Integration of a Well-defined BIM Manufacturing External Module with CAD via Associative Features

by

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A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

in

Engineering Management

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Abstract

Currently, the building information modeling (BIM) has been widely applied as a powerful tool to model and manage buildings and infrastructure. However, the BIM system only provides engineers with an overall architecture, engineering and construction (AEC) view of the building and the information generated cannot be consistently transferred to modular manufacturers who use computer-aided design (CAD) systems as their major design tool. As a result, redundant communication is needed to carefully align customer requirement and order details. Human errors pose further barriers for information interoperability. In order to conquer this deficiency, a feature-based approach is applied to integrate BIM with CAD via an externally developed module. Based on the proposed approach, a case study of slider windows and casement windows are conducted, which proves the effectiveness of the proposed method and its potential impact on the industrial practice. An ellipse assembly line with modular tooling carts was designed to replace the existing assembly line in order to save space and increase manufacturing capacity. A fixture platform was designed to demonstrate the concept of design for manufacturing. Aided by an ERP system, the implementation of the proposed BIM/CAD associative feature also supports design for manufacturing which enhances the efficiency of part handling and assembling in manufacturing processes.

Preface

This thesis is my original work. Some parts of this thesis have been published or accepted by the journals or conferences listed below.

1. Muxi Li, Lei Li, and Yongsheng Ma. 2018. "Integration of Well-defined BIM External Module with CAD via Associative Feature Templates." In *proceedings of the 15th Annual International CAD Conference, Paris, France*
2. Muxi Li, Lei Li, and Yongsheng Ma. 2018. "Integration of Well-defined External Module CAD Templates into BIM System via Associative Feature Modeling" *Computer-Aided Design and Applications.*

Acknowledgment

First of all, I would like to express my gratitude to my supervisor, Professor Yongsheng Ma, for his valuable advice and lessons during my research. His guidance over the past two years has benefited me greatly in many different ways. Enthusiastic discussions with him always inspire me with excellent ideas and encourage me to continue to do my best in my work. Thanks for his guidance and support in helping me improve myself and produce this work.

I truly appreciate Mitacs, NSERC, and Durabuilt for their generous financial support to my research. NSERC and Mitacs provided me an opportunity to work at Durabuilt Windows & Doors and gain a lot of valuable industry experience in the past three years. I have learned so much and enjoyed working with all of my colleagues. Many thanks to Roger, Luis, Katarina, Parthasarathi, Sami, Patrick, Yanan and Kris for their help.

I would also like to express my sincere appreciation to my parents, uncle, aunt and my girlfriend, Joyce for their companionship and support. I want to give my deepest gratitude to my research team members: Yanan, Zhengrong, Jiangzuo, and especially Lei, for their advice and assistance. I also want to say thank you to my long-time friends Wu, Eric, Robert, Zheyu, Zhongcheng, and Meng. I would like to devote my thesis to all of you and thank you.

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List of Symbols

BIM	Building information modeling
CAD	Computer-Aided Design
3D	3 Dimensional
4D	4 Dimensional
5D	5 Dimensional
6D	6 Dimensional
7D	7 Dimensional
GDP	Gross Domestic Product
AEC	Architecture, Engineering, and Construction
CAE	Computer-Aided Engineering
LoD	Level of Detail
ERP	Enterprise Resource Planning
BOM	Bill of Material
API	Application Programming Interface
PVC	Polyvinyl Chloride
VB	Visual Basic
CSV	Comma-Separated Values
RD	Research and Development
AR	Augmented Reality
LC	Life Cycle
PLM	Product Lifecycle Management

GIS	Geographic Information System
IFC	Industry Foundation Class
CityGML	City Geography Markup Language
Temp	Temperature
Loc	Location
Cg	Color of Glass
T_{rt}	Type of Roller Track
T_s	Type of Sash
T_f	Type of Frame
W	Rough Opening Width
H	Rough Opening Height
H_s	Sash left and right length
W_s	Sash top and bottom length
P_{fw}	Top and bottom frame part
P_{fh}	Left and right frame part
P_m	Mullion part
P_{sh}	Left and right sash part
P_{sw}	Top and bottom sash part
Assem	Assembly

1 Introduction

1.1 Background and Motivation

In 2010, the construction industry (residential, non-residential, repairing, engineering, and other services) accounted for 6.0% of Canada's gross domestic product (GDP), and the total value stood at $73.8 billion a year. Among that, residential and non-residential building construction contributed $34.2 billion (Statistics Canada, 2018). Based on the market statistics, the GDP in the construction industry increased by 42.7%, whereas the GDP for all industries grew only 20.2%. This fraction has been expanding dramatically in recent years, which has offered a great opportunity to revamp the industry's end products and related technologies. The building information modeling (BIM), a perfect example of the innovation, was introduced to the construction industry.

Nowadays, BIM has become an irreplaceable tool in the architecture, engineering, and construction (AEC) industry. BIM software can provide architecture, engineering and construction professionals an intelligent 3D model-based insight into the project. It can detect failure, conflict, interference and collision of the design, which can save the project time and overall cost with a more efficient plan, design, and construction capability. Compared to traditional computer-aided design (CAD) software (for example AutoCAD (AutoCAD, 2018)), BIM software can estimate the cost of the entire project and provide downstream stakeholders with product data, environment data, and lifecycle data (Azhar, 2011). BIM system helps professionals from the initial design stage until the final construction phase. Specifically, engineers and architects first prepare the schematic architectural model (overall building form) for the project owners. After any design changes are completed upon request by the owner, the consensus design is ready to enter the detailed design model (e.g. with the color of an interior door). The 'detailed design and documentation' (AutoDesk sustainability workshop, 2018) is the 3rd level of details in the BIM system and it provides enough details to get the components ready for fabrication and manufacturing. This type of BIM model contains the precise dimensions, features of the component, and quantities and customization information.

However, in the current BIM systems, some more in-depth manufacturing information such as a window's cross-section profile could not be expressed due to the model size. In fact, the BIM software only shows a 3D view of the items inside a building. It does not contain enough details for manufacturing, which results in the lack of information during the manufacturing process after BIM documents are sent to factories. R&D engineers in manufacturing companies have to work with CAD software or even computer-aided engineering (CAE) software to model and analyze the products used in the building. They also have to synchronize the information between independent software, which reduces the efficiency dramatically.

At present, there is a variety of commercial BIM software such as Autodesk Revit (AutoDesk Revit, 2018), BIMx (Graphisoft, 2018), ArchiCAD (ARCHICAD, 2018) etc., and CAD software such as NX (Simens NX, 2018), SolidWorks (Dassault Systems, 2018), Pro/Engineer (ptc, 2018) etc. However, most of these tools focus on either BIM or CAD and lack the ability to handle other aspects of the product information.

Therefore, the author proposes integrating BIM and CAD with a coherent feature model, which will not only play a key role in achieving manufacturing of digitalized building components without an information granularity problem, but also enhance the ability of those manufacturing companies to rapidly respond to any design changes required by customers. In this paper, the BIM/CAD associative feature concept is proposed to manage geometric and semantic associations between BIM and CAD based on the associative feature regime brought forward by Ma and Tong (Y.-S. Ma & Tong, 2003). In addition, the authors will introduce the application of a data sharing mechanism between BIM and CAD to validate the information consistency which used to be an issue before. By using the proposed feature concept, a BIM/CAD integration framework is developed, which can provide both forward and reverse integration (Li & Ma, 2016), generate necessary manufacturing information, e.g. bill of material (BOM) for manufacturers, and support order driven product development.

1.2 Research Objectives

The aim of this research contains two main focuses: to develop a framework of integrating CAD software and a well-defined BIM manufacturing external module and to design an automated system for parametric design and drafting of building components for the material manufacturing industry, with regard to window design and manufacturing drawings. The associative feature approach has been adopted to incorporate an extended CAD module into BIM system, which is mainly for functional design in the manufacturing domain via a common feature model. It can reduce time on engineering design, and incorporate all the building code requirements and customized decision for manufacturing. Hence, the specific objectives of this research are:

- To develop a framework of integrating the well-defined BIM manufacturing external module with CAD via associative features. A mechanism that could efficiently integrate BIM and CAD system with data consistency.
- To design computer software that redesigns and drafts residential windows by using the prototyped BIM/CAD integration framework. The software can:
    - ➢ Extract BIM data from BIM software
    - ➢ Read all BIM related data and ask users to enter customer requirements
    - ➢ Designate corresponding CAD files and calculate parameters
    - ➢ Regenerate new CAD files, models, and drawings
- To develop a support library and a product parameter relationship data storage file that can:
    - ➢ Manage existing CAD parts, assemblies and drawing templates
    - ➢ Develop profile design calculation connecting data from the BIM software and CAD extrusion size
    - ➢ Develop rule-based components that are defined as a logical decision tree
    - ➢ Develop the software that reads all the data and regenerates CAD models and drawings automatically.

1.3 Thesis Organization

This thesis consists of five chapters. Chapter 1, Introduction, describes the research background, motivation, objectives, and an overview of the thesis study structure. Chapter 2, Literature Review, provides a general summary of the BIM technology, CAD feature, feature-based modeling, associated feature, lean manufacturing, Just-in-time production and order-driven design. Chapter 3, Proposed Methodology, presents the development of integrating a well-defined BIM external module with CAD via Associative Feature Templates and the software development. Chapter 4, Case Study, demonstrates an application of the framework to a window modeling case and its current limitation. The sample software is presented based on the integration of BIM and CAD software via associative future and it is ready to be used in a window and door manufacturing facility. Chapter 5, Conclusion and Future Development, summarizes the research contribution, industry contribution, limitation and suggestions for future work.

2 Literature Review

2.1 Introduction

In this section, a general discussion about the Building Information Modeling (BIM) technology, Level of Detail inside BIM, Integration between BIM and its related computer software and associative feature, is presented.

2.2 Building Information Modeling (BIM) Technology

Building Information Modeling (BIM) has become one of the most promising and effective technologies in the architecture, engineering, and construction (AEC) industry (Azhar, 2011). The term *Building Information Modeling* was first introduced in a paper by G.A. Van Nederveen and F. Tolman in December 1992 Automation in Construction (Van Nederveen & Tolman, 1992). According to National Building Information Model Standard Project Committee, the definition of BIM is:

> *"Building Information Modeling (BIM) is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition.*
>
> *A basic premise of BIM is collaboration by different stakeholders at different phases of the life cycle of a facility to insert, extract, update or modify*

information in the BIM to support and reflect the roles of that stakeholder"(National BIM Standard, 2018).

In the early 1980s, engineers and architects in the AEC industries shifted from hand drawings to CAD thanks to the launch of 2D CAD software such as AutoCAD. By using the software, drawings could be automated more efficiently and accurately compared to traditional hand drawings. Building information modeling was introduced to the industry to create models that "*more closely represent the way buildings go together*" (Rufflelt, 1986). BIM, a subdivision of CAD, is meant to specifically aid in the design and construction of buildings and infrastructure. BIM allows engineers to virtually build the building before the actual construction, and to discover interference and other construction-related issues through the entire construction project. BIM software is usually parametric based, and it can minimize coordination issues. It maintains the multi-directional relationship of all the drawings and model while engineers work on one. One of the most common issues related to 2D-based communication during the design period is the cost and time needed to generate reasonable assessment information about the proposed design. However, these analyses are normally done the last during the 2D CAD design phase, and it is already too late to make important changes (Eastman, 2011). Due to these disadvantages, AEC industries shifted from 2D software to BIM design platform.

The BIM software is more than just a 3D modeling tool. After decades of progress, it now includes further dimensions such as 4D (time), 5D (cost), 6D (operation), 7D (sustainability) and even 8D (safety) (Smith, 2014).

Dimensions	Corresponding BIM approach
3D	Virtual 3D modeling - Enhancement of traditional 2D design in terms of collaboration, visualization and data exchange.
4D	BIM with scheduling - Creates the opportunity for automated construction schedule - Computes task duration and product delivery using sequencing rules to achieve lean manufacturing for the building - Creates the visualization of schedule for the whole project as well as each phase
5D	BIM with cost estimating - Estimates the cost of material, labor and the total project by conceptual design - Compares the alternative technology and material which can help optimize timeframe and total investment of the project - Reduces the time on estimating and improves its accuracy
6D	BIM model with facilities management (FM) - Contains relevant information for embedded elements such as building structure, equipment and other finishes. - Keeps maintenance schedules of building components - Records components failures that are located and repaired
7D	BIM model with sustainability - Enables environment protection program to meet carbon targets for specific projects - Helps analyze the building energy consumption for LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Methodology).

Table 2-1: nD BIM with Description

The Table 2-1 above shows all dimensions of Building Information Modeling (Azhar, 2011; Czmoch & Pękala, 2014; Eastman, 2011; Goyal & Jha, n.d.; Kim, Anderson, Lee, & Hildreth, 2013; T. Lee, n.d.; Nicał & Wodyński, 2016; Smith, 2014). In the Building Information Modeling SmartMarket report (Bernstein & Jones, 2008) by McGraw Hill Construction in 2008, they reported the market status of the AEC industries in 2008 and made a projection for 2009 based on a survey completed by 23 organizations in the construction industry. The key findings were as follows:

- 62% of BIM users would use it on more than 30% of their projects in 2009.
- 82% of BIM experts believed that BIM had a very positive impact on their project productivity.
- 72% of BIM users reported that BIM had had an impact on their internal process of data and project.

BIM is well recognized by the AEC industries for various advantages and there are serval case studies and surveys showing the benefit of using BIM throughout a project. Based on the review, done by Bryde et al. (Bryde, Broquetas, & Volm, 2013), of 35 cases that were studied over a 2-year period from 2008 to 2010, 60% of the projects had the benefit of cost reduction or control; 34.29% saw time reduction and 37.14% experienced communication improvement. More information on the return of investment was discussed by Barlish and Sullivan in a more recent journal paper (Barlish & Sullivan, 2012). The company recognized a saving of 42% on standard costs and a reduction of 67% on project duration compared to similar projects.

BIM differs in various types of use. According to the 2011 survey report by RICS, BIM is suitable for larger and more complex buildings in residential, education, healthcare, commercial and many other building types (RCIS, 2011). These different scenarios influence the application of BIM, the support function of the design, and the model's level of detail (LoD) due to different requirements of the client and user (Volk, Stengel, & Schultmann, 2014).

2.3 Level of Details in Building Information Modeling

During the design process, there are small and big decisions to be made. Engineers and architects usually move from the bigger scale (the shape of the building) to the smaller scale (the color of the door handle). The level of detail (LoD) of the building follows the design process shown in Figure 2-1.

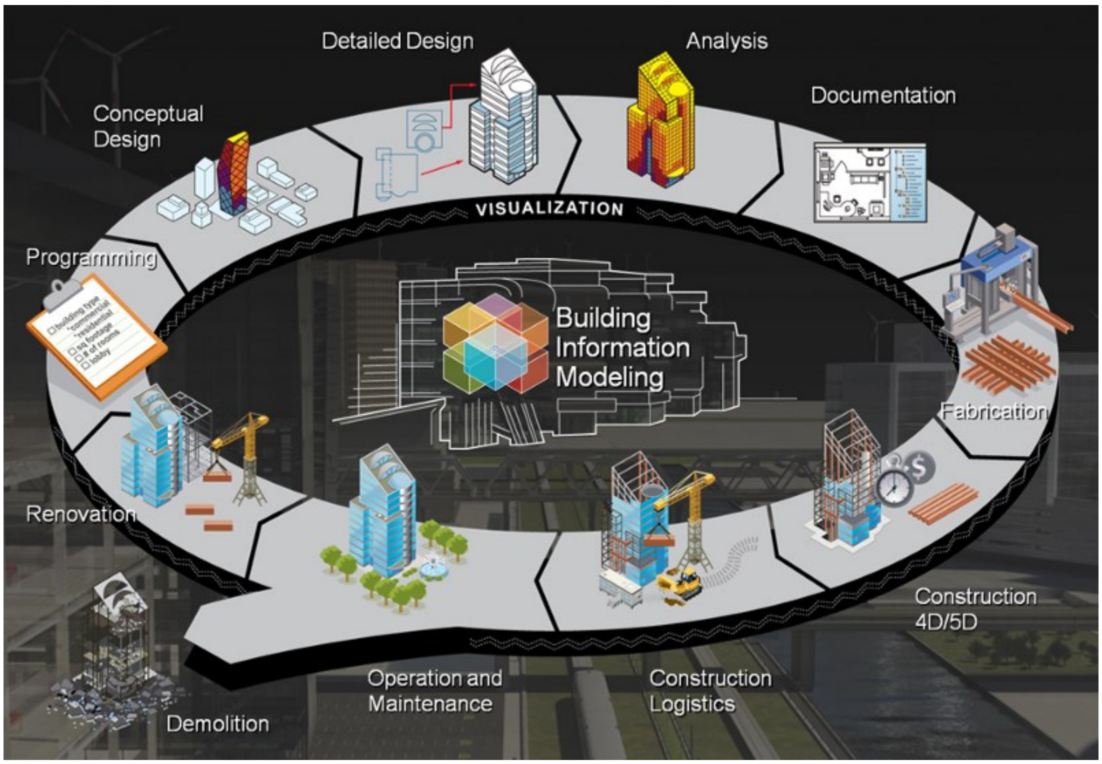


Figure 2-1: Building Information Modeling Workflow (Kristin Dispenza, 2010)

The model becomes more detailed as the building modeling comes closer to completion (AutoDesk Revit, 2017). Based on the Autodesk Revit document, the LoD follows five stages which are introduced in the Table 2-2.

LoD	Design Phase
LoD 100	Conceptual Design - The basic assumption about construction style and schedule. - Conceptual energy analysis helps engineers with choosing their passive design strategies and HVAC options. - The model contains overall dimension, location, and orientation.
LoD 200	Design Development - The model consists of general systems and assemblies with approximate shape, quantities, and size. - The energy modeling becomes more precise and focuses on specific rooms and design elements. - Analysis of the building systems can help designers decide on the final building form, equipment, and overall construction.
LoD 300	Detailed Design and Documentation - Model with specific assemblies and precise dimensions. - Process final detailed energy simulation or fluid simulation analysis and it can support and validate decisions. - Integrate architecture, mechanics, and structure to make sure they function synergistically and on-site construction is smooth.
LoD 400	Construction - Used for fabrication and assembly. - Architects and engineers hand off this model to contractors for the creation of fully detailed shop drawings or send it directly to the factory .
LoD 500	Operations and Maintenance - The final model represents the building. - Can be used for operations, maintenance and retrofits.

Table 2-2: Level of Detail (LoD) with Corresponding Specification

Provided by Bedrick (Bedrick, 2008), the LoDs are defined as conceptual, approximate geometry, precise geometry, fabrication and as-built as follows:

- Approximate geometry LoD represents components as generic elements (e.g., modeling a window component as a generic window without specifying it as a general window component) without defining their specific properties as they will appear in the confirmed final drawings.
- Precise geometry LoD represents components as they appear in confirmed final drawings in the BIM system, and shows detailed material and component properties.
- Fabrication LoD represents details of assemblies as they appear in shop drawings

The table shown in Figure 2-2 from Leita et al.'s research (Leite, Akcamete, Akinci, Atasoy, & Kiziltas, 2011) shows an example of the difference between approximate geometry, precise geometry and fabrication. The approximate geometry was composed of a generic wall element at the very start of the modeling inside BIM system. Next, the precise geometry included the approximate geometry and dimension of the model. The model contained windows and a curtain wall with a total of 12 parts. For fabrication LoD, the model provided more details which could go straight to a manufacturer from the BIM system. This model contained metal studs, interior gypsum, wood framing, Z-channels, batt insulation, rigid insulation, window and etc. which resulted in 240 objects in total.

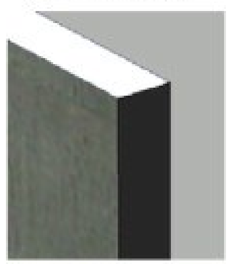
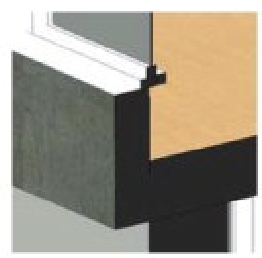
	APPROXIMATE GEOMETRY	**PRECISE GEOMETRY**	**FABRICATION**
Required semantics	Approximate geometry generic/abstract obj.(or entity or class or component) (not specific types)	Approximate Geometry + Exact geometry and shape, specific objects and their properties and associations to other objects, exact locations	*Precise* Geometry + connection details & elements & fabrication specifications
Uses when such LoD is appropriate	Visualization, Conceptual Cost Estimate, Phasing	Detailed Cost Estimate, Scheduling/phasing, Clash Detection, Design Check, Energy Simulation	Clash detection, Fabrication
3D components modeled for the exterior enclosure example	generic wall	Approximate Geometry + window, curtain wall	*Precise Geometry* + metal studs, interior gypsum, wood framing, z-channels, batt in sulation, rigid insulation, hat channels, flashing, cement/aluminum panels, zinc sheeting, zinc window surround, window, curtain wall
Semantics represented for modeled components	approximate geometry and placement of wall	precise geometry and placement, material type of wall, slab, window, curtain wall, topological relations to connecting elements	precise width, height, length, material type, placement, welding size of components listed above
Screenshot			
# of objects modeled for this example	01	12	240

Figure 2-2: An example of how different types of objects are modeled in three LoDs for the exterior enclosure (Leite et al., 2011)

The BIM system, however, could not achieve the full details to the fabrication LoD due to the focus of the BIM system. Increasing the model's LoD will not necessarily mean more molding work but such additional effort can lead to a higher precision and better decisions during design and construction (Leite et al., 2011). It is necessary for some construction projects to reach a high LoD which can help detect possible field clashes.

2.4 Integration of BIM and Other Related Platforms

BIM simulates the construction of projects in a virtual environment. With BIM technology, an accurate virtual model of building is digitally constructed (Azhar, 2011). As researchers believe that by using virtual reality technologies and game engines, games can help engineers and architects to understand architectural designs (Woodbury, Shannon, & Radford, 2001). Yan, Culp, and Graf (Yan, Culp, & Graf, 2011) demonstrate the BIM-Game prototype that integrates BIM and gaming into the architectural visualization. This framework supports an innovative design and play process that allows players to immerse into their own designed environment and to contribute to the design education. Researchers from Germany (Rüppel & Schatz, 2011) integrate BIM with engineering simulation to introduce a serious gaming approach for analyzing the human behavior in extreme evacuation process (such as fire or smoke). Augmented reality (AR), a very useful visualization technique, is now trending worldwide in different research and application areas. AR combining real world and computer-generated data (Milgram, Takemura, Utsumi & Kishino, 1995), can present to users with a better visualization inside a virtual building. Wang et al. (J. Wang, Wang, Shou, & Xu, 2014) claim that traditional visualization of an architectural design by using 3D model and static pictures seems cold and mechanical and will cause problems. They purposely integrate AR and BIM to enhance architectural visualization in a building's life cycle (LC).

Enterprise Resource Planning (ERP) is an enterprise-wide package that tightly integrates all necessary daily-operational business functions into a single system with a shared database (Z. Lee & Lee, 2000). An ERP system can bring enterprises a lot of benefits such as better inventory control, decreased payroll cost and improvement of order tracking (Umble, Haft, & Umble, 2003). ERP systems used to only deal with the management aspect of manufacturing and service enterprises while BIM system were just associated with the AEC/FM industry. Researchers (Holzer, 2014; Santos, 2009) believe that there are many more features of ERP that can be adapted and improved to BIM. Babic, Podbreznik, and Rebolj (Babič, Podbreznik, & Rebolj, 2010) discussed the advantage of linking BIM and ERP system which can help construction stakeholders with better project progress monitoring and material flow management. Nowadays, a lot of engineers and researchers are putting ERP and product lifecycle management (PLM) together for the most up-to-date product data to achieve manufacturing success. As PLM is the most effective way of managing a company's products across their lifecycle, from the initial idea till the end of life of the product (Stark, 2015), researchers (Aram & Eastman, 2013) proposed a conceptual model for functionality integration of PLM platform and BIM system and information flow among the two. Holzer (Holzer,

2014) used structured data streaming from BIM to link with PLM which can be applied to ERP systems across AEC community. As the construction industry is still in early days of exploring connections between these platforms to reach their full potential, researchers working hard to integrate them together are facing a competitive global market.

Geographic Information System (GIS) is a system designed to capture, store, manipulate, analyze, manage, and present different types of geographical data (Martindale, 2018). GIS plays a very important role in managing geology data that can help the civil construction in the site selection process and in emerging important information about buildings. Therefore, integration of BIM and GIS has become an important field of research because BIM and GIS helps engineers to visualize buildings before construction through a 3D virtual model with analysis of geographic information. Isikdag et al. (Isikdag, Underwood, & Aouad, 2008) established a possible software development for transferring BIM (high level of geometric and semantic) data to GIS system seamlessly and automatically by using two different data models- a Schema-Level Model View and a geospatial data model. Irizarry and Karan (Karan & Irizarry, 2012) integrated BIM and GIS to help optimizing location selection of tower cranes on a construction site. This model allows GIS system to output one of the more feasible locations suitable for tower cranes. Next, the BIM tool will generate a 3D model to visualize and verify the optimal location for tower cranes. Irizarry et al. (Irizarry, Karan, & Jalaei, 2013) integrated BIM and GIS into a new system which enables tracking supply chain status and warns stakeholders about delivery delays of construction material.

BuildingSMART has developed the standardized Industry Foundation Class (IFC) to accommodate information interoperability between AEC software (T. W. Kang & Hong, 2015). It was designed to provide a standard building information language and to facilitate data transfer between BIM and other civil related software required by different stakeholders through the project (Solihin, Eastman, Lee, & Yang, 2017). It is now the generic information exchange standard for BIM and it could be imported or exported by most of the BIM in the AEC community (BuildingSMART, 2018). City Geography Markup Language (CityGML) is also an important scheme due to its wide application in the GIS domain. IFC was used to connect with CityGML to integrate BIM and GIS by using the developed GeoBIM extension (de Laat & van Berlo, 2011). The designed GeoBIM extension has been proven that transforming IFC semantics into CityGML can be achieved. Based on their research, conversion from IFC data file to CityGML software is normally performed in lower LODs data file. There are a few researchers that focus on the integration of GIS and BIM based on semantic information by mapping IFC and CityGML. Deng, Cheng, and Anumba generated information mapping rules between IFC and CityGML on their entities and representations using instance-based method (Deng, Cheng, & Anumba, 2016). They also developed the Semantic City Model and this model can capture all the information in BIM and GIS models during mapping in order to store rich information from BIM in CityGML for semantic information.

Borrmann et al. discussed the potential extension between IFC and CityGML for involving multi-level representations of shield tunnels (Borrmann et al., 2015). To realize the information consistency of both semantics and geometry, the authors proposed to apply a procedural geometry to define dependencies between geometric entities among different LoDs. As open data, IFC has become the most widely used interoperable tool for data information synchronization and exchange across different systems. However, IFC shows a few limitations such as limited expression range, and difficulties in partitioning the information and sharing multiple descriptions of the same information (Pauwels et al., 2011). Some researchers (Vanlande, Nicolle, & Cruz, 2008) believe that despite using the open data exchange format such as IFC, data sharing between different architecture platforms is still a difficult task, which needs to be simplified. Therefore, to keep the data consistency and interoperability between BIM and manufacturing, other methods have to be used rather than just the traditional file transfer.

2.5 Feature-Based Application

Back to the late 70s, the feature concept was introduced into computer-aided technologies which usually consist of CAD, CAE, computer-aided manufacture (CAM) and etc. for LC modeling (Hoque, Halder, Parvez, & Szecsi, 2013; Y.-S. Ma, Britton, Tor, & Jin, 2007; Shah & Mäntylä, 1995). Feature was first seen as information sets that contain aspects of form or other property of a solid part while such information sets can be used during design, manufacture and performance

(Salomons, van Houten, & Kals, 1993). In the traditional paradigm, the features were mainly used to represent low level geometrical shapes.

Form Features: After years of developing, form feature has been the focus by researchers working towards feature-based modeling. Traditional form feature is feature specified to some special shapes used inside a product development, such as slot, hole, boss, and chamfer (Au & Ma, 2010). These features are required by computer-aided manufacturing (CAM) operations as they contain specific semantic information about a part geometry (Henderson & Anderson, 1984). Form features were also connected with product function features to present the sketching abstraction for conceptual design of the product (Mukherjee & Liu, 1997). The sketching abstraction can extract designs that are geometrically unlike but functionally similar, so it can help engineers and designers to get ideas about the alternatives design of the product. Ma, Chen, and Thimm claimed that most feature technologies are using the only form features such as feature relationship and product validation (Y.-S. Ma, Chen, & Thimm, 2008).

Machining Features: Machining features were designed to represent the high level geometric and support process planning and CNC machining. It is embedded in the product model and defined as the amount of material removed during machining operations by ISO 1999 (Y.-S. Ma et al., 2008). Joshi and Chang proposed the concept of attributed adjacency graph (AAG) for the recognition of machined features from a 3D representation of solid product(Joshi & Chang, 1988). Later, Gaupta and Nau generated an alternative approach to define the manufacturability of a part (Gupta & Nau, 1995). They claimed that by using the description of the part as collections of machining features and mapping these information among corresponding operation plans, it is feasible to evaluate the manufacturability of each operation plan of the machining parts. Machining features were also used to fulfill flexible manufacturing by bridging CAD and CAM system. Kumar et al. developed a feature recognizer which can recognize the machining features represented in the CAD model (Kumar, Nee, & Prombanpong, 1992). Later, features were developed to interact between multiple platforms for data consistency through feature recognition (De Martino, Falcidieno, & Haßinger, 1998). For example, Mark and David (Henderson & Anderson, 1984) linked CAD and CAM by developing a method which could extract manufacture information from the form feature and arrange it in a high-level data structure for manufacturing process planning. To further integrate CAD and CAM modules into automating process planning tasks, Miao et al. (Miao, Sridharan, & Shah, 2002) exported CAD model of the product in STEP file from the CAD stem to a new designed external machining feature recognition system. This new system was used to connect knowledge-based method to prepare product process plan. However, Miao et al.'s system did not support Computer-aided process planning (CAPP) system. Therefore, Hou and Faddis (Hou & Faddis, 2006) considered the gaps of Miao's system and created a system that can integrate CAD/CAPP/CAM system based on machining features. In the system, machining features were used to transfer machining geometry information from CAPP to CAM systems. By using this system, the process of tool path generation from solid parts can now be automated.

Assembly Features: Assembly features were designed to define relationships among a group of different parts that need to be connected and related (Shah & Rogers, 1993). Every single part inside an assembly could be represented by machining features and geometry features. The concept of the assembly feature, however, contains the notions of design intent, technical function, technological solution, and manufacturing process as well as it provides a specification of part features (DENEUX, 1999). Whitney et al. presented a theory of assembly applicable to assemblies that are statically determinate (Whitney, Mantripragada, Adams, & Rhee, 1999). The theory captured the design intent by creating a connective data model that contains information which is helpful for relevant analyses. This theory has better representation for the design intent of the design assemblies.

Further, features can be categorized according to their various applications and engineering intents, such as CAE feature, component feature, material feature, and functional feature. To achieve parametric configuration modeling, Ma et al. (Yong-Sheng Ma, Tor, & Britton, 2003) used the standard component library to represent all design objects that have the generic nature and can be expanded to include most mechanical components in a collaborative environment. The design of feature-object-based mechanical assembly library was introduced by Ma et al. to enable different types and configurations of assemblies included in a common library framework (Y.-S. Ma et al., 2004).

2.6 Associative Feature

Besides those established feature concepts discussed in the previous section, the associative feature proposed by Ma and Tong can bridge the gap between knowledge-oriented tools and CAD applications for intelligent product development in which the information consistency should be well maintained (Y.-S. Ma & Tong, 2003). It was proposed to represent the relationship between different forms of geometric entities depending on the specific applications. With richly sustainable and multi-facet associated approach, it tracks not only the geometry but also those non-geometrical aspects, e.g. manufacturing and logistic information for engineering projects.

Due to this characteristic, associative features have been employed in many applications. Ma and Bong used associative features to systematically explore collaborative engineering with reference to product lifecycle management (PLM). They (Y. S. Ma & Bong, 2010) defined a fine-grained information access to support intelligent design and manufacturing in which the associative features were used to link engineering knowledge and product geometry. Xie and Ma used associative features to solve the information interoperability issue and explored the universality of product and process model between chemical process engineering and mechanical design domains (Xie & Ma, 2015). Their developed feature model was designed to represent characteristics of multi-domain entities, while inter-domain sharing was supported by data mapping. Au and Ma reported the application of garment pattern by using the associative feature (Au & Ma, 2010). The virtual design features associated with parametric mannequins could solve the mass customization problem between the true measure of customers and regular size of clothes on the market. The associative optimization feature concept was proposed by Liu *et al*. (Liu, Cheng, & Ma, 2016) to complete information transfer between CAD and the structural optimization module. Cheng and Ma proposed a new feature-based CAD modeling method to guide designers to build CAD models that are valid to represent functional design considerations based on the functional feature and the associative feature (Cheng & Ma, 2017). The associative assembly design feature proposed by Ma *et al*. established the associations between part geometry and intermediate geometry which were used to define a part (Y.-S. Ma et al., 2007). Li *et al*. proposed the associative CAE boundary feature to interpret the information in the CAD model and convert it into the mesh and boundary conditions in CAE model (Li, Lange, & Ma, 2017). Incorporating fluid physics features and dynamic physics features, CAE boundary features also contribute to the feature model of an analysis view in multiple-view product development (Li, Lange, & Ma, 2018).

2.7 Fixture Design for Flexible Manufacturing

To secure a higher percentage of the marketplace and increased profit margin, high mix and low volume production are becoming more popular than mass production. This will drive manufacturers to develop new manufacturing processes, tooling and fixtures to achieve rapid turnaround in product development for flexible manufacturing (Boyle, Rong, & Brown, 2011). Fixtures are designed to position workpieces during manufacturing securely, accurately and rapidly (Dorf, Kusiak, &

Wiley InterScience (Online service), 1994). Bi and Zhang claimed that the cost of designing and fabricating a manufacturing fixture is around 10-20% of the total cost of manufacturing (Bi, Biy, & Zhangy, 2010). It is obvious that designing a flexible tooling and fixture can ease the manufacturing difficulty, minimize assembly time and reduce the cost of designing and fabricating. Kang et al. claimed that the fixture design is divided into four stages: setup planning, fixture planning, configuration design and fixture design verification (CAFDV) (Y. Kang, Rong, & Yang, 2003).

Machining feature was introduced early in section 2.5 which is the key feature within setup planning. There are different approaches to setup planning in the late 20th and early 21st century. Sarma and Wright proposed a robust graph-theoretic model for setup planning which permits an efficient and comprehensive method for optimal plans that minimize multiple objectives (Sarma & Wright, 1996). This algorithm selects the accessible faces for features, minimizes the number of setups and merges setup plans to the best squaring routines. Zhou et al. proposed a setup planning system with a product data translator (Zhou, Kuo, Huang, & Zhang, 2002). This system can automatically determine all surfaces of the model and tolerance information in order to direct the tool development. Matrix-based approaches were also implemented in later researches to represent the support of the research towards setup planning. Ong et al. used relationship matrix approach to analyzing the precedence relationships among features (Ong, Ding, & Nee, 2002). This relationship matrix later acted as main constraints for the setup planning optimization with collaboration of a simulated annealing approach and a hybrid genetic algorithm.

Fixture planning has to consider tolerance, constraining, affordability and collision prevention (Boyle et al., 2011). Layout plan was introduced to solve those requirements, and to specify the position and clamping points on the workpiece. Wang et al. presented a fixture planning layout optimization considering repeatability, immobility and stability of fixtures (Y. Wang, Chen, Liu, & Gindy, 2006) . The layout plan is optimized based on the amount of time repeated on the workpiece and the location accuracy. This layout can be considered within the global range and is very suitable for products with complex surfaces. Wu and Chan used genetic algorithms (GAs) for the fixture configuration optimization (N. H. Wu & Chan, 1996). After checking the validity of individual fixture configurations by analyzing contact types in the fixture system, the most statically stable fixture configuration will be carried out by GA. Pseudo-gradient was also introduced to optimize the layout plan. Vallapuzha et al. compared the effectiveness of different methods solving optimal layout of fixture problem (Vallapuzha, De Meter, Choudhuri, & Khetan, 2002). They concluded that continuous GA yielded the best quality among the global solutions and pseudo-gradient techniques are able to converge on local targets with comparably shorter solving time.

Unit design considers both conceptual and detailed scope of locating and clamping unit of the fixture. Conceptual design always focused on the types and quality of the elements in the system and also the general layout (Boyle et al., 2011). Wu et al. designed a geometry-element generator to help design adaptively fixture components with dimensions according to workpiece geometry and its corresponding feature information (Y. Wu, Rong, Ma, & LeClair, 1998). Any locator and clamp can automatically connect with fixture bases. The neural network was also used to support the conceptual unit design. Subramaniam et al. combined the strengths of neural network approaches and genetic algorithms to develop a fixture design system which shows that the design of the fixture system is promising (Subramaniam, Senthil kumar, & Seow, 1999). Detailed designs focused on the definition of different units more related to their dimensions material and geometry aspect. Later, Peng et al. presented a Virtual Reality-based system for interactive modular fixture configuration design (Peng, Wang, Liu, & Yu, 2010). By using a multi-view based modular fixture assembly model, information can be represented and managed to achieve the re-utilization of the element model. This approach can improve intuitive interaction and help 3D positioning of the fixture in the virtual space.

The verification process is able to ensure that all design features during different development steps (setup planning, fixture planning, and configuration design) satisfy the fixture requirements. Trappey and Liu proposed a verification system using quadratic optimization programming (Trappey & Liu, 1992). This verification system consists of four restrictions of the fixture system: force equilibrium based on time, limit of force before deflection, force direction based on model geometry and friction act on the part. Song and Rong highlighted that geometry constraint is the most important consideration during vilification process (Song & Rong, 2005). They proposed the method to detect if the system's geometry constraint status is under constraint or not. This helps designers to improve defect locating and provide guidelines to achieve optimal location. Collision detection is also very important in the verification process. It checks if fixtures are in interference with machine tools and if they collide with each other. Peng et al. claimed that the geometric representation of the polygon models inside the virtual environment could satisfy the requirements of real-time display and collision detection during the vinification process (Peng et al., 2010). Tolerance requirement is also considered a key feature within verification. Wang developed a tolerance analysis technique that describes the impact of localization source tolerance related to geometric errors of machined features (Yu Wang, 2002). It is very important to consider the overall tolerance among different critical points within the fixture layout design.

2.8 Summary

Based on the referenced literature, it can be concluded that the associative feature regime should be the right approach to integrate BIM and CAD applications. To the best of the authors' knowledge, there is no related research on associative feature-based modeling between BIM and CAD. Hence, it is significant to apply associative features to tackle the problems in BIM/CAD interaction.

3 Proposed Methodology

3.1 Introduction

This research focuses on two main objectives: the development of (1) the structure of BIM/CAD integration system and (2) an automated system for parametric design and drafting of building components. A window design and its manufacturing drawings as a case study will be discussed in Chapter 4. The purpose of this research is to fully automate the regeneration of CAD model and the drafting for material component list for the building industry.

3.2 Structure of BIM/CAD Integration System

The computer-aided applications such as CAD, CAE, and BIM, are developed for the special need of different areas in the industry. This has resulted in the specification of one single function, but it cannot automatically synchronize and exchange information between each platform due to the lack of synergy. For example, the technical files such as stress analysis report from CAE system cannot be interpreted by BIM system. In fact, those files have to be transferred into BIM system with a proper data format. Information from CAD cannot be transferred directly into BIM either. The CAD related files have to be converted or manually input by engineers. These issues reduce the efficiency in the product development, hinder the design consistency and sometimes even break down the associations between two applications. BIM/CAD integration should not just be a simple combination of two platforms. It has to bridge the information of two systems efficiently, consistently and validly. Therefore, the associative features are applied in this work to interface BIM and CAD and they can manage geometric and semantic associations between both applications and keep the information consistent. The framework of the BIM/CAD integration system is illustrated in Figure 3-1.

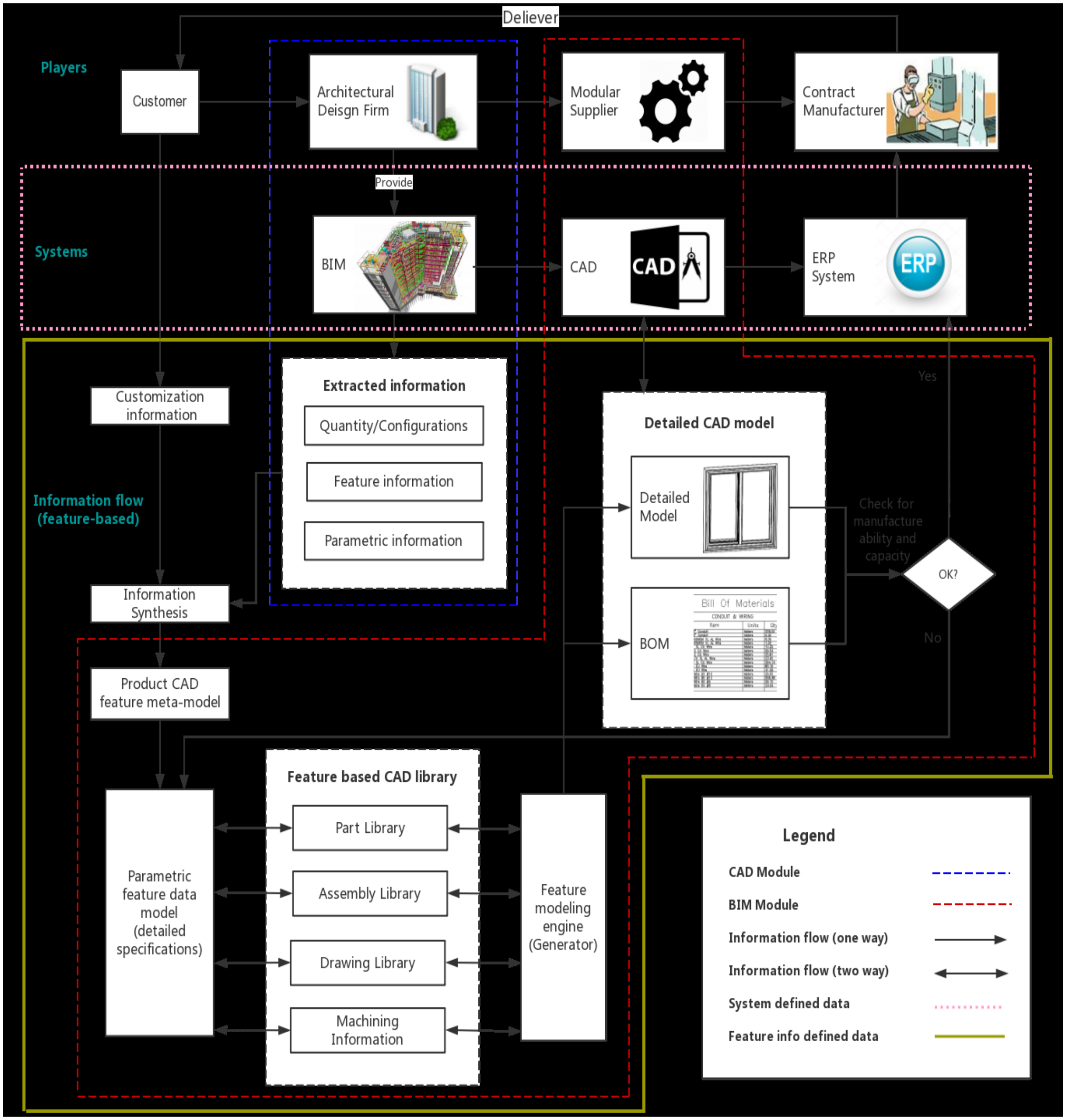


Figure 3-1 General Framework of BIM/CAD Integration

In this system, there are four major players (stakeholders) and they are the customer, architectural design firm, modular supplier and contract manufacturer. Correspondingly, BIM, CAD, and ERP are the components at the system level. After the architecture company negotiates with the customer about the final detailed model, the BIM model will be generated and the information will be extracted from the BIM files. Any important information such as quantity, feature, and parametric information will be excerpted and stored in a dataset. Customization information will also be synthesized with extracted data to provide a shared database. Then the data set will be mapped into a well-defined CAD template. This external database is designed well enough to cover all types of products which can be made by the manufacturer. The detailed model and BOM can be exported by the CAD software, which is essential for the manufacturing process. After verifying the result with the standard and design requirement, the BOM is ready to be sent for manufacturing and the information provided by the CAD model can be updated in the BIM system. The BOM will then be sent to enterprise resource planning (ERP) system in which it cooperates with scheduling and other enterprise data for manufacturing. Finally, the product is delivered to the customer.

The reason for using this innovative associative feature concept is that as shown in the previous literature review, many successful applications existed in the mechanical engineering domain and design background. This concept has proved to be a very effective method to manage different features involved in the product development process. However, in the multi-domain investigations, this feature concept has not been explored in detail. Most recent reference can be found in Xie and Ma's work towards integration of CAD and chemical process (Xie & Ma, 2015). To the best of my knowledge, this method has not been used as the cutting edge field of the construction industry and manufacturing industry. Because of the great potentials of this concept in the multi-domain research, this is the motivation for me to apply this concept. In my research, the new idea of tackling the interoperability levels between BIM and CAD was by using the associative feature. The associative feature is not a traditional feature, and it was proposed to represent the relationship between different forms of geometric entities depending on the specific applications. With richly sustainable and multi-facet associated approach, it tracks not only the geometry but also the manufacturing and the logistics information for engineering projects.

3.3 Implementation of the Proposed BIM/CAD Integration System

The purpose of BIM/CAD integration is to make sure the data consistency during the product design, simulation, analysis, and manufacturing process. It is important to understand the differences between the two platforms and come up with a method to bridge the gap.

3.3.1 Element Reorganization in BIM

Revit uses three important sets of entities in the 3D modeling system: model elements, datum elements, and view-specific elements(Demchak, Krygiel, & Dzambazova, 2008) as shown in Figure 3-2 (a) Essentially, from the engineering informatics point of view, there are in fact three classes of features that contain data structures and mapping graphs such as spatial relationships, component parameters, component geometry, engineering quantities and even building geographic information. The element types are also known as families, which represent the building component models within their corresponding categories. Each instance, also known as a detailed model, is an actual 3D model that is defined and controlled by its family (Bates, Carlisle, Faircloth, & Welch, 2013). This relationship is shown in Figure 3-2 (b). Inside the building information model, the hosts are the elements mostly built on the construction site such as walls, floors, and ceilings. The components are the attached elements associated with manufactured products that will be installed in a building such as windows, doors, and stairs. Figure 3-2 (c) shows the model of a slider window inside BIM. However this model is still in lack of details and could not be sent out directly for manufacturing.

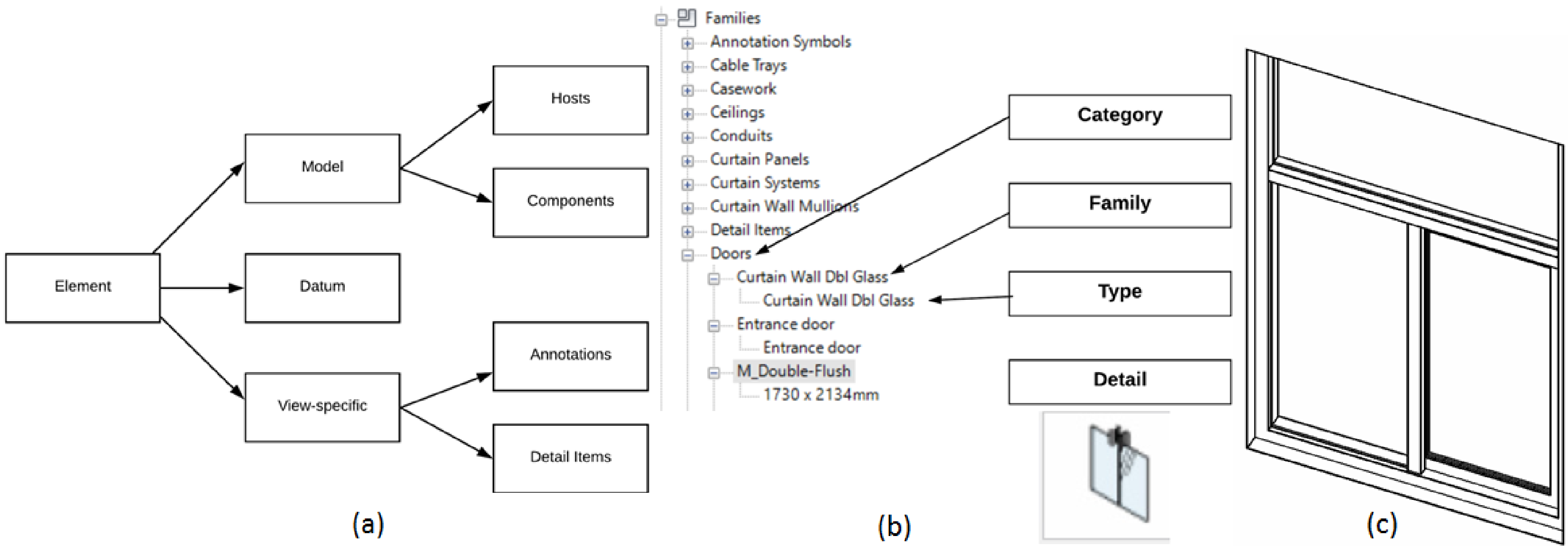


Figure 3-2: (a) Elements of Revit (b) Revit Families and (c) Detailed Model of Slider Window inside BIM

Every family, sheet, 2D, 3D view and schedule are stored in the same underlying building information database. As engineers and architects working on drawings and schedule views, the data and relationships are collected and integrated back into the project. The parametric design enables Revit to change anything at any time with ease. For example, when an engineer copies an existing window to a new location, the window will dimension equally as the previous model, and the relationship of spacing is also maintained. After the design phase, the schedule function can display the list of any type of element in the project. It will extract properties information from the element in a project and list them in the data files.

3.3.2 BIM/CAD Associative Features

The information from a BIM system, however, cannot be directly used to fabricate windows and doors due to the complex geometry of the manufactured components. Prior to the manufacturing process, detailed 3D models are required to verify the possible interferences of the model, and a BOM can provide the required cutting dimensions for the raw material as well as the information of all components required inside the product for the assembly line. The type and parameters of a BIM window or door feature can be extracted by using Revit application programming interface (API) or generated by Revit schedule feature, and then a data set of a separate window or door product CAD model will be produced. In order to achieve the automatic interpretation of the CAD result, a series of customized window features are defined so that it corresponds to customer's choices, such as the lamination material of the window frame or the type of glass used on the window.

This set of feature properties could not be included in BIM due to its different focus compared to CAD software. In fact, the BIM system is only designed to embed objects, create visualization and input general information into a 3D special model (Azhar, 2011) How the proposed feature concept interacts with the other features in the integration system for a sample slider window is shown in Figure 3-3.

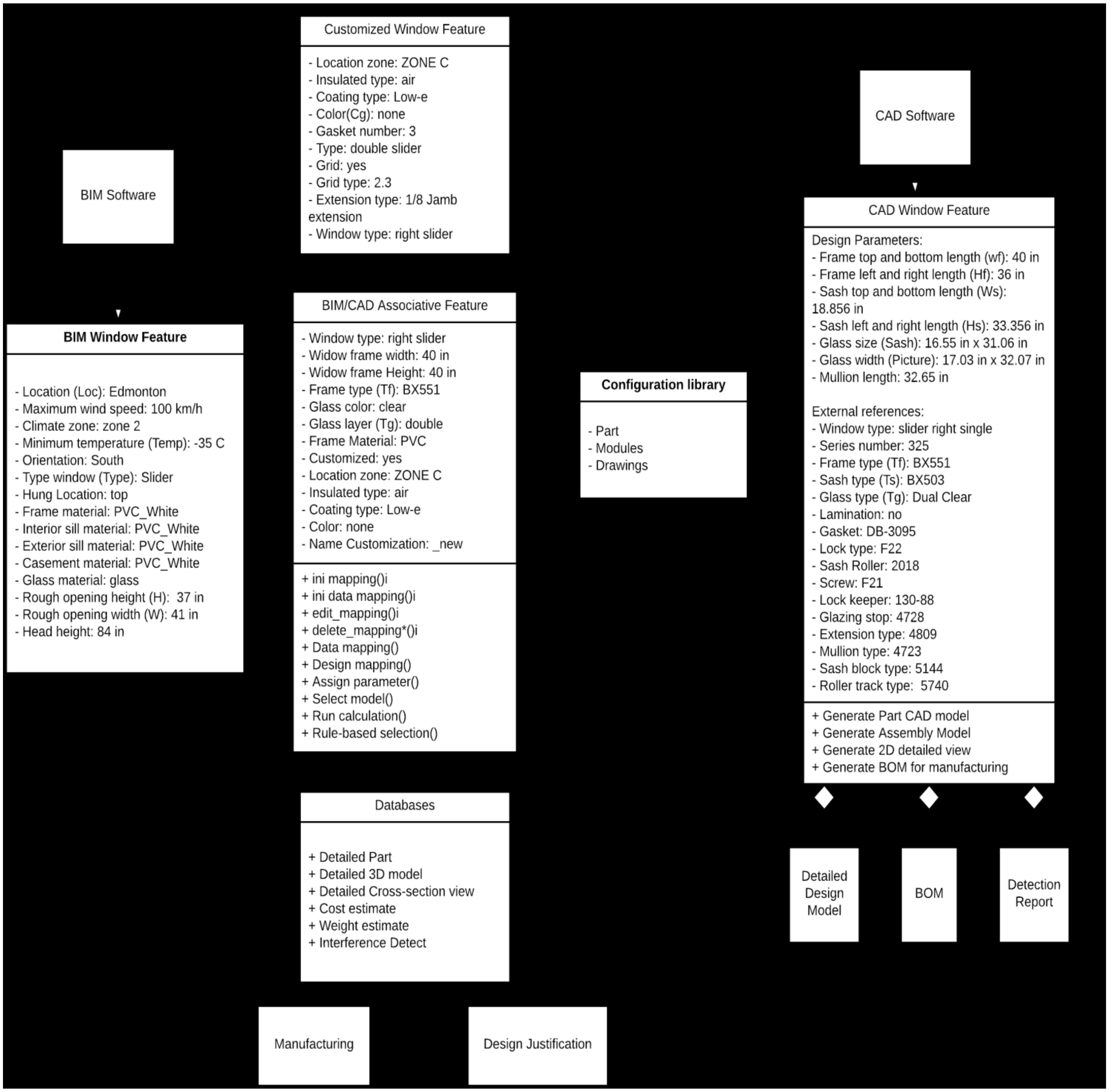


Figure 3-3: Semantic Associations in BIM/CAD Integration Referring to Window Features

3.3.3 A Well-Defined External Module CAD Templates

Inside a window or door manufacturing model, components such as *frames*, *sashes,* and *mullions* can be modeled according to characteristic parameters. Parametric modeling is used in external module CAD library with SolidWorks. This library uses a feature-object method and has the advantage of being able to process different parameters with all types of configurations of assemblies included (Y.-S. Ma et al., 2008). All the parts are grouped together and formed into series of typical *smart types*, e.g. *major/sub-types*, and stored as a supporting toolkit template file for the system (Yong-Sheng Ma et al., 2003) CAD templates also cover associated child templates for drawing, assemblies, and BOMs. Each individual product also has its own relationship data files. They are well-defined and can be generated by running SolidWorks API functions. Based on the input from BIM data set, the requirement and customized specification data structures and associations are embedded into the template with SolidWorks. The BIM/CAD associative features have been adopted to map the design-driven semantic parameters with constraints to build the CAD models based on data sharing (Gujarathi & Ma, 2010). When instantiated, the embedded functions then use BIM customer specifications to select and calculate all the required geometrics and analysis parameters according to the standard design procedure and building codes. Most of the decisions and customization steps can be processed automatically.

3.4 The Design and Prototyping of the Integration between BIM and CAD for Windows via Associative Features

The sample slider window is designed with company profile and can fulfill the CSA-A440 standard. Location of the building (zone), level of the building, emissivity rate, color and specific customer requirement are considered to select the type, design, and dimension of the glass. The frame of the window is designed by the window type inside the building model, and its dimension is decided depending on the opening on the wall inside the building model. The hardware of the window such as locking system, screws, or hinges are selected to match the window type.

3.4.1 Data Extracted from BIM System

The data from BIM system was exported by using Revit API tool (Jeremy Tammik, 2012). The code can be found in his personal website. By using this tool, the schedule of the whole project can be exported from the BIM system to a CSV file. The schedule from Revit can provide the quantities and material take off for the whole project. In this way, it can create another view of the project in the quantitative aspect. Figure 3-4 shows the different BIM schedule inside Revit software and Figure 3-5 shows the sample view of the schedule files inside the BIM (Revit) program.

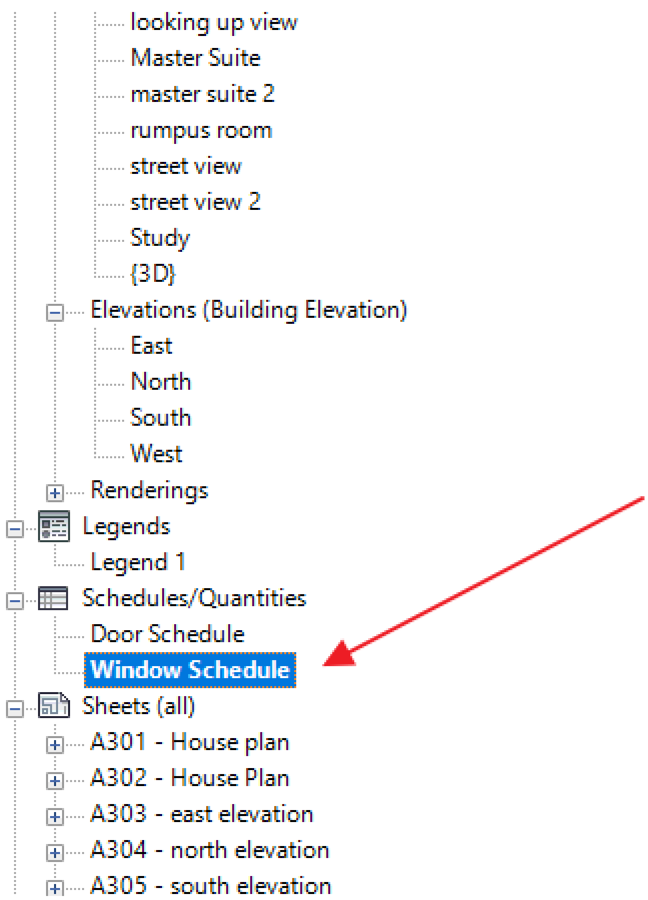


Figure 3-4: Schedules inside BIM

<Window Schedule>

A	B	C	D	E
Mark	Location	Window Style	Width	Height
1		Slider 450	610	457
2		Slider 450	611	2313
3		Slider 450	611	2313
4		Slider 450	611	2313
5		Slider 191	611	2313
6		Slider 191	611	2313
7		Slider 191	611	2313
8		Casement 700	611	2313
9		Casement 700	611	2313

Figure 3-5: Window Schedule inside Revit

The traditional method of exporting required data into a CSV file follows the following procedure:

- A user first selects the component from the category list, for example, windows/doors.
- Next, the user selects the field of the component, such as “window style”, “height” and “width” of the windows.
- A schedule is created and saved into a txt file.
- The user saves the txt file into a CSV file to maintain an open data exchange

This procedure is very tedious. And there are always scenarios that some design changes have to be applied to the manufacturing. To manually track design changes, it requires a great deal of work and that’s why synchronization is important. This is also the reason why Revit API is introduced in this chapter. Figure 3-6 shows a sample CSV file exported from BIM, and this is the information extracted from the BIM.

```
"Window Schedule"          ""        ""        ""        ""        ""
"Mark"   "Location"        "Window Style"      "Width"   "Height"
""       ""        ""      ""        ""        ""        ""        ""
"1"      ""        "Slider 450"      "610"     "457"     ""        ""
"2"      ""        "Slider 450"      "611"     "2313"    ""        ""
"3"      ""        "Slider 450"      "611"     "2313"    ""        ""
"4"      ""        "Slider 450"      "611"     "2313"    ""        ""
"5"      ""        "Slider 191"      "611"     "2313"    ""        ""
"6"      ""        "Slider 191"      "611"     "2313"    ""        ""
"7"      ""        "Slider 191"      "611"     "2313"    ""        ""
"8"      ""        "Casement 700"    "611"     "2313"    ""        ""
"9"      ""        "Casement 700"    "611"     "2313"    ""        ""
```

Figure 3-6: CSV File Exported from Revit

3.4.2 External Module CAD Templates Design

CAD libraries are designed for mechanical engineers to simply drag and drop components into the design to save time on creating reusable geometry. Often, the enterprise's CAD system library stores specific components such as screws, bearings, gearboxes, and quick insert and retrieval to the new assemblies or drawings (Vaxiviere & Tombre, 1992). In the window's model, they not only contain standard hardware such as screws, glazing tapes, and locks but also different frame and sash profiles to ensure the parametric modeling for all types of window model. The mates among the parts inside of an assembly are all pre-defined and locked inside of those base templates. The constraints between all the parts are set up front, such as *coincident, parallel* and *symmetric* mates.

Standard components are exported from manufacture's specification and rebuilt in Solidworks. Some manufacturers do not provide 3D CAD drawings (such as .stl, .sldprt, .igs etc..), therefore, engineers need to build 2D diagram to 3D solid components.

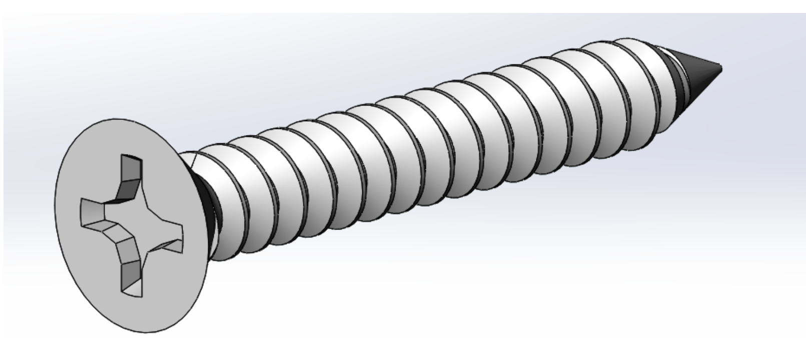


Figure 3-7: ISO View of the F21 Screw in Solidworks

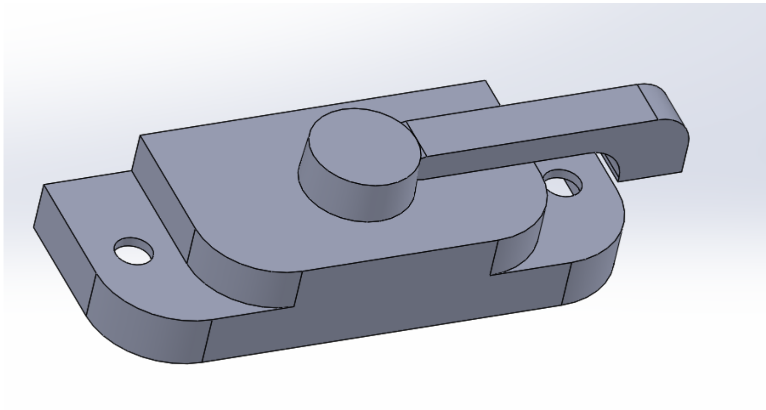


Figure 3-8: ISO View of Aluminum Sash Lock in Solidworks

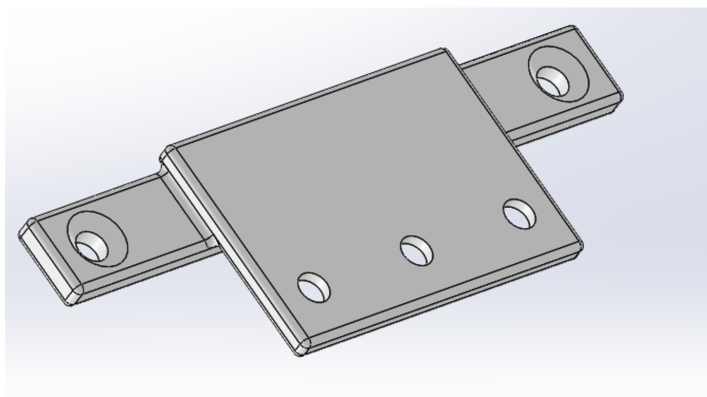


Figure 3-9: ISO View of Mullion Key in Solidworks

Some components, for example, sashes, frames, and glazing stops, are based on parameters. Those parts are mainly extruded from a cross-section of the profile. After extruding from 2D to 3D, parts such as sash and frame have to be cut into the 45-degree angle at the end of the profile, therefore, it can be assembled into a rectangular shape. Parts like glazing stops are just a sample extruding 3D part of the cross-section without any other feature. There are also some parts such as mullions which have some special punches for the hardware in the middle and some special cut for the fit at the end of the profile. These parts were extruded into 3D, then cut into the special punch shape by hole wizard feature or cut feature in the Solidworks.

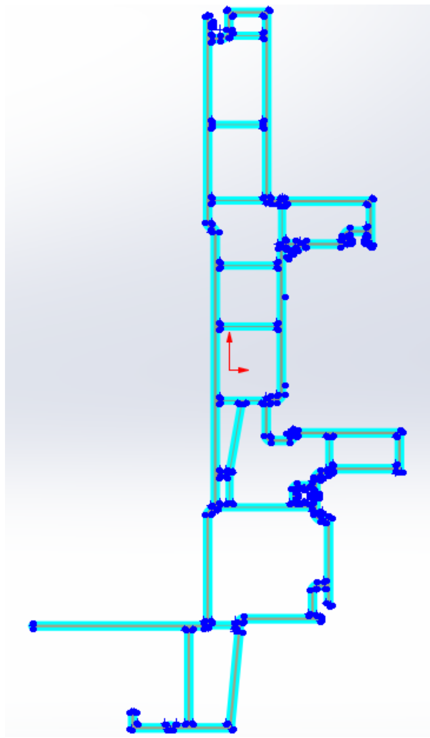


Figure 3-10: Cross Section View of a BX551 Frame Exported from AutoCAD

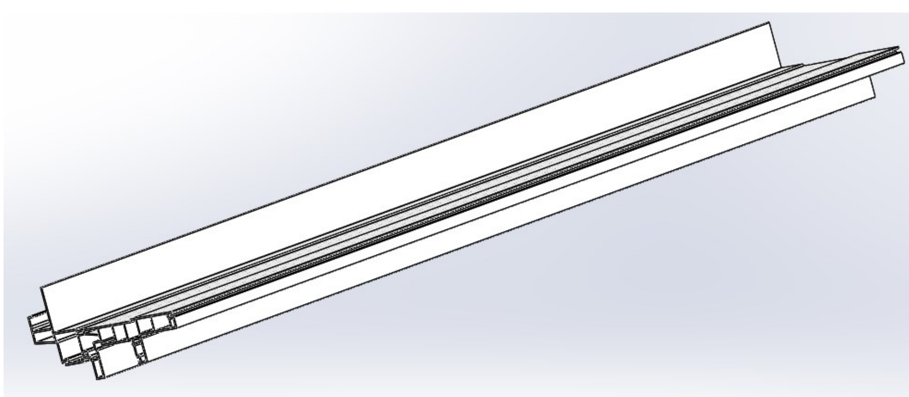


Figure 3-11: ISO View of Un-angled BX551 Frame in Solidworks

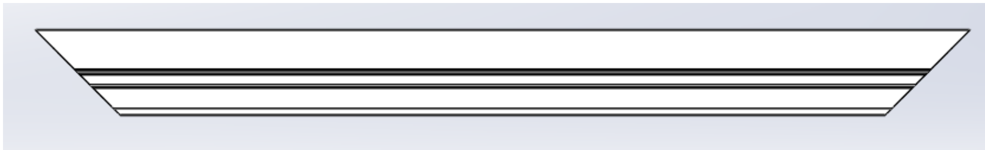


Figure 3-12: Finished BX551 Frame in Solidworks with 45 Degree Cut

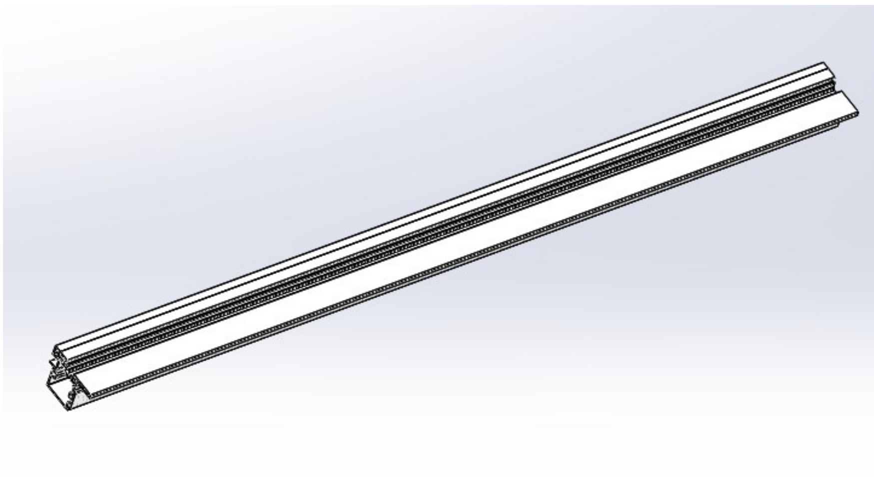


Figure 3-13: Extruded 4723 Mullion in Solidworks

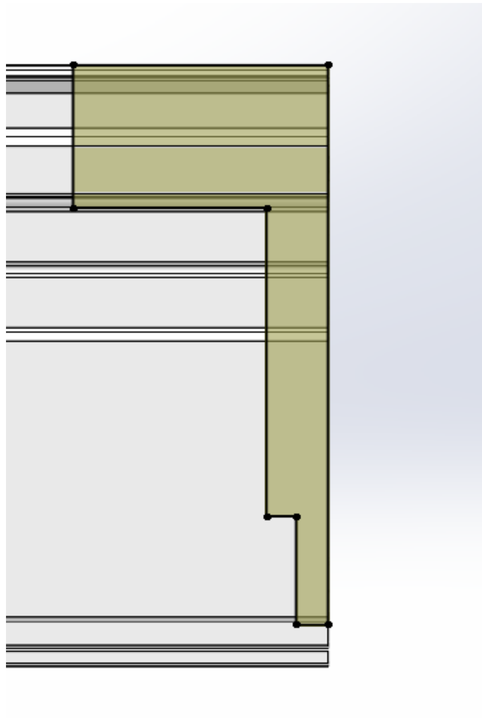


Figure 3-14: Detail of Extruded-cut for 4723 Mullion in Solidworks

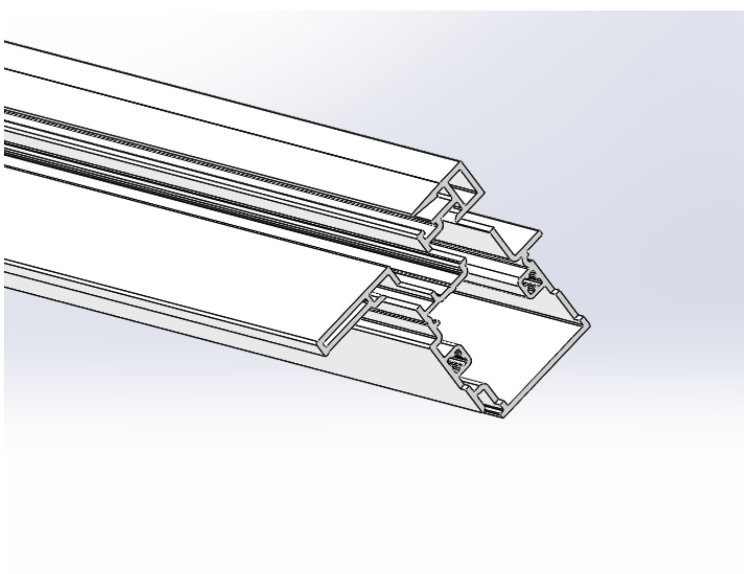


Figure 3-15: Detail View for 4723 Mullion in Solidworks

3.4.3 Profile Design Calculations

The relationships between the opening size of the wall and the length of polyvinyl chloride (PVC) frame profiles are based on engineering considerations. The relationships vary in different series of products due to the unique thickness and cross-section of each product type. In this work, the variation can be processed by the generic engineering calculation approach embedded in a program which can fulfill customer's requirement and design specification. All of the calculations are controlled by BIM/CAD associative features and considered as constraints of the design. These relationships are saved as a sub-program aside from the main functions in which each sub-program will match the corresponding series of the product. Each sub-program demonstrates the internal relationships and logics of a single product. The main program and sub-program are implemented by Visual Basic (VB) programming language. The rough opening width (W) and height (H) are treated as input from the BIM model.

The calculation of the frame size is based on rough opening on the wall. The deduction is based on the thickness of water infiltration, glue and other material that may cause a gap between the window and rough opening. The width (top and bottom) of the frame can be calculated as

$$W_f = \quad - \tag{3.1}$$

The height (left and right) of the frame is given by the following equation

$$H_f = \quad - \tag{3.2}$$

The height of a mullion can be calculated as the height of the frame minus the width of the cross-section

$$H_m = \quad - \tag{3.3}$$

The height of the sash can be found as the height of the frame minus the gap left for the roller and hollow on the top

$$H_s = \quad - \tag{3.4}$$

The height of the sash interlock equals to the height of the sash

$$H_{si} = \tag{3.5}$$

The width of the sash is given by the following formula

$$W_s = \quad - \tag{3.6}$$

The length of the roller track should be determined from the width of the frame and gap left for installation

$$W_{rt} = \quad - \tag{3.7}$$

The pocket cover equals the height of sash

$$H_{pc} = \tag{3.8}$$

The type of the frame will be determined according to the thickness of the wall inside the BIM model. According to the building codes, the profile must be able to fit between the exterior and the interior of the wall. The type of the profile will be determined based on the wall thickness.

3.4.4 Design for Specific Glass Based on Geographic Locations and Climate Attributes

As aforementioned, the program can generate a data model based on the parameters and geometry. However, there are some components inside the window that are rule-based, such as locks and glass. Those are usually controlled by engineering rules, regulated standard and design experience. Customized window feature is introduced to help decision making in the integration system. These rule-based paradigms are effectively implemented in a VB code to make sure the design will adhere to the entire requirement and ensure the information consistency.

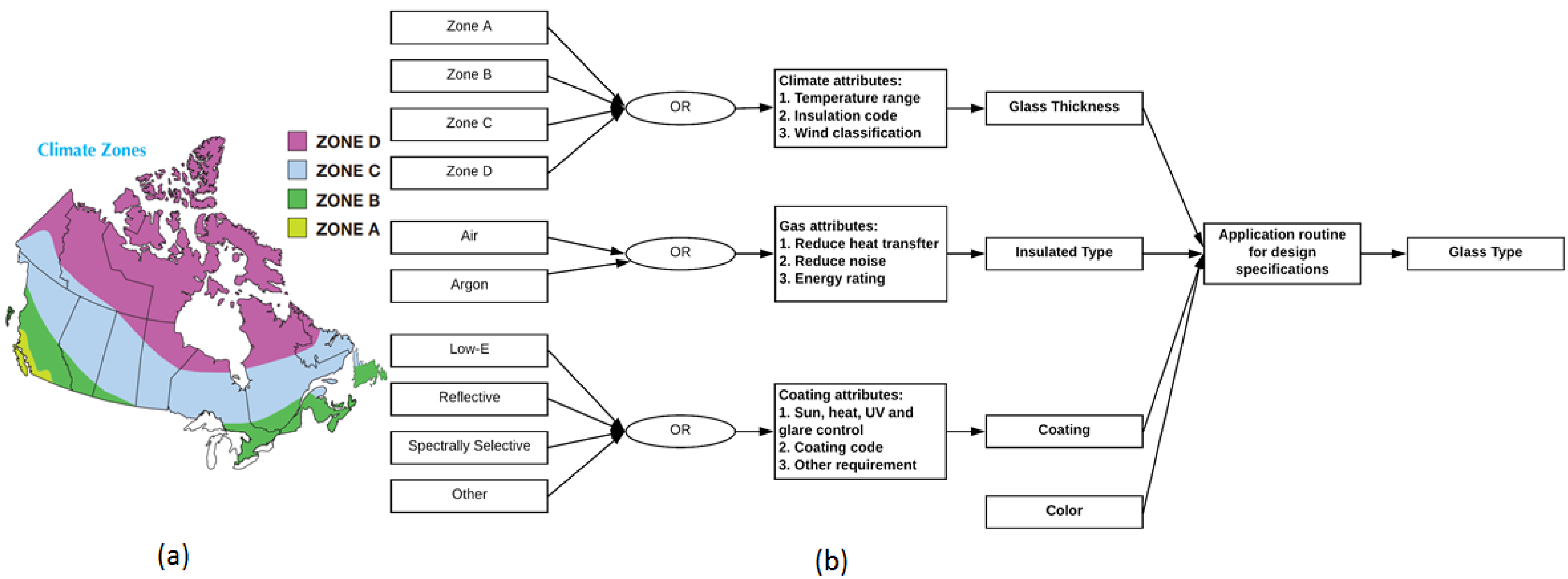


Figure 3-16: Climate zones of Canada and the related logics (a) Climate zones of Canada and (b) Logics for choosing a glass according to customer requirements

Figure 3-16 illustrates a logic structure of the customized window feature for the decision making on the glass selection. The location will be based on geography information (climate zones) to define the thickness of the glass. The insulated air will be inputted according to customer requirements to help minimize heat transmission between the interior and exterior. The coating which could either reduce heat transmission or reflect particular wavelength will be selected by customers as well. These three elements will then decide which type of glass will be used in the CAD model and this information will be eventually sent to the manufactory.

3.4.5 Data Storage by CSV File Development

Two types of comma-separated values (CSV) file are used in the software. The first CSV file type was introduced in section 3.4.1 as it was designed to store BIM data such as parameters and properties of the component. The second type of CSV file was designed to represent all the relationships between parameters. Some sample relationship can be found in section 3.4.4. This CSV file will guide the program to calculate different parameters inside an assembly. A sample CSV file is shown in Figure 3-17.

Name	Base on	Symbol	Number	Description
4720_W	W	"-"	0.5	Frame Width
4720_H	H	"-"	0.5	Frame Height
5740-WT1	W	"-"	40	Sash Track
4724_W	0.5*W	"-"	52	Sash Height
4724_H	4720_H	"-"	20	Sash Width
4725	4724_H	"*"	1	Sash Interlock
4723	H	"-"	62	Mullion

Figure 3-17: Parameter Relationship CSV

Some sample calculations based on the equations defined on section 3.4.3 are shown below in order to demonstrate the logic behind this CSV file.

After the data is imported to the BIM CSV, the rough opening size of the window width (W) and height (H) are updated to become the driven parameters. Some sample calculations are explained as follows:

The program will read the driven parameter “W” and the compute sign “-”, and the frame width parameter “W_f” can be calculated based on equation (3.1) and then updated as “4720_W”:

$$4720\_W = \quad - \tag{3.9}$$

The program can calculate the length of sash interlock “H_{si}” based on the parameter relationship stored inside the CSV file as well. As the program reads the driven parameter “4724_H” with the compute sign “*” which means those two parameters are equal. And “H_{si}” can be calculated based on equation (3.5) and then updated to “4725”.

$$4724\_h = \tag{3.10}$$

3.4.6 Parameter Semantic Map of BIM/CAD Associative Feature Modeling

As previously discussed, BIM/CAD associative features collect parameters from the BIM and then combine them with customized window features required by customers for further processing by CAD. As described in section 5.1, all parameters are semantically connected to each other in the engineering calculation. In order to make sure all the parameters in the design are associated, the relationship between parameters has to be identified and well developed. Figure 3-18 below shows all the relationships between parameters, customer requirements, CAD parts, and the CAD assembly. Changes in any parameters or customer requirements will impact the whole design. All the relationships between parameters are saved in comma-separated values (CSV) files for each product.

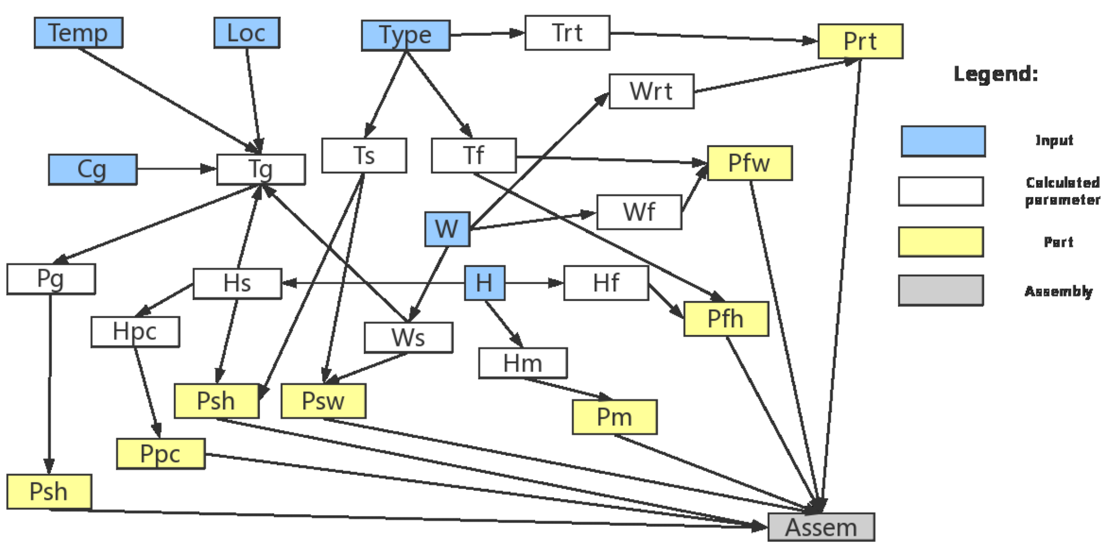


Figure 3-18: Parameter Semantic Map for a Slider Window

The links between parameters and parts inside BIM/CAD associative features follow certain patterns according to its driven parameter, design procedure, and production limitation. Semantic was designed to illustrate interpretation and representation of the information. To be specific, the terminology *semantic* evolves in my research is refer to terminology, relationship, knowledge and types of products in the design intent. In Figure 3-18, parameters and customer requirements are colored in blue while parameters generated by BIM/CAD associative features have no filled color. Those parameters are directly linked to BIM parameters and elements useful for CAD model rebuilding. Yellow boxes indicate the CAD parts stored in a well-defined CAD library. After the relevant parameters are calculated, the CAD software will generate new parts and assemble them into the new CAD assembly.

3.4.7 BIM/CAD Program Development

Figure 3-20 is a screenshot of VB programming language code under visual studio 2005 environment within Solidworks Visual Studio Tools for Application. Within Solidworks API, the main programming languages used are VB, VBA, VB.Net, and C#. In my research, VB is employed as the main programing language. As VB is easy to learn and has an integrated development environment (IDE), a lot of programmers use it to develop APIs. Figure 3-19 shows the workflow of the program.

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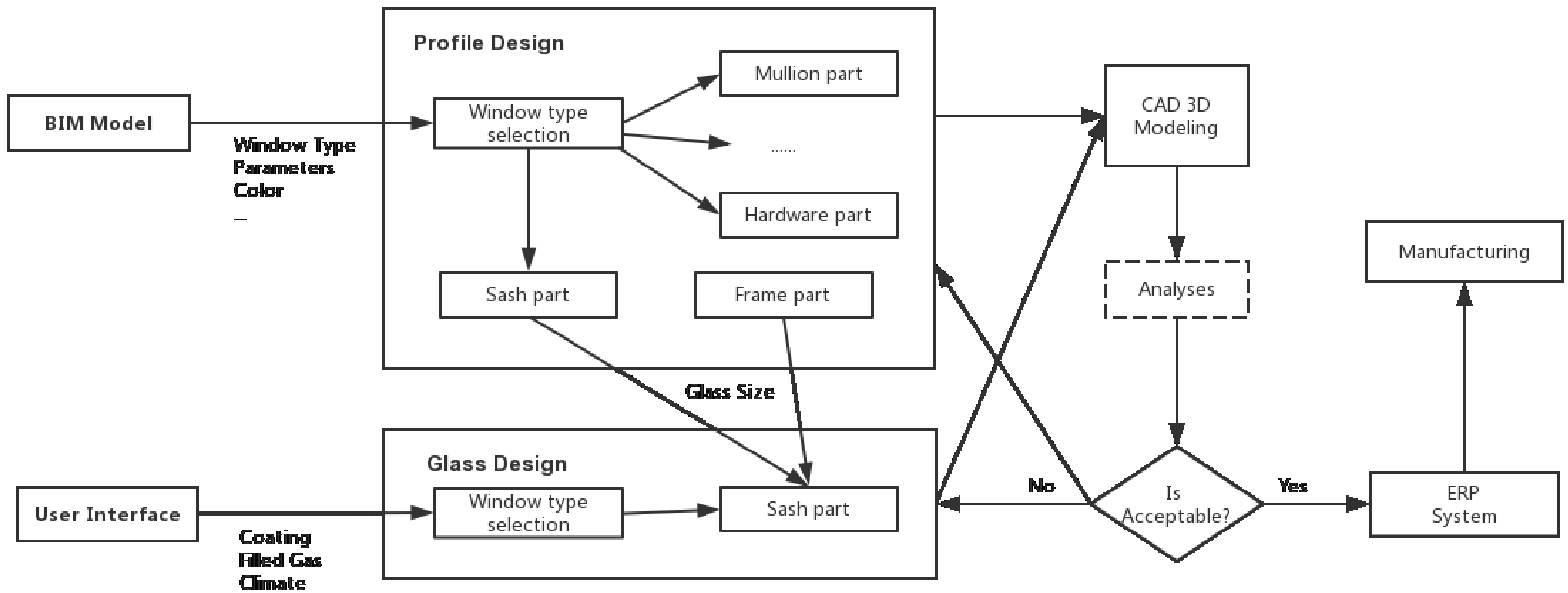


Figure 3-19: System Logistic Work Flow

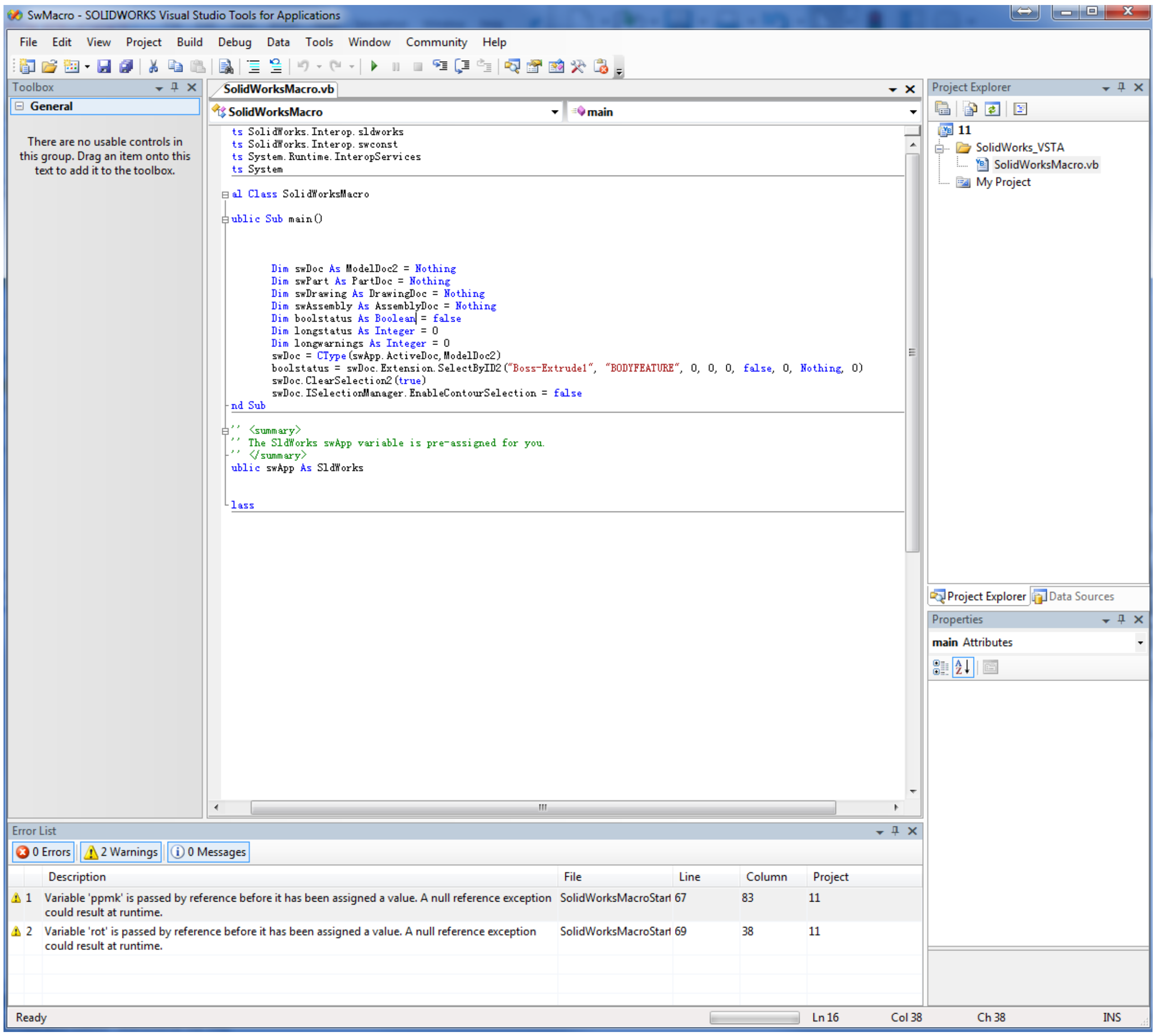


Figure 3-20: User Interface of Visual Studio for Solidworks

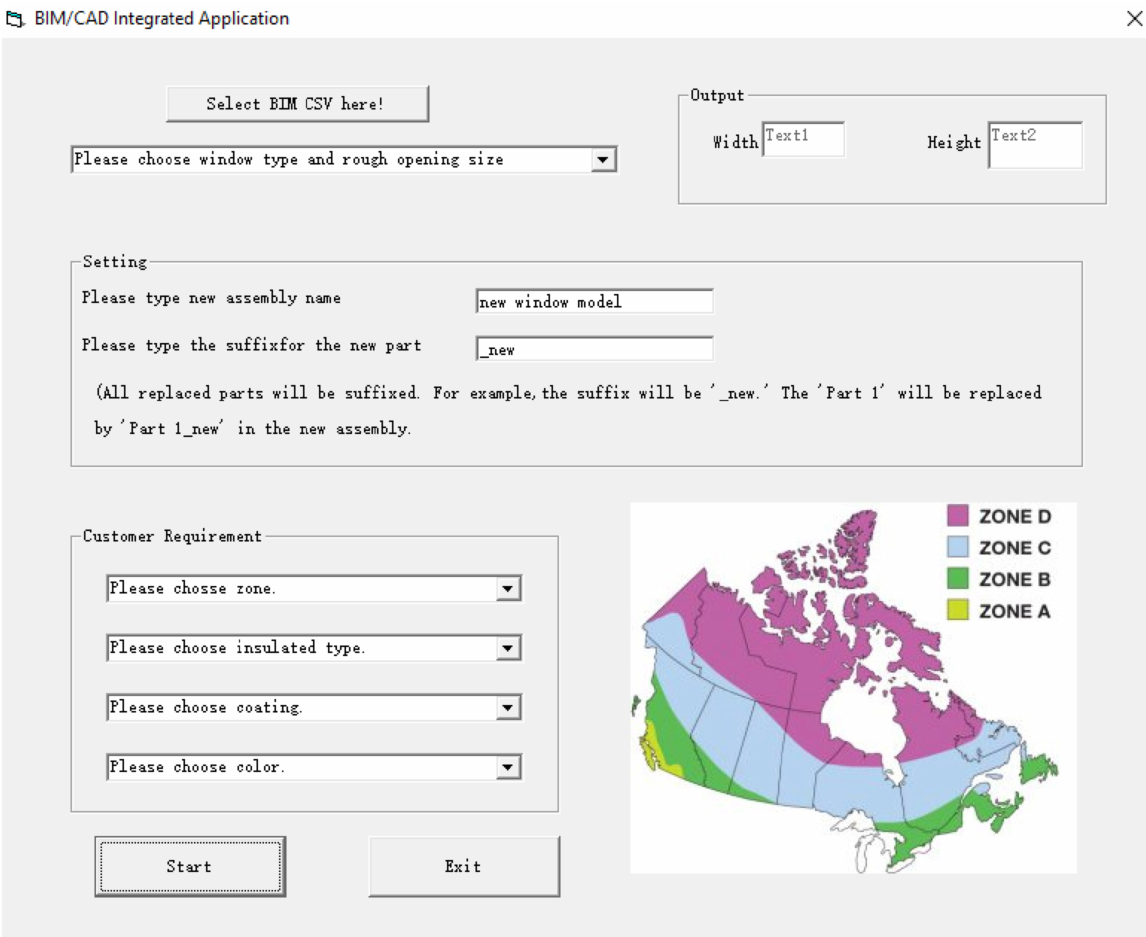


Figure 3-21: Graphic User Interface of the Software

Figure 3-21 is the graphic user interface of the program. The CSV file generated by BIM can be selected and called by the software. The user of this software then can choose which window will be modeled based on the specific CSV file. In addition, the user can choose the unique suffix for a particular requirement. The type of glass will be assigned as the user chooses the different setting of the glass customer requirement combo box. Then, the CAD model and corresponding BOM will be automatically generated by SolidWorks and store into a new file with requested suffix. All programming codes are attached in the appendix for reference.

Button	Functionality	Interface Messages
Select BIM CSV here!	Upon clicking this bottom, a file window pops up where user can pick the file.	- Warning: Please select CSV file - CSV selected
Start	Start the application, calculate all the parameters, re-model the part and assembly, and generate BOM.	- Could not find Solidworks. Please open the Solidworks! Warning: No Solidworks! - Starting!
Exit	Upon clicking this, the program will be closed	

Table 3-1: Interpretation of Buttons on Interface

Item Box	Functionality	Example Selection
Please choose window type and rough opening size.	Require user to choose the window type and size from the CSV file.	- 450 Series Size 72 in x 68 in - 191 Series Size 62 in x 46 in - 750 Series Size 66 in x 48 in
Please choose zone.	Ask user to choose the zone of the project.	- ZONE A - ZONE B - ZONE C - ZONE D
Please choose insulated type.	Ask user to choose insulated type of the window.	- Air - Argon
Please choose coating.	User will choose different coating for the glass	- Low-E - Reflective - Spectrally Selective
Please choose color.	Ask user to choose the color for the frame	- White - Black - Cream - Rosewood

Table 3-2: Interpretation of Options on Interface

Some important code is discussed below:

```
Private Sub Command1_Click() 'Read by click
        Open "d:a.txt" For Input As #1
        Dim Lines As String 'Declares storage
        Dim NextLine As String
        Dim i As Integer

        Do While Not EOF(1)
           On Error Resume Next
           Line Input #1, NextLine 'go to line one
           Lines = Lines & NextLine & Chr(13) & Chr(10)
        Loop
        Close #1
        Text1.Text = Lines
End Sub

Private Sub Command2_Click() 'Write
        Open "d:a.txt" For Output As #1 'open txt file
        Print #1, Text1.Text
        Close #1
End Sub
```

Figure 3-22: Pseudocode of Collecting Data into Software

The partial programming code above is to collect data from the BIM and upload to the software. When a user clicks on the “Select BIM CSV here!” button in the user interface, a Windows open dialog box will pop up and allow the user to select a CSV file. The software will detect if the selected file is in “.CSV” format. If the user chooses a file format other than CSV, the software will trigger an error message and display “Warning: Please select CSV file.” Otherwise, the application will inform the user that file has successful selected.

```
    If Str <> "Name" Then
        ReDim Preserve Part_Name(i)
        ReDim Preserve Part_modValue(i)
        Part_Name(i) = Str 'read name into string
        Debug.Print Part_Name(i)
        Str = Split(lineValue, ",")(1)    'read line 2
        Str = Replace(Str, """", "") 'replace the ""
        If Str = "W" Then  'read file to new parameter for width
            Base = assWidth
        ElseIf Str = "H" Then 'read file to new parameter for height
            Base = assHeight
        End If
        Operator = Split(lineValue, ",")(2)    'read line 3
        Operator = Replace(Operator, """", "")
        Str = Split(lineValue, ",")(3)    'read line 4
        Var = CDbl(Str)
        If Operator = "*" Then
            Part_modValue(i) = Base * Var 'calculate the value if the operator is times
        ElseIf Operator = "-" Then
            Part_modValue(i) = Base – Var 'calculate the value if the operator is minus
        End If
    End If
    i = i + 1
Loop
Close #1                    'close file
End Sub
```

Figure 3-23: Pseudocode of Software Reads CSV File and Calculate Parameters

The above function demonstrates how the software defines the type of the product. After the user selects the product type in the first CSV file, the software finds the corresponding CSV file in the database. For example, the software reads the first product within the CSV file export from BIM system and recognizes it as a 450 slider window with 46 inches width and 40 inches height. Next, it finds the corresponding calculation template for the 450 slider window. It updates the design parameters for different parts by following the calculation rules inside the CSV file. These parameters are stored and wait to be input into Solidworks for remodeling.

Window Schedule 2		
Family	Width	Height
450series	46	40
650series	80	72

(a)

Name	Base on	Symbol	Number	Description
4720_H	W	"-"	0.5	Frame Width
4720_H	H	"-"	0.5	Frame Height
5740-WT1	W	"-"	3	Sash Track
4724_W	0.5*W	"-"	1.15	Sash Width
4724_H	H	"-"	2.65	Sash Height
4725	H	"-"	2.65	Sash Interlock
4723	H	"-"	3.35	Mullion

(b)

Figure 3-24: Two Types of CSV in the Program (a) Sample from BIM; (b) Calculation Template

```
Sub subToCheckSWRunning(bool As Boolean)
        'chech Solidworks is running or not
        On Error Resume Next
        Dim s, objWMIService, colProcessList, objProcess
        s = "sldworks.exe"
        Set objWMIService = GetObject("winmgmts:{impersonationLevel=impersonate}!\\.\root\cimv2")
        Set colProcessList = objWMIService.ExecQuery _
        ("Select * from Win32_Process Where Name='" & s & "'")
        For Each objProcess In colProcessList
        bool = True
        Next
End Sub

Private Sub CmdStart_Click()
        Dim i As Integer
        i = 0
        Call subToCheckSWRunning(boolstatus) 'Test if SolidWorks is working
        If boolstatus = False Then 'Exit the app if solidworks is not working
           MsgBox "Could not find Solidworks. Please open the Solidworks!", vbOKOnly, _
              "Warning: No Solidworks!"
           Exit Sub
        End If
End Sub
```

Figure 3-25: Pseudocode of Software Checks if Solidworks is Opened

This function checks if the user has already opened the Solidworks application. If Solidworks could not been found in the Windows task process list, an error message will ask the user to open Solidworks. Otherwise, this application will continue to process all the calculation and functions in Solidworks.

```
Dim assName As String 'assembly name
Dim assStr As String
Dim ori_partName As String 'part name before
Dim mod_partName As String 'part name after
assName = Right(assPathName, Len(assPathName) - InStrRev(assPathName, "\")) 'get folder name
assName = Left(assName, InStr(assName, ".") - 1) 'get folder name
Set swModel = swApp.OpenDoc6(assPathName, 2, 0, "", longstatus, longwarnings) 'open assembly
Set swConf = swModel.GetActiveConfiguration 'get setting of model
Debug.Print assPathName
Set swRootComp = swConf.GetRootComponent
Debug.Print assPathName
vChildComp = swRootComp.GetChildren 'get parts in the assembly
Dim KKname As String
For i = 0 To UBound(vChildComp)
   Set swChildComp = vChildComp(i)
   KKname = swChildComp.Name2
   Debug.Print KKname
   swPathName = swChildComp.GetPathName
   Debug.Print swPathName
            & ">"
    swType = Right(swPathName, Len(swPathName) - InStrRev(swPathName, ".")) 'get type
    swName = Right(swPathName, Len(swPathName) - InStrRev(swPathName, "\")) 'get name
    swName = Left(swName, InStr(swName, ".") - 1)
    For j = 1 To UBound(Part_Name)
       oriPartName = Part_Name(j)
       modPartName = Part_Name(j) & Form1.Txt_modPartName.Text
       If (swName = oriPartName And swType = "SLDPRT") Then
         assStr = swModel.GetPathName
```

```
boolstatus = swModel.Extension.SelectByID2(KKname & "@" & assName, "COMPONENT", 0, 0, 0, False, 0, Nothing, 0)
            boolstatus = swModel.ReplaceComponents(App.Path & "\1\" & modPartName & ".SLDPRT", "", True, True)
            Debug.Print boolstatus
            boolstatus = swModel.EditRebuild3 'rebuilt
            Debug.Print App.Path & "\1\" & modPartName & ".SLDPRT"
            Debug.Print boolstatus
        End If
    Next j
    If swType = "SLDASM" Then
        CompReplace swPathName
    End If
    boolstatus = swModel.EditRebuild3 'rebuilt
Next i
End Sub
```

Figure 3-26: Pseudocode of Software Rebuilt the Model

The code above demonstrates the procedures to rename the new parts and assemblies after the modeling. The purpose of designing this function is to help maintain the stability of the CAD library. First, the application user is required to enter unique suffix for the parts and assemblies in the user interface. This software will open the window model from the CAD library which is chosen by the user in the interface. Next, the software will read and record the name of parts and assemblies in the window assembly model. The suffix will be added to the corresponding new parts and assemblies after rebuilding the model based on parametric modeling. The new parts and assemblies will be saved to a new location for the user and this will prevent affecting the future normal operations.

After scanning all the parts in the assembly, the software will generate a new part document for all the parts in the assembly. It will find the extrude feature in the part and update the new parameter for the corresponding part based on the design logic from the CSV file in Figure 3-24. Then, the software will save the new part into a new part document. The parts and assemblies will be rebuilt in the SolidWorks to generate new drawings (BOM) for the model.

```
Sub ModifyPart(partIndex As Integer)
        Debug.Print partIndex
        Dim PartName As String
        Dim modPartName As String
        PartName = Part_Name(partIndex)
        Debug.Print PartName
        Set swModel = swApp.NewDocument(App.Path & "\1\" & PartName &
        ".SLDPRT", 0, 0, 0) 'open original part
        modPartName = PartName & Form1.Txt_modPartName.Text
        Debug.Print modPartName
        longstatus = swModel.SaveAs3(App.Path & "\1\" & modPartName &
        ".SLDPRT", 0, 2) 'save as new part
        swApp.CloseDoc PartName & ".SLDPRT" 'close original file
        Set swModel = swApp.NewDocument(App.Path & "\1\" & modPartName &
        ".SLDPRT", 0, 0, 0) 'open new part
        Set swFeature = swModel.FirstFeature 'find first feature
        While Not swFeature Is Nothing
          FeatType = swFeature.GetTypeName 'get first feature type
          FeatName = swFeature.GetNameForSelection(FeatType) 'get feature name
          If FeatName = "Boss-Extrude1" Then 'find the extrude feature
            Set swFeatureData = swFeature.GetDefinition 'get feature definition
            swFeatureData.SetDepth True, Part_modValue(partIndex) / 1000 'change
        extrude length
            retval = swFeature.ModifyDefinition(swFeatureData, swModel, Nothing)
          End If
          Set swFeature = swFeature.GetNextFeature 'go to next feature
        End While
        boolstatus = swModel.EditRebuild3 'rebuilt
        swModel.Save2 0 'sace
        swApp.CloseDoc modPartName & ".SLDPRT" 'close
End Sub
```

Figure 3-27: Pseudocode of Software Rebuilt the Assembly and Save into New Files

3.5 Design for Manufacturing

During the windows and doors assembly process, welded steel structures called workbenches are used for positioning, holding and providing manufacturing space for parts during the assembly. In this section of the thesis, the author presents a new tooling concept called fixture platform, in which some new part handling carts are designed to connect between workbenches and stations.

Windows and doors are made up of wood, PVC, glass, and other materials. Different tooling and workbenches are used for holding in position or manufacturing window parts during the assembly. These workbenches and fixtures are designed and dedicated to only one particular assembly step. For another step on the assembly, a different and dedicated fixture must be developed. This is always costly, time-consuming and requiring a lot of factory space. The traditional workbenches and fixtures tend to focus on just one configuration and lack flexibility. Modern windows and doors manufacturers always have two different sets of techniques used in the manufacturing process: large-batch production for the same type of products and one batch production for the high mix but low volume products.

3.5.1 Ellipse Assembly Line Designed for Casement Manufacturing

To solve the problem that has been identified, research team in Durabuilt and me studied the approach of modular tooling. The tooling includes cutting tools, jigs, and fixtures designed for manufacturing. Modular tooling uses standardized profile, caster, holder and connector that put all pieces together. Fixture and frame can be easily adjusted. This solution increases flexibility in the fixture.

Modular tooling is the first level of flexibility in the manufacturing tooling (Kihlman & Engström, 2002). It's always been based on standardized frame and connection. Nowadays, modular tooling has a wide range of frames and corresponding supporting parts to ensure they can serve the purposes of the proposed design. Modular tooling has been widely used in various industries for a long time, such as automation, automotive manufacturing, retail, robotics and etc.

Extruded aluminum profiles are the most commonly used in building these tools. 80/20 (80/20 Inc., 2018) and Flexqube (FlexQube, 2018) are the two leading companies in the modular tooling field. The profiles provided by these companies always come in different length and profile. Based on the customer's design requirement, the choice of profile varies from ½-inch wide to 3-inch wide. Compared to the traditional welded station, the modular tooling has the following advantages:

- Easy to clean and maintain
- Weighing less than steel
- Corrosion resistant
- Similar cost compared to the steel
- Frame that is not welded - very flexible, could be reused

The profiles are fastened together by screws, corner connectors, anchor fasteners and end fasteners, which are also carried by the supplier of the profiles. Corner connectors are designed to be extremely strong and are comparable to welding. These connections provide infinite positioning along the mating profile's T-slot which allows a larger degree of adjustability (80/20 Inc., 2018). By learning from the existing workbenches and assembly table (Figure 3-28), I helps Durabuilt design a new assembly line.

The existing casement line is an assembly line which assembles hardware for casement. This line has 8 workers and 8 workbenches corresponding to every casement window manufactured in Durabuilt. The workbenches can be seen in Figure 3-28.

Figure 3-28: Old Casement Workstation

The new casement line is designed as a flexible and fully synchronized workshop that follows a sequenced production according to the daily shipment schedule and truck routings. The assembly line is designed into an ellipse shape as shown in Figure 3-29. The old assembly desk has the following drawbacks:

- Operators have to walk back and forward to retrieve parts.
- Operators are specialized - they tend to work on just one task and leave.

In the time study of Figure 3-30, the workers are divided into teams based on the different task time and the bottleneck of the whole production. The assembly line will be balanced according to the time of each line task for a higher production level. The ellipse-shaped design helps the company achieve the following advantages:

- Gaining space, around 20% spacing saving
- Having operators work in teams, increase work efficiently by more than 30%
- Operators able to go behind and help each other
- Easy to balance the workload and able to solve the bottleneck issue

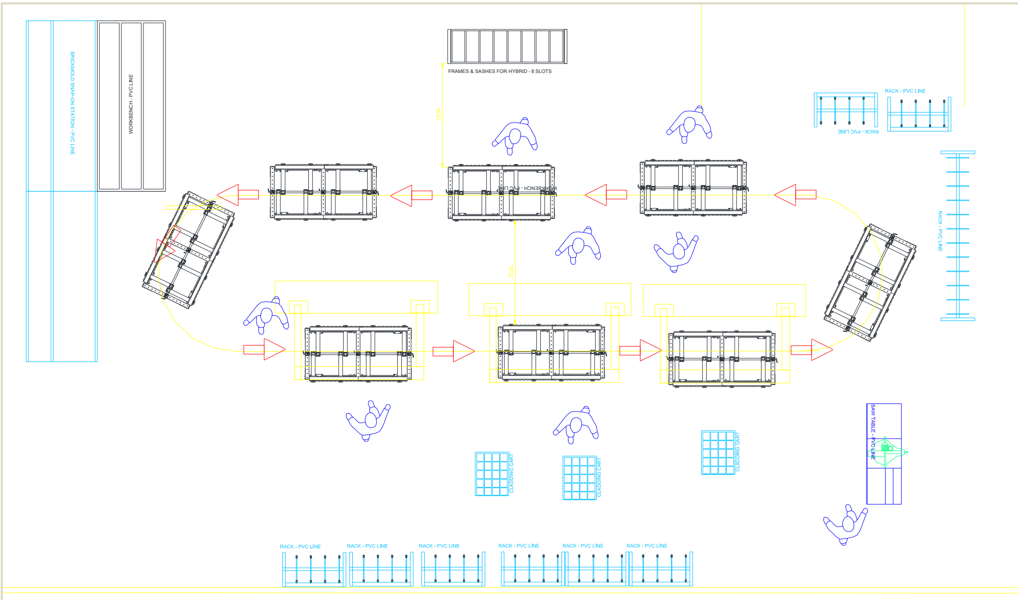


Figure 3-29: Ellipse Assembly Line Layout Map

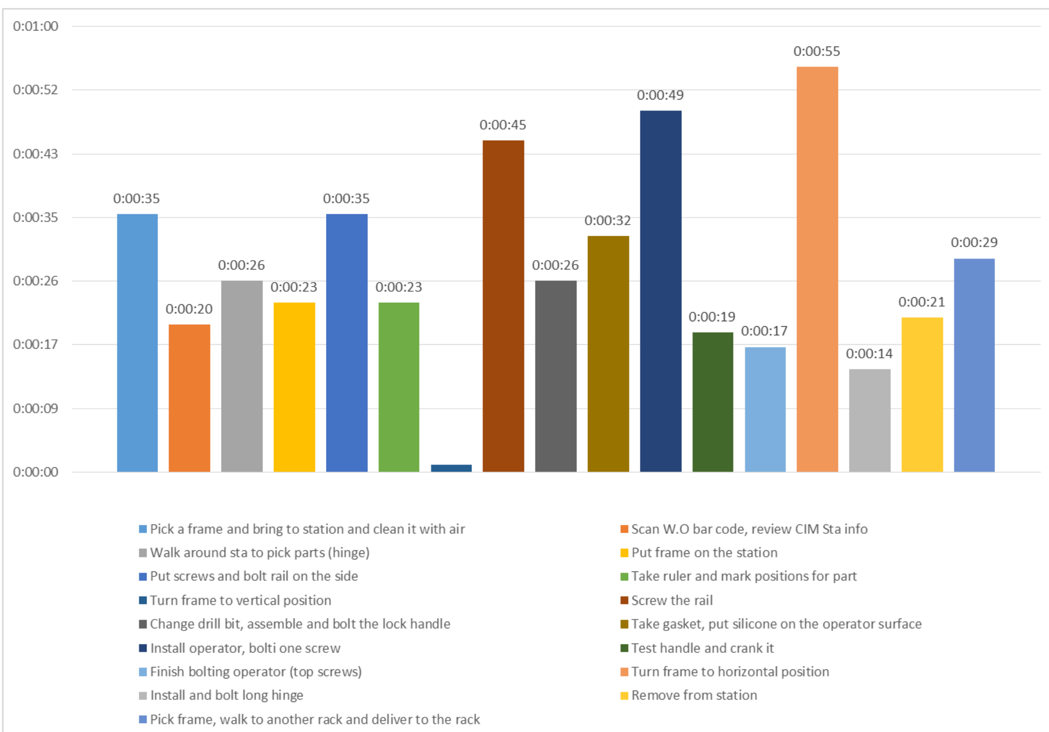


Figure 3-30: Time Study for the Casement Line

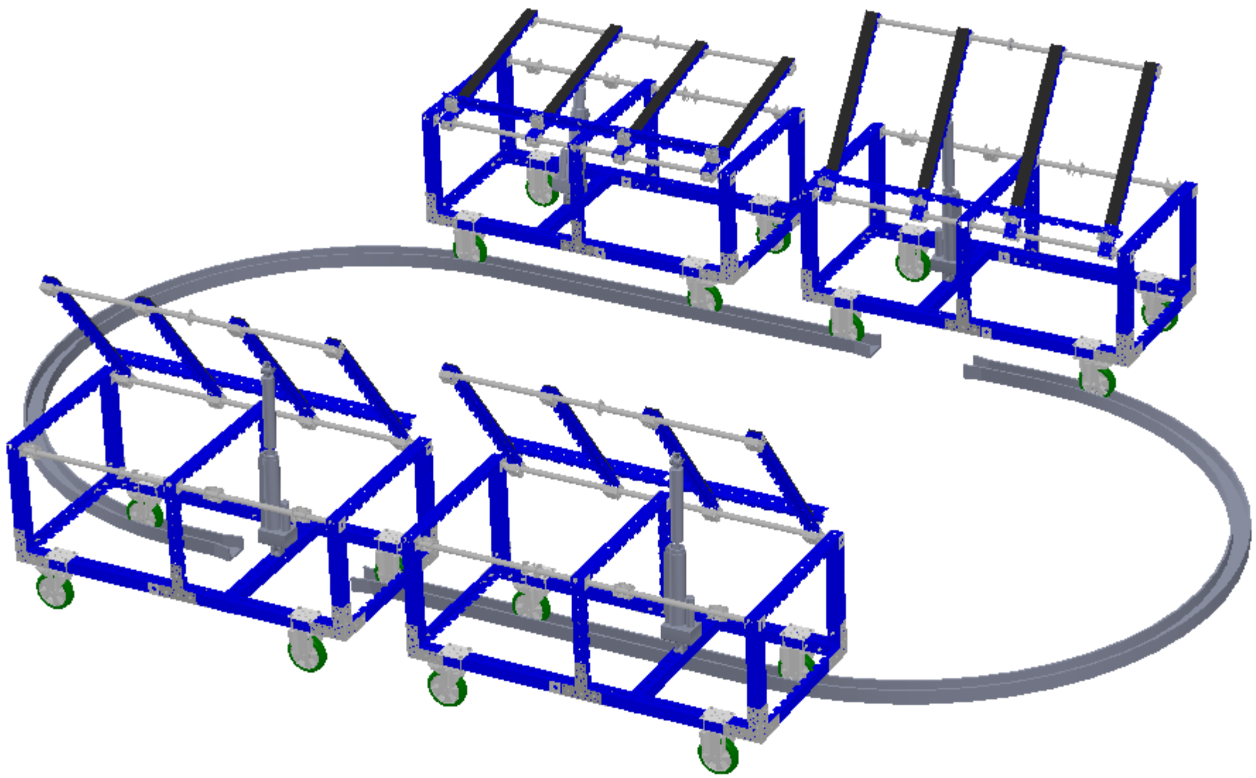
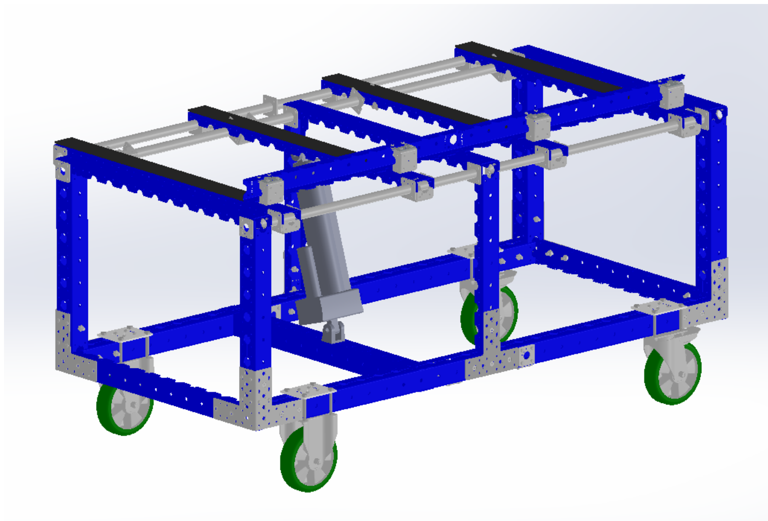


Figure 3-31: Ellipse Assembly Line Design for Casement Manufacturing with Modular Tooling



(a)

(b)

Figure 3-32: Modular Tooling Workbench under different working positions (a) Modular Tooling Workbench Closed Position (b) Modular Tooling Workbench Opened Position

3.5.2 Fixture Platform Designed for Manufacturing

Using the concept of BIM/CAD integration system discussed in Section 3.3, a well-designed ERP system, the manufacturing process, and the manufacturing feature, a new concept is being developed - fixture platform designed for manufacturing. The general framework can be found in Figure 3-33. After the BIM/CAD integrated system exports the CAD detailed model and the BOM, the manufacturing BOM can later be extracted from designed BOM. The manufacturing BOM and design BOM are totally different. The design BOM contains a list of components that will be used inside of the product and it is unique for the single type of the product. Manufacturing BOM is the cut list of the product. It contains all of the cut length of the profile. Schedule of production and raw material plan can later support process-planning information system for process plan, fixture relocating and machine allocation. The width and height of the window will be read by the ERP system. After ERP verifies the manufacturing machining feature, manufacturing procedure, design configuration with the CAD model, the ERP system will help the fixture platform to set the fixture sizing to the corresponding product.

As mentioned earlier in the Figure 3-33, the relationship of design configuration, manufacturing process, manufacturing feature and fixture are defined as followed:

- Fixture is designed based on manufacturing feature of the product.
- Manufacturing feature is based on achieved manufacturing process.
- Process is dependent on the manufacturing configuration

Those four key components are all connected and interacted to support the fixture platform designed for manufacturing. By studying historical data of the customer order size for the patio door, Fixtures are designed and has a re-sizing range from 4ft to 12ft. Next designed configuration of patio door was studied to make sure every configuration can fit-in the width of the fixture. The manufacturing process helped to understand the optimal position of manufacturing. Combine with the ergonomic design, the range of motion and fixture type are selected and implemented to the design. Manufacturing features are implemented on the fixture design to help establish fixture design and connect design rules stored in the knowledge base. The fixtures are designed in Figure 3-34.

This fixture was later connecting with ERP system. After manufacturing, BOM was input into ERP system. The ERP system can calculate the fixture opening width by the width of the patio door. When operators receive an order, as long as they select the order number from the workstation computer, the fixture will adjust the corresponding opening width which is extracted from the ERP system. It helps save time in adjusting and changing fixture position and layout.

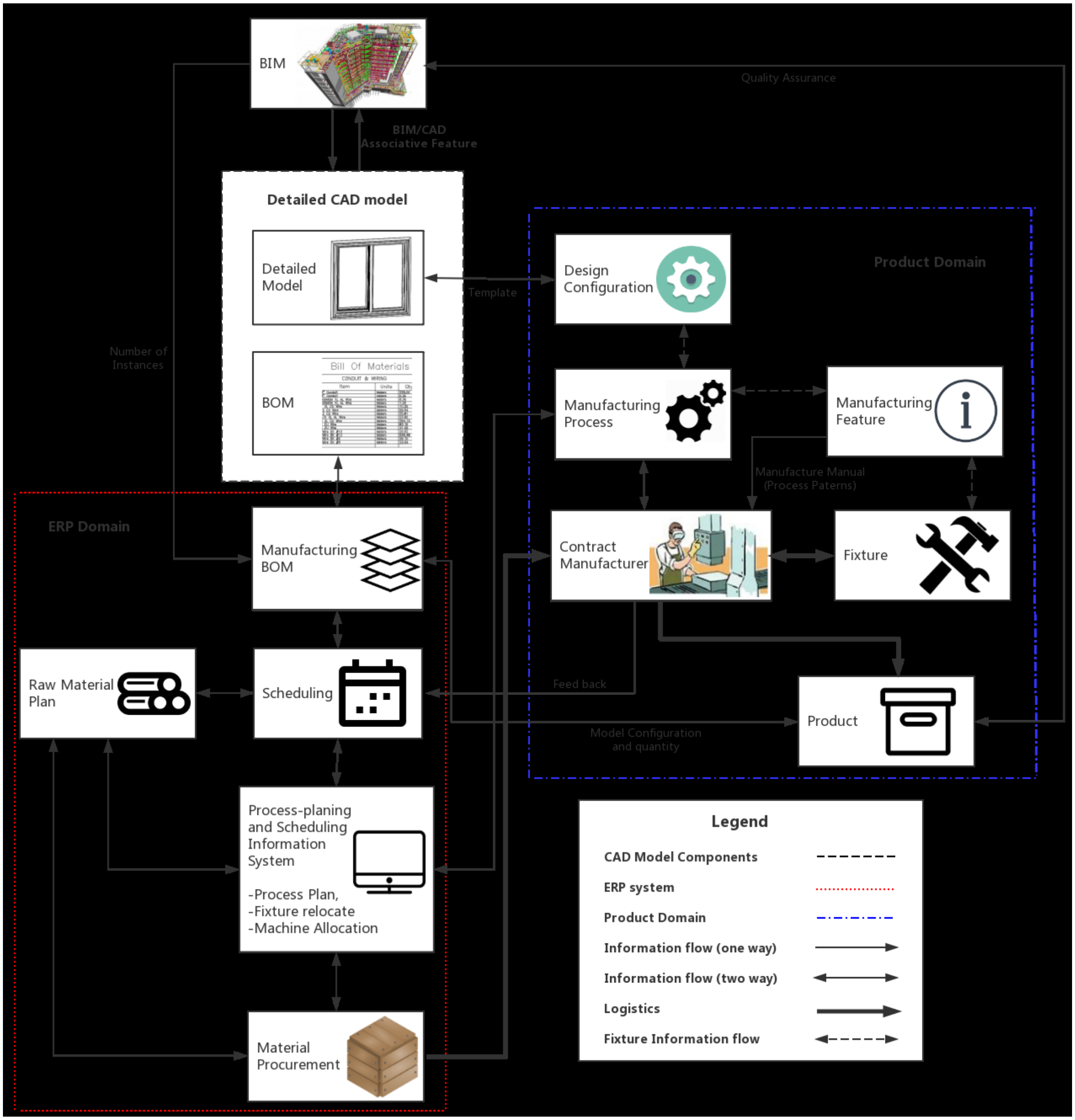
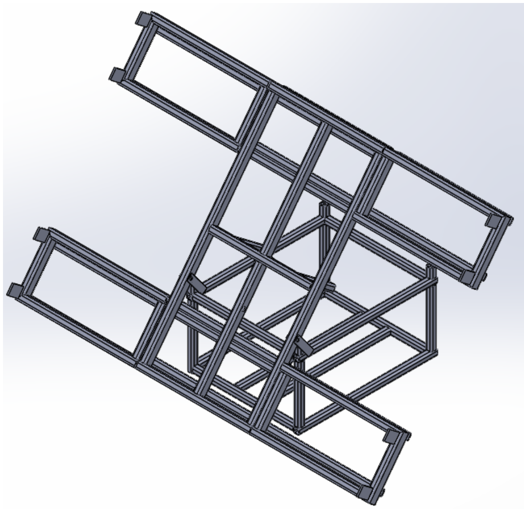
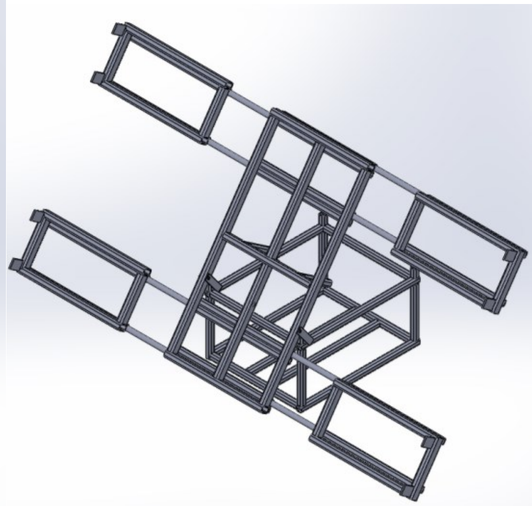
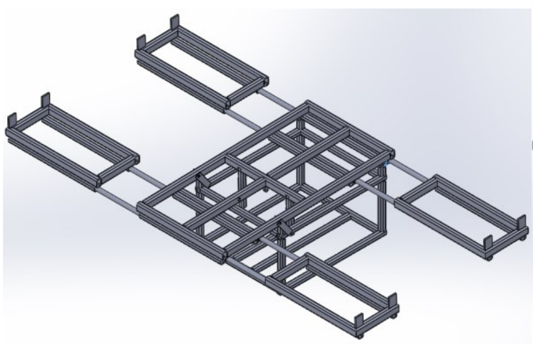


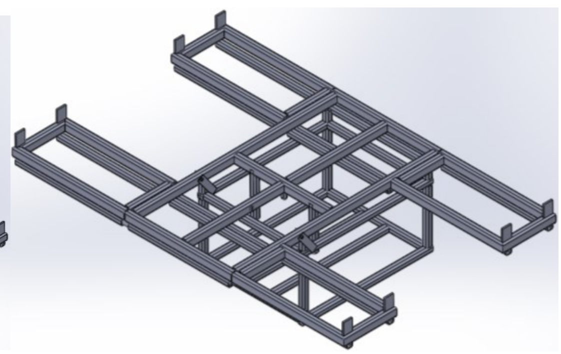
Figure 3-33: Framework of Fixture Platform Designed for Manufacturing





(a) (b)





(c) (d)

Figure 3-34: Fixture Platform Designed for Manufacturing (a) standing and fully closed, (b) standing and fully opened, (c) collapsed and fully closed and (d) collapsed and fully opened.

4 Case Study

The proposed methodology has been partially designed and implemented in a window manufacturing company in Edmonton, Canada. Durabuilt Windows and Doors manufacture windows and doors for homeowners and home builders. Their main production are patio doors, entry doors and different type of windows. The case study was designed to help engineers in Durabuilt to convert windows parts from BIM model to CAD drawings and bill of material efficiently with information consistency.

4.1 Background of the Case Study

4.1.1 Type of Windows

The most common window in the market are sliders, single hungs, casements, awnings, geometric shapes and pictures which can be found in Figure 4-1.

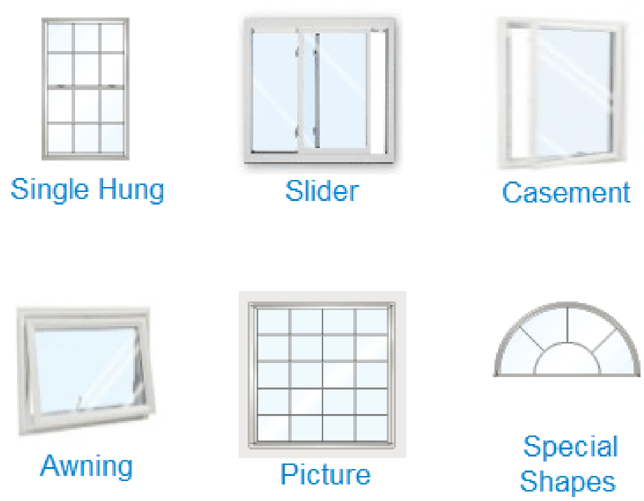


Figure 4-1: Types of Residential Windows

Slider windows are windows slide to the left or right for easy open capabilities allowing in natural light and air. Customers choose them for rooms facing walkways, patio and walkway since they open and close without extending out from the surface of the wall. A single slider window, a sash slides to open. In a double slider, both sashes slide to give both ends slide open. Horizontal sliders are most popular products in Durabuilt due to the comparably cheaper price, favorite for modern style house, high reliability and also satisfying bedroom egress requirements for an emergency.

A single hung often referred to as a sash window, the bottom sash moves up to open and allow in air flow while the top sash is fixed in place and does not move or tilt in. Comparatively, on a double hung, both sashes in the window frame are operable. They both move up and down which is easier to clean. Similar with slider window, it opens and closes easily without protruding. Therefore, they are excellent choice for rooms facing walkways and patios.

Picture is a fixed window that does not open. They are good choice for letting in natural light without cold air in areas of a room. Picture windows are stationary on the wall just like a ‘picture’ and designed to be used alone to let the view into the room or combined with venting windows to create large combinations.

Casement windows are windows have no obstructive railings, easily hand-crank open and have interior screens. They are hinged at the side and open outward like a door. Most of the casement windows have a hand crank to open, but some are simply pushed open. Casement windows are ideal for hard to reach place such as over a kitchen sink. And they are perfect for installation in almost any area of the home for people who could struggle with lifting and sliding a window.

Awning windows are hinged on the top and designed to open outward. Awning windows provide additional airflow to a room without letting in rain or falling leaves. Screens are on the inside of the window where can be protected by the frame. Awning windows are usually combined with a picture window for added ventilation. With the crank of a handle, awning windows are easy to open and fit in hard to reach places. The most important advantage of this kind of windows is they can even be opened during a rain shower as it open outward and upward.

Shape (geometric) windows are windows that can add character and beauty into space of your home. The most popular shape window in Durabuilt is half round, it usually combines with standard windows to make a visual statement. This style of window brings softness to rooms with high ceiling such as a dining room, and it juxtaposes the straight corners of rectangular windows.

4.1.2 Window Order and Manufacturing Flow

In Durabuilt, an order follows the following steps from the customer entering the company till the order being delivered. This process is shown in Figure 4-2.

- The customer walks-in with the blueprint/BIM file/CAD file/verbally request
- The sales team gives the customer a quote based on the size, material, type of window, color (based on the pricing system used by sells team/if the product

is overly complicated, check price with Research and Development (R&D) team)

- R&D team checks special order for meeting building code and other standards
- Sales team uploads the order to the ERP system
- Customer pays an upfront deposit
- The order then is sent to the scheduling team by ERP system
- The scheduling team schedules the order expected delivery date
- The scheduling team next schedules the corresponding manufacturing date
- Purchasing team checks material for the special order
- Bill of Material (BOM) and cut sheet sent to scheduling system by ERP system
- Scheduling team print manufacture stickers for manufacturing
- Workers manufacture the windows/doors
- Quality assurance team processes selective examination / On-site testing if requested by customer
- Product delivered to the customer

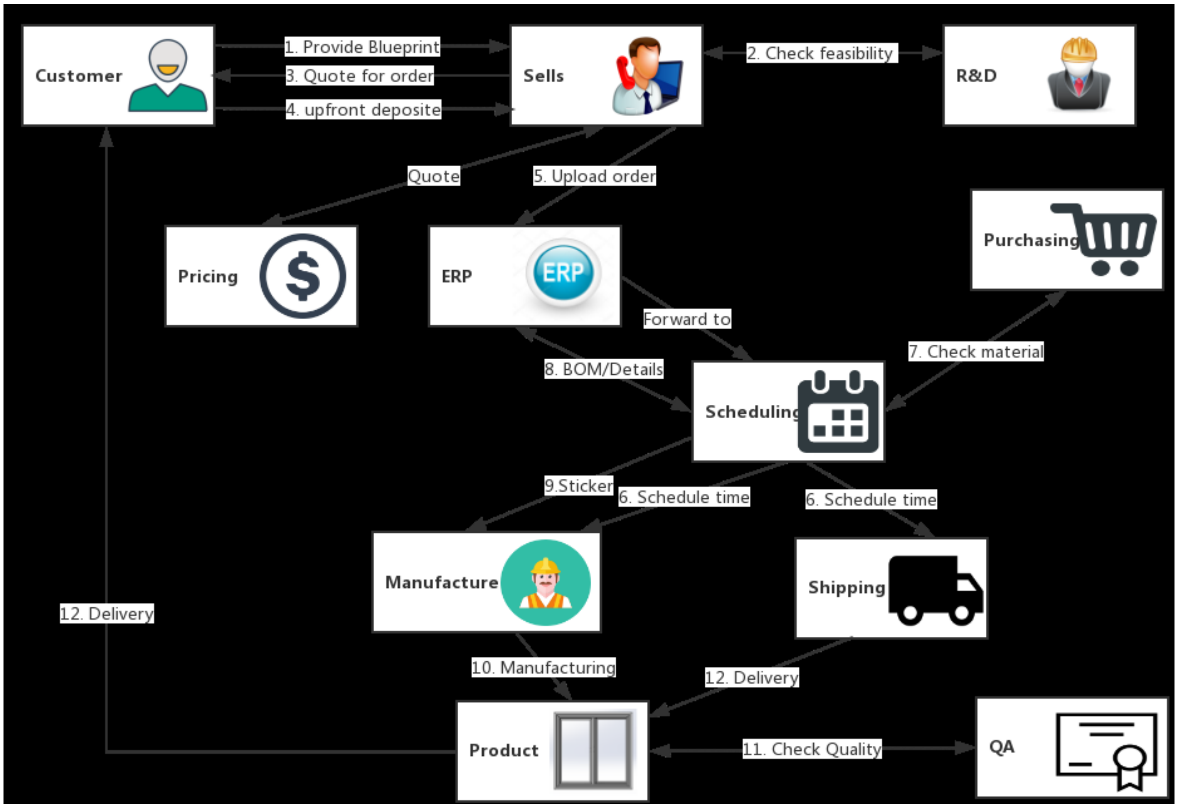


Figure 4-2: Durabuilt Order and Manufacturing Flow

4.2 Using BIM/CAD Associative Features for Design a Slider Window and a Casement Window

To demonstrate the application of BIM/CAD associative features, a software prototype which can design a slider window is developed in Chapter 3. This software can read CSV files, map data with a well-defined CAD library and then regenerate CAD models for manufacturing. By employing the VB program language, this software achieves engineering calculations, design knowledge and data management in product development. In the integration system, Revit 2017 is used for collecting building information data while SolidWorks is used for CAD modeling. During the research, the authors use a slider window and a casement window as a sample case to demonstrate the concept of the proposal and the general framework. However, this system can be easily adapted to other building components such as doors, elevators, and etc. because the associative regime is a generic regime to make this system valid regardless of the object of the model.

4.3 Demonstration of the Example Product Design Case

According to the proposed BIM/CAD integration system, the program was added to help engineers to re-design windows for the project. The BIM model in Figure 4-3 is a three-level house in Edmonton, Alberta, Canada. The BIM model was provided by the client from an architecture company. After the design engineer from Durabuilt review the BIM file. He exported the CSV file by using the API discussed earlier in section 3.4.1. Figure4-4 was the CSV file exported from Revit for this case study.

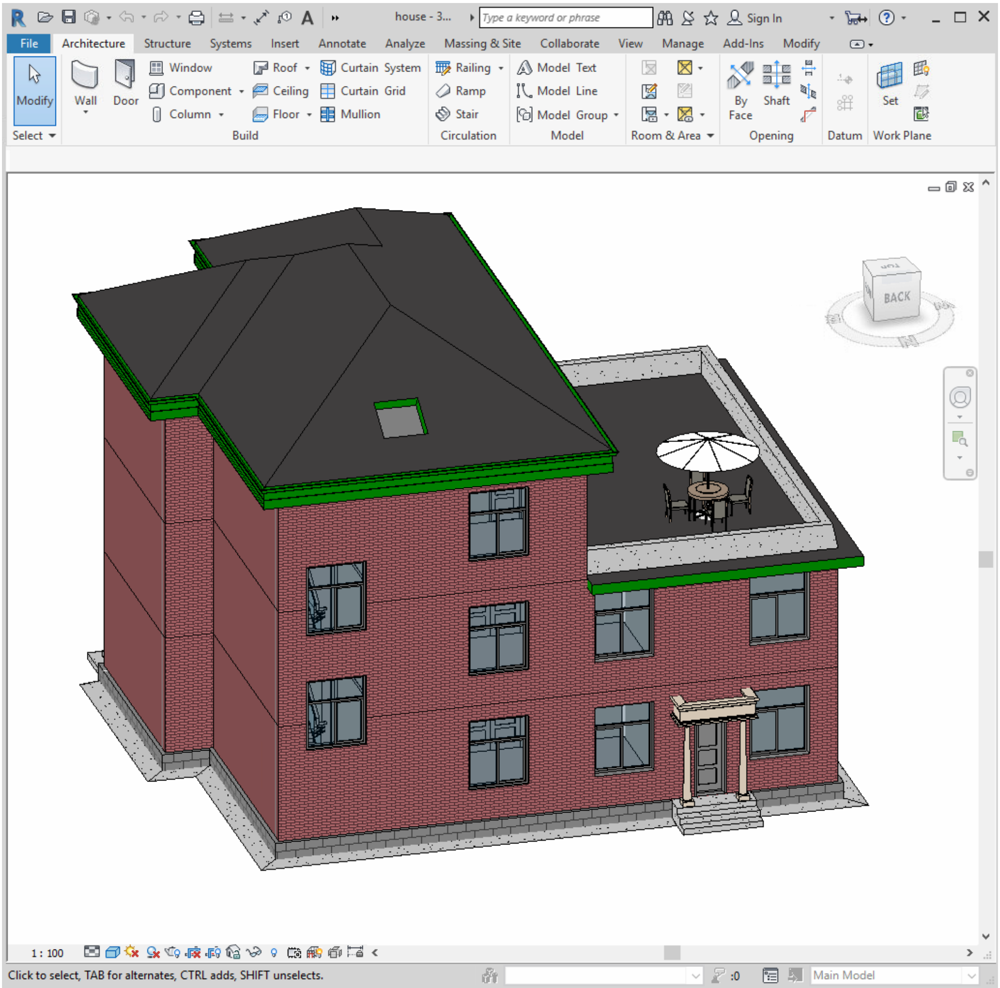


Figure 4-3: Sample BIM Model for the Case Study

```
"Window Schedule"       ""       ""       ""       ""       ""
"Mark"  "Location"      "Window Style"    "Width"  "Height"
""      ""      ""      ""       ""       ""       ""       ""
"1"     ""      "Slider 450"      "1500"  "1800"   ""       ""
"2"     ""      "Slider 450"      "1500"  "1800"   ""       ""
"3"     ""      "Slider 450"      "1500"  "1800"   ""       ""
"4"     ""      "Slider 450"      "800"   "1000"   ""       ""
"5"     ""      "Slider 191"      "600"   "400"    ""       ""
"6"     ""      "Slider 191"      "800"   "800"    ""       ""
"7"     ""      "Slider 191"      "611"   "1200"   ""       ""
"8"     ""      "Casement 700"    "611"   "2313"   ""       ""
"9"     ""      "Casement 700"    "611"   "2313"   ""       ""
```

Figure 4-4: Program input

After selecting the BIM CSV file in the BIM/CAD Integrated Application, the user selected the first window from the drop-down list. The window was a 450 series slider with 1500 width and 1800 height.

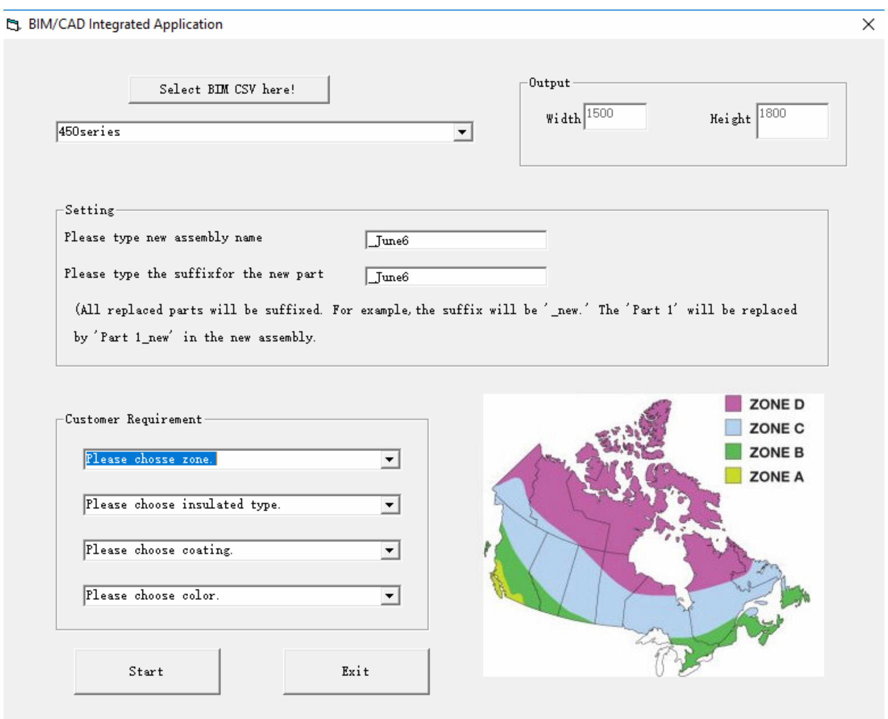


Figure 4-5: Sample Input for Program

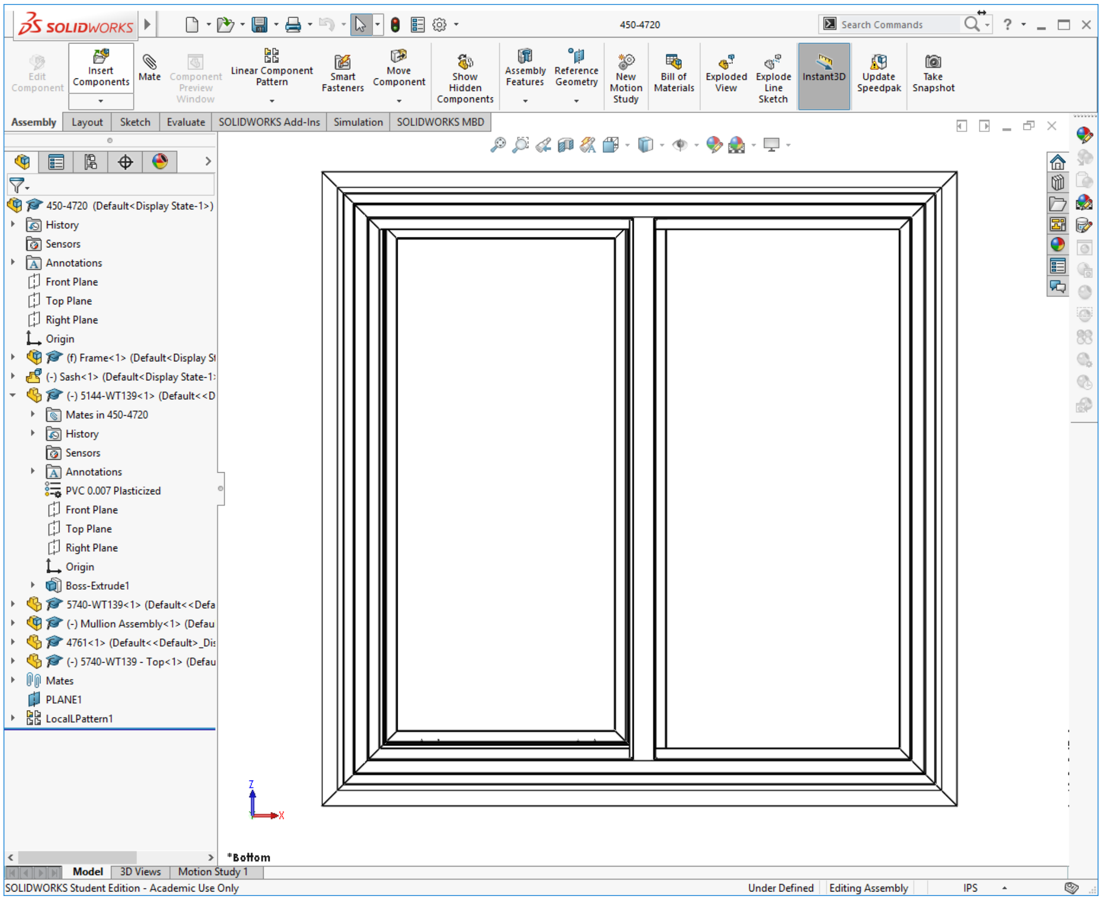
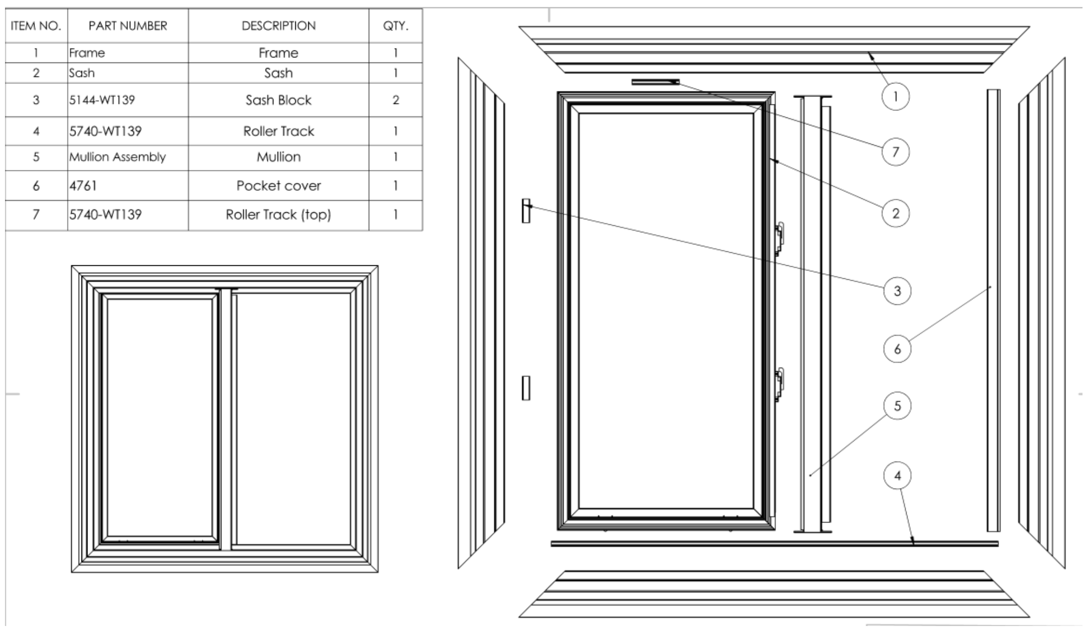


Figure 4-6: Output CAD Model of Sample Slider Window in Solidworks

After choosing other settings and clicking “Start”, the program started running and Solidworks started re-modeling the whole CAD model. Figure 4-6 was the output of this 450 slide window. This model contains full design details and satisfies all design requirements. The CAD part models can also be integrated into BIM system and give engineers and customers a detailed view of the project. The collision detection feature by SolidWorks is able to detect collisions with all the components of the window when moving the sash, which guarantees that this model is feasible and accurate. A sample corresponding BOM can be found in Figure 4-7, which can provide manufacturers with specifications for production. The BOM is further extended to contain all the fabrication information such as the dimensioned cutting list which can simplify and accelerate the material preparation process and thus enhance productivity.



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Frame	Frame	1
2	Sash	Sash	1
3	5144-WT139	Sash Block	2
4	5740-WT139	Roller Track	1
5	Mullion Assembly	Mullion	1
6	4761	Pocket cover	1
7	5740-WT139	Roller Track (top)	1

Figure 4-7: BOM of Sample Slider Window Exported from Solidworks for Manufacturing

This was also implemented on a casement window in the same BIM model. After selecting the BIM CSV file in the BIM/CAD Integrated Application, the user selected the eighth window from the drop-down list. The window was a 700 series casement with 611 widths and 2313 height. Same as the procedure above, by clicking “Start”, the program started running and Solidworks started re-modeling the casement CAD model. The sample CAD model of a casement can be found in Figure 4-8 and the sample BOM for the casement window can be found in Figure 4-9.

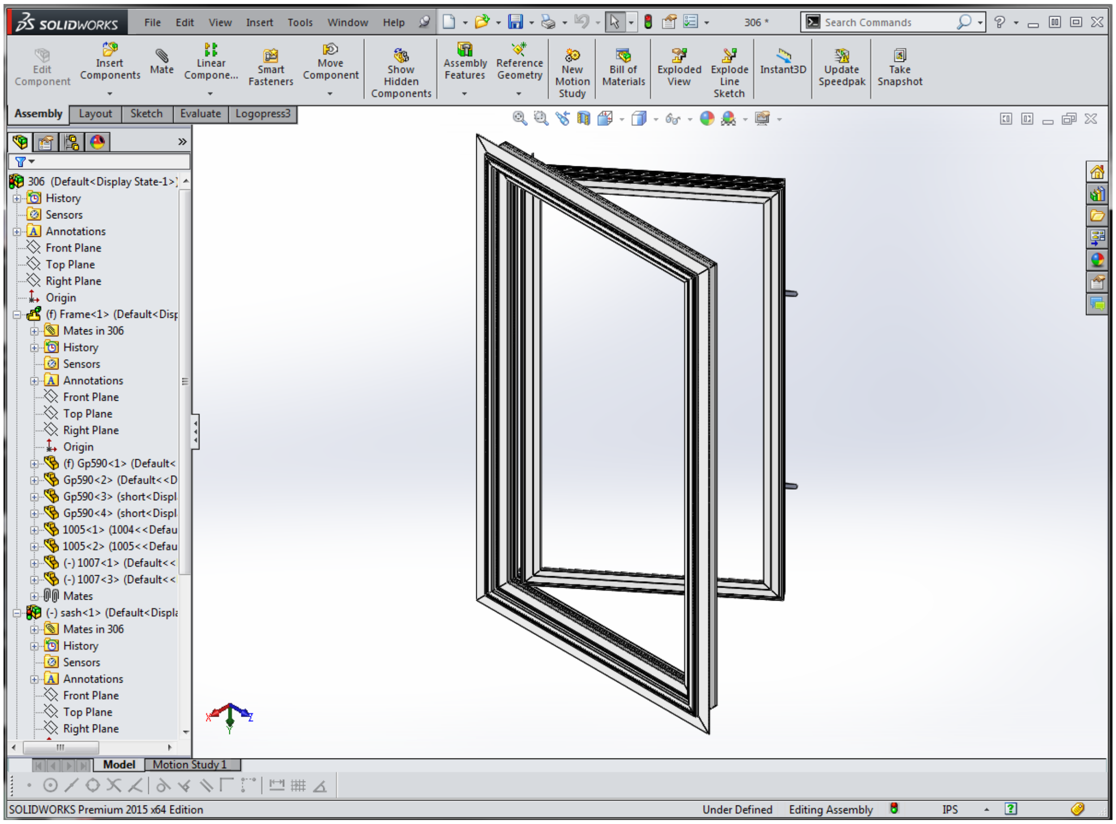
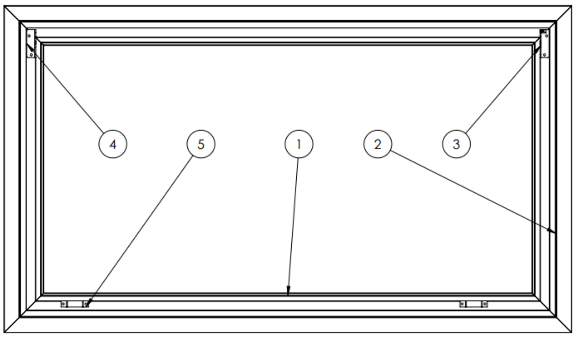
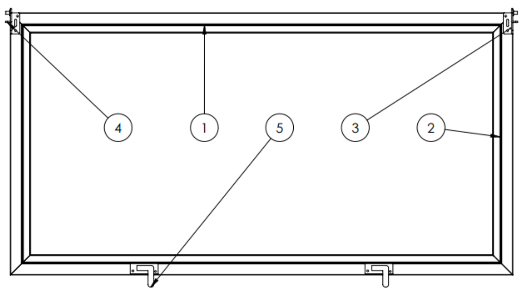


Figure 4-8: Output CAD Model of Sample Casement Window in Solidworks



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	GP590	Long frame	2
2	GP590	Short frame	2
3	1005TLFBHD-W	White HD top frame brackets LF (BX6860L)	1
4	1005TRFBHD-W	White HD top frame brackets RG (BX6860R)	1
5	1007LP-W(BX6826)	Lever pocket (BX6826)	2



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	GP103	Long sash	2
2	GP103	Short sash	2
3	1002RWBHD-W	Right window (sash) bracket (BX6862R)	1
4	1003LWBHD-W	Left window (sash) bracket (BX6862L)	1
5	1006LL-W (BX6825)	Lever lock (BX6825)	2

Figure 4-9: BOM of Sample Casement Window Exported from Solidworks for Manufacturing

A time study is conducted by comparing the time used in each phase with traditional method and the proposed BIM/CAD integration system, respectively. By using a well-defined CAD library in collaboration with the BIM system, the time could be saved by around 90%. The whole process is seamless, making it human error free when creating the detailed CAD models, which also contributes to the modeling efficiency enhancement.

Feature Category	Example
Form Feature	• Profiles • Parameters
Assembly Feature	• Mate • Constraint • Screw Location • Assembly Information
Machining Feature	• Tooling • Assembly Process • Manufacturing Process

Table 4-1: Feature Category Vs. Example for Case Study

Representation of different features in a window product design can be found in Table 4-1. The form feature, assembly feature and machining feature are linked, represented and connected by the associative feature.

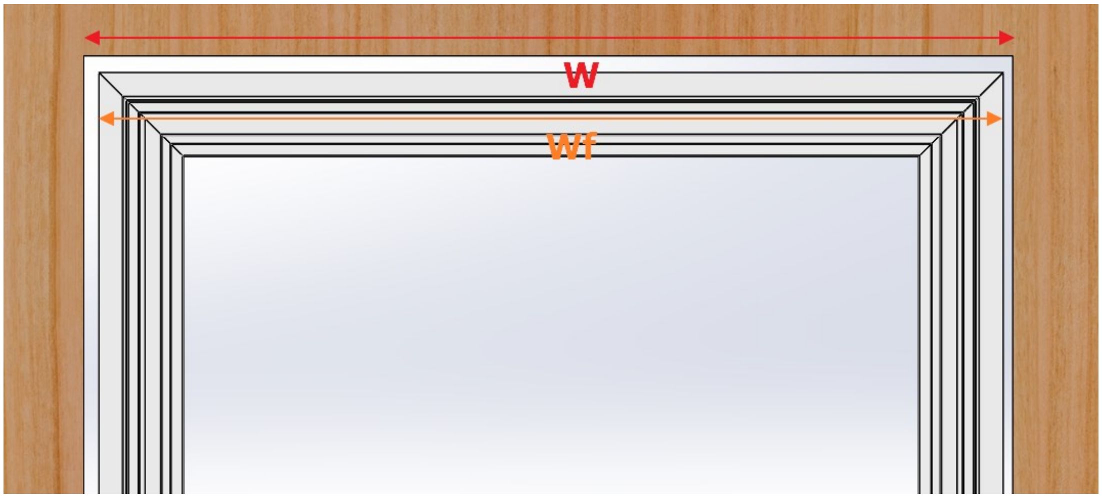


Figure 4-10: Associative Feature between Rough Opening Width and Window Frame Width

The associative features manage the associativity between the entities of the platforms. For example, Figure 4-10 shows the associativity between the frame and the wall. This relationship follows the Equation 3.3.

4.4 Demonstration of Ellipse Assembly Line for Casement Manufacturing

The ellipse assembly line is built in Durabuilt for casement manufacturing. This line is currently under construction as shown in Figure 4-11. The track will be 20-feet long and its radius will be 10 feet. The blue modular tooling workbench will be 8-feet long and 3-feet wide. The assembly line will be also adjusted based on the feedback from the workers once it is completed. According to the experiment, it will be able to reduce the space for the existing assembly line by 20% and increase at least 30% of the working capacity.

Figure 4-11: Ellipse Assembly Line for Casement Manufacturing

4.5 Demonstration of Fixture Platform Designed for Manufacturing

As discussed above in Chapter 3.5.2, the fixture platform was designed for manufacturing as shown in Figure 4-12 and Figure 4-13. Once the manufacturing BOM was converted from BIM by using BIM/CAD associative feature, it would be transferred into the ERP system. The fixture opening width would be calculated by the width of the patio door. When the operators received an order, the fixture will adjust the corresponding opening width which was extracted from the ERP system once the operators selected the order number from the workstation computer. It helps save time in adjusting and changing fixture position and layout. The fixture platform designed for manufacturing would be further developed to be powered by the pneumatic system and connected to the company's ERP system by a micro-computer.

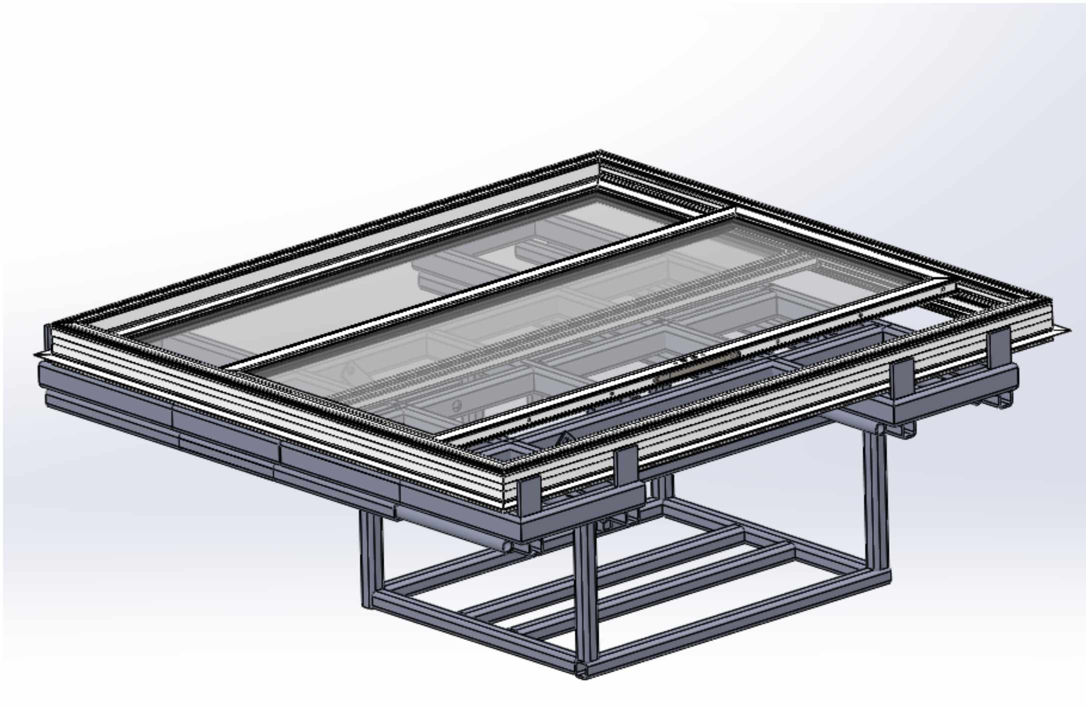


Figure 4-12: ISO View of Fixture Platform Designed for Manufacturing

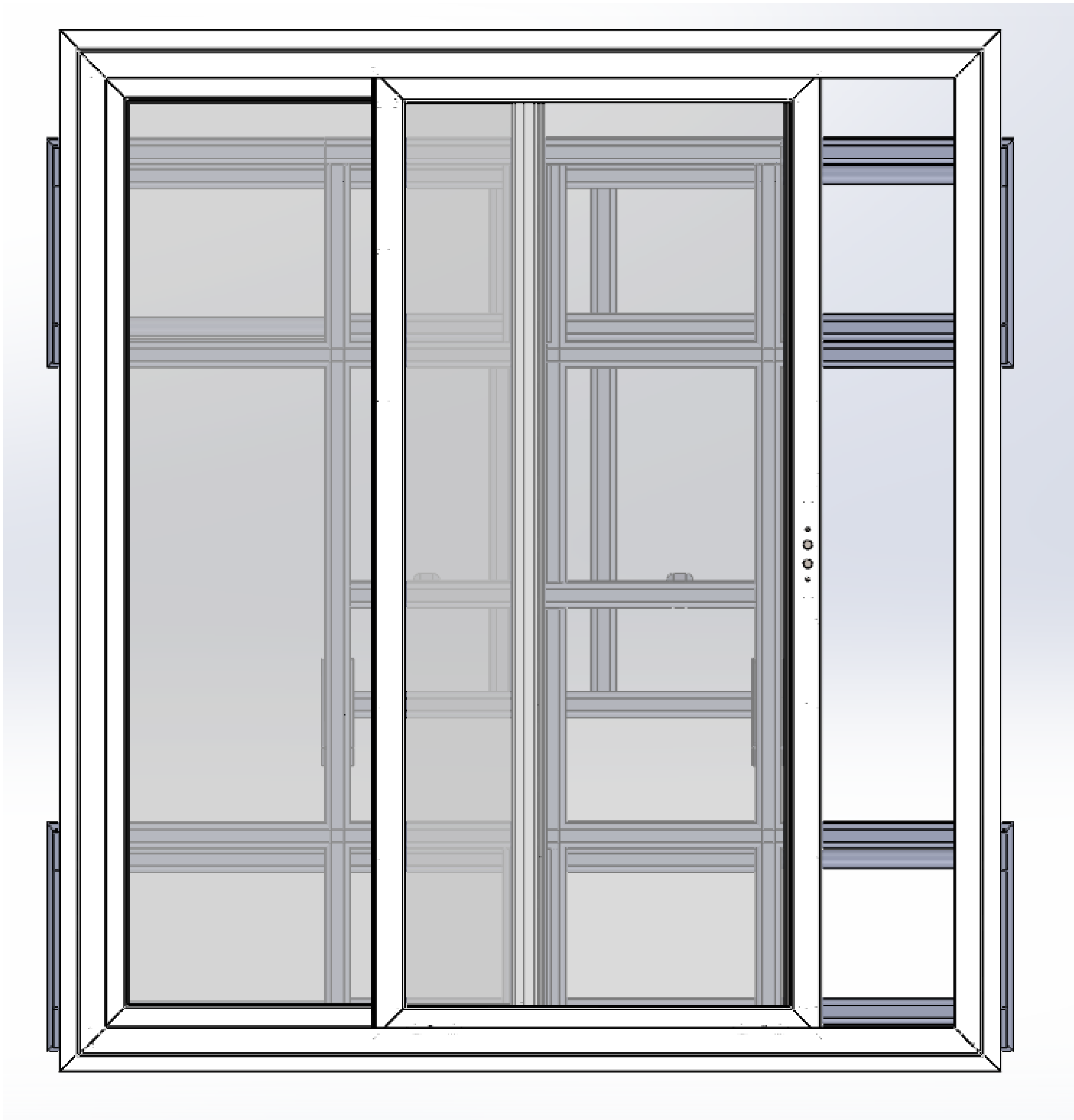


Figure 4-13: Top View of Fixture Platform Designed for Manufacturing

5 Conclusion and Future Development

5.1 Conclusion

This thesis explores the mechanism of BIM/CAD integration based on the concept of the *associative feature*. An overall mapping framework for BIM and a well-defined external modular CAD library has been suggested. This framework represents the cycle of parametric and knowledge-based product design, CAD modeling, change justification, validation, and manufacturing. It concludes that the associative feature is an effective tool for managing both geometry association and semantic portion of the feature. By using the associative feature, data consistency and design changes can be easily managed between BIM and manufacturing requirement.

A prototyping system has been implemented to show the effectiveness of the proposed method. The Revit API was used to export data from BIM system. Solidworks API was used to automate the remodeling of all the parts, assembly, and drawing for different windows. The input of this program contains the size, quantity and classes information from BIM system within a CSV file, customer specific requirements for the window, and the customer suffix for identification. The CAD library contains CAD CSV files with design logic of the product, CAD parts, assemblies, and drawing templates. This algorithm mainly serves two purposes. First, it can quickly calculate all essential parameters needed to remodel the existing CAD template by using all engineering relationships inside the corresponding CSV file. Second, it can regenerate the new model and bill of material (BOM) with a customized suffix and store them separately with the original templates. Aided by an

ERP system, the implementation of the proposed system also supports design for manufacturing which enhances the efficiency of part handling in manufacturing processes.

The case study of a slider window is used to test the CAD/BIM integrated system. It is evident that the association between the BIM system and CAD model can be established. The BIM/CAD associative feature is an effective method to bridge the gap between BIM and CAD system. Based on a time study, engineers and technical professionals can save more than 90% time by implementing this system with ensured quality. It should be noted that the proposed method is not limited to the shown case; it can also be applied in other scenarios such as the design of components in modular construction. The ellipse assembly line designed for casement manufacturing was designed and built. This demo assembly line was tested and was able to increase the work capacity by 30%. The fixture platform was designed in Solidworks in order to connect manufacturing tooling with manufacturing BOM by an ERP system.

5.2 Future Work

In practice, the parametric development of building components is highly demanded with the trend of customization based on various requirements from customers. Therefore, this BIM/CAD integration system is suitable for order-driven manufacturing in which the adaption to sudden changes in parameters or features of the product is vital. In the future, this BIM/CAD interacting mechanism can be potentially merged into an enterprise resource planning (ERP) system to facilitate lean manufacturing.

As shown in Chapter 2, integrating BIM and GIS is popular in the construction industry. As GIS contains the information on geography, it would be interesting to connect BIM, GIS, CAD, and ERP altogether. With GIS and BIM linked, all the geographic information can be connected to BIM. This, for example, can help the system define the location of the building or get the temperature and wind information at the specific location.

As commitment from Durabuilt windows and doors, the ellipse assembly line and fixture platform will be futher invested and optimized in the future.

Reference

80/20 Inc. (2018). 80/20 Inc. Handbook. Retrieved June 16, 2018, from http://catalogs.8020.net/?bookcode=egt13flx

Aram, S., & Eastman, C. (2013). Integration of PLM Solutions and BIM Systems for the AEC Industry. https://doi.org/10.22260/ISARC2013/0115

ARCHICAD. (2018). About ARCHICAD — A 3D architectural BIM software for design & modeling. Retrieved June 13, 2018, from http://www.graphisoft.com/archicad/

Au, C. K., & Ma, Y.-S. (2010). Garment pattern definition, development and application with associative feature approach. *Computers in Industry*, *61*(6), 524–531. https://doi.org/10.1016/J.COMPIND.2010.03.002

AutoCAD. (2018). AutoCAD For Mac & Windows | CAD Software | Autodesk. Retrieved June 13, 2018, from https://www.autodesk.ca/en/products/autocad/overview

AutoDesk Revit. (2017). Design Phases & BIM Level of Detail | Sustainability Workshop. Retrieved April 26, 2018, from https://sustainabilityworkshop.autodesk.com/buildings/design-phases-bim-level-detail

AutoDesk Revit. (2018). Revit | BIM Software | Autodesk. Retrieved June 13, 2018, from https://www.autodesk.com/products/revit/overview

AutoDesk sustainability workshop. (2018). Design Phases & BIM Level of Detail | Sustainability Workshop. Retrieved May 27, 2018, from https://sustainabilityworkshop.autodesk.com/buildings/design-phases-bim-level-detail

Azhar, S. (2011). Building Information Modeling (BIM): Trends, Benefits, Risks, and Challenges for the AEC Industry. *Leadership and Management in Engineering*, *11*(3), 241–252. https://doi.org/10.1061/(ASCE)LM.1943-5630.0000127

Babič, N. Č., Podbreznik, P., & Rebolj, D. (2010). Integrating resource production and construction using BIM. *Automation in Construction*, *19*(5), 539–543. https://doi.org/10.1016/J.AUTCON.2009.11.005

Barlish, K., & Sullivan, K. (2012). How to measure the benefits of BIM — A case study approach. *Automation in Construction*, *24*, 149–159. https://doi.org/10.1016/J.AUTCON.2012.02.008

Bates, R., Carlisle, S., Faircloth, B., & Welch, R. (2013). PLEA2013 -29th Conference, Sustainable Architecture for a Renewable Future Quantifying the Embodied Environmental Impact of Building Materials During Design: A Building Information Modeling Based Methodology. Retrieved from https://kierantimberlake.com/files/posts/243/quantifyin.pdf

Bedrick, J. (2008). Organizing the Development of a Building Information Model AIA Vice President, Virtual Building and Design Webcor Builders Published in

AECbytes. Retrieved from http://m.aecpe.com/08-08-20 MPS.pdf

Bernstein, H. M., & Jones, S. A. (2008). Modeling (BIM) Building Information Transforming Design and Construction to Achieve Greater Industry Productivity. Retrieved from http://images.autodesk.com/latin_am_main/files/mcgraw-hill_construction_bim_smartmarket_report_december_2008.pdf

Bi, Z. M., Biy, Z. M., & Zhangy, W. J. (2010). Flexible ® xture design and automation: Review, issues and future directions. *Article in International Journal of Production Research Z. M. Bi on Int. J. Prod. Res*, *17*(13). https://doi.org/10.1080/00207540110054579

Borrmann, A., Kolbe, T. H., Donaubauer, A., Steuer, H., Jubierre, J. R., & Flurl, M. (2015). Multi-Scale Geometric-Semantic Modeling of Shield Tunnels for GIS and BIM Applications. *Computer-Aided Civil and Infrastructure Engineering*, *30*(4), 263–281. https://doi.org/10.1111/mice.12090

Boyle, I., Rong, Y., & Brown, D. C. (2011). A review and analysis of current computer-aided fixture design approaches. *Robotics and Computer-Integrated Manufacturing*, *27*(1), 1–12. https://doi.org/10.1016/J.RCIM.2010.05.008

Bryde, D., Broquetas, M., & Volm, J. M. (2013). The project benefits of Building Information Modelling (BIM). *International Journal of Project Management*, *31*(7), 971–980. https://doi.org/10.1016/J.IJPROMAN.2012.12.001

BuildingSMART. (2018). IFC Introduction - buildingSMART. Retrieved May 30, 2018, from https://www.buildingsmart.org/about/what-is-openbim/ifc-introduction/

Cheng, Z., & Ma, Y. (2017). A functional feature modeling method. *Advanced Engineering Informatics*, *33*, 1–15. https://doi.org/10.1016/J.AEI.2017.04.003

Czmoch, I., & Pękala, A. (2014). Traditional Design versus BIM Based Design. *Procedia Engineering*, *91*, 210–215. https://doi.org/10.1016/J.PROENG.2014.12.048

Dassault Systems. (2018). 3D CAD Design Software. Retrieved June 14, 2018, from https://www.solidworks.com/

de Laat, R., & van Berlo, L. (2011). Integration of BIM and GIS: The Development of the CityGML GeoBIM Extension (pp. 211–225). Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-12670-3_13

De Martino, T., Falcidieno, B., & Haßinger, S. (1998). Design and engineering process integration through a multiple view intermediate modeller in a distributed object-oriented system environment. *Computer-Aided Design*, *30*(6), 437–452. https://doi.org/10.1016/S0010-4485(97)00096-1

Demchak, G., Krygiel, E., & Dzambazova, T. (2008). *Introducing Revit architecture 2009 : BIM for beginners*. Wiley Pub. Retrieved from https://www.wiley.com/en-ca/Introducing+Revit+Architecture+2009%3A+BIM+for+Beginners-p-9780470260982

DENEUX, D. (1999). Introduction to assembly features: an illustrated synthesis methodology. *Journal of Intelligent Manufacturing*, *10*(1), 29–39. https://doi.org/10.1023/A:1008912429442

Deng, Y., Cheng, J. C. P., & Anumba, C. (2016). Mapping between BIM and 3D GIS in different levels of detail using schema mediation and instance comparison. *Automation in Construction*, *67*, 1–21. https://doi.org/10.1016/j.autcon.2016.03.006

Dorf, R. C., Kusiak, A., & Wiley InterScience (Online service). (1994). *Handbook of design, manufacturing, and automation*. Wiley.

Eastman, C. M. (2011). *BIM handbook : a guide to building information modeling for owners, managers, designers, engineers and contractors*. Wiley. Retrieved from https://books.google.ca/books?hl=en&lr=&id=-GjrBgAAQBAJ&oi=fnd&pg=PA305&dq=building+information+modeling&ots=PfkHfX6mpm&sig=YGy2Y6V9jCt37YhIvhfiPOMrarw#v=onepage&q=building information modeling&f=false

FlexQube. (2018). Material Handling Carts Make Production Easier! | FlexQube®. Retrieved June 9, 2018, from https://www.flexqube.com/flexqube-news/material-handling-carts-make-production-easier

Goyal, M., & Jha, K. N. (n.d.). DEVELOPMENT OF A 4-D MODEL FOR APPLICATION IN CONSTRUCTION MANAGEMENT. *I.I.T. Madras*. Retrieved from http://www.iaarc.org/publications/fulltext/isarc2007-3.1_3_129.pdf

Graphisoft. (2018). BIMx and BIMx PRO: the mobile app for exploring BIM on handheld devices. Retrieved June 13, 2018, from http://www.graphisoft.com/bimx/

Gujarathi, G. P., & Ma, Y.-S. (2010). Generative CAD and CAE integration using common data model. In *2010 IEEE International Conference on Automation Science and Engineering*. IEEE. https://doi.org/10.1109/COASE.2010.5584195

Gupta, S. K., & Nau, D. S. (1995). Systematic approach to analysing the manufacturability of machined parts. *Computer-Aided Design*, *27*(5), 323–342. https://doi.org/10.1016/0010-4485(95)96797-P

Henderson, M. R., & Anderson, D. C. (1984). Computer recognition and extraction of form features: A CAD/CAM link. *Computers in Industry*, *5*(4), 329–339. https://doi.org/10.1016/0166-3615(84)90056-3

Holzer, D. (2014). Fostering the Link from PLM to ERP via BIM (pp. 75–82). Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-662-45937-9_8

Hoque, A. S. M., Halder, P. K., Parvez, M. S., & Szecsi, T. (2013). Integrated manufacturing features and Design-for-manufacture guidelines for reducing product cost under CAD/CAM environment. *Computers & Industrial Engineering*, *66*(4), 988–1003. https://doi.org/10.1016/J.CIE.2013.08.016

Hou, M., & Faddis, T. N. (2006). Automatic tool path generation of a feature-basedCAD/CAPP/CAM integrated system. *International Journal of Computer Integrated Manufacturing*, *19*(4), 350–358. https://doi.org/10.1080/09511920500504354

Irizarry, J., Karan, E. P., & Jalaei, F. (2013). Integrating BIM and GIS to improve the visual monitoring of construction supply chain management. *Automation in Construction*, *31*, 241–254. https://doi.org/10.1016/J.AUTCON.2012.12.005

Isikdag, U., Underwood, J., & Aouad, G. (2008). An investigation into the applicability of building information models in geospatial environment in support of site selection and fire response management processes. *Advanced Engineering Informatics*, *22*(4), 504–519. https://doi.org/10.1016/J.AEI.2008.06.001

Jeremy Tammik. (2012). The Building Coder: Exporting Parameter Data to Excel, and Re-importing. Retrieved May 29, 2018, from http://thebuildingcoder.typepad.com/blog/2012/09/exporting-parameter-data-to-excel.html

Joshi, S., & Chang, T. C. (1988). Graph-based heuristics for recognition of machined features from a 3D solid model. *Computer-Aided Design*, *20*(2), 58–66. https://doi.org/10.1016/0010-4485(88)90050-4

Kang, T. W., & Hong, C. H. (2015). A study on software architecture for effective BIM/GIS-based facility management data integration. *Automation in Construction*, *54*, 25–38. https://doi.org/10.1016/J.AUTCON.2015.03.019

Kang, Y., Rong, Y., & Yang, J. C. (2003). Computer-Aided Fixture Design Verification. Part 1. The Framework and Modelling. *The International Journal of Advanced Manufacturing Technology*, *21*(10–11), 827–835. https://doi.org/10.1007/s00170-002-1399-7

Karan, E. P., & Irizarry, J. (2012). OPTIMIZING LOCATION OF TOWER CRANES ON CONSTRUCTION SITES THROUGH GIS AND BIM INTEGRATION. *Journal of Information Technology in Construction (ITcon)*, *17*(17), 351–366. Retrieved from http://www.itcon.org/2012/23

Kihlman, H., & Engström, M. (2002). Affordable Reconfigurable Tooling. https://doi.org/10.4271/2002-01-2645

Kim, H., Anderson, K., Lee, S., & Hildreth, J. (2013). Generating construction schedules through automatic data extraction using open BIM (building information modeling) technology. *Automation in Construction*, *35*, 285–295. https://doi.org/10.1016/J.AUTCON.2013.05.020

Kristin Dispenza. (2010). The Daily Life of Building Information Modeling (BIM) - Buildipedia. Retrieved June 2, 2018, from http://buildipedia.com/aec-pros/design-news/the-daily-life-of-building-information-modeling-bim

Kumar, A. S., Nee, A. Y. C., & Prombanpong, S. (1992). Expert fixture-design system for an automated manufacturing environment. *Computer-Aided Design*, *24*(6), 316–326. https://doi.org/10.1016/0010-4485(92)90049-G

Lee, T. (n.d.). Scheduling, Estimating, and BIM: a Profitable Combination. Retrieved from https://search.proquest.com/docview/208171251/fulltextPDF/18209F8186C648A3PQ/1?accountid=14474

Lee, Z., & Lee, J. (2000). An ERP implementation case study from a knowledge transfer perspective. *Journal of Information Technology*, *15*(4), 281–288. https://doi.org/10.1080/02683960010009060

Leite, F., Akcamete, A., Akinci, B., Atasoy, G., & Kiziltas, S. (2011). Analysis of modeling effort and impact of different levels of detail in building information models. *Automation in Construction*, *20*(5), 601–609. https://doi.org/10.1016/J.AUTCON.2010.11.027

Li, L., Lange, C. F., & Ma, Y. (2017). Association of design and computational fluid dynamics simulation intent in flow control product optimization. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 95440541769735. https://doi.org/10.1177/0954405417697352

Li, L., Lange, C. F., & Ma, Y. (2018). Artificial intelligence aided CFD analysis regime validation and selection in feature-based cyclic CAD/CFD interaction process. *Computer-Aided Design and Applications*, 1–10.

https://doi.org/10.1080/16864360.2018.1441230

Li, L., & Ma, Y. (2016). CAD/CAE associative features for cyclic fluid control effect modeling. *Computer-Aided Design and Applications*, *13*(2), 208–220. https://doi.org/10.1080/16864360.2015.1084190

Liu, J., Cheng, Z., & Ma, Y. (2016). Product design-optimization integration via associative optimization feature modeling. *Advanced Engineering Informatics*, *30*(4), 713–727. https://doi.org/10.1016/J.AEI.2016.09.004

Ma, Y.-S., Britton, G. A., Tor, S. B., Jin, L.-Y., Chen, G., & Tang, S.-H. (2004). Design of a Feature-object-based Mechanical Assembly Library. *Computer-Aided Design and Applications*, *1*(1–4), 397–403. https://doi.org/10.1080/16864360.2004.10738281

Ma, Y.-S., Britton, G. A., Tor, S. B., & Jin, L. Y. (2007). Associative assembly design features: concept, implementation and application. *The International Journal of Advanced Manufacturing Technology*, *32*(5–6), 434–444. https://doi.org/10.1007/s00170-005-0371-8

Ma, Y.-S., Chen, G., & Thimm, G. (2008). Paradigm shift: unified and associative feature-based concurrent and collaborative engineering. *Journal of Intelligent Manufacturing*, *19*(6), 625–641. https://doi.org/10.1007/s10845-008-0128-y

Ma, Y.-S., & Tong, T. (2003). Associative feature modeling for concurrent engineering integration. *Computers in Industry*, *51*(1), 51–71.

https://doi.org/10.1016/S0166-3615(03)00025-3

Ma, Y.-S., Tor, S. B., & Britton, G. A. (2003). The development of a standard component library for plastic injection mould design using an object-oriented approach. *The International Journal of Advanced Manufacturing Technology*, *22*(9–10), 611–618. https://doi.org/10.1007/s00170-003-1555-8

Ma, Y. S., & Bong, C. H. (2010). Fine grain associative feature reasoning in collaborative engineering. *International Journal of Computer Applications in Technology*, *37*(3/4), 210. https://doi.org/10.1504/IJCAT.2010.031937

Martindale, J. (2018). Research Guides: Mapping and Geographic Information Systems (GIS): What is GIS? Retrieved from https://researchguides.library.wisc.edu/GIS

Miao, H. K., Sridharan, N., & Shah, J. J. (2002). CAD-CAM integration using machining features. *International Journal of Computer Integrated Manufacturing*, *15*(4), 296–318. https://doi.org/10.1080/09511920110077502

Milgram, P., Takemura, H., Utsumi, A., & Kishino, F. (1995). Augmented reality: a class of displays on the reality-virtuality continuum. In H. Das (Ed.) (Vol. 2351, pp. 282–292). International Society for Optics and Photonics. https://doi.org/10.1117/12.197321

Mukherjee, A., & Liu, C. R. (1997). Conceptual design, manufacturability evaluation and preliminary process planning using function-form relationships in stamped metal parts. *Robotics and Computer-Integrated Manufacturing*, *13*(3), 253–270. https://doi.org/10.1016/S0736-5845(97)00007-0

National BIM Standard. (2018). Frequently Asked Questions About the National BIM Standard-United States™ | National BIM Standard - United States. Retrieved April 21, 2018, from https://www.nationalbimstandard.org/faqs#faq1

Nicał, A. K., & Wodyński, W. (2016). Enhancing Facility Management through BIM 6D. *Procedia Engineering*, *164*, 299–306. https://doi.org/10.1016/J.PROENG.2016.11.623

Ong, S. K., Ding, J., & Nee, A. Y. C. (2002). Hybrid GA and SA dynamic set-up planning optimization. *International Journal of Production Research*, *40*(18), 4697–4719. https://doi.org/10.1080/00207540210155864

Pauwels, P., Van Deursen, D., Verstraeten, R., De Roo, J., De Meyer, R., Van de Walle, R., & Van Campenhout, J. (2011). A semantic rule checking environment for building performance checking. *Automation in Construction*, *20*(5), 506–518. https://doi.org/10.1016/J.AUTCON.2010.11.017

Peng, G., Wang, G., Liu, W., & Yu, H. (2010). A desktop virtual reality-based interactive modular fixture configuration design system. *Computer-Aided Design*, *42*(5), 432–444. https://doi.org/10.1016/j.cad.2009.02.003

ptc. (2018). Pro/ENGINEER | PTC. Retrieved June 13, 2018, from https://www.ptc.com/en/products/cad/pro-engineer

RCIS. (2011). RICS 2011 Building Information Modelling Survey Report. Retrieved from http://scan2bim.info/wp-content/themes/scan2bim/files/rics_2011_BIM_Survey_Report.pdf

Rufflelt, S. (1986). Architectural design exposed: from computer-aided drawing to computer-aided design. *Environment and Planning B: Planning and Design*, 385–389. Retrieved from http://journals.sagepub.com/doi/pdf/10.1068/b130385

Rüppel, U., & Schatz, K. (2011). Designing a BIM-based serious game for fire safety evacuation simulations. *Advanced Engineering Informatics*, *25*(4), 600–611. https://doi.org/10.1016/J.AEI.2011.08.001

Salomons, O. W., van Houten, F. J. A. M., & Kals, H. J. J. (1993). Review of research in feature-based design. *Journal of Manufacturing Systems*, *12*(2), 113–132. https://doi.org/10.1016/0278-6125(93)90012-I

Santos, E. T. (2009). BIM AND ERP: FINDING SIMILARITIES ON TWO DISTINCT CONCEPTS. Retrieved from https://www.irbnet.de/daten/iconda/CIB14803.pdf

Sarma, S. E., & Wright, P. K. (1996). Algorithms for the minimization of setups and tool changes in "simply fixturable" components in milling. *Journal of Manufacturing Systems*, *15*(2), 95–112. https://doi.org/10.1016/0278-6125(96)82335-1

Shah, J. J., & Mäntylä, M. (1995). *Parametric and feature-based CAD/CAM:*

concepts, techniques, and applications. Wiley. Retrieved from https://books.google.ca/books?hl=en&lr=&id=8W0E9eK2raMC&oi=fnd&pg=PA1&dq=%5B24%5D%09Shah,+J.+J.%3B+Mäntylä,+M.:+Parametric+and+feature-based+CAD/CAM:+concepts,+techniques,+and+applications.+John+Wiley+%26+Sons.+1995&ots=bdktdT0pUn&sig=1rzG8NKfmInnYMbUpFp1NEJQhxY&redir_esc=y#v=onepage&q=%5B24%5D%09Shah%2C J. J.%3B Mäntylä%2C M.%3A Parametric and feature-based CAD%2FCAM%3A concepts%2C techniques%2C and applications. John Wiley %26 Sons. 1995&f=false

Shah, J. J., & Rogers, M. T. (1993). Assembly modeling as an extension of feature-based design. *Research in Engineering Design*, *5*(3–4), 218–237. https://doi.org/10.1007/BF01608364

Simens NX. (2018). NX. Retrieved June 13, 2018, from https://www.plm.automation.siemens.com/global/en/products/nx/

Smith, P. (2014). ScienceDirect BIM & the 5D Project Cost Manager. *Procedia - Social and Behavioral Sciences*, *119*(119), 475–484. https://doi.org/10.1016/j.sbspro.2014.03.053

Solihin, W., Eastman, C., Lee, Y. C., & Yang, D. H. (2017). A simplified relational database schema for transformation of BIM data into a query-efficient and spatially enabled database. *Automation in Construction*, *84*, 367–383.

https://doi.org/10.1016/j.autcon.2017.10.002

Song, H., & Rong, Y. (2005). Locating completeness evaluation and revision in fixture plan. *Robotics and Computer-Integrated Manufacturing*, *21*(4–5), 368–378. https://doi.org/10.1016/J.RCIM.2004.11.012

Stark, J. (2015). Product Lifecycle Management (pp. 1–29). Springer, Cham. https://doi.org/10.1007/978-3-319-17440-2_1

Statistics Canada. (2018). Construction. Retrieved April 16, 2018, from https://www.statcan.gc.ca/pub/11-402-x/2011000/chap/construction/construction-eng.htm

Subramaniam, V., Senthil kumar, A., & Seow, K. C. (1999). Conceptual Design of Fixtures using Genetic Algorithms. *The International Journal of Advanced Manufacturing Technology*, *15*(2), 79–84. https://doi.org/10.1007/s001700050042

Trappey, A. J. C. ;Liu. C. R., & Liu, C. R. (1992). An automatic workholding verification system. *ROBOTICS AND COMPUTER-INTEGRATED MANUFACTURING, Elsevier*, *Volume 9*(Issue 4-5). Retrieved from http://nthur.lib.nthu.edu.tw/handle/987654321/46721

Umble, E. J., Haft, R. R., & Umble, M. M. (2003). Enterprise resource planning: Implementation procedures and critical success factors. *European Journal of Operational Research*, *146*(2), 241–257. https://doi.org/10.1016/S0377-

2217(02)00547-7

Vallapuzha, S., De Meter, E. C., Choudhuri, S., & Khetan, R. P. (2002). An investigation of the effectiveness of fixture layout optimization methods. *International Journal of Machine Tools and Manufacture*, *42*(2), 251–263. https://doi.org/10.1016/S0890-6955(01)00114-6

Van Nederveen, G. A., & Tolman, F. P. (1992). Modelling multiple views on buildings *. *Automation in Construction*, *1*, 215–224. Retrieved from https://ac.els-cdn.com/092658059290014B/1-s2.0-092658059290014B-main.pdf?_tid=559d2e49-497d-4d6b-ab0f-e999a482622d&acdnat=1524342393_bc3f8e888329c3973fb49fb2f60d6dd3

Vanlande, R., Nicolle, C., & Cruz, C. (2008). IFC and building lifecycle management. *Automation in Construction*, *18*(1), 70–78. https://doi.org/10.1016/J.AUTCON.2008.05.001

Vaxiviere, P., & Tombre, K. (1992). Celesstin: CAD conversion of mechanical drawings. *Computer*, *25*(7), 46–54. https://doi.org/10.1109/2.144439

Volk, R., Stengel, J., & Schultmann, F. (2014). Building Information Modeling (BIM) for existing buildings — Literature review and future needs. *Automation in Construction*, *38*, 109–127. https://doi.org/10.1016/J.AUTCON.2013.10.023

Wang, J., Wang, X., Shou, W., & Xu, B. (2014). Integrating BIM and augmented reality for interactive architectural visualisation. *Construction Innovation*, *14*(4), 453–476. https://doi.org/10.1108/CI-03-2014-0019

Wang, Y., Chen, X., Liu, Q., & Gindy, N. (2006). Optimisation of machining fixture layout under multi-constraints. *International Journal of Machine Tools and Manufacture*, *46*(12–13), 1291–1300. https://doi.org/10.1016/J.IJMACHTOOLS.2005.10.014

Whitney, D. E., Mantripragada, R., Adams, J. D., & Rhee, S. J. (1999). Designing Assemblies. *Research in Engineering Design*, *11*(4), 229–253. https://doi.org/10.1007/s001630050017

Woodbury, R. F., Shannon, S. J., & Radford, A. D. (2001). Games in Early Design Education. In *Computer Aided Architectural Design Futures 2001* (pp. 201–214). Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-94-010-0868-6_16

Wu, N. H., & Chan, K. C. (1996). A genetic algorithm based approach to optimal fixture configuration. *Computers & Industrial Engineering*, *31*(3–4), 919–924. https://doi.org/10.1016/S0360-8352(96)00264-1

Wu, Y., Rong, Y., Ma, W., & LeClair, S. R. (1998). Automated modular fixture planning: Accuracy, clamping, and accessibility analyses. *Robotics and Computer-Integrated Manufacturing*, *14*(1), 17–26. https://doi.org/10.1016/S0736-5845(97)00025-2

Xie, Y., & Ma, Y. (2015). Design of a multi-disciplinary and feature-based collaborative environment for chemical process projects. *Expert Systems with Applications*, *42*(8), 4149–4166. https://doi.org/10.1016/J.ESWA.2015.01.009

Yan, W., Culp, C., & Graf, R. (2011). Integrating BIM and gaming for real-time interactive architectural visualization. *Automation in Construction*, *20*(4), 446–458. https://doi.org/10.1016/J.AUTCON.2010.11.013

Yu Wang, M. (2002). Tolerance analysis for fixture layout design. *Assembly Automation*, *22*(2), 153–162. https://doi.org/10.1108/01445150210423198

Zhou, F., Kuo, T.-C., Huang, S. H., & Zhang, H.-C. (2002). Form Feature and Tolerance Transfer from a 3D Model to a Set-up Planning System. *The International Journal of Advanced Manufacturing Technology*, *19*(2), 88–96. https://doi.org/10.1007/s001700200001

Appendix A: VB Code for BIM/CAD Integrated Technology Design Algorithm (Main Function)

```
Attribute VB_Name = "Main App"
Sub readSubCsv(csvFile As String)
Dim lineValue As String
Dim i As Integer
i = 0
Dim Str As String
Dim Base As Double
Dim Operator As String
Dim Var As Double
Open csvFile For Input As #1    'open the CSV file
Do While Not EOF(1)             'define whether read to end of file

   Line Input #1, lineValue          'read data
   Debug.Print lineValue
   Str = Split(lineValue, ",")(0)    'read line one
   Debug.Print lineValue
   Str = Replace(Str, """", "") 'replace the ""
   Debug.Print Str

   If Str <> "Name" Then
      ReDim Preserve Part_Name(i)
      ReDim Preserve Part_modValue(i)
```

```
Part_Name(i) = Str 'read name into string
Debug.Print Part_Name(i)
Str = Split(lineValue, ",")(1)    'read line 2
Debug.Print Str
Str = Replace(Str, """", "") 'replace the ""
Debug.Print Str
If Str = "W" Then  'read file to new parameter for width
   Base = assWidth
ElseIf Str = "H" Then 'read file to new parameter for height
   Base = assHeight
End If
Debug.Print Base

Debug.Print Base

Operator = Split(lineValue, ",")(2)    'read line 3
Debug.Print Operator
Operator = Replace(Operator, """", "")
Debug.Print Operator

Str = Split(lineValue, ",")(3)    'read line 4
Debug.Print Str
Str = Replace(Str, """", "")
Debug.Print Str

Var = CDbl(Str)
```

```
        Debug.Print Var

        If Operator = "*" Then
            Part_modValue(i) = Base * Var
        ElseIf Operator = "-" Then
            Part_modValue(i) = Base - Var
        End If
        Debug.Print Part_modValue(i)

    End If
    i = i + 1
Loop
Close #1                    'close file
End Sub
Sub subToCheckSWRunning(bool As Boolean)
'chech Solidworks is running or not
On Error Resume Next
Dim s, objWMIService, colProcessList, objProcess
s = "sldworks.exe"
Set                                    objWMIService                                    =
GetObject("winmgmts:{impersonationLevel=impersonate}!\\.\root\cimv2")
Set colProcessList = objWMIService.ExecQuery _
("Select * from Win32_Process Where Name='" & s & "'")
For Each objProcess In colProcessList
bool = True
Next
```

```
End Sub
Sub CompReplace(assPathName As String) 'replace the components sub application
Dim swModel  As SldWorks.ModelDoc2
Dim vChildComp As Variant
Dim swChildComp As SldWorks.Component2
Dim swCompConfig As SldWorks.Configuration
Dim sPadStr As String
Dim swType As String
Dim i As Long
Dim j As Integer

Dim swPathName As String 'read through pathname
Dim swName As String
'For i = 0 To nLevel - 1
'    sPadStr = sPadStr + ""
'Next i
Dim swAssy As SldWorks.AssemblyDoc
Dim swConf As SldWorks.Configuration
Dim swRootComp As SldWorks.Component2
Dim nStart As Single
Dim bRet As Boolean
Dim assName As String 'assembly name
Dim assStr As String
Dim ori_partName As String 'part name before
Dim mod_partName As String 'part name after
```

```
assName = Right(assPathName, Len(assPathName) - InStrRev(assPathName, "\"))
'get folder name

    Debug.Print assName

assName = Left(assName, InStr(assName, ".") - 1) 'get folder name

Debug.Print assName

Debug.Print assPathName


Set swModel = swApp.OpenDoc6(assPathName, 2, 0, "", longstatus, longwarnings)
'open assembly

Set swConf = swModel.GetActiveConfiguration 'get setting of model

Debug.Print assPathName

Set swRootComp = swConf.GetRootComponent

Debug.Print assPathName

vChildComp = swRootComp.GetChildren 'get parts in the assembly

Dim KKname As String

For i = 0 To UBound(vChildComp)


   Set swChildComp = vChildComp(i)

   KKname = swChildComp.Name2

   Debug.Print KKname

   swPathName = swChildComp.GetPathName

   Debug.Print swPathName

   'Debug.Print sPadStr & swChildComp.Name2 & "<" &
swChildComp.ReferencedConfiguration _

            & ">"

    swType = Right(swPathName, Len(swPathName) - InStrRev(swPathName, "."))
'get type
```

```
    swName = Right(swPathName, Len(swPathName) - InStrRev(swPathName, "\"))
'get name

    Debug.Print swName

    swName = Left(swName, InStr(swName, ".") - 1)

    Debug.Print swPathName

    Debug.Print swType

    Debug.Print swName

    For j = 1 To UBound(Part_Name)

        oriPartName = Part_Name(j)

        modPartName = Part_Name(j) & Form1.Txt_modPartName.Text

        Debug.Print oriPartName

        Debug.Print modPartName

        Debug.Print swName

        If (swName = oriPartName And swType = "SLDPRT") Then

            assStr = swModel.GetPathName

            Debug.Print assStr

   '

            boolstatus = swModel.Extension.SelectByID2(KKname & "@" & assName,
"COMPONENT", 0, 0, 0, False, 0, Nothing, 0)

            Debug.Print boolstatus


            boolstatus = swModel.ReplaceComponents(App.Path & "\1\" &
modPartName & ".SLDPRT", "", True, True)

            Debug.Print boolstatus

            boolstatus = swModel.EditRebuild3 'rebuilt

            Debug.Print App.Path & "\1\" & modPartName & ".SLDPRT"

            Debug.Print boolstatus
```

```
      End If
    Next j
   Debug.Print assName
   Debug.Print swPathName
    If swType = "SLDASM" Then
      CompReplace swPathName
    End If
    boolstatus = swModel.EditRebuild3 'rebuilt

Next i
End Sub

Sub ModifyPart(partIndex As Integer)
Debug.Print partIndex
Dim PartName As String
Dim modPartName As String
PartName = Part_Name(partIndex)
Debug.Print PartName
Set swModel = swApp.NewDocument(App.Path & "\1\" & PartName & ".SLDPRT",
0, 0, 0) 'open original part
modPartName = PartName & Form1.Txt_modPartName.Text
Debug.Print modPartName
longstatus = swModel.SaveAs3(App.Path & "\1\" & modPartName & ".SLDPRT", 0,
2) 'save as new part
swApp.CloseDoc PartName & ".SLDPRT" 'close original file
```

```
Set swModel = swApp.NewDocument(App.Path & "\1\" & modPartName & ".SLDPRT", 0, 0, 0) 'open new part


Set swFeature = swModel.FirstFeature 'find first feature

While Not swFeature Is Nothing

  FeatType = swFeature.GetTypeName 'get first feature type


  FeatName = swFeature.GetNameForSelection(FeatType) 'get feature name


  If FeatName = "Boss-Extrude1" Then 'find the extrude feature

    Set swFeatureData = swFeature.GetDefinition 'get feature definition

    swFeatureData.SetDepth True, Part_modValue(partIndex) / 1000 'change extrude length

    retval = swFeature.ModifyDefinition(swFeatureData, swModel, Nothing)

  End If


  Set swFeature = swFeature.GetNextFeature 'go to next feature

Wend

boolstatus = swModel.EditRebuild3 'rebuilt


swModel.Save2 0 'sace

swApp.CloseDoc modPartName & ".SLDPRT" 'close

End Sub
```

Appendix B: VB Code for BIM/CAD Integrated Technology Design Algorithm (Supported Function)

```
Private Sub CmdStart_Click()
Dim i As Integer
i = 0
Call subToCheckSWRunning(boolstatus) 'Test if SolidWorks is working
If boolstatus = False Then 'Exit the app if solidworks is not working
   MsgBox "Could not find Solidworks. Please open the Solidworks!", vbOKOnly, _
       "Warning: No Solidworks!"
   Exit Sub
End If

Set swApp = CreateObject("sldworks.application") 'Connect this app with Solidworks
'Input data
assWidth = CDbl(Text1.Text)
assHeight = CDbl(Text2.Text)
Dim subCsvName As String
subCsvName = Combo1.List(ListIndex)
Debug.Print subCsvName
subCsvName = App.Path & "\csv\" & subCsvName & ".csv"
Call readSubCsv(subCsvName)

For i = 1 To UBound(Part_Name)
   Call ModifyPart(i)
```

```
Next i

Dim rootAssPathName As String
Dim modAssName As String
rootAssPathName = App.Path & "\1\Frame.SLDASM"
Debug.Print rootAssPathName
modAssName = Txt_modAssName.Text
Set swModel = swApp.NewDocument(rootAssPathName, 0, 0, 0) 'open original assembly
rootAssPathName = App.Path & "\1\" & modAssName & ".SLDASM"
Debug.Print rootAssPathName
longstatus = swModel.SaveAs3(rootAssPathName, 0, 2) 'save in the new name

swApp.CloseDoc "Frame.SLDASM" 'close the assembly
CompReplace rootAssPathName

Set swModel = Nothing 'clear memory
Set swApp = Nothing 'clear relationshop between this app and Solidworks
MsgBox "Finish Remodeling"
End Sub


Private Sub Combo1_Click()
Debug.Print Combo1.ListCount
Debug.Print UBound(Family)
For i = 2 To UBound(Family)
```

```
    If Combo1.List(Combo1.ListIndex) = Family(i) Then
        Text1.Text = val_Width(i)
        Text2.Text = val_Height(i)

    End If
Next i
End Sub



Private Sub Command2_Click()

End Sub

Private Sub Form_Load()
Dim csvFile As String
Dim lineValue As String
Dim i As Integer
i = 0
csvFile = App.Path & "\csv\Window Schedule 2.csv"        'locate BIM csv data
Open csvFile For Input As #1    'open file
Do While Not EOF(1)            'read to the end
    Debug.Print i

    ReDim Preserve Family(i)
```

```
ReDim Preserve val_Width(i)
ReDim Preserve val_Height(i)

Line Input #1, lineValue        'read single line
Debug.Print lineValue

Family(i) = Split(lineValue, ",")(0)    'read line 1
Debug.Print Family(i)
Family(i) = Replace(Family(i), """", "") 'delect double quotes from the file
Debug.Print Family(i)


val_Width(i) = Split(lineValue, ",")(1)    'read line 2
Debug.Print val_Width(i)
val_Width(i) = Replace(val_Width(i), """", "")
Debug.Print val_Width(i)

val_Height(i) = Split(lineValue, ",")(2)    'read line 3
Debug.Print val_Height(i)
val_Height(i) = Replace(val_Height(i), """", "")
Debug.Print val_Height(i)
If i > 2 Then
  Combo1.AddItem Family(i), i - 3
End If

i = i + 1                  'line loop
```

```
Loop                      'loop
Close #1                  'close file


Combo1.Enabled = True
End Sub

Private Sub Picture1_Click()

End Sub
```