a part are interpreted and translated into manufacturing instructions, whereas in a knowledge-based system, experience obtained from domain experts is structured and stored for it to be reasoned and queried [11]. This is similar to the case of manufacturing construction-oriented products because both fields rely on expert knowledge to generate sound process planning.

The challenges inherent in the implementation of CAPP techniques to automate the process planning of construction-oriented product manufacturing are twofold: 1) CAPP mostly involves removing materials from a single part. However, manufacturing construction-oriented products mainly involves assembling pieces with different materials [27], and 2) features of construction-oriented products are different from that of mechanical parts. To address the first issue, knowledge that is obtained from experience is formulated using ontologies [27], which is based on knowledge models proposed by Lemaignan *et al.* [22] and Liu *et al.* [21]. For frame assemblies, the manufacturing features are closely related part intersections. By categorizing the possible intersections, feasible manufacturing operations can be determined [27]. To resolve the second issue, the features of construction-oriented products must be recognized. While the BIM model provides detailed descriptions of a construction-oriented product, it offers no insight about how the product is to be fabricated. This lack of manufacturing information poses a barrier to closed-loop communication between the product designers, which is previously overcome by the experience of process engineers. To address this issue, an automated machine eligibility determination system (MEDS) was defined as the first step in the automation of the process planning for the manufacturing of wood frame assemblies [33]. By comparing geometric features in a wood frame and the available manufacturing technology, the proposed methodology determines manufacturability of the wood frame.

To summarize, using the information from the BIM model and the current machine eligibility determination system (MEDS), a more generalized framework is needed to encompass 3D features that are encountered in frame assemblies. The remainder of the paper is organized as follows: Section 4.2 discusses the proposed system in detail; Section 4.3 shows the experimental setup and the frame used to validate the proposed framework; Section 4.4 shows the results of the case study; Section 4.5 discusses the implications of the results and limitations of the system; and Section 4.6 concludes this study by providing important results and discussing future research related to this study.

4.2 System Framework: 3D Machine Eligibility Determination System (3D MEDS)

4.2.1 Previously developed system: 2D Machine Eligibility Determination System (2D MEDS)

The system presented aims to extend the 2D framework proposed by An *et al.* to the 3D space, in order to enable manufacturing of steel frame assemblies [33]. The scope of 2D MEDS is to determine if a machine can fabricate a wood frame assembly defined by the BIM model. The schematics of the 2D framework is shown in Figure 4.2. The

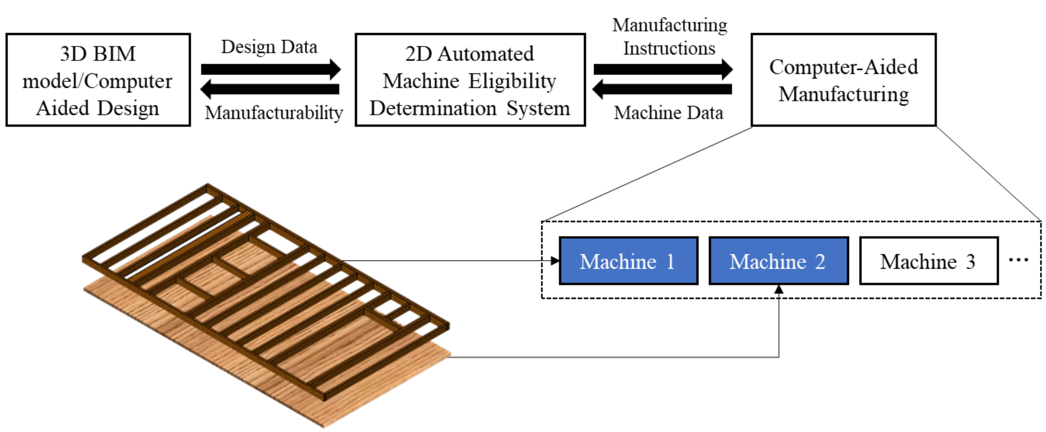


Figure 4.2: 2D MEDS for wood frame assemblies manufacturing.

system 2D MEDS takes building information model (BIM) as input. The data is then loaded into the MEDS and used to determine geometric manufacturing features. Given the detected features, manufacturing rules formulated using ontologies are used to determine the most feasible manufacturing operation. Machine specifications are imported into the system to determine machine eligibility. Once feasible machine is found, the manufacturing instructions can be sent to the target machine.

Note that the wood frame needs to be first aligned with the coordinate system for the 2D MEDS to work. As such, geometric manufacturing features (mating planes) have only 2D features as they lie in xy, yz, and xz planes and the edges of the mating planes will be parallel to the x, y, and z axes.

4.2.2 Proposed framework: 3D MEDS

The 3D MEDS also uses the product information pre-generated in a BIM model and machines specifications as system input. Compared to 2D MEDS, which only detects 2D planes that align with coordinate system, the proposed system (3D MEDS) involves algorithms that detect volumes with arbitrary orientation in 3D space. As

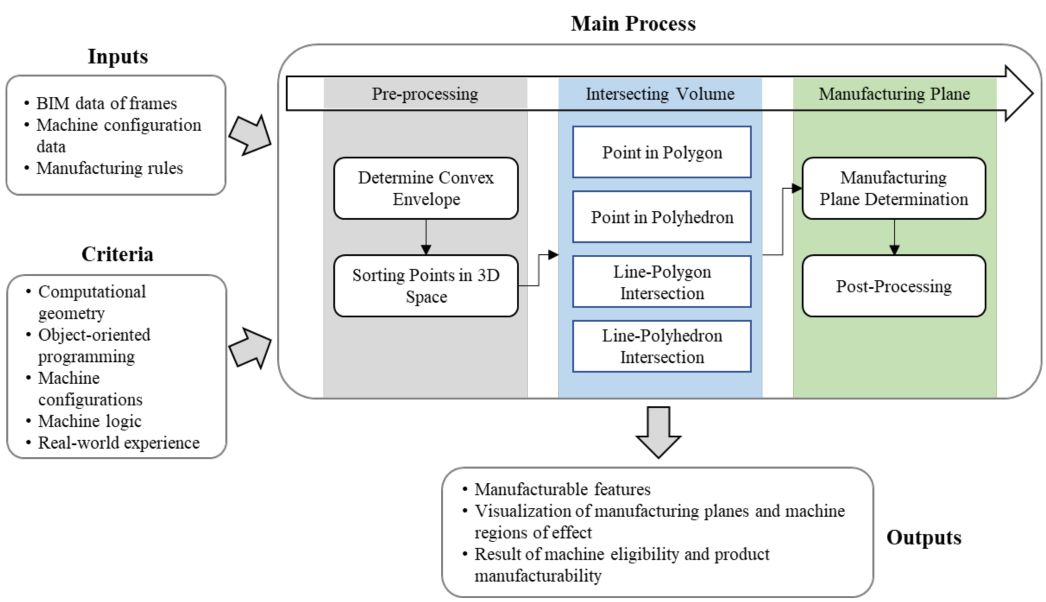


Figure 4.3: Extended MEDS system framework overview.

presented in Figure 4.3, the proposed system (MEDS) architecture can be divided into three modules: 1) pre-processing, 2) intersecting volume detection, and 3) manufacturing plane determination. The proposed framework is developed and implemented using Python programming language due to the diverse frameworks and tools and robust standard libraries that allow complex simulation and visualization [35].

4.2.3 BIM Data Input and Pre-processing

Detailed geometrical data of steel panels is required to determine locations where manufacturing activities are required. As investigated by Liu *et al.*, 'Element ID', element 'MaterialSet', 'FaceArray' and 'LocationPoint' coordinates can be extracted from every building element. The relevant information adapted from Liu *et al.* from the Revit API UML diagram is presented in Figure 4.4 [21]. Considering the con-

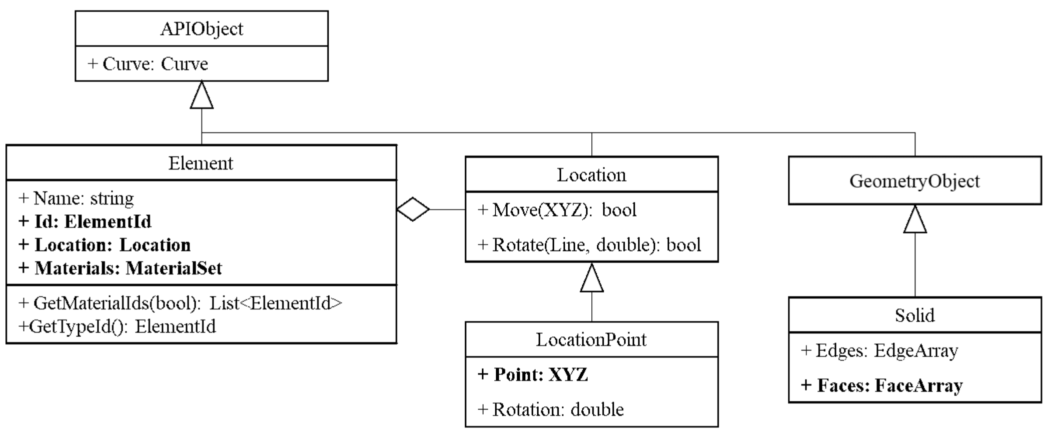


Figure 4.4: UML diagram of Autodesk Revit building elements [21].

struction methodology of steel frames, manufacturing operations only occur on the common area between two or, more rarely, three building elements. Defined by An *et al.*, these areas are the manufacturing planes, the locations where manufacturing operations occur [33]. Manufacturing planes are found on the top and bottom flanges of the intersecting volume. The rest of the details of the light gauge steel (LGS) profile are irrelevant when computing the manufacturing planes of the steel frame panel. Consequently, the LGS member is simplified to a rectangular prism as shown in Figure 4.5.

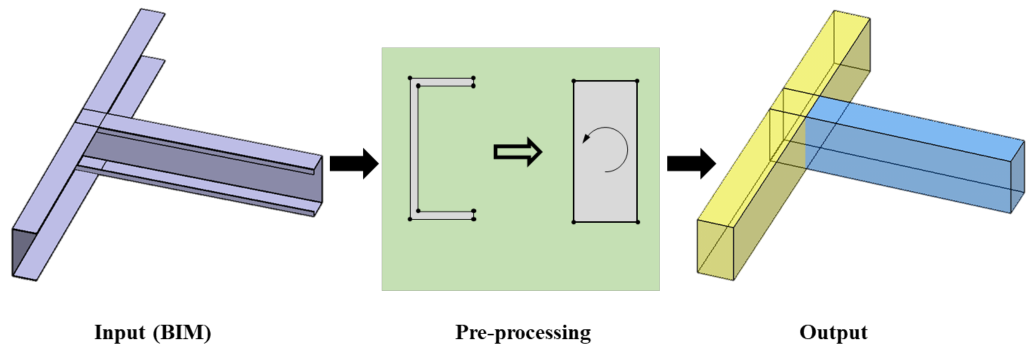


Figure 4.5: Pre-processing of building elements.

Finding Convex Envelope

As shown in Figure 4.5, the sections of steel frame building elements are concave polygons. Concave geometry introduces more points than needed as we only require top and bottom flanges to determine the manufacturing planes. Furthermore, the computational cost increases tremendously due to the geometrical complexity. An algorithm is therefore needed to find the convex profile of the sections, while keeping top and bottom flanges. Graham scan, as one of the most efficient methods of finding all vertices of convex hulls ordered along its boundary, is used to find the convex profile of steel frame elements from its point coordinates [36]. The mechanism of the Graham scan is illustrated in Figure 4.6. By scanning through ordered points, any point that contributes the opposite turn with respect to the initial turn is discarded. The convex

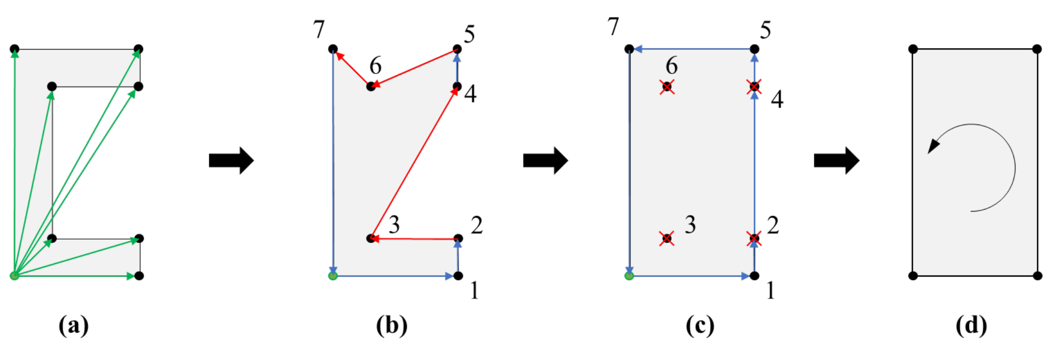


Figure 4.6: Graham scan algorithm. Note that the dimensions of the building element are enlarged for visualization.

envelope of every building element is found using the above procedure. Thanks to the Graham scan, from this point on, computational techniques that handle concave geometries are no longer necessary resulting in significantly less computational time and cost.

The numerical complexity of the algorithm is dictated by the sorting algorithm used. If 'merge sort' algorithm is applied, the complexity is reduced to $\mathcal{O}(n \log n)$, where n is the number of edges of a polygon [37]. 'Merge sort' is used in this study due to its efficiency. 'Merge sort' is a divide and conquer algorithm that works by first dividing the unsorted list into n sublists and repeatedly merging the sublists to generate sorted lists until there is only one list left [37]. The final list will be the sorted list. Applying Graham scan to pre-process all building elements, the total numerical complexity of pre-processing is $\mathcal{O}(mn \log n)$, where m is the number of building elements in a steel frame assembly.

Sorting Points in 3D Space

Points in a face must be ordered counter clockwise (CCW) to carry out the subsequent tasks, such as obtaining line segments of the polygon. While the Graham scan provides sorted points in a face, points in newly generated planes may not be ordered. For any convex polygon in a plane with arbitrary orientation, an inside point, P_c, is first calculated using Equation (4.1):

$$P_c = \frac{\sum_1^n P_i}{n} \quad i = 1, ..., n \tag{4.1}$$

where P_i stands for any vertex of the polygon and n is the total number of vertices of the polygon. Vectors connecting the geometric center and the vertices are then constructed as shown in Figure 4.7. One vector is selected to be the reference vector and the angle between the reference vector and any other vector is calculated using Equation (4.2):

$$\theta_i = \begin{cases} \cos^{-1}(\frac{\vec{v}_i \cdot \vec{v}_{ref}}{|\vec{v}_i \cdot \vec{v}_{ref}|}) & \vec{v}_{ref} \times \vec{v} \cdot \vec{u} < 0 \\ 2\pi - \cos^{-1}(\frac{\vec{v}_i \cdot \vec{v}_{ref}}{|\vec{v}_i \cdot \vec{v}_{ref}|}) & \vec{v}_{ref} \times \vec{v} \cdot \vec{u} < 0 \end{cases} \tag{4.2}$$

where $\vec{u}$ is the normal vector of the plane. Since angles calculated using dot product is in the range of $[0, 180°]$, correction must be applied to the angles greater than 180°. Once all the angles of vectors are calculated, they are sorted in ascending order using

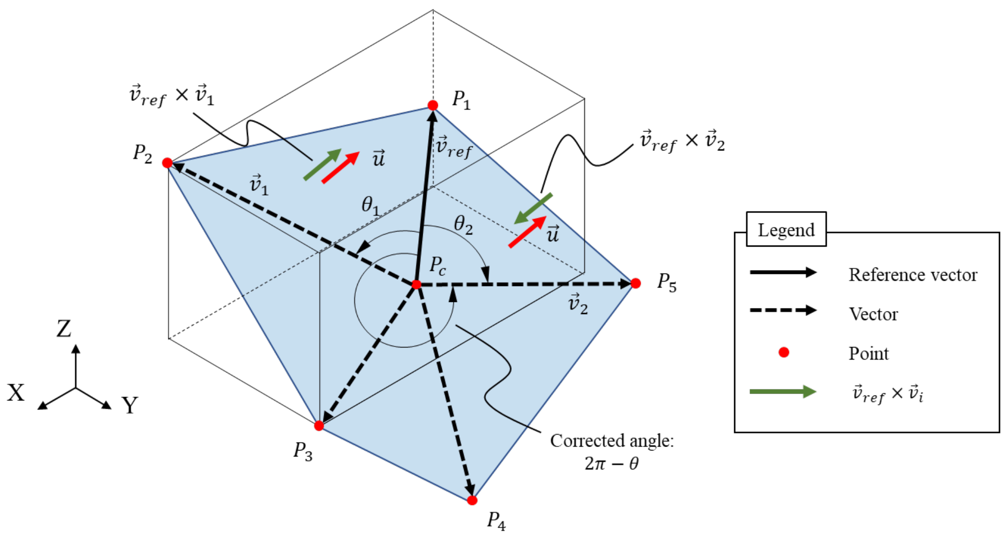


Figure 4.7: Ordering points of a polygon in counter clockwise direction.

'merge sort' [37]. The coordinates of all points are then matched to their respective angles.

4.2.4 Intersecting Volume Determination

Using the system proposed by An *et al*, hard connections are required at locations where two building elements intersect [33]. For wood frames, the contact area of two building elements in contact with each other (technically, the mating plane) is a 2D area. For steel frames, however, the contact region is a 3D volume. To determine the manufacturing plane locations, the volume must first be identified. As discussed in Section 4.2.3, each building element is a polyhedron and is represented by lines and sorted vertices. Therefore, geometrically speaking, finding the intersecting volume between two building elements is equivalent to detecting the intersecting volume between two polyhedra. There are two ways intersecting points between both polyhedracan be generated: 1) the points of one polyhedron are inside or on the other polyhedron, and/or 2) the edges of one polyhedron intersect with the other polyhedron. Using techniques of computational geometry, the intersecting volume can be detected with the aid of some building blocks techniques: 1) point in a polygon, 2) line-polygon intersection, and 3) line intersection. Figure 4.8 illustrates this building block approach used to detect the intersecting volume between two different building elements. By detecting potential intersection between every building element and anything else, all the intersecting volumes in a steel frame assembly can be determined. This will result in $\mathcal{O}(m^2)$ numerical complexity. The following subsections discuss how these techniques can be applied to convex geometry in 3D space.

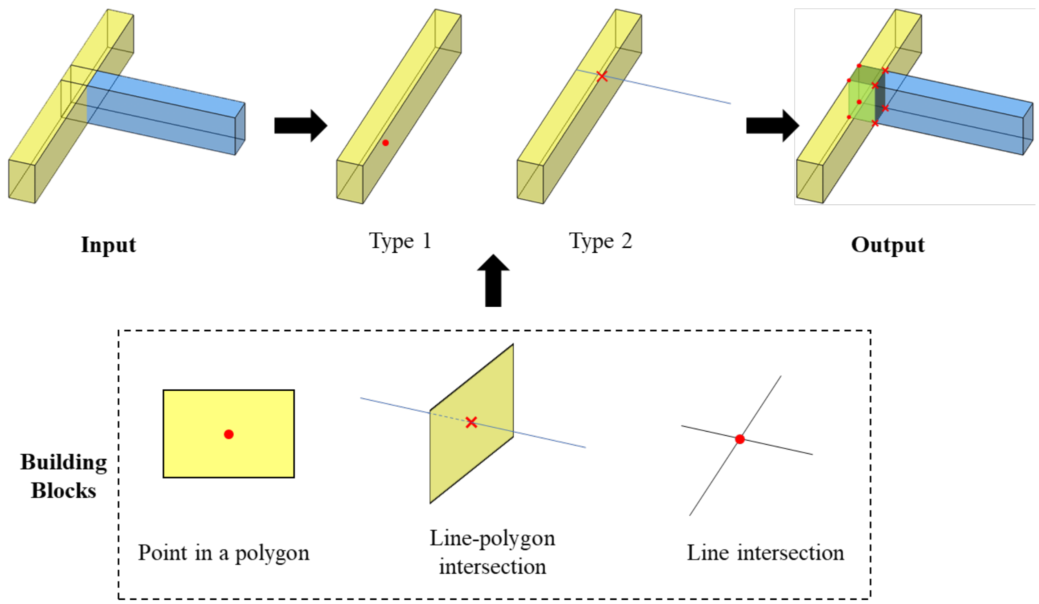


Figure 4.8: Types of volume intersections and building block approach.

Point in a Polygon: Ray Casting Algorithm (RCA)

Since the polygons can be in any plane oriented at an arbitrary angle in 3D space, the current methodology proposed by An *et al.* cannot interpret correctly the intersection, as the method only applies to rectangles in xy, yz or xz plane. 'Point-in-polygon' is one of the fundamental operations of computational operations. In computer graphics, two common approaches have been used: the angle summation method and the ray casting algorithm (RCA) [38]. Using angle summation method, vectors are constructed from the point to the vertices of the polygon. If the sum of angles between every two successive vectors is 360°, the point is inside [39]. However, this method is affected significantly by rounding errors compared to the ray casting algorithm [39, 40]. Therefore, RCA is used in this system. The ray casting algorithm (RCA) works by counting the number of times, m, a ray from infinity crosses the border of the polygon. If the number is an odd number, the point is inside the polygon otherwise the point is outside [41]. Equation (4.3) summarizes the RCA.

$$m \mod 2 = \begin{cases} 0 \rightarrow \text{outside} \\ 1 \rightarrow \text{inside} \end{cases} \tag{4.3}$$

As shown in Figure 4.9 (a) below, points outside the polygon (shown in triangles) have even number cross-border counts whereas the point inside the polygon (shown in cross-mark) has odd number count. RCA can also be applied using the same principles to a concave polygon as shown in Figure 4.9 (b), although concave polygons are beyond the scope of this study. This problem can be further broken down to check

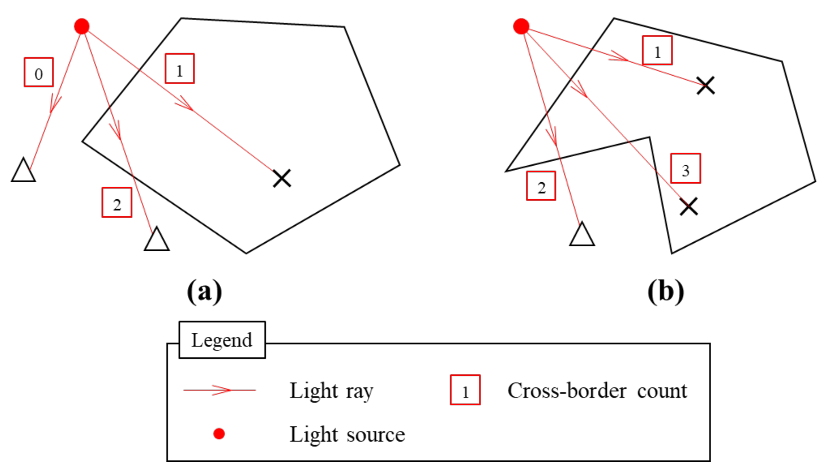


Figure 4.9: Principles of ray-casting algorithm. (a) RCA applied to a convex polygon, (b) RCA applied to a concave polygon.

the relationships between two-line segments: polygon edge, and the light ray. The light source, S, is placed on the extension line from the geometric center, C, and the point to be checked, P, using Equation (4.4):

$$S = C + \frac{P - C}{|P - C|} \cdot c \tag{4.4}$$

where c refers to the circumference of the polygon. The light source is intentionally placed on the extension line of the geometric center and the point to avoid the situation that the ray passes the vertex without entering the polygon. Given the situation where the light source is outside the polygon, possible relationships are presented in Figure 4.10. Note that the robustness of RCA can be affected by points that are

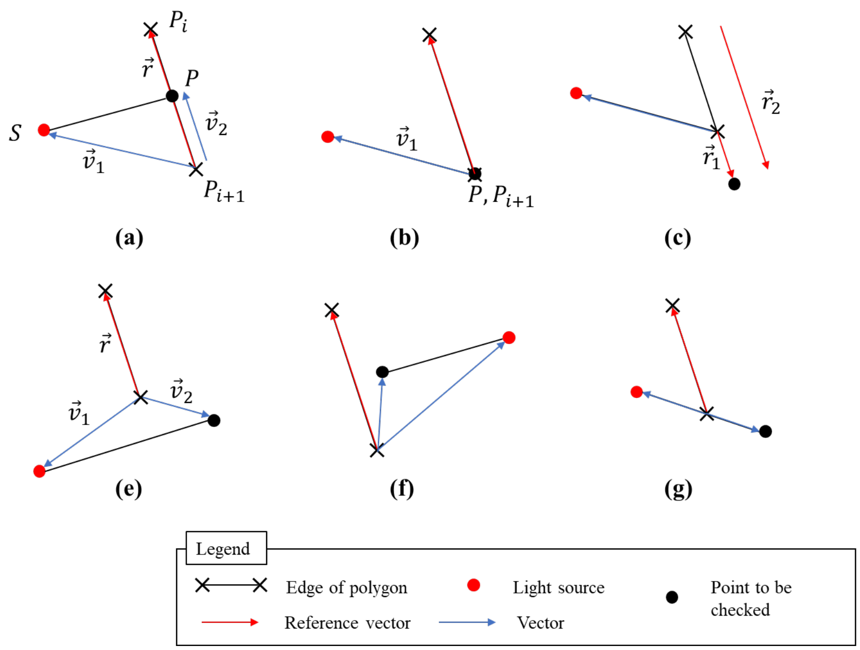


Figure 4.10: Possible relationships between two line segments: (a)(b) the point to be checked is on the edge/vertex, (c) the point is on the extension line of the edge, (d) two-line intersection, (e)(f) no intersection, and (g)(h) line crosses the vertex: point is inside.

really close to the polygon due to machine precision. The manufacturing precision, ϵ, has a chosen value for this study of 10^{-12} mm as the framework needs to be more precise than the precision of any manufacturing machine for which the framework is used. Three conditions are used to figure out which category each point falls into, as defined in Figure 4.10, where P_i denotes the i^{th} point of the polygon. Equation (4.5) can be used to check if S and P are on the same side with respect to the segment

P_iP_{i+1}:

$$(\vec{r} \times \vec{v}_1) \cdot (\vec{r} \times \vec{v}_2) \begin{cases} < -\epsilon, & \text{case(d), (e), (g) or (h)} \\ > \epsilon, & \text{case(f)} \\ \text{otherwise}, & \text{case(a), (b) or (c)} \end{cases} \tag{4.5}$$

where $\vec{r} = \overrightarrow{P_{i+1}P_i}$, $\vec{v_1} = \overrightarrow{P_{i+1}S}$ and $\vec{v_2} = \overrightarrow{P_{i+1}P}$. Case (c) can be recognized if Equation (4.6) is satisfied:

$$\vec{r}_1 \cdot \vec{r}_2 > \epsilon \tag{4.6}$$

where $\vec{r_1}$ and $\vec{r_2}$ are constructed as shown in Figure 4.10. Cases (g) and (h) can be isolated from Equation (4.5) by comparing if$\vec{v_1}$ and $\vec{v_2}$ are colinear using Equation (4.7):

$$-\epsilon \leq |\vec{v}_1| \cdot |\vec{v}_2| - |\vec{v}_1 \cdot \vec{v}_2| \leq \epsilon \tag{4.7}$$

Cases (d) and (e) are distinguished by checking if the polygon edge is on the opposite side of the light source and the point using Equation (4.8).

$$(\overrightarrow{PS} \times \overrightarrow{PP_i}) \cdot (\overrightarrow{PS} \times \overrightarrow{PP}_{i+1}) \begin{cases} < -\epsilon, & \text{case(d)} \\ > \epsilon, & \text{case(e)} \end{cases} \tag{4.8}$$

Figure 4.11 shows the process of checking if a point is inside a polygon using RCA:

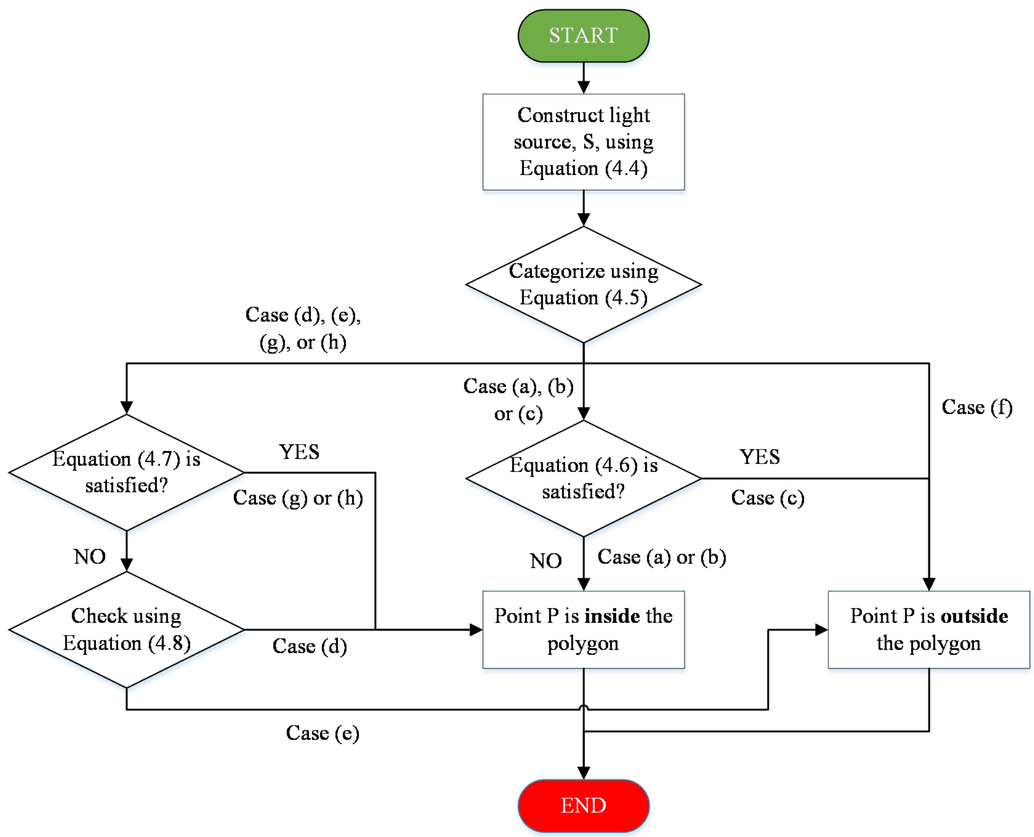


Figure 4.11: Flowchart of checking a point in a polygon using RCA.

Line-Polygon Intersection

RCA can also be used to check if a point is inside a polyhedron by checking if the intersecting point between the ray and the face of the polygon is on the face of said polyhedron. Similar to the RCA applied to "point in a polygon" as illustrated in Section 4.2.4, the light source is placed on the extension line of the segment formed by the geometric center of the polyhedron and the point to be checked. If a ray crosses the border of the polyhedron, two conditions must be satisfied: 1) the point and the light source must be on the opposite side of the face of the polyhedron, and 2) the intersection point between the ray and the face must be inside the face. As shown in Figure 4.12, the light source, S, and the point, P, are first projected to the plane

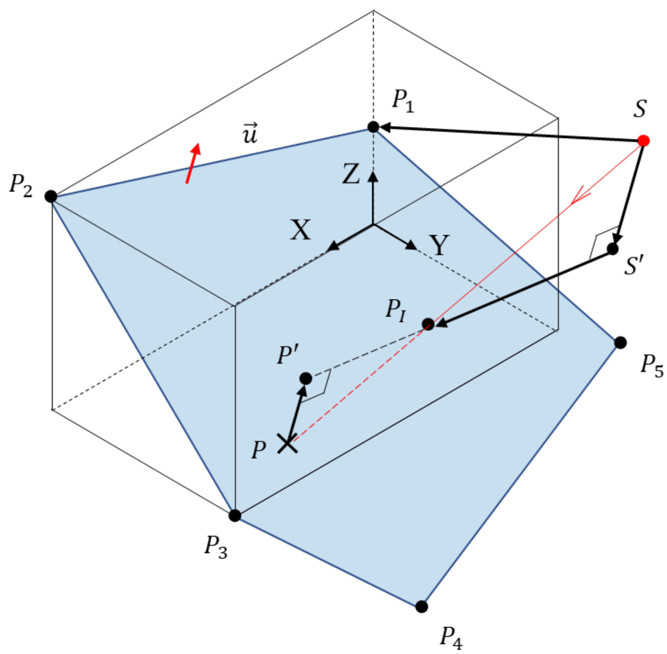


Figure 4.12: Checking if a point is inside a polyhedron using RCA.

resulting in S' and P', respectively. Condition 1 can be checked using Equation (4.9):

$$\overrightarrow{PP'} \times \overrightarrow{SS'} < -\epsilon \tag{4.9}$$

Note that two triangles $\Delta PP'P_I$ and $\Delta SS'P_I$ are similar. The similarity ratio, t, is calculated using Equation (4.10):

$$t = \frac{PP'}{SS'} = \frac{P'P_I}{S'P_I} \tag{4.10}$$

Using Equation (4.11), the intersection point, P_I, can be calculated:

$$P_I = S' + \frac{1}{1+t} \cdot \overrightarrow{S'P'} \tag{4.11}$$

If $P_I \in F$, Condition 2 is satisfied which indicates the light ray crosses the border of the polyhedron. Repeating the above procedures, cross-border count is calculated. Whether P_I is inside the face can be checked using RCA.

Note that if the point to be checked is on the face of the polyhedron, the dot product in Equation (4.9) is close to zero. That is, using the tolerance ϵ defined in Section 4.2.4:

$$-\epsilon \leq \overrightarrow{PP'} \cdot \overrightarrow{SS'} \leq \epsilon \tag{4.12}$$

Whether a point is in a polyhedron can be confirmed by iterating all the faces of the polyhedron until the above two conditions are satisfied. Furthermore, line-polyhedron intersection can be found by replacing the light ray by the line. As such, intersection volume between two building elements can be detected.

3D Line Intersection

As shown in Figure 4.13, finding the overlapping area may involve calculating the intersection point between two-line segments. Adapting the approach proposed by Goldman [42], the intersection point, P_I, between two line segments in the same plane can be determined using Equation (4.13):

$$P_I = P_1 + t \cdot \vec{v}_1 = P_2 + s \cdot \vec{v}_2 \tag{4.13}$$

where the parameter, t, is calculated as:

$$t = \frac{\mathbf{det}(\begin{bmatrix} P_2 - P_1 & \vec{v}_2 & \vec{v}_1 \times \vec{v}_2 \end{bmatrix})}{|\vec{v}_1 \times \vec{v}_2|^2} \tag{4.14}$$

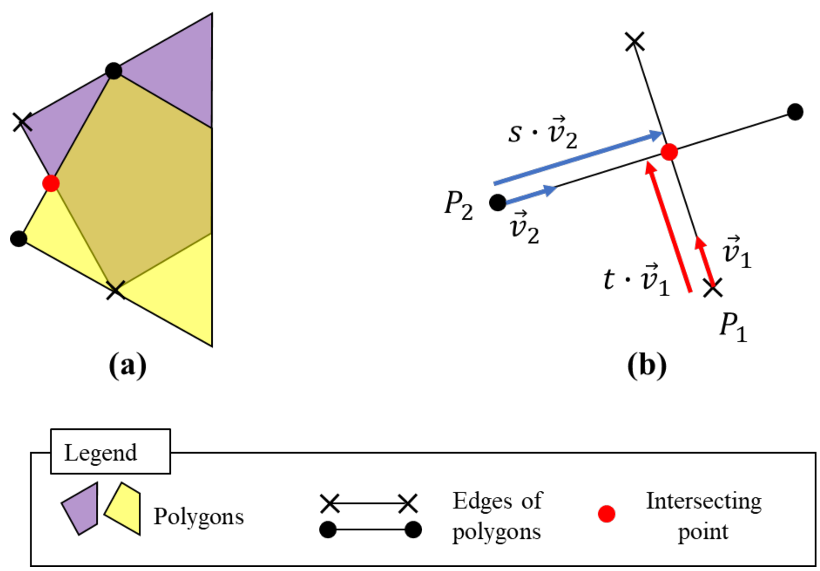


Figure 4.13: Line intersection in 3D space.

4.2.5 Manufacturing Plane Determination

Manufacturing plane formed by two building elements

Possible interactions between two LGS members are shown in Figure 4.14. The

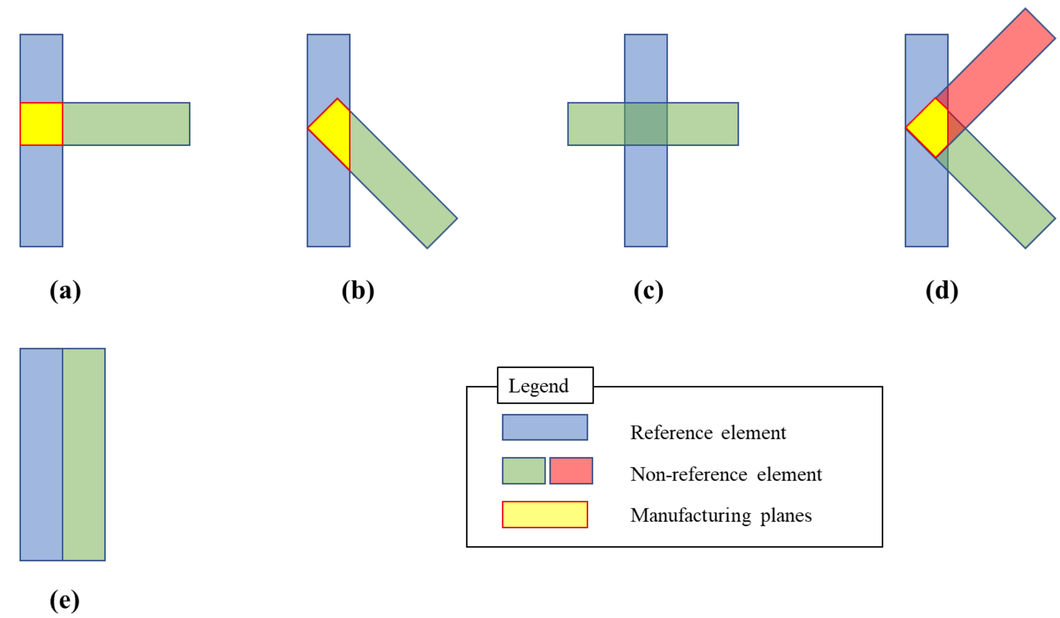


Figure 4.14: Line intersection in 3D space.

procedures of determining manufacturing planes formed by two building elements are as follows. First, check if there is any intersection between two building elements i and j. The intersection needs to be a volume as shown in Equation (4.15):

$$V_{ij} = V_i \cap V_j \in \mathbb{R}^3 \tag{4.15}$$

Then, faces are generated using the points of V_{ij}. To satisfy Equation (4.15), combining with possible interactions as shown in Figure 4.14, two conditions must be met: 1) four vertices of the non-reference element must be inside the reference element, and 2) edges of major dimension of the non-reference element must intersect with reference element. The first condition is equivalent to checking whether points are inside the polyhedron (reference element) as stated in Section 4.2.4. The second condition is similar to finding the intersection point between a line and a plane as stated in Section 4.2.4. In this case, the light source in Section 4.2.4 is replaced by the point of the non-reference element.

Determining Overlapping Area

In the case of angled bracings, flanges of the stud and two bracings could overlap to form a manufacturing plane. Since screw fastening can only occur at the common area between three building elements, the overlapping area needs to be determined. As discussed in Section 4.2.5, the manufacturing planes between the bracings and the stud are two trapezoids. The overlapping area is a polygon that is defined by the points that are: 1) inside each polygon, and 2) formed by line intersections. This is shown in Figure 4.15. Point in a polygon can be checked using RCA presented in Section 4.2.4. And the intersection point between two-line segments can be calculated using the method shown in Section 4.2.4. The pseudo code of determining the overlapping area is as follows:

1. Points that define the first polygon, A_1, that are inside the second polygon, A_2, are detected as shown by red dots in Figure 4.15 (a);

2. Points that define A_2 that are inside A_1 are detected as represented by purple dots in Figure 4.15 (b);

3. Lines are constructed from each detected intersecting point in A_2 to the subsequent point that is outside A_2. The intersections between these lines and the polygon A_2 are determined using Equation (4.13);

4. Unique points detected using Step 1 – 3 above are the points that define the overlapping area as shown in green in Figure 4.15 (d). These points are then sorted for post processing.

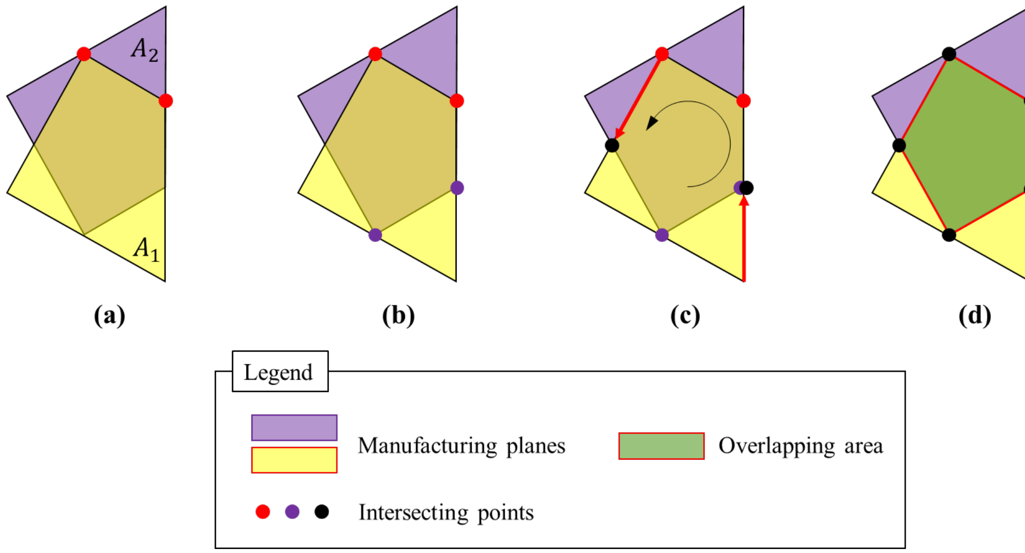
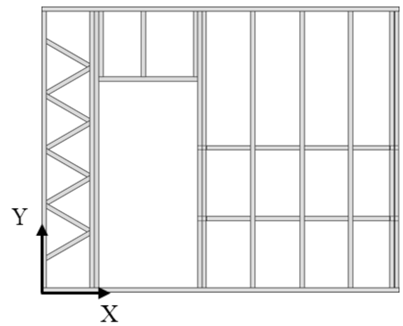
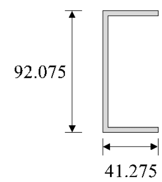


Figure 4.15: Determining overlapping area between two polygons.

4.3 Experimental Setup and Case Study

A steel frame is studied to validate the proposed framework: the panel with vertical studs, horizontal and angled bracings, and a door component. Since any intersection in steel frame is a volume in 3D space, and angled bracings form intersections among three building elements, this panel is sufficient to validate the proposed framework. The panel is built in 3D modeling software Revit. Relevant specifications of the steel panel obtained from the BIM is presented in Table 4.1. The steel framing machine prototype (SFMP), as shown in Figure 4.16, is used as the manufacturing resource (i.e., machine) for this study. The SFMP is a semi-automated steel framing machine designed and built by research group at the University of Alberta, Canada. The initiative was taken to increase the productivity and accuracy of the steel framing process. A recipe file containing all the screw fastening locations is first downloaded into the programmable logic controller (PLC). An operator then places the top and bottom tracks and the electromagnets will be activated to secure the tracks. The operator will then assemble the entire frame based on the shop drawing. Once the frame is assembled, the squaring system will sequentially drag the frame to screw fastening locations defined in the recipe file, and the screw fastening system will use

Table 4.1: Summary of relevant panel specifications.

Panel Design	**Panel 1**
Shop Drawing	
Frame Dimensions (mm)	$X = 3048$, $Y = 2438.4$, $Z = 92.075$
Sectional Properties	

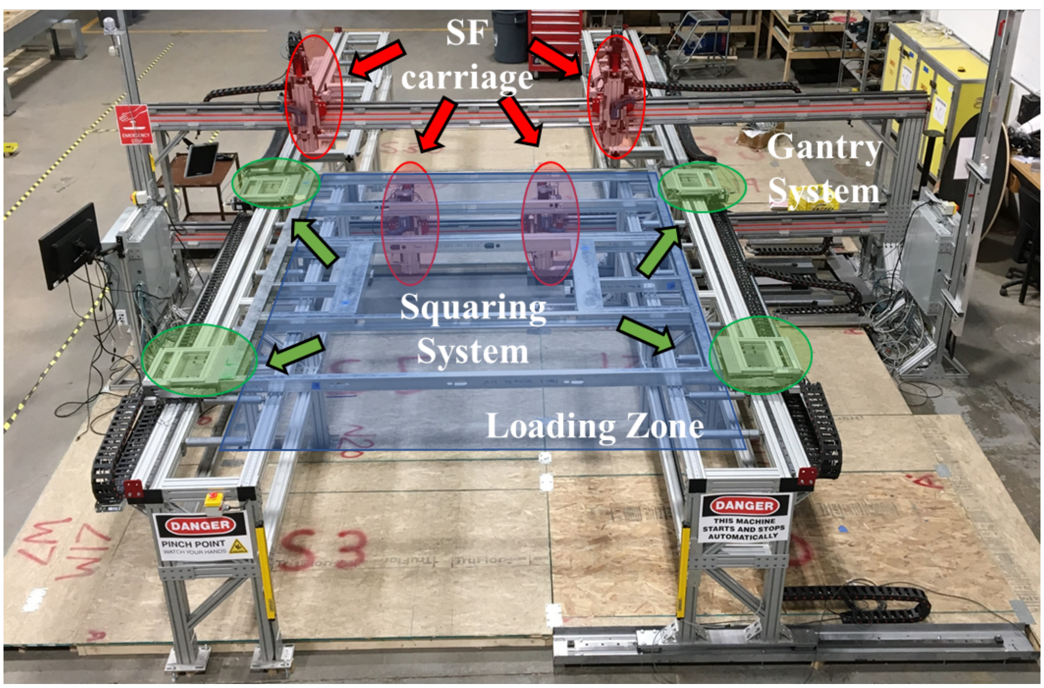


Figure 4.16: Steel Framing Machine Prototype.

screws to secure the connections. It has been proven that the SFMP produces fast and accurate steel frame assemblies for mid-rise buildings [17]. Relevant machine specifications for the SFMP used in this study are summarized in Table 4.2.

Table 4.2: Summary of SFMP machine specifications.

System	**Work Direction**	**Work Range (mm)**	**Collaborative Systems**	**Tool Direction**
Squaring System	Z	0 – 3200	-	-
Gantry System (Right)	Z	0 – 3658	-	-
Top SF System	Z	50 – 200	Squaring System, Gantry System	$(0, 0, -1)$
Bottom SF System	Z	0 – 20	Squaring System, Gantry System	$(0, 0, 1)$

4.4 Results

The simulated steel frame and the detected manufacturing planes are compared to the manufacturing planes determined based on experience. The machine eligibility of SFMP is determined and matched to the knowledge of design personnel of the machine. The overview of simulated frame with manufacturing planes is presented in Figure 4.17 (a). Manufacturing planes are expected at the top and bottom flanges of two intersecting elements. The detected manufacturing planes occur at the expected locations. Figure 4.17 (b) shows the details of horizontal bracings. Note that the manufacturing planes of the bracings are only detected at the ends of the bracings since no manufacturing operation is required at other locations, even though the bracings are intersecting with the studs. This result agrees with common practice in construction industry. The detailed view of angled bracings is shown in Figure

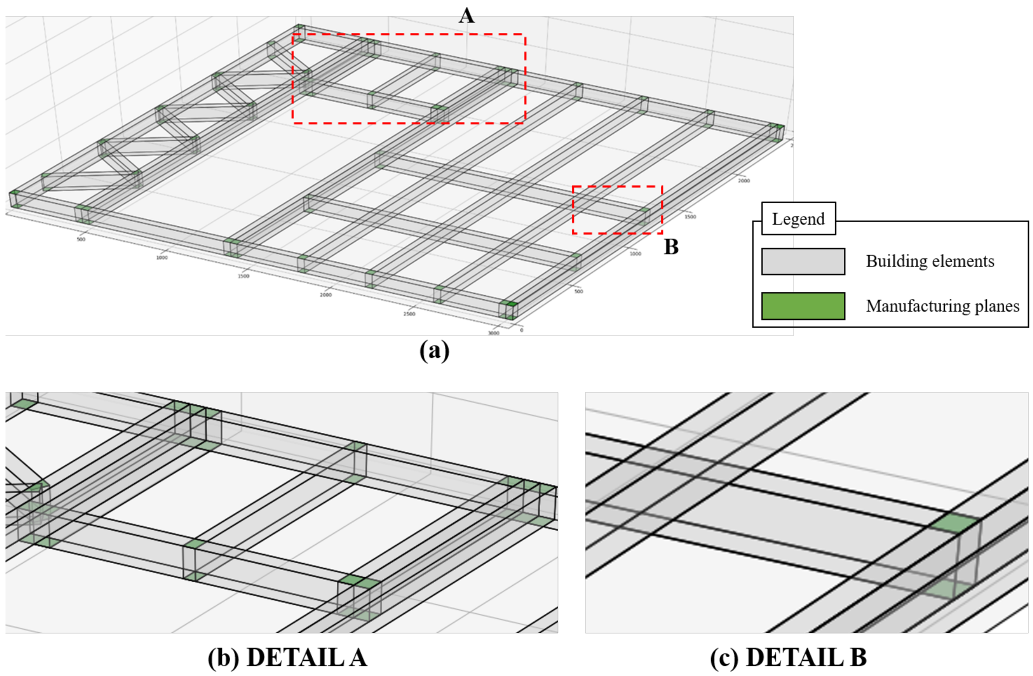


Figure 4.17: Simulated frame and manufacturing planes. (a) overview of simulated frame with manufacturing planes, (b) details of cripples, and (c) details of horizontal bracings.

4.18. As observed in Figure 4.18 (a), the angled bracings between the first two studs generate overlapping manufacturing planes. As discussed in Section 4.2.5, manufacturing operations only happen at common intersecting areas. The overlapping areas are detected as shown in Figure 4.18 (b). Since the angled bracings are oriented at an angle in 3D space, this result indicates that the 3D MEDS framework developed in Section 4.2 accurately determines, based on 3D geometrical data, the locations where manufacturing operations are to occur. Using the ontologies stated in Section 4.2.1, the most feasible manufacturing operation for fabricating steel frame assemblies is screw fastening. As a result, the region of effect (ROE) of top and bottom screw fastening systems are determined and visualized in Figure 4.19. The manufacturing planes determined previously are included in the ROEs which indicates that the

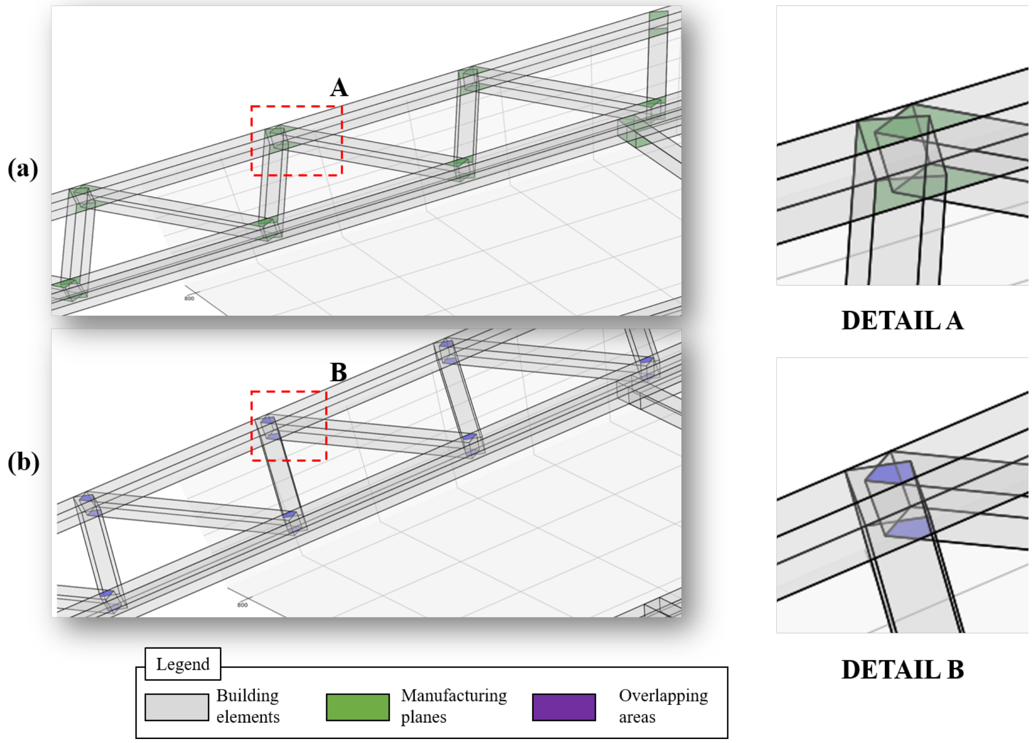


Figure 4.18: Overlapping areas of manufacturing planes. (a) overlapping manufacturing planes, and (b) overlapping areas.

SFMP can feasibly accomplish the manufacturing of the given steel frame.

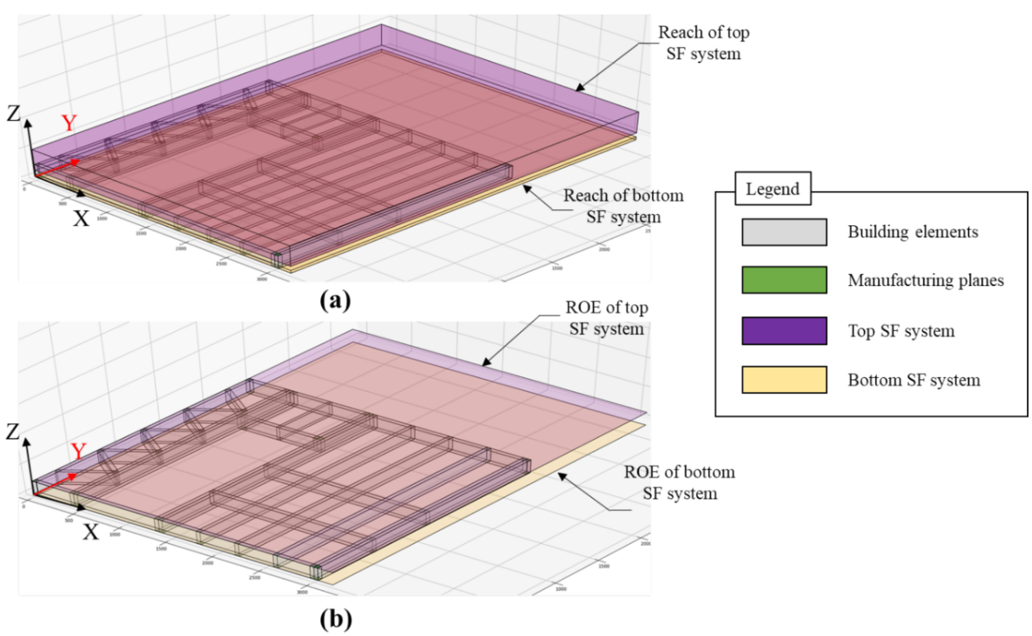


Figure 4.19: Reach and ROE of screw fastening (SF) systems: (a) reaches of SF systems, and (b) ROEs of SF systems.

4.5 Discussions and Limitations

Determining machine eligibility is the critical first step in automated process planning for frame assemblies manufacturing. The machine eligibility determination system (MEDS) framework proposed by An *et al.*, has been extended from 2D to 3D space. As observed in Section 4.4, the extended system is validated and shown to accurately determine the intersecting volumes and manufacturing planes in a given steel frame assembly. This proves that the proposed framework is applicable to frame assemblies that have 3D geometrical features. As discussed in Section 4.2.4, the accuracy of the system is 10^{-12} mm as computers have only finite precision. This accuracy is sufficient to for MEDS as it is far more accurate than most manufacturing technologies to date.

Some limitations are encountered while testing the developed system. First, the system ignores the contact area between two building elements even if the area can be detected. In building steel frame assemblies in Canada, lateral connections are required between two "back-to-back" building elements [43]. Since the framework ignores the detailed cross-section of the building elements and treats it as a convex polygon, the system cannot tell which way the element is oriented at the current version of the framework. More manufacturing rules need to be defined to address this issue.

Second, the time complexity of the developed system also has an adverse effect with respect to using it as a real-time system. Using the steel frame in Section 4.3, the simulation is run and timed for 70 trials. The average time is 41.6 seconds and the standard deviation is 1.62 seconds. Although the framework can be applied to steel frames with different type of 3D features, the current iteration of the proposed framework would not allow the system to be implemented in real-time due to the intensive computations required. Furthermore, a steel-framed facility usually consists of many steel frame assemblies. The time required to analyze all the assemblies grows quadratically. As stated in Section 4.2.3 and Section 4.2.4, the pre-processing of geometries has $\mathcal{O}(mnlogn)$ and intersection volume detection has the complexity of $\mathcal{O}(m^2)$ due to the nested iterations through m building elements. Since m is usually larger than n, the complexity of 3D MEDS is $\mathcal{O}(m^2)$.

4.6 Conclusions

The emergence of modular construction has resulted in frame assemblies being fabricated in a controlled factory environment. With the increasing use of automated machines, automated process planning is in demand and necessary to achieve agile manufacturing. To accomplish this objective, machine eligibility must be determined based on the BIM model of the products to be manufactured. The proposed machine eligibility determination framework detects 3D intersecting volumes in steel frame assemblies by employing techniques from computational geometry to first process the input geometry to lower the amount of computation, then detect intersecting regions of building elements using building blocks, and finally calculate manufacturing planes that require manufacturing operations, such as screw fastening. The method successfully determines the locations of manufacturing planes of the frame assembly and is validated using the automated steel framing machine designed and built at the University of Alberta. Study shows that it takes 41.6 ± 1.62 seconds to analyze the steel frame. In the future, the complexity of the system will be thoroughly studied and potentially reduced to make it a real-time system.

Chapter 5

Conclusions

5.1 Conclusions

Using ontologies, knowledge in product, manufacturing, and operation domains are formally specified. In product ontology formulation, knowledge of frame intersections are geometrically categorized and defined. Manufacturing operations needed for previously defined intersections are formulated using expert knowledge. By defining the relationships between product and operation formulations, feasible manufacturing operations can be determined.

To determine machine capabilities of wood frame assemblies manufacturing, the 2D Machine Eligibility Determination System (2D MEDS) first calculates mating planes of a wood frame assembly defined in the building information modeling (BIM) software. Using the manufacturing rules formulated in the ontology models, feasible manufacturing operations are determined. Manufacturing planes are then calculated and compared with the region of effect (ROE) of the appropriate machine. The eligibility of a machine to manufacture the BIM-defined wood frame is confirmed if the machine can carry out all required manufacturing operations. The proposed system was validated using two wood frame assemblies with different complexities. The results show that the MEDS accurately determines the machine's capability of manufacturing wood frame assemblies.

In addition to applying the 2D MEDS to wood frame assemblies, the applicability of the system is extended to encompass 3D geometrical features that are commonly encountered in steel frame assemblies. Using techniques from computational geometries, the intersecting volumes of building elements can be determined and the manufacturing planes of frame assemblies are found. The machine eligibility for the manufacturing of steel frame assemblies are determined using the aforementioned method. By testing the 3D MEDS on a complex steel frame, it is proven that the proposed system successfully determines the machine eligibility given a steel frame.

Several advantages of the MEDS are observed:

1. Determination of the machine eligibility given the BIM model of frame assemblies is now an automated process. The time and cost required for such process is reduced;

2. The system is based on plausible experience gained from the past instead of expertise of current personnel;

3. The MEDS is a generalized system which can be used for different processes apart from framing (such as sheathing).

5.2 Statement of Contributions

The major contributions of this research are summarized below:

1. Formulated the knowledge model of frame assemblies manufacturing in product, manufacturing, and machine domains (Objective 1);

2. Developed the general BIM-based framework machine capabilities decision support system for frame assemblies manufacturing (Objective 2);

3. Programmed and implemented the Machine Eligibility Determination System (MEDS) for wood and steel frame assemblies manufacturing (Objective 3).

5.3 Research Limitations

This research has the following limitations:

1. The region of effect (ROE) formulation only applies to machinery with linear actuators so that the 3D ROE is a rectangular prism. The ROE of systems with rotary motions, such as robot manipulators, is yet to be defined.

2. The time complexity of the developed system is quadratic, which is also referred to as "brute force approach". Due to the intensive computation time required, current state of the proposed framework would not allow the system to be implemented in real-time;

3. The MEDS relies heavily on the rules which may be specific to each company;

4. The MEDS ignores the thickness of steel frame elements. This could affect eligibility of machines as the parameters of manufacturing operation may depend on the thickness of the elements;

5. Pre-processing of steel frame building elements converts the concave geometry of the cross-sections into convex profiles. This, however, makes the direction of the building elements indistinguishable.

5.4 Future Work

As shown in Figure 5.1, the developed system is a building block to further development in related fields. To address the limitations in Section 5.3, the following future research is recommended:

1. Develop mathematical model that precisely describes the region of effect of multi-degree-of-freedom robot manipulators;

2. Incorporation of varying tool orientation of manufacturing systems would make the system suitable for a robotic manufacturing environment, which is trending in construction-oriented product manufacturing;

3. Real-time machine eligibility determination system (MEDS) could provide instant feedback to designers about if the designed product can be manufactured in the early design stage. This results in enhanced manufacturability of frame assemblies;

4. For manufacturing operations that are related to orientation of building elements, consideration of directions of the building elements will extend the applicability of the system.

Furthermore, automated process planning for frame assemblies manufacturing require research input:

1. By providing the optimized sequence of manufacturing operations required in frame assemblies manufacturing, process planning can be automated;

2. Further development can provide time and cost estimation capabilities. Automated production scheduling can be achieved.

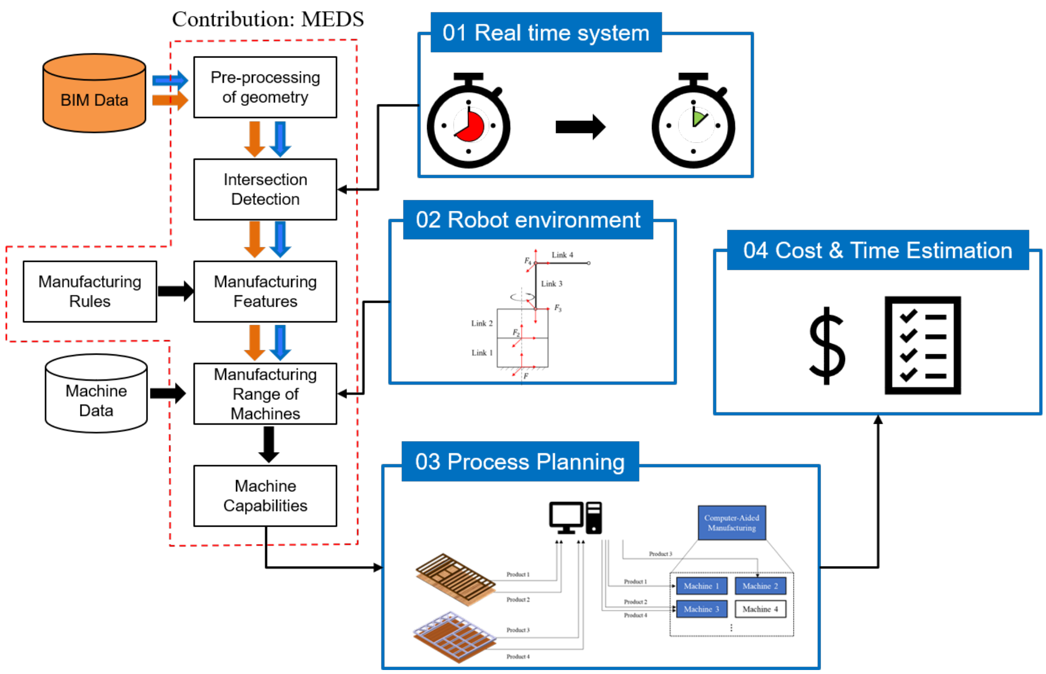


Figure 5.1: Future directions based on MEDS.

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Appendix A: Commonly seen mating planes in wood frame assemblies

As discussed in Chapter 2, intersections of wood frames are defined mathematically. This chapter provides details about these formulations.

A.1 Naming rule

The name of intersections consists of two parts: (1) building elements involved, and (2) type of configuration. The full name of an intersection is the combination of these components separated by an underscore. For wood frames, building elements are categorized based on their functionality and summarized below: Type of configuration

Table A.1: Types of building elements

Notation	**Type**
S	stud
P	plate
J	jack stud
C	cripple
H	header
T	track

indicates two states of building elements: (1) 'L' or 'T' connection, and (2) horizontal or vertical orientation.

A.2 Definition

'SP_LV' is shown in Figure A.1 and is defined in Equation (A.1):

$$(E_1 \in \text{stud} \wedge E_2 \in \text{plate}) \wedge (v_3 - v_2 \geq u_2 - u_1) \wedge (u_1 = 0 \wedge u_2 = u_{max}) \tag{A.1}$$

'SP_TV' is shown in Figure A.2 and is defined in Equation (A.2):

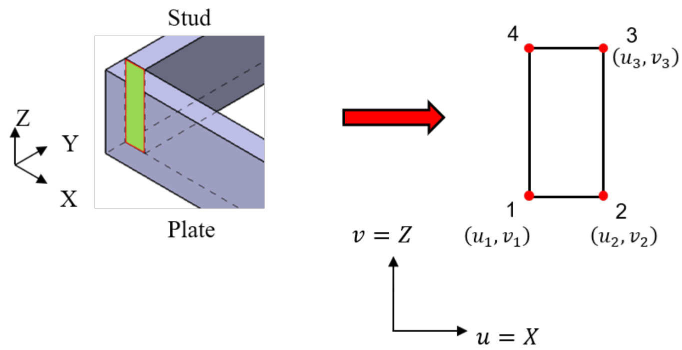

Figure A.1: 'SP_LV' connection.

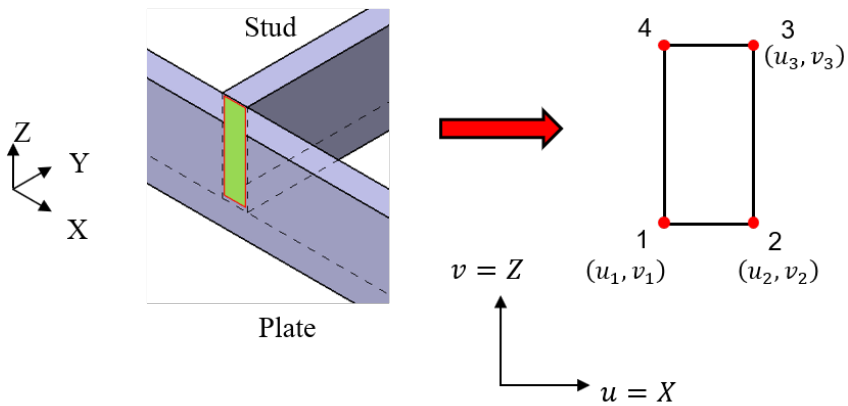

Figure A.2: 'SP_TV' connection.

$$(E_1 \in \text{stud} \wedge E_2 \in \text{plate}) \wedge (v_3 - v_2 \geq u_2 - u_1) \wedge (u_1 \neq 0 \wedge u_2 \neq u_{max}) \qquad (A.2)$$

'SP_TH' is shown in Figure A.3 and is defined in Equation (A.3):

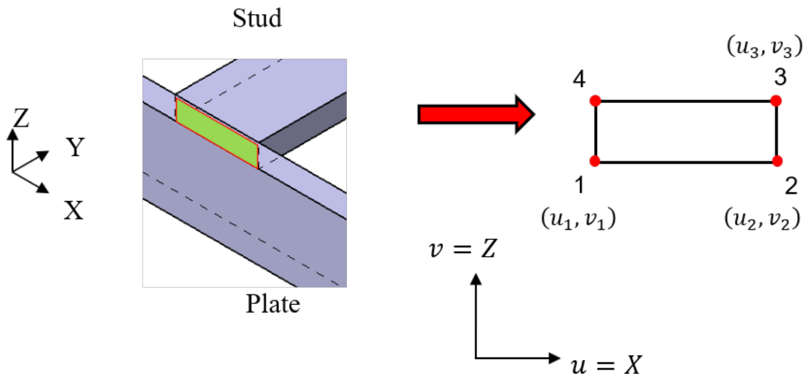

Figure A.3: 'SP_TH' connection.

$$(E_1 \in \text{stud} \wedge E_2 \in \text{plate}) \wedge (v_3 - v_2 \leq u_2 - u_1) \wedge (u_1 \neq 0 \wedge u_2 \neq u_{max}) \qquad (A.3)$$

'SDP_LV' is shown in Figure A.4 and is defined in Equation (A.4):

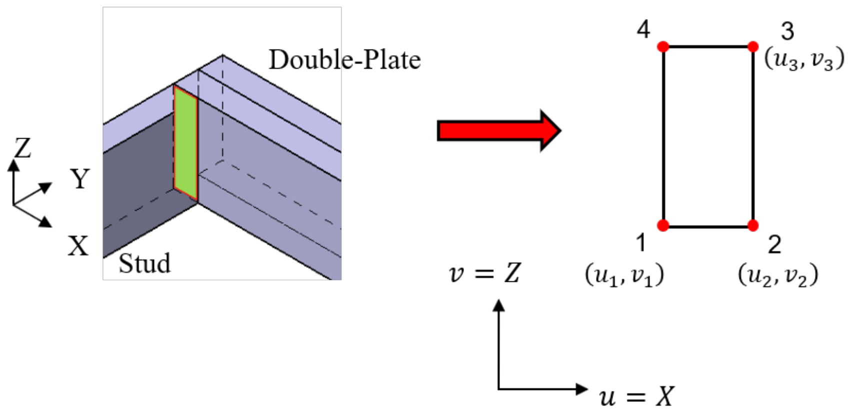

Figure A.4: 'SDP_LV' connection.

$$(E_1 \in \text{stud} \wedge E_2 \in \text{double plate}) \wedge (v_3 - v_2 \geq u_2 - u_1) \wedge (u_1 = 0 \wedge u_2 = u_{max}) \quad \text{(A.4)}$$

'SDP_TV' is shown in Figure A.5 and is defined in Equation (A.5):

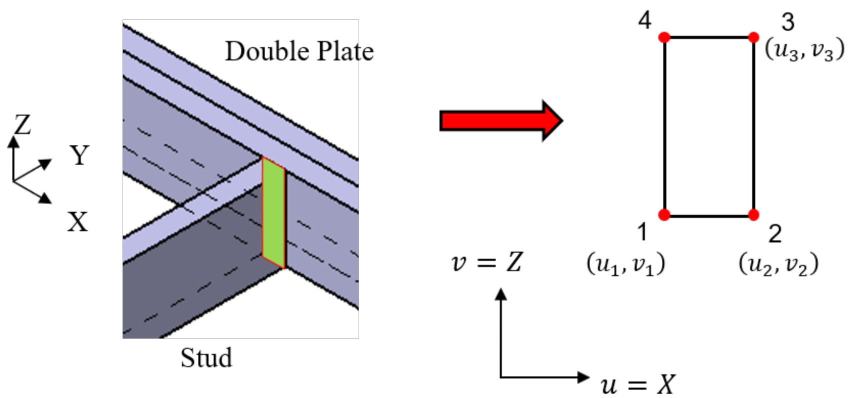

Figure A.5: 'SDP_TV' connection.

$$(E_1 \in \text{stud} \wedge E_2 \in \text{double plate}) \wedge (v_3 - v_2 \geq u_2 - u_1) \wedge (u_1 \neq 0 \wedge u_2 \neq u_{max}) \quad \text{(A.5)}$$

'SDP_TH' is shown in Figure A.6 and is defined in Equation (A.6):

$$(E_1 \in \text{stud} \wedge E_2 \in \text{double plate}) \wedge (v_3 - v_2 < u_2 - u_1) \wedge (u_1 \neq 0 \wedge u_2 \neq u_{max}) \quad \text{(A.6)}$$

Stud-stud connection 'SS' is shown in Figure A.7 and is defined in Equation (A.7):

$$E_1, E_2 \in \text{stud} \quad \text{(A.7)}$$

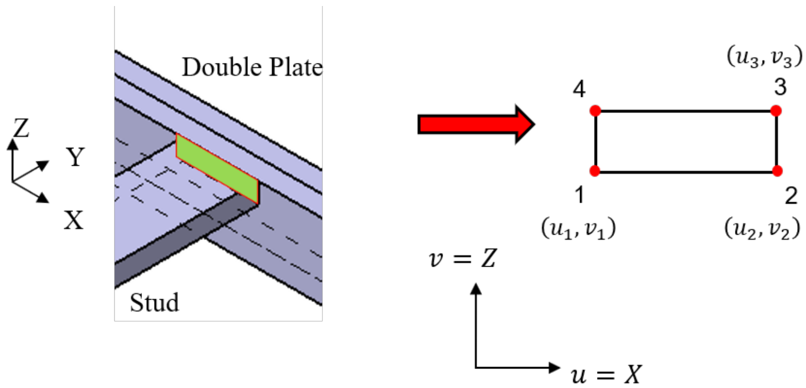

Figure A.6: 'SDP_TH' connection.

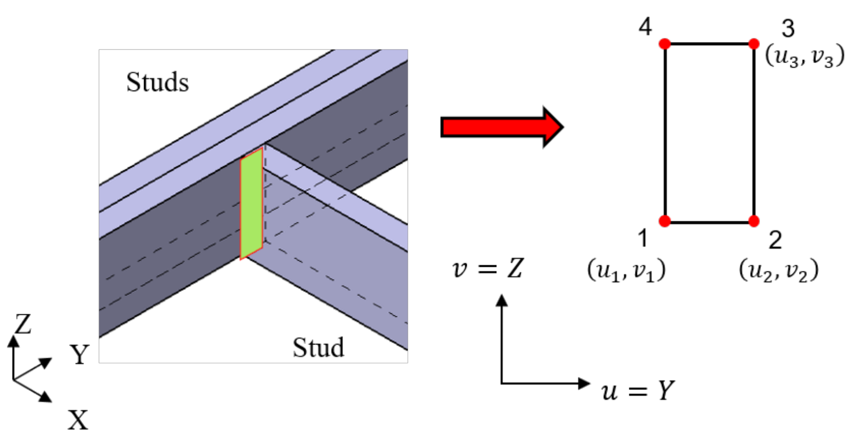

Figure A.7: 'SS' connection.