

**Integrating Building Information Modelling (BIM), Cost  
Estimating and Scheduling for Buildings Construction at the  
Conceptual Design Stage**

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## **Abstract**

Estimating the construction time and cost of a building project is an essential task of construction manager, which benefits owners, engineers and contractors. Construction duration and cost, in particular, have profound influence on the outcome of a project at the conceptual stage of its life. The conventional methods used to estimate the time and costs of construction projects are based on 2D models, which need much time and effort from engineers, estimators and schedulers who are involved in preparing them because all of this process is done manually, especially when the project has several design alternatives. Considering that, Building Information Modelling (BIM), which is a technology that enhances data transfer and ensures cooperation among designers, engineers, and contractors, can provide an efficient way for cost estimating and schedule planning. On the other hand, sustainability has drawn more and more attention by the construction industry, this is because a project's construction process has crucial impacts on society, the environment, and the economy. Modular Construction has been proven to ensure sustainable construction by reducing the negative impacts on the environment, reducing construction time, and improving manpower productivity. This research aims at developing an integrated model that interrelates BIM with construction cost estimation, scheduling, and sustainability at the conceptual design stage of projects. The aim is to reduce the preparation time and increase the efficiency of making major decisions for both conventional construction and modular construction.

The proposed model consists of five modules, including a data collection module, a cost estimation module, a scheduling module, a sustainability evaluation module, and a 5D integrated module. Plug-ins were developed in the model to link BIM tool (i.e., Autodesk Revit) with

Microsoft Excel to ensure automatic data transfer among these modules all within a BIM platform so that owners and designers can quickly generate a reliable construction cost estimate, construction schedule, preliminary sustainability evaluation, as well as construction process simulation.

## Table of Content

Acknowledgement .....	ii
Abstract.....	iii
Table of Content .....	v
List of Tables .....	x
List of Figures.....	xi
List of Abbreviation.....	xvi
Chapter 1 Introduction .....	1
1.1    General background .....	1
1.2    Research Objectives.....	2
1.3    Methodology .....	2
1.4    Thesis organization .....	3
1.5    Expected Contribution.....	4
Chapter 2 Literature Review.....	5
2.1    Introduction .....	5
2.2    Building Information Modelling.....	6
2.2.1    BIM Definition.....	6
2.2.2    The application of BIM in construction management .....	7
2.3    Modular Construction .....	10
2.3.1    Definition of Modular Construction .....	10

2.3.2	The benefit of modular construction.....	11
2.3.3	The application of modular construction .....	14
2.3.4	Application of BIM in modular construction.....	16
2.4	Cost Estimation .....	19
2.4.1	Definition of cost estimation.....	19
2.4.2	The method of cost estimation.....	20
2.5	Schedule Planning.....	23
2.5.1	Definition of schedule planning.....	23
2.5.2	The method of schedule planning.....	24
2.6	Sustainability.....	26
2.6.1	The sustainability in building environments.....	26
2.6.2	The impacts of sustainability .....	27
2.6.3	The assessment of sustainability.....	28
2.6.4	Using BIM and modular construction to support sustainability.....	29
2.7	Summary .....	30
Chapter 3 Methodology .....		32
3.1	Introduction .....	32
3.2	Proposed Model's Components and Relationships.....	34
3.3	Data resources and collection.....	36
3.4	BIM-based automated estimation method.....	39

3.4.1	Cost estimate module.....	39
3.4.1.1	Cost estimation for traditional construction.....	41
3.4.1.2	Cost estimation for modular construction.....	41
3.4.1.3	Construction cost adjustment.....	42
3.4.2	Schedule planning module.....	44
3.4.2.1	Schedule planning for traditional construction.....	46
3.4.2.2	Schedule planning for modular construction.....	47
3.4.3	Sustainability module.....	49
3.4.4	Integrated 5D module.....	50
3.5	Summary.....	52
Chapter 4 Model Development.....		54
4.1	Introduction.....	54
4.2	Database Collection and Development.....	55
4.2.1	Architectural families collection.....	55
4.2.2	Cost data collection.....	58
4.2.3	LEED information collection.....	60
4.3	3D BIM modelling.....	60
4.4	Cost estimation.....	64
4.4.1	Cost data input.....	64
4.4.2	Plug-in Development.....	65

4.4.3	Preparation of data extraction .....	66
4.4.4	Cost calculation.....	72
4.5	Schedule Planning.....	75
4.5.1	Duration calculation.....	75
4.5.2	Plug-in development.....	77
4.5.3	Automatically transfer data to Microsoft Project.....	80
4.6	Sustainability evaluation .....	80
4.7	Integration of a 5D module .....	83
4.8	Summary .....	86
Chapter 5 Model Validation.....		87
5.1	Real case project information.....	87
5.2	3D architectural modelling.....	88
5.3	Construction cost estimation for the case project.....	92
5.4	Schedule Planning.....	96
5.5	Sustainability evaluation .....	104
5.6	5D module of the developed model .....	106
5.7	Analysis and Comparison.....	110
Chapter 6 Conclusion and future work .....		114
6.1	Conclusion.....	114
6.2	Research Contribution.....	115

6.3	Limitations of the research.....	116
6.4	Recommendation for future work .....	117
	References.....	119
	Appendix A Sample of the Revit family database.....	136
	Appendix B Sample of the Quantity Takeoff extracted from the proposed project in Revit .....	141
	Appendix C Construction schedule of the proposed hotel project .....	145
	Appendix D Copy of the Code used to develop the plug-in in Microsoft Visual Basic.....	152
	Appendix E Data processing before construction scheduling .....	155

## **List of Tables**

Table 2.1 The nDimension of BIM application (Masood et al., 2013).....	9
Table 2.2 Environmental, social and economic benefits from sustainable plastics (Ahn et al., 2014) .....	27
Table 3.1 The components and associated description of the TaskID .....	45
Table 5.1 The potential LEED points of the materials and components of the proposed hotel.....	106

## List of Figures

Figure 2.1 Relations between building life cycle (LC) stages as well as functional, informational, technical and organizational issues of BIM (Volk et al., 2014).....	7
Figure 2.2 Typical layout of rooms clustered around a core (Lawson et al., 2013).....	15
Figure 2.3 Typical corridor arrangement of modules (Lawson et al., 2013) .....	16
Figure 3.1 General flowchart of research methodology.....	33
Figure 3.2 Model’s main Modules and their Relationship.....	35
Figure 3.3 Data collection process.....	39
Figure 3.4 Cost estimation flowchart.....	44
Figure 3.5 The process of schedule planning for both traditional construction and modular construction	48
Figure 3.6 The sustainability evaluation process .....	50
Figure 3.7 Flowchart of the integrated 5D module.....	52
Figure 4.1 The main tools used in the development of the integrated model .....	55
Figure 4.2 Organization of the family into two different database .....	56
Figure 4.3 Properties of one type of window .....	57
Figure 4.4 3D view of an awning window.....	58
Figure 4.5 Assembly cost of doors from R.S. Means (R.S. means online database, 2016).....	59
Figure 4.6 Loading the family database into Revit.....	61

Figure 4.7 The process of creating shared parameters.....	63
Figure 4.8 Inputting the cost data into families' properties .....	64
Figure 4.9 The dropdown menu of the BIMiTs plug-in.....	66
Figure 4.10 Configure the template for data extraction .....	67
Figure 4.11 The finished template for data exporting.....	68
Figure 4.12 Adding new columns in the template workbook for the convenience of the cost estimate .....	69
Figure 4.13 The process of creating the merged sheet.....	71
Figure 4.14 Finished merged worksheet of the extraction template .....	72
Figure 4.15 The data type of the door category from the project.....	73
Figure 4.16 All the exported data about the doors in the project.....	74
Figure 4.17 Customizing the exported template for the duration calculation.....	77
Figure 4.18 VBA code of the plug-in for exporting data to Microsoft Project.....	79
Figure 4.19 Insert the potential LEED points into the window properties .....	81
Figure 4.20 The LEED points can be shown in this column after data abstraction .....	82
Figure 4.21 Exporting the 3D model from Revit to Naviswork .....	84
Figure 4.22 Appending the 3D model and linking the appropriate schedule in Naviswork .....	85
Figure 5.1 Floor plan of the proposed hotel.....	88
Figure 5.2 The 3D exterior view of the proposed Express Hotel.....	89

Figure 5.3 Inserting the cost value and LEED points of one type of window into Revit .....	90
Figure 5.4 Assigning a TaskID to the windows in Zone A at Level 1.....	91
Figure 5.5 Assigning the TaskID “L_A” to a module on the ground floor.....	92
Figure 5.6 Click Data Link for data exporting.....	93
Figure 5.7 Choosing exporting data and extracting data from Revit to Excel .....	94
Figure 5.8 Working out the construction cost subtotal of the floor category.....	95
Figure 5.9 Working out the duration of each element in the floor category .....	97
Figure 5.10 Merged sheet of the data from the 3D model .....	98
Figure 5.11 The data is organized and ready to export to Microsoft Project (conventional construction).....	100
Figure 5.12 The schedule plan for conventional construction of the proposed hotel .....	101
Figure 5.13 The data is organized and ready to export to Microsoft Project (modular construction) .....	103
Figure 5.14 The schedule plan for modular construction of the proposed hotel.....	104
Figure 5.15 Take the maximum value as the LEED points of the door category .....	105
Figure 5.16 The 3D model is exported to the NWC format.....	106
Figure 5.17 Setting the construction activity sets in Naviswork.....	107
Figure 5.18 The cost data and duration of each construction activity are integrated in Naviswork .....	108
Figure 5.19 Simulation process of conventional construction .....	109
Figure 5.20 Simulation process of modular construction .....	110

Figure A.1 The sample of Revit family collection.....	136
Figure A.2 Storing the family in the external database.....	137
Figure A.3 The MasterFormat organization of the families external database.....	138
Figure A.4 The UniFormat organization of the families external database.....	139
Figure A.5 Loading the external families database into Autodesk Revit.....	140
Figure B.1 The QTO of the door category of the proposed project.....	141
Figure B.2 The QTO of the door category of the proposed project (cont.) .....	142
Figure B.3 The QTO of the door category of the proposed project (cont.) .....	143
Figure B.4 The QTO of the door category of the proposed project (cont.) .....	144
Figure C.1 The construction schedule of conventional construction for the proposed project.....	145
Figure C.2 The construction schedule of conventional construction for the proposed project (cont.) .....	146
Figure C.3 The construction schedule of conventional construction for the proposed project (cont.) .....	147
Figure C.4 The construction schedule of conventional construction for the proposed project (cont.) .....	148
Figure C.5 The construction schedule of modular construction for the proposed project .....	149
Figure C.6 The construction schedule of modular construction for the proposed project (cont.).....	150
Figure C.7 The construction schedule of modular construction for the proposed project (cont.).....	151
Figure E.1 Sorting the duration data of construction activity by TaskID .....	155
Figure E.2 Calculation of cost and duration subtotal after sorting data.....	156

Figure E.3 Assigning the start date of the proposed project ..... 157

Figure E.4 The data for scheduling is ready to export to MsProject by using the plug-in..... 158

## **List of Abbreviation**

3D CAD	3-Dimensional AutoCAD
AEC	Architecture, Engineering and Construction
APBSA	Automated Productivity-based Schedule Animation
API	Application Program interface
ASTM	American Society of Testing and Materials
BEAT	Building Environmental Assessment Tool
BEES	Buildings for Environmental and Economic Sustainability
BIM	Building Information Modelling
BREEAM	Building Research Establishment Environmental Assessment Method
CAD	Computer-aided Design
CIC	Computer Integrated Construction
CPM	Critical Path Method
ESF	Economic Sustainability Factor
ESF	Environmental Sustainability Factor
GBC	Green Building Challenge
GBTool	Green Building Tool
HVAC	Heating, Ventilation and Air Conditioning

IFC	Industry Foundation Classes
IS	Information System
IT	Information Technology
LC	Life Cycle
LCA	Life Cycle Assessment
LCCA	Lifecycle Cost Analysis
LEED	Leadership in Energy and Environmental Design
MBI	Modular Building Institute
MEP	Mechanical, Electrical, and Plumbing
NBIMS	National BIM Standards
NIST	National Institute of Standards and Technology
PERT	Program Evaluation Review Technique
PTD	Prevention through design
QS	Quantity Surveyor
QTO	Quantity Takeoff
RFID	Radio Frequency Identification
SSF	Social Sustainability Factor
USGBC	United State Green Building Council

VC            Virtual Construction

VE            Virtual Environment

# **Chapter 1**

## **Introduction**

### **1.1 General background**

The construction industry, as a traditional industry with a long history, is one of the many industries that influence the economic backbones of many countries. Its progress is always related to the development of society and the advancement of technology. Construction costing and scheduling are essential factors to be considered at the early stages of a construction project because they are of high importance to investors before moving to the detailed design of a proposed project. This is why owners and decision makers are always eager to know the project's cost and duration at the preliminary stage, based on which they can make reliable decisions on the proposed project within a short period. However, cost estimation and scheduling have been seen as two complex processes in the field of construction engineering and management because they involve the estimation of the quantity of work, collection of cost and duration data, arrangement of resources for construction activities, which are time-consuming and labour intensive, especially for projects with several alternatives. The emergence of BIM improves the efficiency of estimating the cost and duration of projects, as BIM enables users to integrate a variety of data into one model, where these data can be shared among, transferred to, and extracted from different tools for cost estimation and schedule planning purposes.

BIM can also provide an efficient way to do sustainability evaluation, which is always a consideration when making decision, especially for public facilities. This research focuses on how BIM can enhance the implementation of sustainability assessment for proposed projects at the preliminary stage.

Furthermore, modular construction is always considered by many construction companies for improving the sustainability of construction and shortening construction cost and schedule. This research also considers modular construction with the attempt to use BIM to optimize the preparation process of modular construction at the conceptual design stage of a building project's life.

## **1.2 Research Objectives**

Based on the general background and the literature review, this research aims at developing a model that integrates BIM with cost estimating, scheduling and sustainability assessment at a project's preliminary stage for both conventional and modular construction. By using this proposed model, decision makers can quickly obtain a reliable preliminary budget and schedule, a sustainability evaluation, as well as a project construction simulation, so that they can have an efficient overview of the proposed project to make appropriate judgements and decisions at the conceptual design stage when detailed information is limited.

## **1.3 Methodology**

The methodology of this research describes how to integrate BIM with cost estimation, schedule planning and sustainability evaluation to provide users with an integrated model to use at the conceptual stage of building projects. More than 300 kinds of design families are collected and stored in an external database. Most of these families are green families and can be loaded automatically into BIM tool (i.e., Revit) and used to develop the 3D architectural model of proposed projects. The cost data collected from R.S. Means and the LEED points collected from suppliers' websites can be linked to the associated families in BIM tools. In order to achieve an automatic data transfer, this proposed methodology attempts to use the Application Program

interface (API) of BIM tool to enable users link the external database with BIM tool for 3D model development. Furthermore, the methodology customizes the Application Program Interface (API) of BIM tool to make an automatic data transfer from that tool to Excel, which would improve the efficiency of Taking off the Quantities (QTO), which is the basic of cost estimation and schedule planning. Moreover, the 5D module that integrates BIM with cost estimation and scheduling will also be introduced in the methodology to enhance the reliability of estimation for both conventional and modular construction at the conceptual design stage of projects.

#### **1.4 Thesis organization**

This thesis is divided into six chapters as follows:

- 1) Chapter 1 is the overview of the research.
- 2) Chapter 2 is the review of the literature related to the main topics discussed in this research: BIM, modular construction, cost estimation, schedule planning, and sustainability. This literature provides the basic definitions, information about previous related studies, and related methodologies in the cost estimation and scheduling areas, as well as sustainability assessment.
- 3) Chapter 3 describes the methodology of developing the integrated model and the different modules that fulfill the objectives of this research.
- 4) Chapter 4 explains the physical development of the proposed model for the accomplishment of cost estimation, scheduling, 3D model development, sustainability assessment, and 5D model development at projects' conceptual stage.
- 5) Chapter 5 is the validation that uses a real proposed hotel project to examine the capability of the model for assisting in improving the efficiency of cost estimation and

scheduling, as well as for conducting sustainability evaluations and construction simulations for both conventional and modular construction at the conceptual design stage.

- 6) Chapter 6 presents the conclusions, research contributions, and limitations of this research, and recommends future work to expand the scope of the current model.

## **1.5 Expected Contribution**

Considering the traditional methods applied in cost estimation and scheduling in construction management, this research is dedicated to improve the efficiency and reliability of using these methods by integrating BIM with cost and duration estimation. The main expected contributions are follows:

- 1) Developing plug-ins in BIM tool to enhance the data extraction, which means the 3D architectural model data can be exported automatically from BIM tool to Excel and other analysis applications for cost estimation and scheduling.
- 2) Creating a plug-in in Microsoft Excel for automatic data transfer between it and Microsoft Project.
- 3) Creating new shared parameter “TaskID” in BIM tool, which is used to identify construction activities in different construction types (conventional, modular) to make the model’s application more generic.
- 4) Creating a new parameter “LEED points” in BIM tool to store the LEED information in each element used in the 3D model of projects.

## **Chapter 2**

### **Literature Review**

#### **2.1 Introduction**

BIM is becoming popular due to its dramatic benefits for architecture, engineering and construction (AEC) industry. BIM can also bring advantages to cost estimation and schedule planning, which are the two essential processes at the conceptual stage of construction projects. Also, the application of BIM concept in modular construction satisfies the pursuit of developers for short construction schedule and sustainable construction. This chapter provides a comprehensive literature review covering the following areas:

- 1) Building Information Modeling by reviewing its definition, areas of application, and benefits to the construction industry.
- 2) It reviews the studies on modular construction, which includes the definition and history of modular construction, the application and benefits of modular construction, and how BIM can help modular construction overcome the related challenges.
- 3) It highlights the literature for construction cost estimation and schedule planning by reviewing the concepts, the importance, and the methods used in these two processes and their respective advantages and disadvantages.
- 4) Towards the end, sustainability, which is a big topic in 21<sup>st</sup> century, is reviewed. It reviews the definition and meaning of sustainability in AEC industry, sustainability assessment methods, and how BIM and modular construction can influence the sustainability of building projects.

## **2.2 Building Information Modelling**

### **2.2.1 BIM Definition**

BIM has been very much talked about in the building industry in the past decade; when the AEC companies introduce their advanced technology; when the contractor describes what they use in the projects in the bidding process; when scholars discuss the trends of the building industry. Thirty years ago, Eastman, of Georgia Tech College of Architecture and Computing, was one of the first people to raise this concept: “Building Information integrates all of the geometric model information, the functional requirements and capabilities, and piece behavior information into a single interrelated description of a building project over its lifecycle. It also includes process information dealing with construction schedules and fabrication processes” (Eastman et al., 2008). Similarly, Associated General Contractors of America (AGC, 2009) describes BIM as a tool to develop a data-rich, object-oriented, intelligent, and parametric digital representation of the facility and to improve the process of delivering the facility. Compared with these summarizing definitions, Succar (2008) provided a specific description of BIM as Modelling (such as shaping, forming, presenting and scoping); Information (an organized set of data, meaningful and actionable) and Building (a structure, an enclosed space, a constructed environment) for a functioning tool for the virtual construction, analysis, scenario based simulation, integration, costing, constructability, destruction and even maintenance of facilities.

However, there is no agreement on a unified definition for BIM, due to different perspectives. Based on the evaluation of the business sense of BIM, Arandamena et al. (2008) concluded that for some, BIM is only a software application; for some, BIM is a process for designing and documenting building information; and for others, it is a new approach to practice and improve the profession for implementing of new contracts, policies, and relationships amongst project

stakeholders. Moreover, BIM can be defined as “little bim” in a narrow sense and “BIG BIM” from a broad perspective. Figure 2.1 shows the scope of BIM in the narrow and broader senses, showing that BIM can be divided into interrelated functional, informational, technical and organizational parts during the life cycle (LC) stages in the broader sense, while from a narrower perspective, BIM is seen as a digital building model, which is a central information management hub or repository (Eastman and Sacks, 2011).

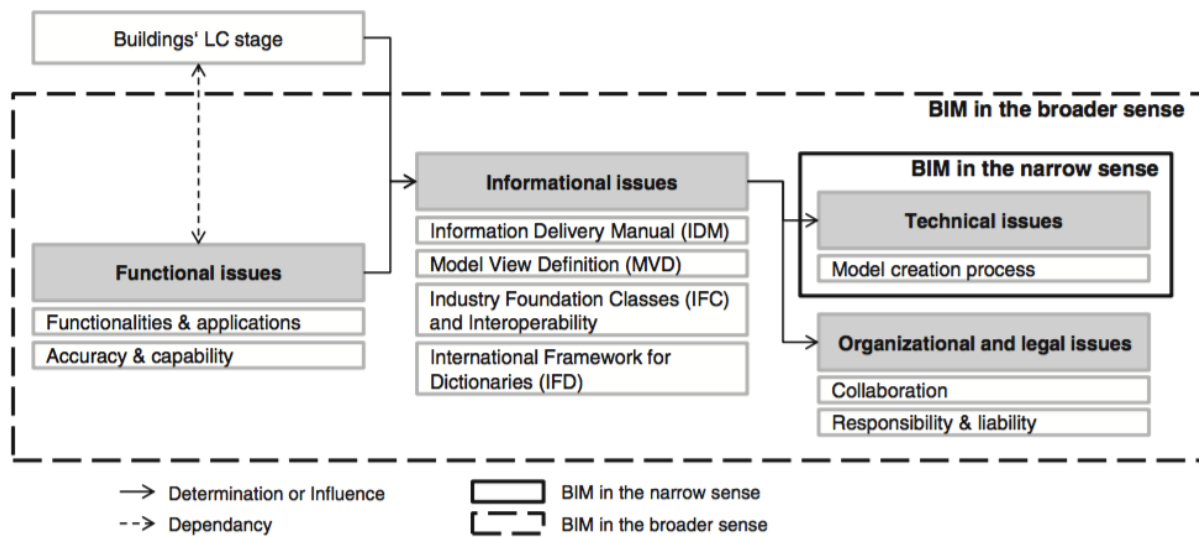


Figure 2.1 Relations between building life cycle (LC) stages as well as functional, informational, technical and organizational issues of BIM (Volk et al., 2014)

## 2.2.2 The application of BIM in construction management

Technology such as VC, 3D CAD, IS, CIC, and IT (standing for Virtual Construction, 3-Dimensional AutoCAD, Information Systems, Computer Integrated Construction, and Information Technology, respectively) are not new to the building industry (Barlish and Sullivan, 2012). Most of these applications have focused on how to help integrate the many functions of the building industry to create a more information sharing process. For example, 3D modelling and VC are usually used to generate or extract the 2D drawings from 3D building models to

improve efficiency in documentation, and to export the data embedded in objects contained in the models to obtain schedules and lists of materials. Currently, BIM has extended these ideas from drawing and schedule production to the creation, management, and communication of information about the building, which has addressed its quality and consistency. Because of the ability to integrate the databases underlying the model, BIM becomes nD (n-Dimension) BIM based on the 3D special model, such as 4D BIM (adding construction scheduling) and 5D BIM (adding cost accumulation). Masood et al. (2013) conceived Table 1 after reviewing several research studies to show the nDimension of BIM applications that have been adopted in different regions of the world (such as Germany, Finland, Sweden, USA, and Canada). Volk et al. (2013) did similar work on the application and use for BIM in the building industry. They found that due to the various design, engineering, construction, maintenance and deconstruction services during the building life cycle, the potential applications and required functionalities of BIM in building projects may vary. Azhar (2011) has concluded that: depending on the stakeholders and the requirements of projects, the major applications of BIM are: 1) Visualization, 2) Fabrication/shop drawings, 3) Code reviews, 4) Cost estimating, 5) Construction sequencing, 6) Conflict interference, 7) Forensic analysis, and 8) Facilities management. Volk et al. (2013) also indicated that their research focus extends to expert functionalities for new buildings, such as energy and carbon reduction analysis, construction progress tracking, deviation analysis, and jobsite safety.

Table 2.1 The nDimension of BIM application (Masood et al., 2013)

Dimension	Application
3D Coordination	Visually interface checking with mechanical, electrical, and plumbing (MEP) integration reduce conflicts
Design and Constructability Reviews	Analyze design for practicality and identification of errors and omissions
4D Scheduling and Sequencing	Activities sequencing with visualization. Simulation for update time and resource schedule
5D Cost Estimation	Material quantities are extracted automatically and changed when any changes are entered in model. Micro and Macro Costing Models.
6D Procurement	Integration of subcontractor supplier and vendor data into isolated models.
Prefabrication	Optimization of prefabricated construction components. Integration with MEP components.
Structural Analysis	External analytical engine develop architecture design to structure and then analyzed for loading.
Lightening Analysis	Creation of effective, efficient, ambient and constructible lightening systems with enhancement in quality, cycle time and cost.
Mechanical (HVAC) Analysis	Clash, conflict and overlapping detection with computerized visualization.
Energy Analysis	Energy analysis, delighting, orientation analysis, solar analysis, building, massing analysis and site analysis with Virtual Environment (VE).
7D Operation and Maintenance	Facilities management for renovations, repairs, restorations, space planning, and operations maintenance. Security management and safety information such as emergency lighting, emergency power, egress, fire extinguishers, fire alarm, smoke detector and sprinkler systems. Radio Frequency Identification (RFID) application for gathering information from real world components into BIM.
GIS based Visualization	The model satisfies and enhanced visualized system by incorporating of as-built site photographs
8D Modeling with PTD	Risk assessment of design component of facility for prevention through design.

Due to advances in these technologies, there is an increasing trend of applying BIM in the AEC industry. McGraw-Hill Construction (2011) conducted a survey among 82 architects, 101

engineers, 80 contractors, and 39 owners in the United States, and published a report about BIM's use in the AEC industry with the following key findings: 1) 43% of architects used BIM on more than 60% of their projects, 2) 82% of BIM users believed that BIM had a positive influence on their projects, 3) 66% of those respondents believed that the use of BIM increased their chances of winning projects, and 4) 79% of BIM users think that the use of BIM improved projects' outcomes, such as fewer requests for information and less field coordination problems. Farnsworth et al. (2014) conducted another survey in commercial construction and found that the top five applications of BIM used by commercial contractors included clash detection, 3D modelling, team collaboration, constructability issues, and sales.

## **2.3 Modular Construction**

### **2.3.1 Definition of Modular Construction**

In the highly competitive, fast-paced building industry, modular construction is regarded as an “opportunity to breakthrough achievement” in the National Research Council's 2009 report on improving productivity in the construction industry (McGraw-Hill Construction, 2011). Actually, modular construction is not a new concept and even has a long history. During World War II, due to the need for lots of accommodations for military personnel, modular construction was increasingly used, especially in Japan and Europe. At that time, modular construction used lightweight materials so that they could be shipped anywhere and assembled without skilled labor (The Steel Master Building Systems, 2001). This is why people believed that the structure of modular construction to be inferior in quality if compared to traditionally-constructed buildings over the past century. However, through modern technology, this image has changed. With the advancement of technology, the materials used in modular construction are now similar

to those used in site-built buildings, and the modules are built in a controlled plant, so the outcome is often indistinguishable from conventional site-built buildings (Mullens, 2004).

Modular construction is a term describing factory-built building units completely assembled or fabricated in a manufacturing plant away from the jobsite, then transported and assembled on site (Pasquire, 2002). In a similar definition, O'Brien (2000) said that modular buildings usually consists of multiple rooms with three-dimensional units, which are build and pre-assembled completely with trim work, mechanical, electrical and plumbing components installed, while Carlson (1991) indicated that the sections and modules are typically 95% finished when they leave the factory. Fabris (2013) provided a comprehensive and vivid explanation for modular construction as follow: "Prefabrication of modular structures yields complete or near-complete building sections, including mechanical and electrical systems, finished walls, floors and ceilings, and sometimes even finishes. Once they arrive at the job site, a crane puts the pieces in place and the construction team assembles them like giant Lego blocks".

### **2.3.2 The benefit of modular construction**

The potential for a faster construction schedule may be the biggest attraction when owners or contractors consider modular construction. Based on a survey of 809 constructors, architects and engineers, McGraw-Hill Construction (2011) concluded that two-thirds (2/3) of companies who currently use modularization/prefabrication experience shortened project schedules, with 35% experiencing decreases of 4 weeks or more compared to comparable site-built projects. One of the reasons is that modular construction allows contractors to work in parallel, building the structure even before site work begins, while for conventional construction projects, construction begins with site preparation, followed by construction of the foundation, then framing, and so on (Fabris, 2013). Fabris (2013) also pointed out that the most time savings is from the assembly-

line environment of prefabrication. For example, the MEP system with the same dimensions in different projects can be cut and assembled as a whole and workers can also complete the sections of HVAC ductwork in factory to save the time for installing ductwork and piping in smaller sections on site. Gary Sadler (Modular Construction, 2013) stated that: “Constructing the building in a sheltered, climate-controlled factory eliminates delays due to bad weather, another time-savings attribute especially in cold weather areas”. The time-saving benefit of modular construction provides critical assistance with scheduling in public sectors such as hospitals and higher education where project deadlines are always inflexible (McGraw-Hill Construction, 2011).

Since on-site construction work is both labour intensive and expensive, shortening the duration can always bring significant cost savings. During the early 1980s, based on experience on construction projects involving modularization, researchers Glaser et al. (1979), Kliewer (1983), and Marcin (1982) found that there is about 10% savings in the capital cost of a project if it uses modular construction and the main source of savings is during the construction phase. Construction work often has limited profit margins, so this small savings in cost will make a strong impact on the involved stakeholders. Thirty years later, McGraw-Hill Construction (2013) surveyed 809 firms, and the result showed that 42% of the respondents get a reduction of 6% or more in their budget by using modular construction. As their report summarizes, the sources of cost reduction can also be from the following advantages: 1) prefabricated materials cost less; 2) reliance on expensive on-site labour is reduced; 3) overtime pay and other unexpected labour costs can be avoided; 4) use of on-site resources such as water can be reduced; 5) basic site support facilities can be reduced in size. Even though the expensive transportation costs and higher design and engineering costs pose a challenge to the companies involved, the avoidance

of unexpected expenses during the construction process compensates for the slightly higher cost, especially for public sectors when they have inflexible budgets.

Another critical benefit of modular construction is sustainability, which is an important subject in the 21<sup>st</sup> century. The Modular Building Institute (MBI) published a report to explain how modular buildings contribute to the US Green Building Council's Leadership in Energy and Environmental Design (LEED™). It concludes that the reasons that modular construction is more beneficial to sustainability are: 1) Less materials waste, 2) Less exposure of materials to inclement weather during construction process, 3) Less site disturbance, 4) Safer construction, 5) Flexibility, 6) Adaptability, and 7) Shortened building times (MBI, 2009). To be specific, Lawson et al. (2013) proposed that modular construction provides these opportunities to improve the sustainability of projects: 1) The construction waste of modular construction is reduced to less than 5%, while the construction waste rate of traditional construction is 10% to 15%; 2) The number of visits to the site is dramatically reduced by up to 70%, which means it saves gasoline and decreases air pollution; 3) Because the main equipment used by modular construction is a crane, the noise and disruption can be reduced by 30% to 50% compared to traditional construction; 4) Modular construction usually uses lightweight materials, so the embodied energy of the construction materials is also reduced; 5) The frequency of the accidents and safety issues decreases by over 80% relative to site-built construction. Furthermore, off-site construction produces less negative effects and damage on surrounding environments (Wortman, 2007). In addition, Nahmens and Ikuma (2012) suggested that the capabilities of modular construction such as incorporating environmentally friendly materials in a factory setting, upgrading inventory control and waste management practices, and reducing damage to raw materials will further improve the building's sustainability.

### **2.3.3 The application of modular construction**

Modular construction is not new for the building industry. In the U.S., modern modularization started in the early 1900s when Aladdin and Sears Roebuck Company sold prefabricated houses to customers as mail-order homes. Japan, as one of the earliest users of modular construction, still applies modular construction methods, especially when earthquakes occur and high quality residential buildings are needed after natural disasters. Because of high labor and material costs in Australia, many companies switched to modular construction and imported modular bathrooms and kitchens that were manufactured in China for volume builder home designs (Ham and Luther, 2014).

Since modular construction can enhance efficiency and avoid the inherent risks of on-site construction, such as weather delays and conflicting crews, the public sector prefers to adopt modularization. A report reveals that 49% of healthcare buildings, which have similar interior layouts of rooms are using modular construction or prefab construction, and it is based on the particular benefit of shortened schedules through modularization. Following that is dormitory and higher education with 42% that adopt modular construction to obtain faster construction rates and steady quality (McGraw Construction, 2011). The consistent designs of some commercial buildings are well-suited to modular construction; for example, big chains such as McDonald's, Taco Bell, Starbucks, and KFC are trying to achieve relatively fixed schedules and unified built units.

Modular construction not only brings standardization to the building industry, but also variability. This is why adopters are using modular building processes on a wide variety of commercial and residential buildings. Lawson et al. (2013) raised two typical arrangements of modules to prove that modular construction is not a barrier to creativity. Modular rooms, pairs of rooms, corridor

modules, and balcony systems can generate different types of layouts based on the building's function. Lawson et al. (2013) proposed two typical layouts that consider the spatial relationship of modules around a stabilizing concrete core. Figure 2.2 is a layout of three rooms clustered around a core, and Figure 2.3 is the typical corridor arrangement of six types of modular units. These two kinds of layout can be used in high-rise office buildings, hotels, dormitories, etc.

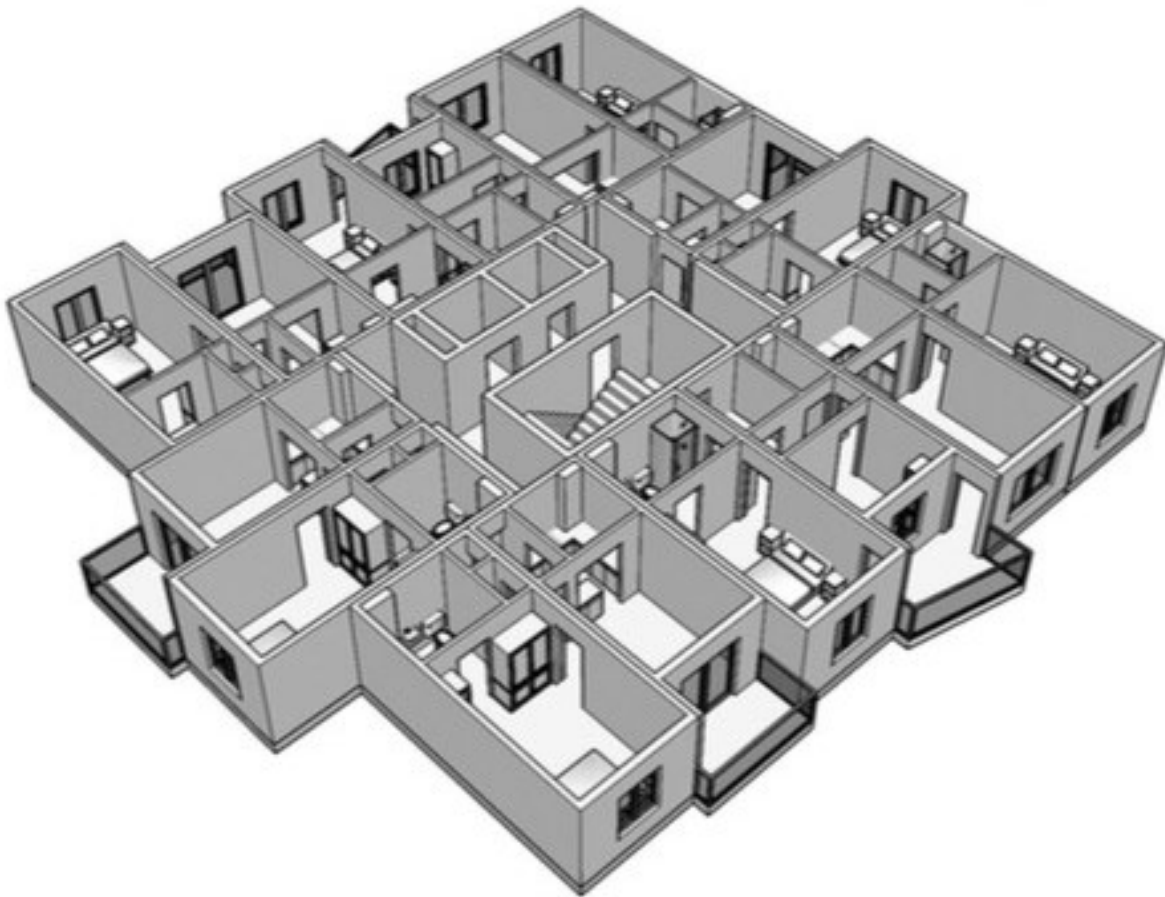


Figure 2.2 Typical layout of rooms clustered around a core (Lawson et al., 2013)

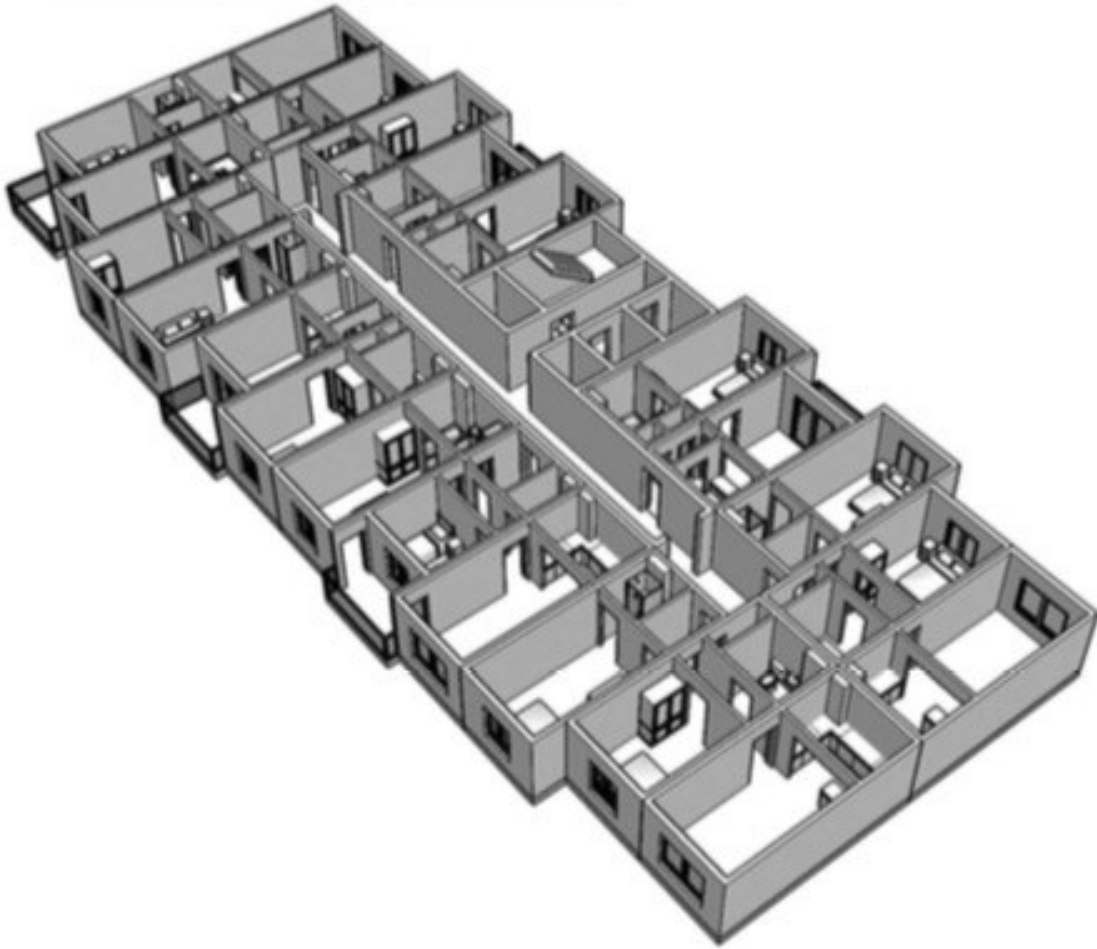


Figure 2.3 Typical corridor arrangement of modules (Lawson et al., 2013)

#### **2.3.4 Application of BIM in modular construction**

As discussed above, modular construction provides significant advantages, including the reduction of the overall schedule, the improvement of cost control, less environmental impact on the surroundings, and enhancement of on-site safety performance. This is why modular construction became a growing trend in the AEC Industry (Giles and Lara, 2006). Despite this, the inherent complexity of modular construction means that it still faces challenges related to removing the traditional market social stigmas in the AEC industry (Jellen and Memari, 2013). According to Lu (2008) and McGraw-Hill (2011) the reasons that inhibit application can be 1) the lack of understanding of how to coordinate system interaction, 2) insufficient knowledge of

how to manage the complicated site and related logistics, 3) the need for high coordination among each of the disciplines at all stages, 4) the requirement of precise design for the production phase, and 5) lack of proper tools. Additionally, in comparison with site-built construction, designers need to consider the production plans, transportation plans from factory to site, and installation process in modular construction (Moghadam et al., 2012).

Fortunately, these challenges can be overcome gradually by integrating BIM. McGraw-Hill Construction and the National Institute of Standards and Technology (NIST) consider that the rise of BIM technology to be the major factor fueling the interest in modular construction and prefabrication (McGraw-Hill, 2011). Lu and Korman (2011) found that BIM can create a digital and intelligent model that provides a virtual construction solution for design (3D), schedule (4D), cost (5D), and life-cycle analysis (6D). The ability to integrate the architectural and structural design, modularity concepts, and framing best practices into one model make BIM the right technology for modular construction due to its multidisciplinary nature (Alwis et al., 2012). Nawari (2012) identified the potential advantages of BIM that can lead to enhancements through off-site construction, including: increases in speed, improvements in safety, sustainability, constructability, and optimization of the module-manufacturing process. Ramaji and Memari (2015) suggested additional incentives of BIM in modular construction; it can assist in complicated structures, the high cost of rework, lower tolerances and repetitive work. Furthermore, Lu and Korman (2010) displayed a case study in which a firm who used BIM for modular construction saved \$220,000 overall for a \$44 million dollar project over the same company who did not use BIM.

Evidence shows more potential gain if both modular construction and BIM are integrated in different aspects. Korman and Lu (2011) argued that before the adoption of BIM, the

coordination of MEP system limited the widespread use of modularization and raised major problem for designers and industrial factories in complex projects. BIM can significantly help generate 3D and 4D models for designers, manufacturers and contractors to improve interaction in a more visual way and enhance the design in MEP systems, which was always related to congested space, interference, and complications (Barham et al., 2011; Korman and Simonian, 2008; Peterson et al., 2011).

Also, the structural behaviour of modular systems is different from that of traditional stick-built structures. A well-structured BIM model is required to support the manufacturing process for design and drafting, therefore Alwisy et al. (2012) developed a computer tool called MCMPro that incorporates BIM and is based on CAD parametric modelling and manufacturing requirements in the 3D model to develop sets of shop and fabrication drawings. Since the modules are finished in the plant, while designers and contractors cannot inspect the production process in person, design and structural deficiencies can be the biggest drawback of modular construction. Linga (2015) argued that this problem can be properly rectified by BIM to real-time-monitor the offsite construction by using a camera and providing instructions and measurement. According to their surveys, Ikerd (2008) and Aldea et al. (2012) stated that companies who use collaborative information technology such as BIM will gain a competitive advantage by utilizing new processes for the structural sector of the AEC industry.

The multidisciplinary nature of modular construction implies that it holds a huge amount of information related to physical and nonphysical aspects. Information transfer is the key to success in modular construction. The “I” in BIM stands for information, which contains data about geometry, location, material suppliers, cost, operation and maintenance schedule and introduction, flow rates, and even clearance requirements for an air-handling unit (CRC

Construction Innovation, 2007; Solnosky et al., 2014). Salazar et al. (2006) believed that, regarding communication and coordination among AEC teams, BIM has been proven a technology that advances the information transfer process. To support the utilization of BIM in modular construction, Ramaji and Memari (2015) created a modified version of the National BIM Standard (NBIMS) method by incorporating production information management for information exchange standardization in multi-story modular building projects, which addressed the interoperability issue in the building industry.

BIM can also properly resolve the transportation issue raised by large component delivery. Ezcan et al. (2013) stated that the new generation of BIM could include the states and attributes of the elements stored in the model and could facilitate the reassembly of smaller components into larger components.

## **2.4 Cost Estimation**

### **2.4.1 Definition of cost estimation**

A cost estimate is the main type of target data to obtain at the outset of any project, enabling the project manager to define the project budget (El-Reedy and Mohamed, 2012). The United States Government Accountability Office (2009) regards cost estimates as the summation of the individual cost elements of the future costs of a program using established methods and valid data. Cost estimating is the technical process of predicting costs of construction, as defined by CIOB (1997). Kwakye (1994) described cost estimating as the technical process or function undertaken to assess and predict the total cost of executing items of work in a given time using all available project information and resources. Carr (1989) considered that cost estimates can be divided into two groups: direct and indirect costs or variable and fixed costs. Since cost

estimating is usually associated with tendering, Green (1989) compared estimating and tendering using systems concepts, estimating being classified as a closed system and tendering as an open system, and he said that cost estimating takes place in a relatively sheltered environment while tendering takes place in a changing and dynamic environment.

Akintola (2000) considered that cost estimating is crucial to construction contract tendering, providing a basis for establishing the likely cost of resource elements of the tender price for construction work. Jrade and Alkass (2007) agree with Akintola that cost estimating is one of the most important and critical phases of a construction project and that a new cost estimate must be developed depending on the availability of design drawings and specifications during these phases: the conception phase, the development phase, the construction phase, and the disposal phase. Smith (1995) emphasized that cost estimating is very important as it enables firms to determine their direct costs for projects and where the “bottom line” is for carrying out some responsible measures. This is why accurate and consistent cost estimation is the key to any organization responsible for bidding, budget submission, contract negotiations and financial decision making (Rast and Peterson, 1999). Akintoye and Skitmore (1991) took the contracting business as an example: overestimated costs result in a high tender price being submitted, which could be unacceptable to clients; on the other hand, an underestimated cost could lead to a situation where a contractor incurs losses on the contracts awarded by clients and the profit in the construction industry generally is already lower than in other industries.

#### **2.4.2 The method of cost estimation**

The process of cost estimation is always complicated and involves 24 main factors including: complexity of the project, scale and scope of construction, market conditions, method of construction, site constraints, client’s financial position, buildability, location of the project, and

so on (Akintoye, 2000). Uman (1991) considered it to be difficult to develop a standard process from which to develop a cost estimate system for construction as a result of such factors as extreme diversity in building systems, methods, projects, suppliers, contractors, and workforce. Bennett and Barnes (1979) indicated that an ideal cost model cannot be developed as the actual costs of construction will depend on many factors, including contractors' individual selection of construction resources and methods, and the timing and sequence of operations. However, cost estimation methods have been developed for various types and purposes of construction projects. Ntuen and Maillik (1987) have summarized techniques or modelling tools for cost estimating, which are classified into four groups: experienced-based (algorithms, heuristics, expert system programming); simulation (heuristics, expert models, decision rules); parametric (regression, Bayesian, statistical models, decision rules); and discrete state (linear programming, classical optimization, network, PERT, CPM). Vergara and Boyer (1974) advocated a probabilistic approach that emphasized the opinion that the reliability of cost estimate depends on the level of detail. Daschbach and Apgar (1988) and Shash and Al-Khaldi (1992) have documented the use of parametric cost estimating techniques, for example, simple arithmetic formulae and statistical formulae. Klumpar (1990) showed how to estimate costs based on the method of capital cost estimation, which uses correlation techniques, a combination of materials, labour, and plant cost factors to generate an installation cost for facilities. To achieve improvement in cost estimation, Bryan (1991) produced a method using the assembly pricing technique (also called work module pricing). Staub and Fischer (2000) gave four primary methods used in construction costs: project comparison estimating, area and volume estimating, assembly and system estimating, and unit price and schedule estimating.

However, most of these approaches are manual and use paper-based quantity take-off (QTO). Errors in quantity and cost estimates may arise in the cost estimate process, such as forms of arithmetic errors (addition, subtraction, or multiplication), transposition errors (errors in copying quantities), omission (overlooking parts of the design), poor references (scaling from papers instead of using the dimensions indicated), and unrealistic waste factors (Halpin, 2006). In addition to this, sometimes changes in architect's drawings may not be updated appropriately, accurately, or in a timely manner to enable the quantity surveyor (QS) to change aspects of the cost affected by these changes of drawings (Aibinu and Venkatesh, 2013). What is more, when there is poor communication of design changes owing to a lack of team integration, it is hard to make design decisions in an efficient and effective way because by the time changes, critical design decisions may have been made based on an inaccurate estimate.

Prompted by these problems, computer-based approaches emerged and obtained an extensive consensus. Jrade and Alkass (2007) developed a computer-integrated system for doing parametric cost estimates of projects to improve the efficiency of decision making. Njeem (2012) created deterministic and stochastic methods based on computer-aided design to obtain cost estimates at the feasibility stage. BIM can be regarded as an IT-based information process, while cost estimation is human information process (Xu et al., 2013). As a technological advancement, BIM is an innovative solution for cost estimation. McCuen (2009) believes that BIM can provide a platform for integrated information exchange through a single model that reduces design errors and omissions with a significant reduction on preparation time in the design phase, and also minimizes the time for modification of cost estimates. From a cost estimation view, BIM can be used to perform automatic extraction of quantity and BIM-based estimating could improve the efficiency of the QS if they could make good use of this new digital workflow (Aibinu and

Venkatesh, 2013). Goucher and Thurairajah (2012) also identified the benefits of using BIM for cost estimates, including the ability to work collaboratively, the speed, improvement of visualization, advanced cost advisory services, and automated quantity take-off.

## **2.5 Schedule Planning**

### **2.5.1 Definition of schedule planning**

Predicting, planning, and controlling the schedule for construction projects are critical requirements for effective project implementation in the construction industry. Hendrickson et al. (1987) defined construction planning as a “fundamental and challenging activity in the management and execution of construction projects”. Hendrickson et al. (1987) emphasized that construction schedule planning involves the choice of construction technologies, the definition of work tasks, the estimation of the required resources and duration for individual tasks, and the identification of any interactions or constraints among the different tasks. Cherneff and Sriram (1996) deemed the term planning in construction as a tool that can be used in the artificial intelligence field, relating to a series of problems in which the goal is to assemble a sequence of operators to obtain a goal state from the initial problem state. Fischer and Kam (2001) argued that there are differences between a “plan” and a “schedule” in construction management. While “plan” means activities and their logic-inherent relationships, “schedule” shows temporal information.

In the statement of Chevallier and Russell (1988), effective planning is one of the most important elements of a successful construction project. Hendrickson et al. (1987) believed that a good construction plan is the basis for determining the project budget and the schedule of the project. On the contrary, poor schedules can lead to cost increases or delays. Assaf and Al-Hejji (2005)

also emphasized that a delay means loss of revenue through lack of production facilities and rentable space or a dependence on present facilities for the owner and higher overhead costs because of a longer work period, higher material costs through inflation and high labor costs for contractors. This is why Zhang and Gao (2013) found that schedule planning and control has been one of the most important issues in the fast-paced construction industry.

### **2.5.2 The method of schedule planning**

The schedule of the construction process is subject to many variables and unpredictable factors, such as the performance of parties, resource availability, environmental conditions, involvement of other parties and contractual relations, so planning the schedule is one of the main tasks of the contractor. Julian et al. (2007) believed that developing a construction schedule was very difficult because constructors need to disassemble the structure into workable packages, identify the relationships among these packages, and configure an order of implementing these packages step by step.

In the past, construction planning relied upon the manual formulation of plans and was usually performed in an intuitive and unstructured fashion with considerable reliance on engineering judgment. Few computer-based aids for activity scheduling existed, other than project templates or past project networks that can be adapted to the particulars of a new project (Hendrickson, 1987). Lately, the development of computers and programming languages has helped to improve the situation. Heesom and Mahdjoubi (2004) proved that computer-based decision support tools provide the construction planners with the ability to plan construction tasks efficiently using techniques such as the Critical Path Method (CPM) and Critical Chains. With the emergence of Computer-aided Design (CAD), the geometric information of elements can be extracted from CAD drawings, and generate activities for each product. Cherneff et al. (1991) created an

automated construction-planning program by combining a CAD system with knowledge-based programming and database techniques. Vaughn (1996) suggested that 4D CAD could illustrate the construction sequence with 3D computer graphics to help project participants manage their projects through an advanced understanding of the construction schedule. Chen et al. (2012) proposed an intelligent scheduling system by applying simulation techniques to find a near-optimum schedule plan according to projects' objectives and constraints. The Gantt chart, as one of the mainstream tools in schedule planning, is still being used by project managers. Autodesk (2007) reported that Gantt charts have long been a staple in project planning, but they leave something to be desired when it comes to visualizing a project schedule.

Undoubtedly, BIM also impacts construction planning deeply. The 4D model allows planners to link components in the 3D BIM model to the corresponding tasks and time in the BIM platform. This represents a visual representation of a project timeline, which again raises the probability of resolving conflicts before the construction of the project (Zhang and Gao, 2013). Gelisen and Griffis (2013) proposed a methodology called Automated Productivity-based Schedule Animation (APBSA), a dynamic scheduling approach to report the construction activity duration variances and animate the progress of a project in a BIM environment to enhance productivity. Faghihi et al. (2014) created a novel approach of using geometric information and the list of all components from the BIM Model of the project to develop construction sequencing for installation, and to provide visually interactive communication between the planning process and 3D models.

## **2.6 Sustainability**

### **2.6.1 The sustainability in building environments**

The construction industry is one of the world's largest contributors to waste and pollution, drawing worldwide attention. There are reports showing that 17% of the world's fresh water withdrawals, 40% of the energy, 72% of the electricity and 50% of fossil fuel is used by construction activities, such as developing, maintaining and operating, while these activities produced 30% to 50% of the total waste and 39% of CO<sub>2</sub> emissions (Ahn et al., 2009; Roodman and Lenssen, 1995; USDOE, 2011). Sustainability has become a serious topic in the construction industry due to the negative environmental impact it has. The United Nations (UN) World Commission on Environment and Development's 1987 Brundtland Report stated that "sustainability is to meet people's basic needs and improve their quality of life while simultaneously ensuring the natural systems, resources, and diversity upon which they depend on are maintained and enhanced for both today and future generations". The purpose of sustainability in the building industry is to protect and preserve land and sites, improve indoor environmental quality and decrease the environmental impacts of materials, reduce construction waste, save water and optimize energy performance (Ahn et al., 2013). Specifically, Kibert (1994) introduced seven principles and features of sustainable construction in his research: 1) conserving; 2) reusing; 3) renewing/recycling; 4) protecting nature; 5) using nontoxic materials; 6) economic benefits; and 7) providing quality products. Green building is the term always associated with sustainable construction, and sometimes "green building" and "sustainable construction" are used interchangeably. The American Society of Testing and Materials (ASTM) Standard E<sub>2114-06a</sub> defined green buildings as the kind of buildings that provide not only the specified building performance, but also the function of minimizing disturbance to and

improving the functioning of local, regional and global ecosystems both during and after its construction and maintenance.

### 2.6.2 The impacts of sustainability

Numerous pieces of evidence prove that sustainable development can have a positive influence on the building industry. Sustainability has three critical dimensions: environmental, social and economic, which are regard as the “three pillars of sustainability.” Ahn et al. (2014) presented Table 2 to show the benefits in these three aspects.

Table 2.2 Environmental, social and economic benefits from sustainable plastics (Ahn et al., 2014)

<b>Environmental Benefits</b>	<b>Social Benefits</b>	<b>Economic Benefits</b>
Protecting air, water, land ecosystems	Improving the quality of life for individuals and society as a whole	Improving economic growth
Conserving natural resources (fossil fuels)	Alleviating poverty	Reducing energy consumption and costs
Preserving animal species and genetic diversity	Satisfying human needs	Raising real income
Protecting the biosphere	Incorporating cultural data into development	Improving productivity
Using renewable natural resources	Optimizing social benefits	Lowering infrastructure costs
Minimizing waste production or disposal	Improving health, comfort, and well-being	Decreasing environmental damage costs
Minimizing CO <sub>2</sub> emissions and other pollutants	Having concern for inter-generational equity	Reducing water consumption and costs
Maintaining essential ecological processes and life support systems	Minimizing cultural disruption	Decreasing health costs
Pursuing active recycling	Providing education services	Decreasing absenteeism in organizations
Maintaining the integrity of the environment	Promoting harmony among human beings and between humanity and nature	Improving the Return on Investment (ROI)
Preventing global warming	Understanding the importance of social and cultural capital	
	Understanding multidisciplinary communities	

Bosch and Pearce (2003) summarized the benefits of sustainable practices based on a literature review of multiple research papers and found that sustainable buildings can save energy, water, and other resources over the whole life of the facility, and can decrease liability and impact on the environment; additionally, it can improve academic performance and student behavior in schools, increase employee satisfaction, productivity, and health, and employee retention, and reduce absenteeism. Additionally, according to the US Green Building Council (USGBC, 2003), sustainable construction can bring better risk management. For instance, reusing building elements can help to reduce liability with relation to construction waste disposal and avoid future lawsuits concerned with non-compliance with related legislation. With people's improved awareness of sustainability, faster sales and leasing of green properties can mitigate the financial risk for developers.

### **2.6.3 The assessment of sustainability**

Various green building assessment systems have been developed and widely adopted to evaluate the sustainable performance of buildings. Shen et al. (2007) developed a checklist for sustainability performance to help with understanding of the major factors determining projects' sustainability performance. Based on the literature review and interview discussions with different stakeholders, they found that the factors can be classified into three categories: economic sustainability factors (ESF), social sustainability factors (SSF), and environmental sustainability factors (ESF).

There are mainly two kinds of tools, classified by methodology: One group is based on the criteria system that assigns points to a series of parameters, such as BREEAM (Building Research Establishment Environmental Assessment Method from the U.K.), GBTool (Green Building Tool from Canada), LEED (Leadership in Energy and Environment Design from the

United States), and EcoProfile (from Norway). Another group, based on life cycle assessment (LCA), includes such tools as BEES (Buildings for Environmental and Economic Sustainability from the U.S.), BEAT (Building Environmental Assessment Tool from Denmark), and EcoQuantum from the Netherlands (Ali and Al Nsairat, 2009). Todd et al. (2001) made a comparison among several assessment systems and found that Green Building Challenge (GBC) has the most potential benefits and is an international assessment adopted by various countries. However, many other research papers have argued that LEED guidelines have played a significant role in supporting sustainability in the construction industry. LEED can provide a comprehensive building evaluation, which includes measures such as construction activity, pollution prevention, and conservation of existing natural areas (USGBC, 2009b). Overall, these various assessment and standards systems support and ensure the sustainability in building industry.

#### **2.6.4 Using BIM and modular construction to support sustainability**

There are many measures that can help to meet the requirements of sustainability. As discussed in section 2.2.2, one of the advantages of modular construction is that it can ensure sustainable construction. According to McGraw-Hill (2011), more than 83% of contractors who responded believe that modularization reduces on-site waste, and 66% of contractors believe it reduces the amount of material used on a project.

Also, BIM, as a data-rich, object-oriented, intelligent, and parameterized tool, can aid in performing complex sustainable performance analysis to ensure sustainability. In order to assess building performance in early stages, decision makers require access to comprehensive information about building forms, materials, components and context at the early stage. Because BIM holds multi-disciplinary information, it offers an opportunity for sustainability analysis to

be performed during the design stage (Autodesk, Inc., 2008; Azhar et al., 2009). Krygiel and Nies (2008) summarized the following aspects in which BIM can assist with sustainability analysis: 1) Building orientation (to select the best orientation to reduce energy required); 2) Building massing (to analyze the building form and optimize the building envelope); 3) Daylighting analysis; 4) Water harvesting; 5) Energy modeling (to reduce energy needs and to analyze renewable energy options); 6) Sustainable materials (to reduce the amount of material needs and to use recycled material).

## **2.7 Summary**

This chapter has reviewed the literature regarding to Building Information modeling, modular construction, cost estimate, schedule planning and sustainability. These referenes and knowledge are the foundation of integrating BIM, cost estimate and scheduling in modular construction at the conceptual design stage of building projects.

From past studies, it has introduced the definition of BIM from different perspectives, and it has presented that because of the benefits of BIM, this technology has been widely used in AEC industry. This chapter has also reviewed the literature on modular construction, which can enhance the efficiency and sustainability in building industry. It has presented the concept and applications of modular construction and summarized its economical, time-saving and environmental advantages. From this review, this chapter has noted that the adoption of BIM in modular construction can help to overcome the challenge of modular construction.

Furthermore, in this chapter, two important processes in project implementation, cost estimate and schedule planning were reviewed and the potential integration with BIM was considered while reviewing the past researches. This chapter has described these two processes' concepts,

significance and the traditional methods used in these two areas. It was found that the conventional methods were mainly manual, time-consuming, and based on paper work, and sometimes these methods can lead to errors that negatively influence the decision making. While other studies showed that there is a big benefit in using the BIM concept for cost and duration estimates due to its ability to improve their accuracy and efficiency.

At last, this chapter has also covered the literature related to sustainability and has presented its definition and benefits in economic, social and environmental dimensions. It also listed some sustainability assessment tools that ensure the implementation of sustainable practices in building projects. According to the recent researches, BIM and modular construction are regarded as crucial measures to promote sustainability in the building industry.

Overall, construction projects are becoming progressively larger and much more complex, the traditional cost and time estimate methods can not satisfy the accuracy and efficiency requirements. Additionally, with the pursuit of sustainable development, modular construction becomes more prevalent and beneficial. This research aims to integrate BIM with cost estimate and schedule planning to generate an automated estimation method for modular construction at the conceptual design phase.

## **Chapter 3**

### **Methodology**

#### **3.1 Introduction**

This chapter describes the development process of an integrated model that uses BIM to improve efficiency of the process of estimating project's cost and duration for both conventional and modular construction, and introduces the referring data, information, methods, formulas and tools used in this model.

There are four main modules in the proposed model, including 1) a cost estimate module; 2) a scheduling module; 3) a sustainability module; and 4) a 5D simulation module. The cost estimate module involves designing how to extract the Quantity Takeoff (QTO) from the 3D architecture model, the unit price of materials, labor and equipment cost needed for the construction of a project. The schedule module explains the assembly process and duration estimate for the construction of a proposed project. The sustainability module consists of using the materials and resources section of LEED to evaluate the sustainability of modular projects. The 5D BIM module refers to integrating the 3D model with cost estimation and scheduling all within a BIM platform to simulate the construction assembly process and display the cost and duration of the corresponding construction stage. These modules make up an integrated BIM model, which allows owners and designers to obtain the cost, duration and sustainability of projects in an efficient way at the conceptual design stage.

Before developing these modules, this chapter considers the collection of all necessary data and information and their storage in a database, which can be linked to BIM tools. This external

database consists of series of 3D families that includes information about the cost and the LEED points that may be earned if used in the design.

Furthermore, the integration of the modules will be introduced in this chapter and this is one of the significant expected contributions of this research. This integration relates to the development of new plug-ins in BIM tools to fulfill automated data transfer between different software.

Figure 3.1 shows the general flowchart of the whole model and its interrelated modules, showing the components and relationships among them, as well as the data transfer route.

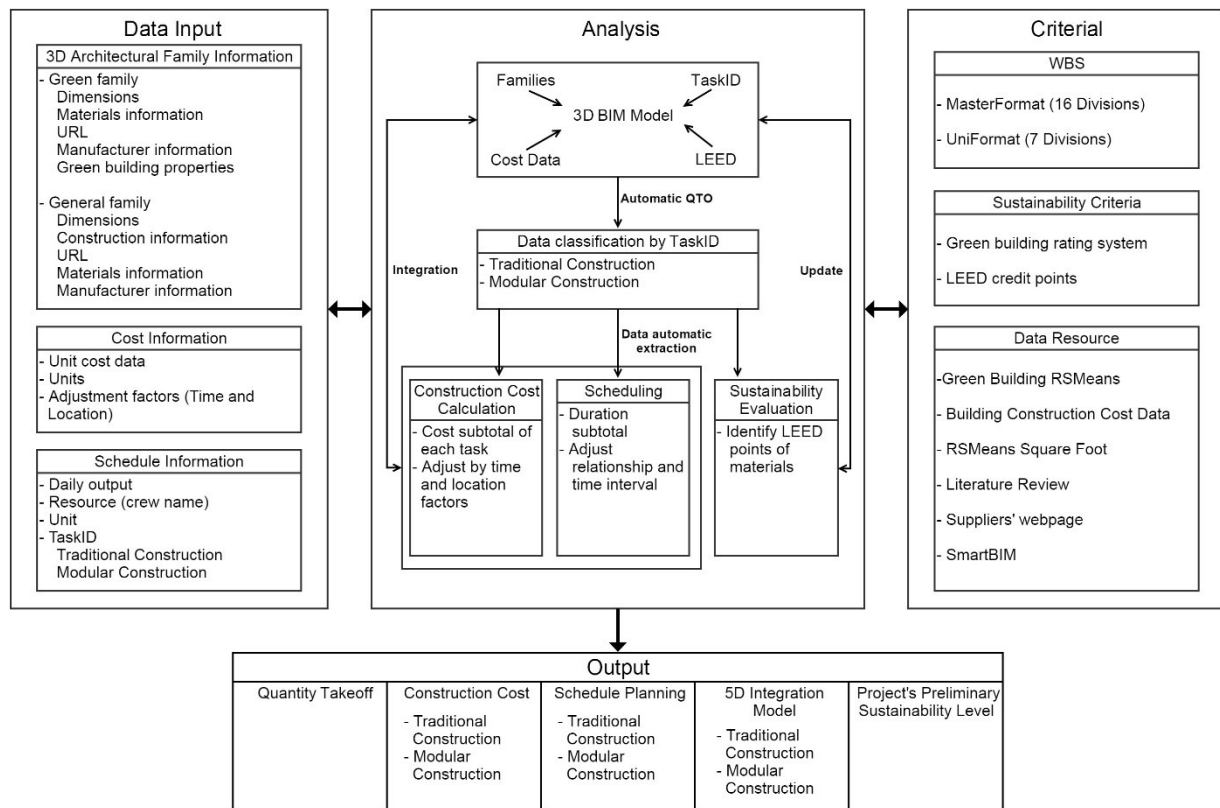


Figure 3.1 General flowchart of research methodology

### **3.2 Proposed Model's Components and Relationships**

As discussed in the literature review, cost estimation and schedule planning are two critical components at the early stages of a project, which can provide decision makers with valued information, especially when the project offers various alternatives. Improving the estimation technology with smart tools is one of the main objectives of this model. Also, the awareness among owners, engineers, constructors, and facilities managers about the significance of sustainability in the construction industry increased considerably over the past few decades. Meanwhile, modular construction has been proven to bring advantages such as shortening time, saving cost and promoting sustainability. This research proposes a methodology for integrating BIM tools with cost and duration estimation for stakeholders who make decisions in traditional construction or modular construction at the conceptual design stage.

In order to achieve this goal, an integrated model that combines the following modules is created: a database module; a 3D module; a cost estimation module; a scheduling module; a sustainability evaluation module and a 5D simulation module. Figure 3.2 shows the main components of the whole model and the relationships among its different modules.

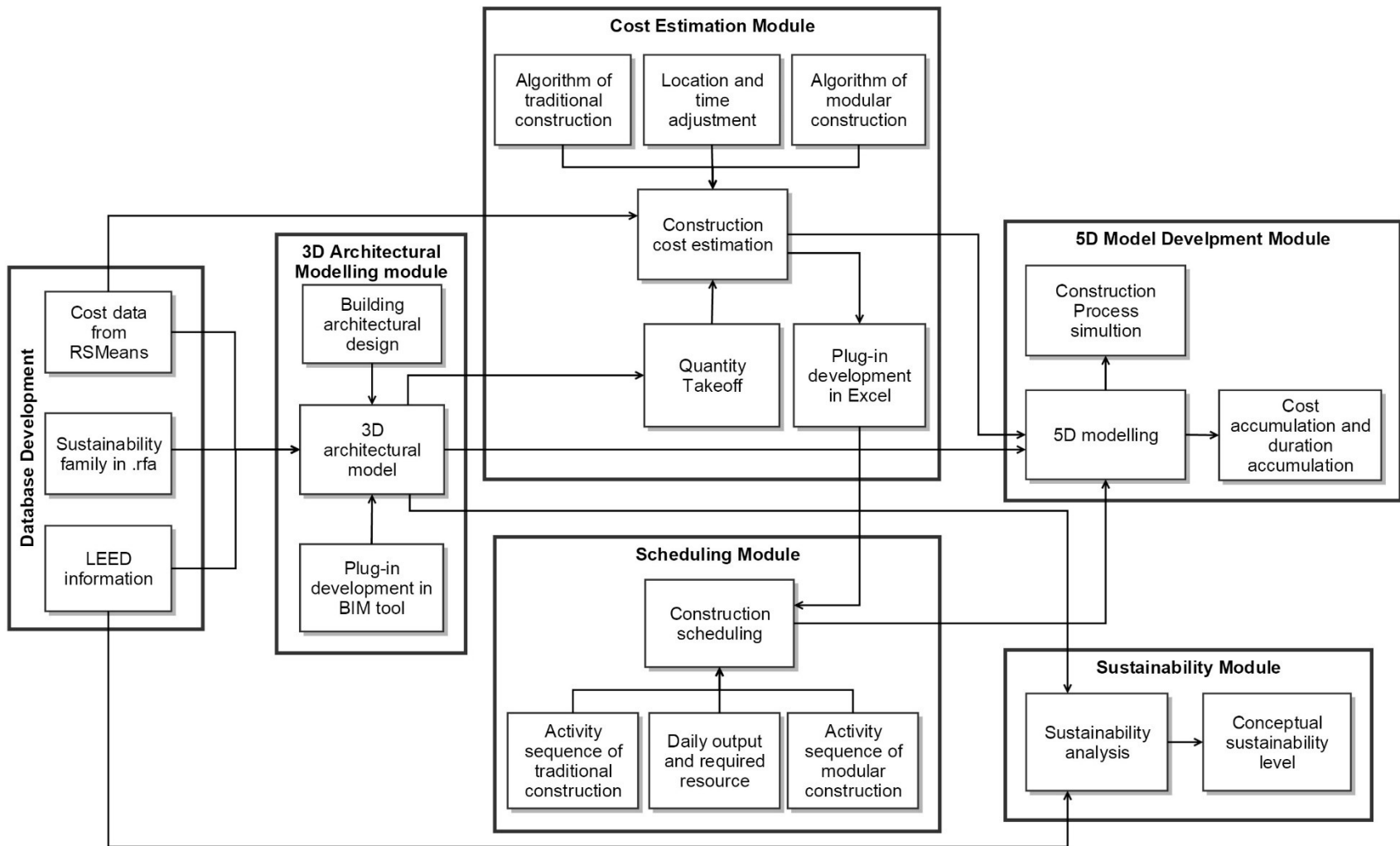


Figure 3.2 Model's main Modules and their Relationship

### 3.3 Data resources and collection

Database development is the foundation of this model, because it offers the data and basic information to the building development module, cost estimate module, schedule planning module, and sustainability module. The content of this database is determined by the objectives and requirements of the proposed model, as follows:

- I. Provide information about the different element types (wall, floor slabs, windows, doors, etc.) for the development of various kinds of buildings;
- II. The elements used in the model require corresponding properties, such as dimension, unit, material, as well as the 3D visual views for building development and construction simulation;
- III. Create an identification ID number so that each element can be identified and referred to in the different modules;
- IV. The format of the elements can be imported and used easily by BIM tools;
- V. Collect the unit cost of each type of element;
- VI. Easy link between cost information and the corresponding element;
- VII. Collect information about the activities duration for both traditional construction and modular construction;
- VIII. Collect the LEED points of green materials that are used in the sustainability module.

Based on these requirements, the database can be divided into four parts: family collection, cost data collection, duration data collection and the materials' LEED credit information:

- 1) Family collection

The architecturally and structurally designed families are components used in any proposed building. These families can be windows, doors, floor slabs, columns, beams, and roof slabs, and each one stores specific properties. Autodesk Revit (BIM tool) families will be used in this model because these families hold lists of properties, which are the basic information for building models, such as dimensions, materials, manufacturer information, and structural specifications. Customized attributes for cost estimation and LEED information can also be inserted (as will be explained below). These families are saved in RFA (Revit Architecture file) or RVT (Revit project file) format, and can be stored in an external database and linked with a BIM tool by a default path, so that when users open the BIM tool, these families with their properties will be loaded automatically. After the RVT families are assembled, each type of family is assigned a keynote based on the MasterFormat or UniFormat work breakdown structure (WBS) so that users can identify the family and refer to it in an efficient way when doing cost estimation and schedule planning.

The external database of families is collected from suppliers' web pages, the USGBC system, the SmartBIM Library website (<http://library.smartbim.com>), the Arcat website (<http://www.arcat.com>), and other published data. These families can be stored and classified according to either the CSI MasterFormat 2010 (16 divisions) and/or the UniFormat II (7 divisions). Each type of family in these two systems has a unique keynote, which is used to identify it when calculating the cost and duration of proposed projects. Appendix A provides an illustration about how these collected families are stored in the database.

## 2) Cost data collection

Since one of this research's objectives is to promote sustainability, the cost data used in this model are collected from RSMMeans Square Foot Costs 2010, RSMMeans Green Building

Construction Cost Data 2013 and RSMeans Building Construction Cost Data 2013, which are published by North America's leading publisher of construction cost information. The cost data consist of information related to construction cost and duration estimation for 85,000 previous building projects in the U.S. and Canada. There are two kinds of unit cost data. One is unit bare cost, sorted based on MasterFormat, which consist of material cost, labor cost, and equipment cost. Another kind of data is assembly unit cost, which includes material and installation costs. These two kinds of cost data are sorted based on MasterFormat's 16 main divisions and UniFormat's 7 divisions, respectively.

### 3) Duration data collection

There are two kinds of duration data for the model. One is for traditional construction and another is for modular construction. The traditional one is based on RSMeans Building Construction Cost Data 2013, which provides information about the crew daily output and labour hours for each completed element. For modular construction, the duration data is mainly based on the empirical data from McGraw-Hill Construction and case studies on different types of modular construction projects.

### 4) LEED information collection

Since this research is focused on the conceptual stage, when the project information is limited and the designs are not very detailed, sustainability performance is mainly represented by the materials used in projects. LEED information consists of the requirements and criteria of LEED v4 for Building and Construction published by USGBC. Also, detailed information about sustainable materials including potential LEED points are collected from suppliers' and manufacturers' web pages as well as the SmartBIM green database.

Figure 3.3 shows the process of collecting and storing the data in the database, and represents the relationships among the data. The cost data and LEED information are stored in the form of green families by making new customized types of attributes, which will be discussed in Section 3.4.

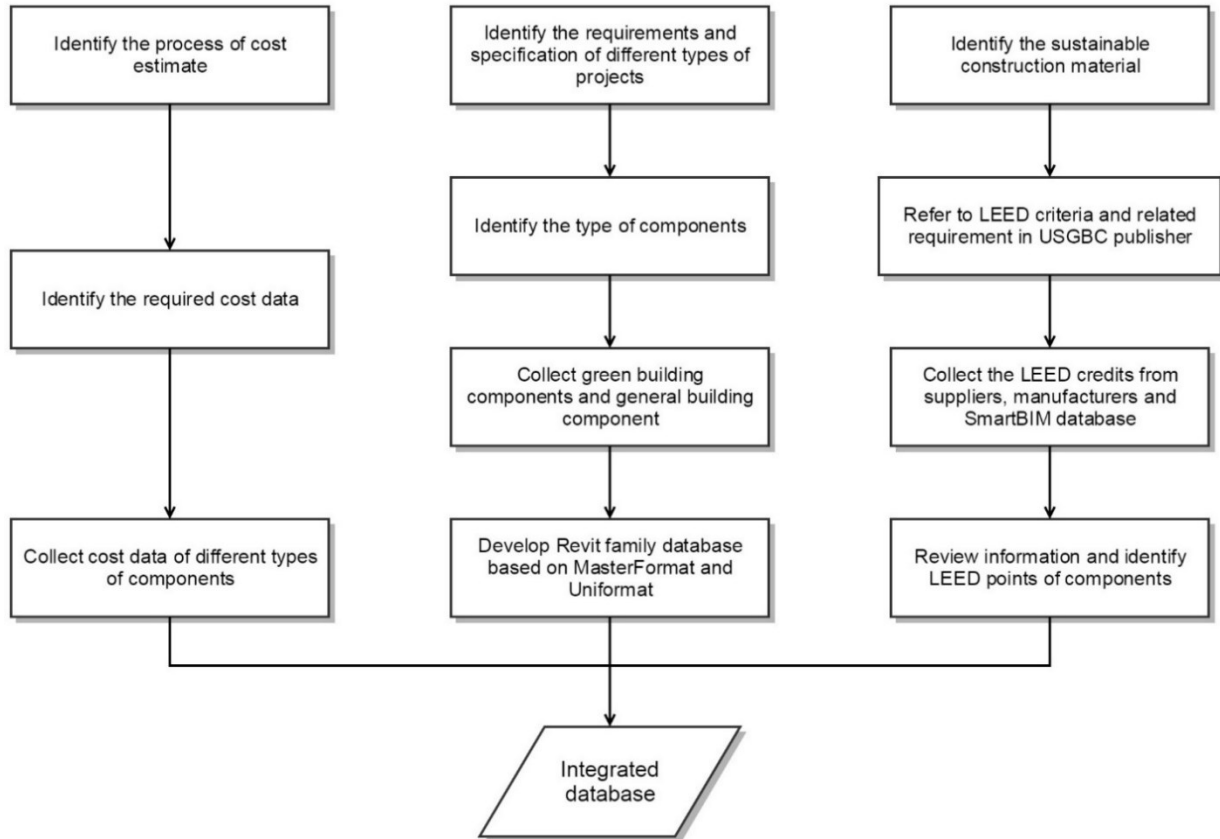


Figure 3.3 Data collection process

### 3.4 BIM-based automated estimation method

#### 3.4.1 Cost estimate module

This module aims to help users obtain the reliable construction cost of their projects quickly at the conceptual stage when the project information is limited. Depending on the conditions and

requirements of users, this module provides two methods for calculating the construction cost for both conventional and modular construction.

The required determinants of the cost calculation are unit cost and accurate quantity. As discussed in Section 3.3, the unit cost of components comes from RS Means. This module uses the assembly section cost data from RS Means Green Building Cost Data 2013, which is arranged according to the 7 divisions of the UniFormat II classification system. Assembly cost data can provide a fast and reasonably accurate way to determine the construction cost, so it is often used during the early stage of the design development to compare the costs of various alternatives on the total building cost (RS Means Green Building Cost Data, 2013). After collecting the cost data, they are inserted into the corresponding properties of the families stored in BIM tool, which means when users review and refer to each type of component, the cost data can be easily obtained from the properties' list.

Another critical factor for determining the accuracy of the total construction cost is quantity. The quantity of components represents the amount of work each component that is used in the building project will need. This amount is the basis for calculating the required materials, labour and equipment hours for construction projects. The process of measuring in detail the materials and labor needed to complete a construction project is called Quantity Takeoff. In the past, estimators usually did QTO based on paper based 2D drawings and technical specifications, but this process is time-consuming and leads to some unnecessary errors that negatively influence the total cost estimation. The emergence of BIM has solved this problem by creating accurate 3D architectural models by using BIM tools that provide the total quantity of each type of element used in these models and allowing users extract the precise quantity of components for construction cost estimation. In this module a plug-in is created and loaded into the BIM tool for

QTO, which fulfills the automatic extraction of quantities from the 3D model in an easy way if compared to the time-consuming and low-efficiency method of traditional QTO. This automatic data extraction includes not only the quantity of elements, but also the unit cost, material information, keynotes, TaskID (which will be discussed in the scheduling module section), family type, unit, and other attributes of each element in the 3D BIM model.

After obtaining the unit cost data and quantity of each type of element, different algorithms are used to calculate the construction cost, which will be discussed in detail in the following sections of this Chapter.

#### **3.4.1.1 Cost estimation for traditional construction**

For the traditional type of construction, this model will use the following equation to calculate the direct construction cost:

$$\text{Total Direct Cost}_{\text{Traditional}} = \sum(\text{unit cost of item} \times \text{quantity of the item}) \quad 3.1$$

in which unit cost is collected from RSMeans Building Construction Cost 2013, which includes material and installation costs, and the quantity is automatically extracted from the 3D architectural BIM model. The total construction cost in this model is direct cost without considering the overhead and profit.

#### **3.4.1.2 Cost estimation for modular construction**

For modular construction, according to literature reviews and the survey of McGraw-Hill Construction (2013), it is found that because of the reduction of expensive onsite labor cost and resources required, modular construction has a certain degree of savings of construction costs. This module introduces a coefficient from the survey of McGraw-Hill Construction to estimate

the construction cost of modular construction. The following equation represents the calculation of the construction cost of modular construction used in this model:

$$Total\ Direct\ Cost_{Modular} = \sum(\text{unit cost of item} \times \text{quantity of the item}) \times (1 - X\%) \quad 3.2$$

in which unit cost is also collected from RSMeans Building Construction Cost 2013, and X is the percentage of cost saving due to the modular construction compared with traditional construction. According to the results of the survey conducted by McGraw-Hill Construction (2011), 42% of the experienced respondents found that modular construction could reduce their budgets by 6% or more. Considering that construction work often has tight profit margins and even relatively small savings in cost can bring a considerable impact on each stakeholder, this model uses 6% as a value for this coefficient.

### 3.4.1.3 Construction cost adjustment

After calculating the construction cost, this model will adjust this cost for time and city location. For the location adjustment, this model uses RSMeans City Cost Indexes (CCI) which covers 731 U.S. and Canadian cities. Using the index of a specific city, this model can easily convert the total cost calculated based on the national averaged cost data to expected building costs in another city. The following equation illustrates the process of this adjustment:

$$C_A = \frac{I_A}{100} \times C_{NAC} \quad 3.3$$

Where,

$C_A$  = The construction cost after location adjustment of City A.

$I_A$  = Index for City A (a percentage ratio of a specific city's cost to the national average cost at a stated time period).

$C_{NAC}$  = Construction cost based on National Average Cost (obtained from Equations 3.1 or 3.2).

Meanwhile, this model considers the inflation rate and applies equation (3.4) to adjust the construction cost for time difference:

$$C = C_A(1 + i)^n \quad 3.4$$

Where

$C$  = The construction cost after inflation adjustment.

$C_A$  = The cost after location adjustment from equation 3.3.

$i$  = Inflation rate.

$n$  = Number of years.

The value of  $C$  is the final estimated cost for traditional construction or the cost for modular construction after time and location adjustment.

Figure 3.4 presents the conceptual data flow of the cost estimating module for both conventional construction and modular construction.

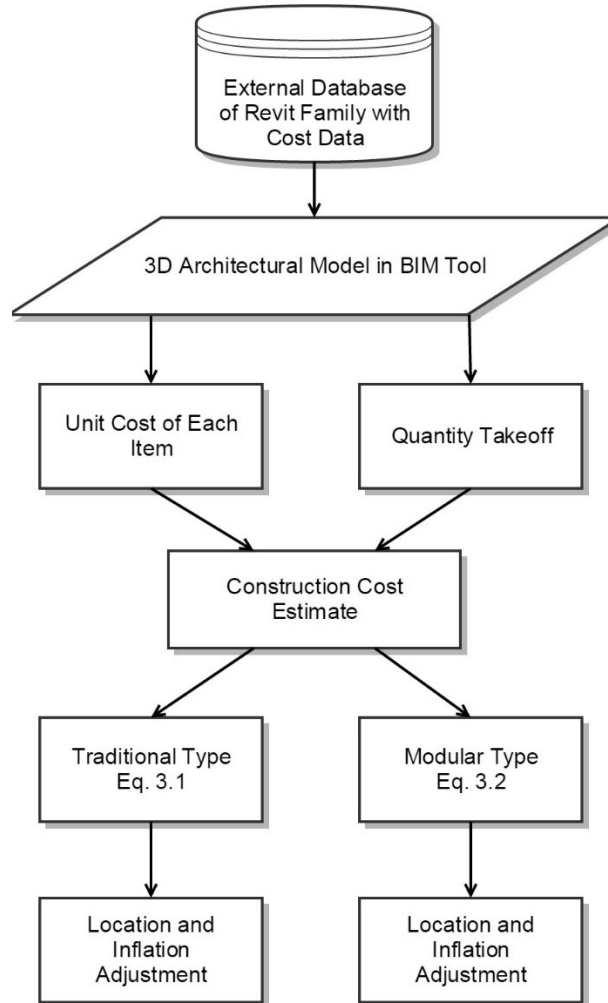


Figure 3.4 Cost estimation flowchart



### 3.4.2 Schedule planning module

In this model, the development of the construction scheduling module is based on the 3D architectural model and cost estimate module. Schedule planning involves these aspects of construction projects: activities break down, resources assignment and time arrangement. This module is suited for both conventional on-site construction and modular construction.

Firstly, because of various conditions and constraints of different construction projects, the various types of schedule planning are possible. This influences the different methods of breaking down the project into construction activities. Some construction processes are divided

layer by layer, some are divided by zones, and some are divided by modules. Because of these various activity break-downs, this model creates a new attribute named “TaskID” in the properties list of the families in the BIM tool to store information about each activity and its associated elements, in an attempt to help users to locate and identify the element no matter what breaking down method used in the schedule planning. The TaskID is an alpha-numeric number that is divided into two sets, one for conventional construction and another for modular construction. Table 3 illustrates the components and associated descriptions of the TaskID.

Table 3.1 The components and associated description of the TaskID

<b>Conventional Construction</b>		<b>Modular Construction</b>	
			
The first digit means which level the construction task is at.	The alphabet stands for which construction zone the construction task is in.	The digit stands for which level the construction unit is at.	The alphabet stands for the assembly sequence of the modular unit.
The second and the third digit stand for the sequence of the construction task. For instance, 01 stands for floor flat installation, 02 stands for wall flat installation.			

After inserting the “TaskID” into the 3D architectural BIM model for the different construction activities, each element of the proposed building in the BIM model has its dimension, unit cost, TaskID, family type, and other related attributes information stored in the database. This information can be automatically imported into Microsoft Excel from the BIM tool by the plug-

in created in the cost estimate module to complete the QTO. These quantity data can be classified and sorted based on the TaskID or keynotes to obtain a quantity subtotal of different types of construction tasks, and then be used while calculating the activities duration.

### 3.4.2.1 Schedule planning for traditional construction

For conventional on-site construction, the duration calculation refers to the data from RSMeans Building Construction Cost Data 2013 that provides the crew information, daily output and labour hours of completion, and unit of measurement for each construction element. Daily output represents the productivity of the crew, which means the amount of work the crew can finish in 8 working hours per day. The crew information includes labour resources and equipment required to accomplish each construction task. Combining these two data and the quantity of each task from QTO, equation (3.5) is used to calculate how many work hours are required to finish an element during the construction of a project.

$$\text{Duration}(\text{hrs}) = \frac{\frac{Q}{\text{DO}/8\text{hrs}}}{n_{\text{crew}}} \quad 3.5$$

where Q is the quantity of the element, DO is daily output of a crew, and the  $n_{\text{crew}}$  is the number of crew to complete this element, which depends on the availability of the resources.

Because each task consists of several elements, for instance, task A represents the 10 windows in Zone A at floor 1, the subtotal cost and duration of each task are calculated by using equations 3.6 and 3.7 as follows:

$$\text{Task}_i \text{ Cost Subtotal} = \sum (\text{cost of item}_i) \quad 3.6$$

$$\text{Task}_i \text{ duration Subtotal} = \sum (\text{duration of item}_i) \quad 3.7$$

where  $item_i$  is the elements that have the same TaskID.

After calculating the duration of each task, all information needed for scheduling has been collected. Exporting this information, such as task name, TaskID, subtotal duration, subtotal cost, crew name, construction type and planned start date, to related schedule planning software is done by using a plug-in to fulfill the automatic data transfer. Then, according to the different circumstances of the projects, such as available on-site manpower, weather conditions, and space constraints, the subsequence relationship and time interval between adjacent tasks to plan the schedule of the proposed construction project is adjusted accordingly.

#### **3.4.2.2 Schedule planning for modular construction**

For modular construction, this module only considers the assembly time that is used on the construction site. The assembly duration has been collected from practical cases in different countries. For instance, in England, the Wolverhampton University spent 8 months to finish a 25-storey student apartment with 820 units; in New York, for the tallest modular residential building B2 in the U.S., with 920 units, it took 30 minutes to load a module; in Japan, the common time to finish a two-stories apartment with 8 units is 1.5 days; in China, an experienced company can build a 30-storey hotel using modular construction in 360 hours; etc. This model adopts 2.6 hours as the initial value of assembly time for a regular size module; however, this value can be adjusted according to the condition and availability of resources (manpower and machinery).

The scheduling of modular construction is based on the quantity of units associated with the project and the assembly time of a unit. Similar to the process of planning a schedule for traditional construction, this model uses a TaskID to identify and classify the elements, which

means that each unit has a unique TaskID for the construction sequence. Then based on the classification by TaskID, each unit is assigned an assembly time and crew resources. Afterward, the duration, subtotal of the construction cost, crew name, TaskID, planned starting date, and construction type are automatically exported to the appropriate software to plan the schedule. These values can be adjusted based on the conditions of the construction project. Figure 3.5 presents the conceptual data flow of this scheduling module.

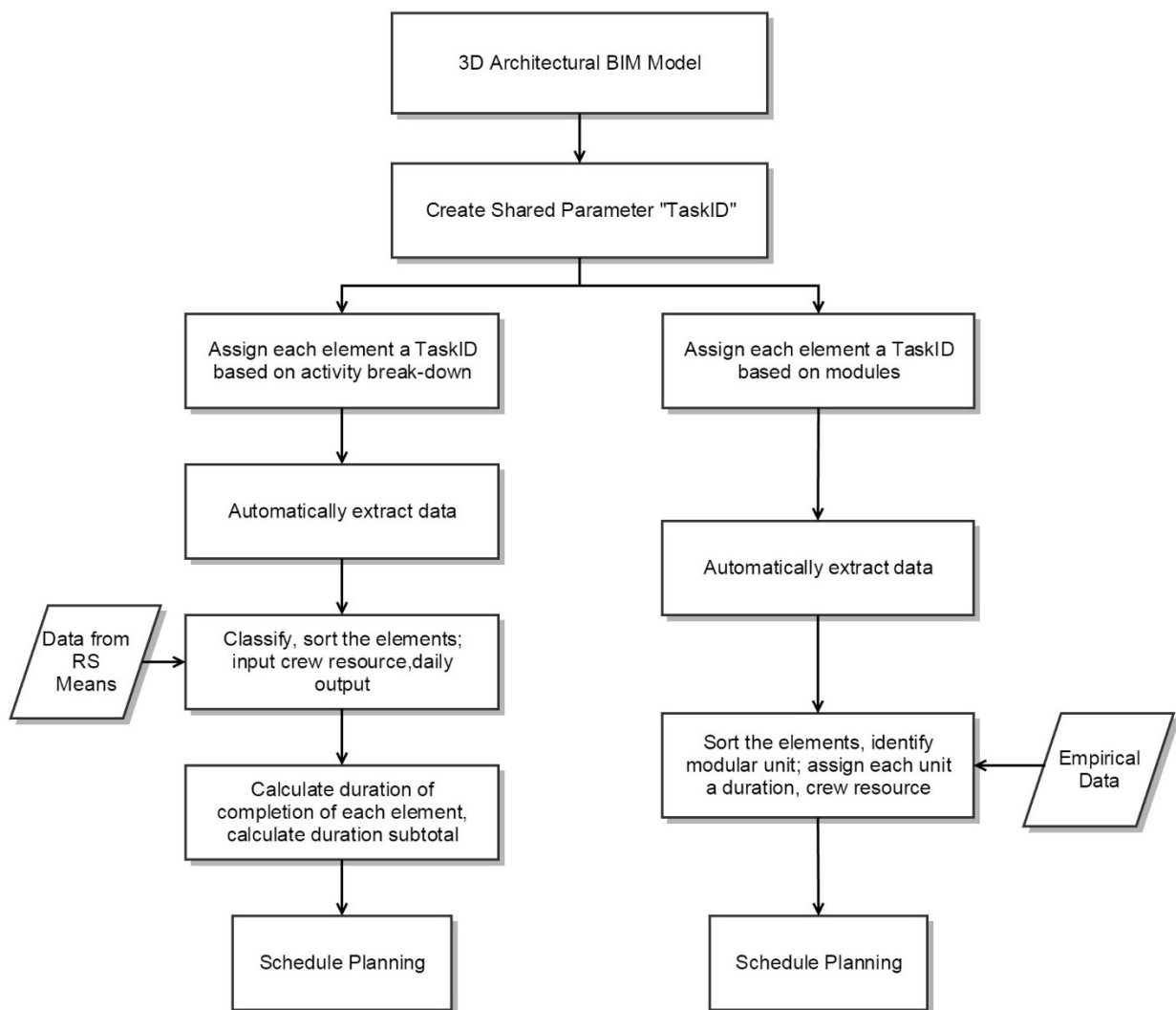


Figure 3.5 The process of schedule planning for both traditional construction and modular construction

### **3.4.3 Sustainability module**

This module aims to assist users in preparing a preliminary evaluation of the sustainability performance of a proposed project at the conceptual design stage when the project information is not detailed and enough. After considering the available information, this module applies the LEED rating system as the sustainability assessment standard. As stated above, the sustainable families in this model are collected from the supplier's webpage and related databases such as the SmartBIM database, which can provide part of the LEED information for the materials or components. Also, according to the LEED v4 for Building Design and Construction published by USGBC, users can use the detailed sum of credits for the material and resources to evaluate the potential LEED points of the materials or components used in the projects.

These potential LEED points can be stored in the families as a shared parameter in the BIM tool, so that when the data for each element is automatically extracted from the 3D BIM model, the LEED points can be output at the same time for the sustainability analysis. Because each category of component might have different types of material, for instance, windows can be wood or aluminum, the potential LEED points that might be earned would be different. In order to evaluate the most LEED points can be earned by the materials used in the proposed projects, this module takes the maximum value when one category has several types of materials and different LEED points. After collection of the LEED points of each category, these are summed up to get the subtotal of credits for the material and resources section of the proposed model, so that designers and owners have an approximate idea of the sustainability of the proposed project when using these materials. When users are not satisfied with the outcome, it is convenient for them to change the materials and input the corresponding LEED credit to obtain a new subtotal of potential LEED points. Figure 3.6 explains the methodology of this module.

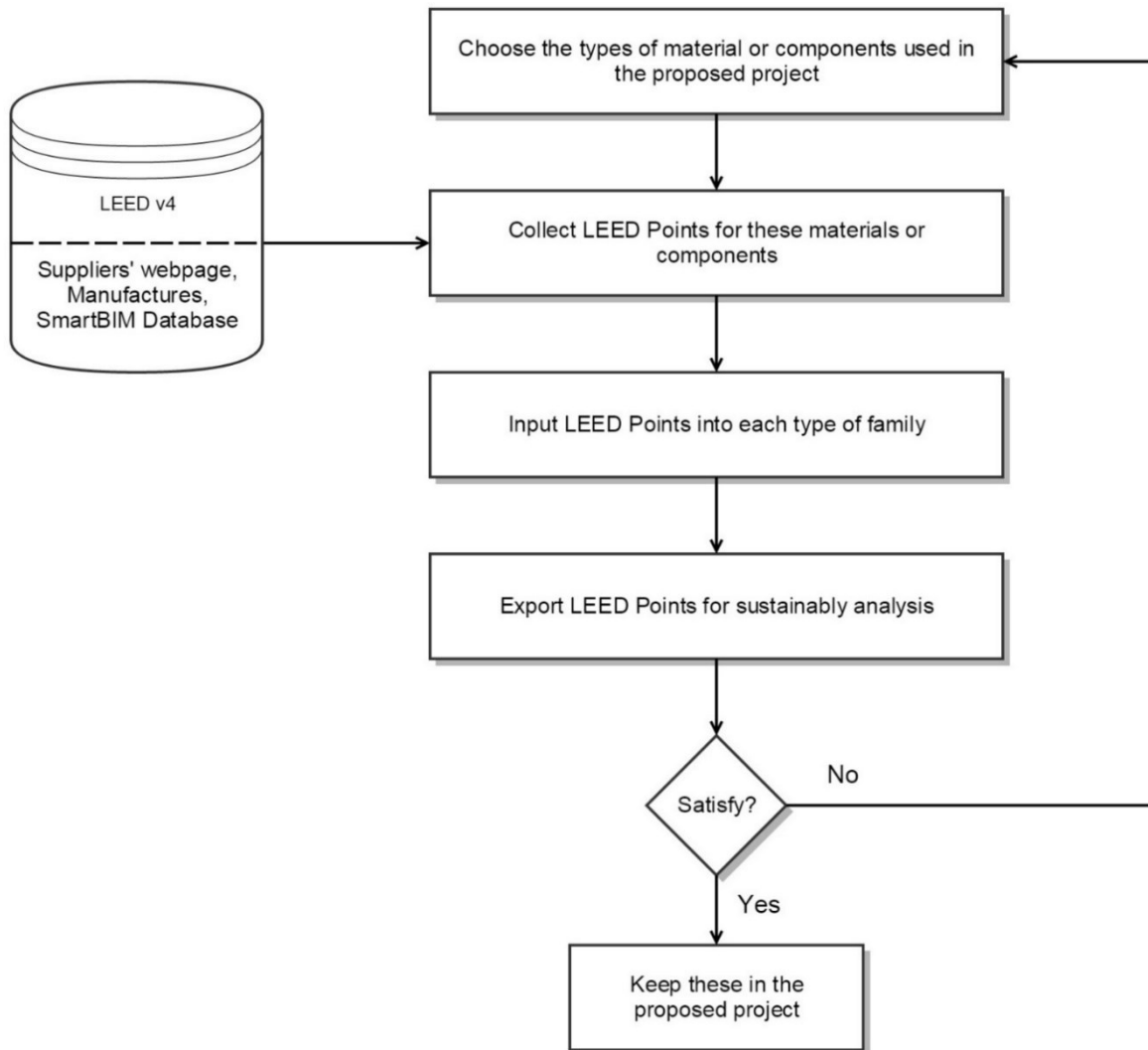


Figure 3.6 The sustainability evaluation process

### 3.4.4 Integrated 5D module

This module illustrates the integration of a 3D BIM model with cost estimation and schedule planning, creating a comprehensive model for owners, designers and contractors to see the construction process before putting the project on site, and to identify the accumulated cost and time that has been used for each construction stage. To achieve this 5D module, the model

mainly relies on the automatic data transfer among BIM tools and the developed plug-ins in the cost estimate module, and the scheduling module.

As stated by Hemio and Salonen (2002), data transfer is based more on sharing than on sending in the future. BIM tools share the same standards and specifications, such as Industry Foundation Classes (IFC), which provides a data representation and file format used to define an architectural model to facilitate interoperability in the building industry. This is why data can be transferred and shared conveniently among a group of vendors who might use different BIM software. This module attempts to transfer the 3D architectural model from Autodesk Revit to Autodesk Naviswork, a BIM tool for construction project model and data integration. After transferring the 3D model data into Naviswork, based on the different break-downs of the proposed project, each element is assigned to an appropriate set that can be used in the construction simulation. Meanwhile, the cost data, duration, required resources, planned starting date, and construction time of each single task are automatically integrated into the BIM tool, while linking this information with the corresponding tasks of the construction project, so that all the valuable data about cost estimation and scheduling is gathered. The 5D module has been developed by integrating the 3D model with cost estimation and schedule planning, providing critical information via the simulation so that users can see the construction process as well as the accumulation of cost and time values over the different construction stages. Through this module, users can have an appropriate understanding of the whole project at the conceptual stage, and the potential risks in the construction schedule and budget might be recognized and predicted, so that designers can modify the conceptual design model of the project in the next detailed design stage.

Figure 3.7 shows the flowchart of this integrated 5D module.

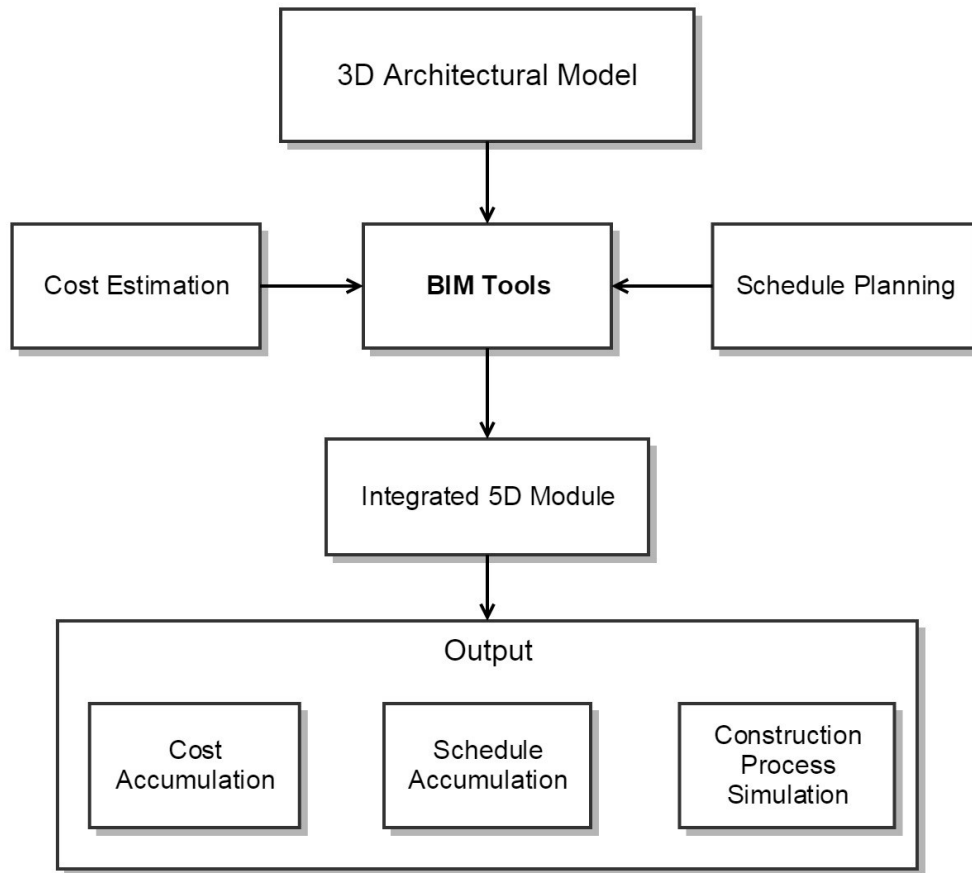


Figure 3.7 Flowchart of the integrated 5D module

### 3.5 Summary

Based on the literature review and the summary of past research, this chapter explained the methodology to develop a model that provides owners and engineers with reliable and quick estimation of projects' construction cost and time, and a preliminary evaluation of sustainability performance within an integrated BIM environment at the conceptual design stage.

To begin with, this chapter has described a database development methodology, which is based on collecting Revit families and RS Means cost information. This database is the foundation of the other three modules: the cost estimate module, the scheduling module, and the sustainability module. Subsequently, this chapter has explained how the data can be efficiently input, stored,

transferred and shared among these modules on a BIM platform. The most important contribution of this methodology is that data can be automatically transferred among the BIM tools and other analysis software, shortening the preparation time for the cost estimate and for the scheduling of construction projects.

This chapter also introduced different equations and adjustment methods for both traditional construction and modular construction in both the cost estimate module and the schedule planning module, improving reliability of the estimation at the conceptual stage. It also stressed the utilization of LEED information in BIM tools to obtain preliminary sustainability assessment. Lastly, it highlights the development of a 5D module that integrates the 3D BIM model with related cost and duration information, providing users with a vivid simulation of project construction process and accumulation of cost and schedule.

## Chapter 4

### Model Development

#### 4.1 Introduction

This chapter explains how the physical model is developed based on the proposed methodology. Firstly, it introduces the process of collecting families, unit costs, and LEED information, and storing them in an external database in RVT format that is linked to the BIM tool. The existing Revit families are used to build the proposed 3D architectural model in AutoDesk Revit and the cost data and LEED information are inserted into the properties of these families so that each element in the 3D model is a collection of the architectural information, cost data, LEED information, and other valuable information. In the proposed model new attribute, “TaskID”, is created for each element in the Revit file so that it can be applied for the different types of construction (conventional and modular construction). Next, this chapter emphasizes the automatic extraction of these data for cost estimation, schedule planning, and preliminary sustainability evaluation. Two plug-ins are developed in the model to improve the efficiency of extracting the QTO from the 3D model to Excel and to facilitate the data transfer from Excel to Microsoft Project for schedule planning. This model also links all the modules with Naviswork to integrate a 5D module to simulate the construction stages and display their construction costs and accumulated duration. Figure 4.1 presents the tools used in the development of the integrated model.

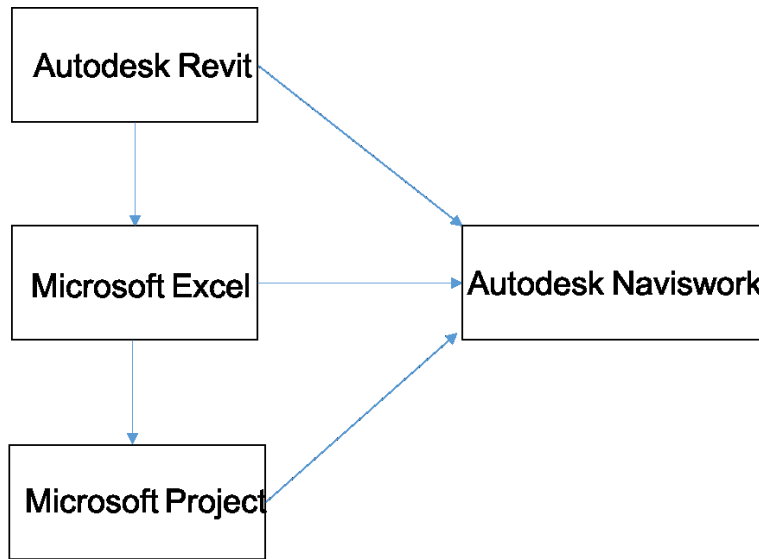


Figure 4.1 The main tools used in the development of the integrated model

## 4.2 Database Collection and Development

### 4.2.1 Architectural families collection

As mentioned before, architectural families are the basis of the 3D model in BIM, and they are the carriers of all the physical information of the proposed model. These families are collected from different sources such as SmartBIM Library, ARCAT online resources and manufacturer web pages. These resources enable users to download and share more than 77,000 family types, and many of them are manufacturer-specific and loaded with product and sustainability information. In order to make it convenient for users to refer to these families, an external database has been created and linked to this model with more than 300 types of frequently used families to store and access their data in a systematic way. As Figure 4.2 shows, the external database file is categorized into two standards, one being MasterFormat and the other being UniFormat, which are two different work breakdown structure systems with different numbering. Using this, designers can easily load families into the 3D model of a project regardless of the breakdown system they use.

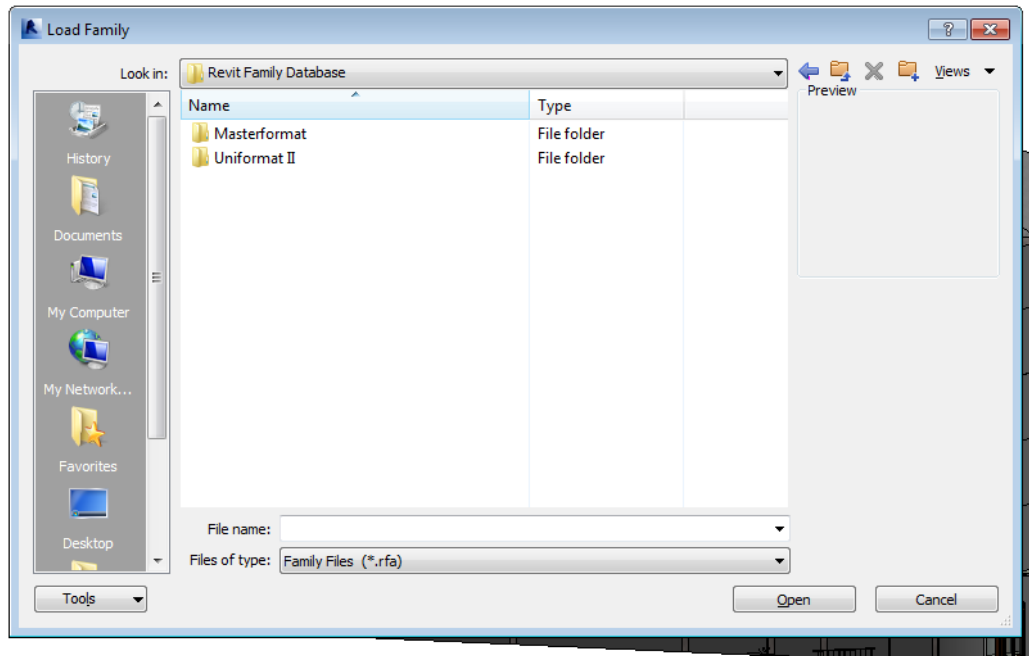
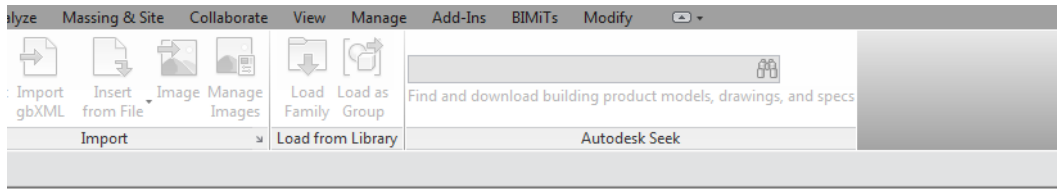


Figure 4.2 Organization of the family into two different database

The format of these families is RFA, which is a format that can be easily loaded into and saved from Autodesk Revit. When the families are loaded into the BIM tool, the inherent properties of the products or components, and other attributes customized by the producer will be loaded at the same time. Some families also provide information about green building properties, which are very helpful for the sustainability evaluation. Figure 4.3 displays detailed properties of one type of windows in the family database, while the BIM tool also provides a 3D view of the family, as shown in Figure 4.4, from which designers can preview the detailed appearance from different perspectives during the design stage. Furthermore, some of the attributes, such as dimensions,

can be easily edited based on the designers and project needs where the result can then be saved as a new type of family.

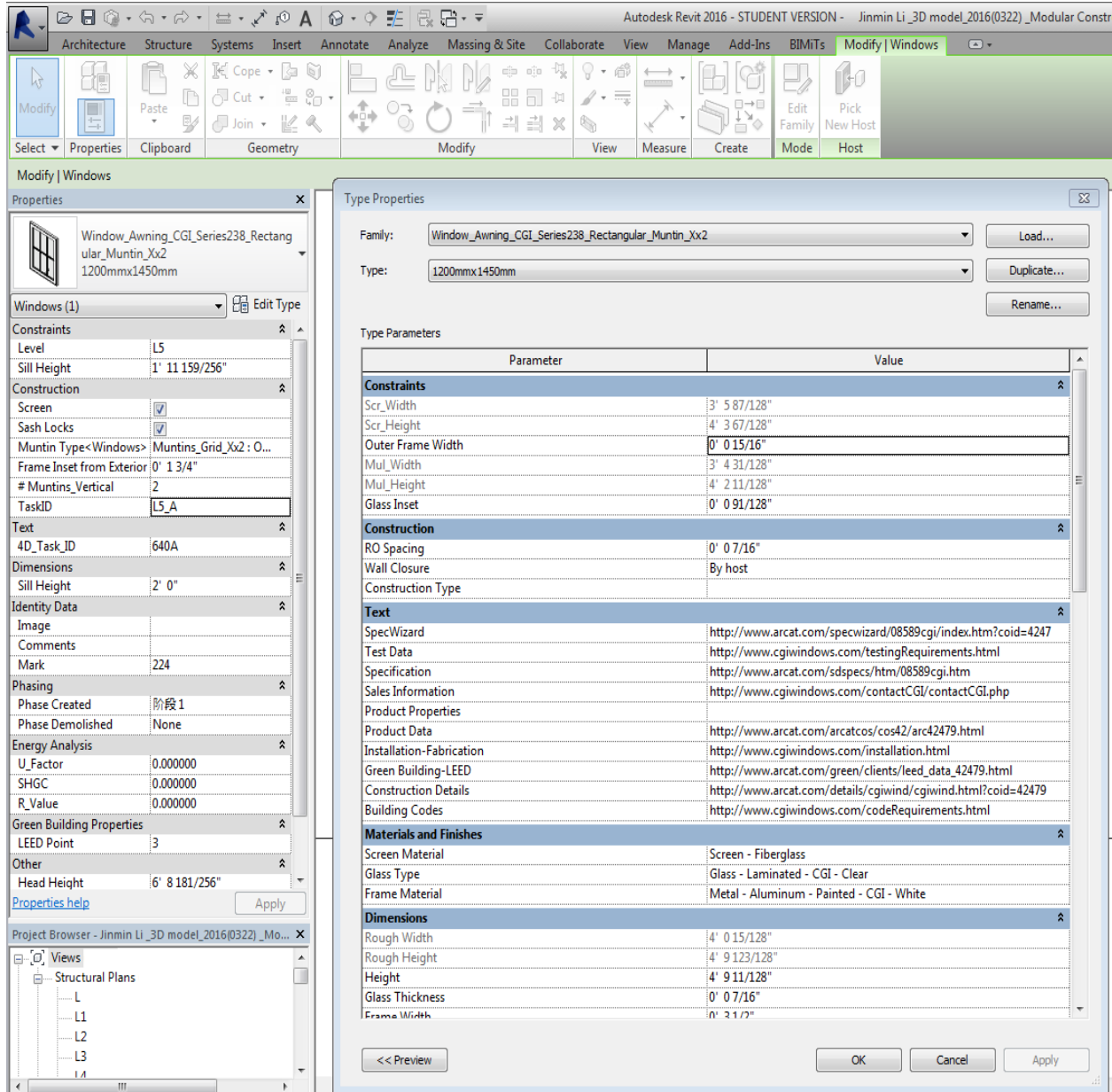


Figure 4.3 Properties of one type of window

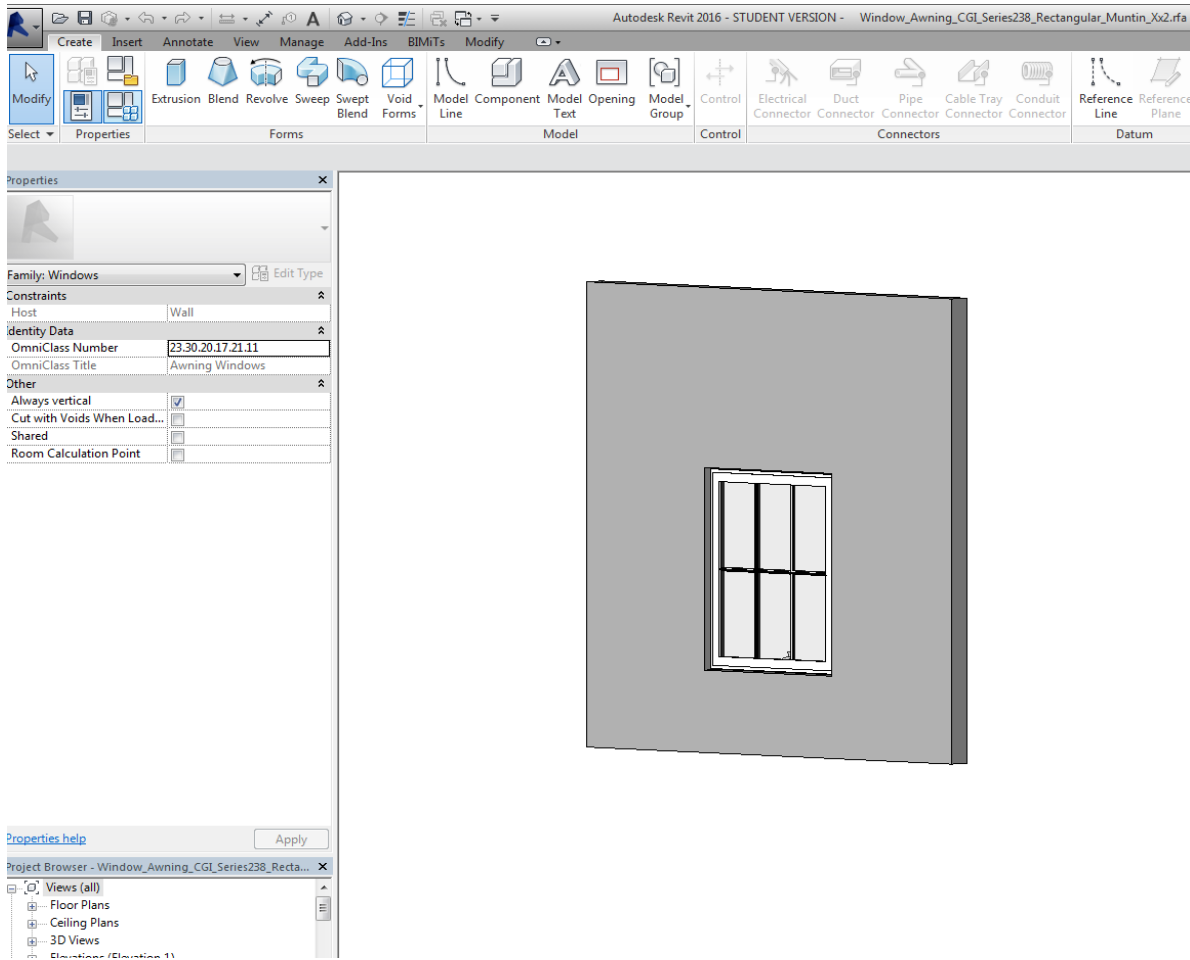


Figure 4.4 3D view of an awning window

#### 4.2.2 Cost data collection

This model applies RSMeans as a source of its construction cost data, therefore it is designed to be used at the conceptual design stage where limited information about the project is known. The construction cost data are mainly collected based on the UniFormat assembly, which consists of 7 divisions. Figure 4.5 illustrates the information for wood doors provided by RSMeans. There are different types of doors under the division C1020 Interior Doors, where the material cost and installation cost of doors are both displayed. The cost obtained from RSMeans can be inserted into the corresponding family as a property. This process will be described in detail in Section 4.3.

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Search Data Manage Estimates Square Foot Estimator Life Cycle Cost Alerts and Trends Reference Items My Favorites

Search Here

Cost Data: .....Assemblies Type: Assembly Labor Type: Standard Union Location: OTTAWA (C21)

Search: What are you searching for? All Include My Custom Data Release: Year 2016 Quarter 2

**UNIFORMAT II** **C1020120 Wood Door/Wood Frame** **Total 35 records found**

Assembly Number	Description	Unit	Material	Installation	Total
C10201200800	Wood Door/Wood Frame				
C10201200801					
	<b>TYPE FACE SIZE FRAME DEPTH</b>				
C10201201600	Hollow core/flush lauan 3'-0" x 7'-0" pine 3-5/8"	Ea.	357.78	240.38	598.16
C10201201620		Ea.	368.46	252.35	620.81
C10201201760		Ea.	630.12	396.03	1026.15
C10201201780		Ea.	646.14	409.85	1055.99
C10201201800	birch 3'-0" x 7'-0" pine 3-5/8"	Ea.	347.10	240.38	587.48
Upgrade to access complete data. <a href="#">Click here to subscribe!</a>					
C10201201820		Ea.			
C10201201960	6'-0" x 7'-0" pine 3-5/8"	Ea.			
C10201201980		Ea.			
C10201202000	oak 3'-0" x 7'-0" oak 3-5/8"	Ea.			
C10201202020		Ea.			
C10201202160	6'-0" x 7'-0" oak 3-5/8"	Ea.			

Measurement System : English + Create New Estimate **Total 35 Records Found**

Figure 4.5 Assembly cost of doors from R.S. Means (R.S. means online database, 2016)

### **4.2.3 LEED information collection**

As mentioned in the methodology chapter, the proposed model uses LEED to evaluate sustainability performance by applying LEED v4 for Building Design and Construction as the rating system to determine the LEED points gained from the material and resources section, which includes the following prerequisites and credits: storage and collection of recyclables, building reuse, construction and demolition waste management planning, building life cycle impact reduction, building product disclosure and optimization, and construction and demolition waste management. The LEED information also can be collected from suppliers' web pages and publishers' web pages, such as those of SmartBIM and ARCAT. These resources can provide the potential LEED points of the green components or the LEED credits obtained by the sustainable materials used in the project. The collected LEED points are inserted into green BIM families so that users can know how many LEED points may be earned by the families when designing the proposed architectural model.

### **4.3 3D BIM modelling**

3D modelling is the critical part of the model because it is related to the reliability of cost estimation and schedule planning. The keys of 3D modelling are the degree of accuracy, visualization ability, as well as easy editing and data transfer abilities. Autodesk Revit is one of the BIM tools that satisfies these requirements and is being widely used in AEC industry. Revit integrates architectural, structural, and MEP design into one platform so that designers from different areas can complete the whole model at the same time. This proposed model focuses on 3D architecture modelling at the conceptual design phase by using the collected families.

Firstly, as shown in Figure 4.6, the families are loaded into Revit from the external database so that Revit stores all the types of families for different kinds of building projects, such as

apartments, hotels, and office buildings, and designers can easily edit the attributes (such as dimensions) of families to satisfy the design requirements. The completed 3D model not only provides the 2D floor architectural and structural floor plan of each floor, and the 3D appearance, but also shows each vertical view and section view from any perspective, so that designers can modify and fix the building design in an efficient way.

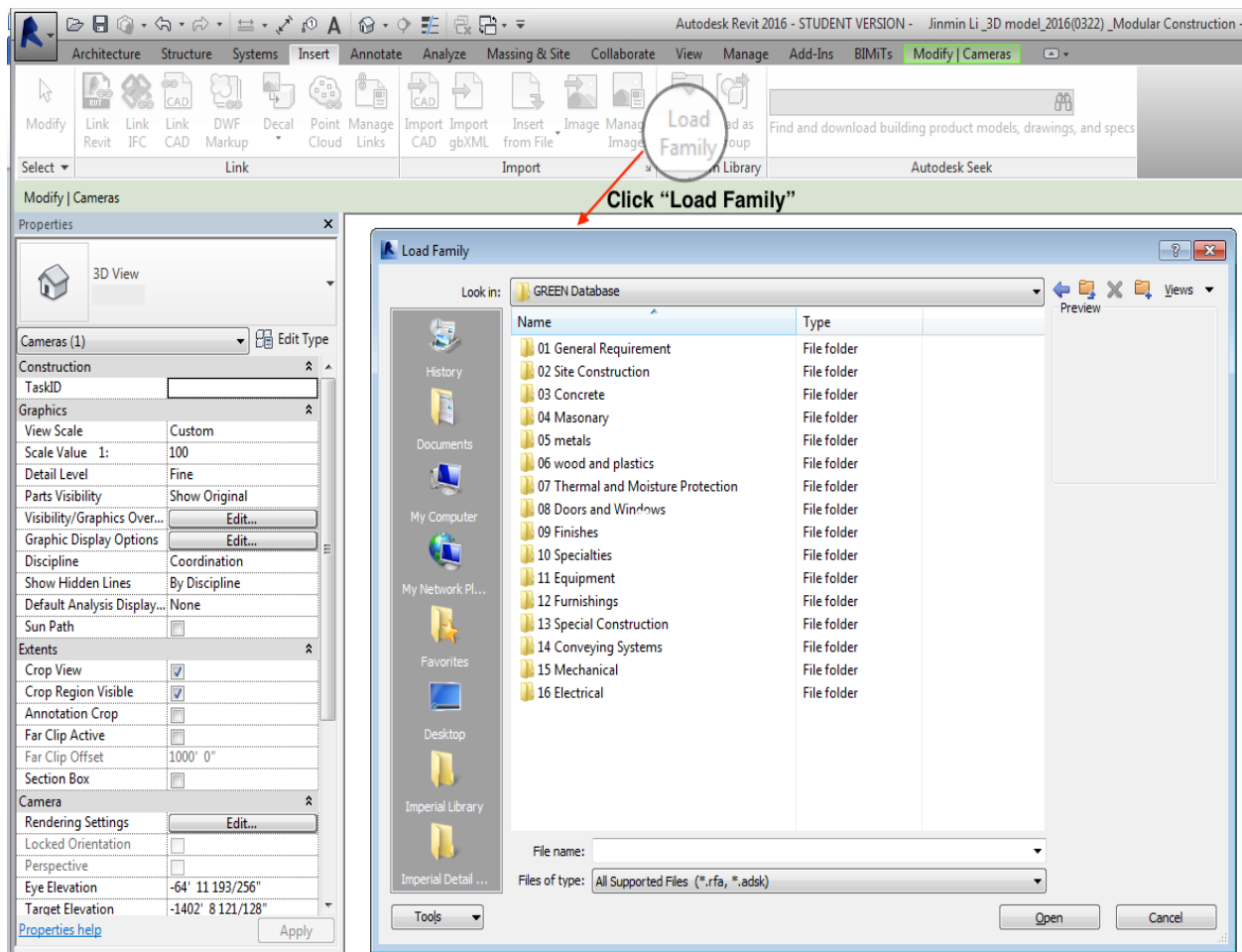


Figure 4.6 Loading the family database into Revit

After finishing the 3D physical modelling, the proposed model attempts to create two shared parameters in the properties list for the convenience of the following: cost estimation, schedule planning, and sustainability evaluation. One parameter is named "TaskID", which is used to

identify which construction activity each element belongs to. For instance, if we consider the installation of all the windows of the first room on the first floor as a construction activity and assign a TaskID “L1\_A” to each window in this room, the windows with this TaskID “L1\_A” are considered as a task package during the planning and scheduling stage. This is the crucial basis of sorting and summarizing data for cost estimation and scheduling, especially for modular construction. Another created parameter is “LEED Points” used to store the potential LEED information of each type of family, so that designers can directly recognize the sustainability benefit by using the different materials and components at the conceptual design stage. Figure 4.7 shows the process of creating these two shared parameters in Revit and the outcome of the properties list.

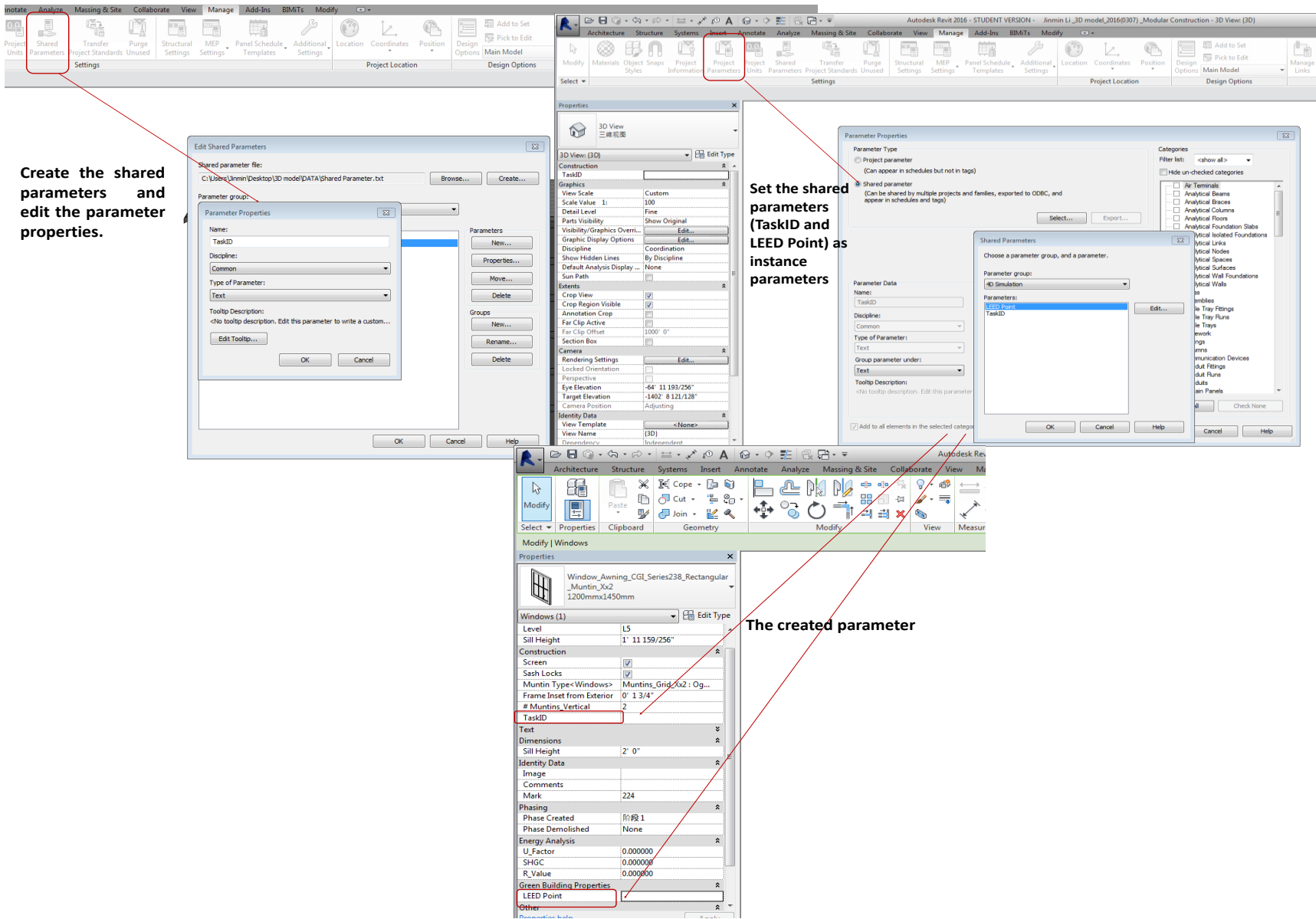


Figure 4.7 The process of creating shared parameters

## 4.4 Cost estimation

### 4.4.1 Cost data input

After loading the families into Revit and creating the 3D model, this developed model inserts the unit cost collected from R.S. Means into each type of family in Revit so that the unit cost data is stored in the 3D model as well. Figure 4.8 shows the “properties type” of a type of window after inputting the cost data, which means each type of component in the 3D model building has its associated cost data.

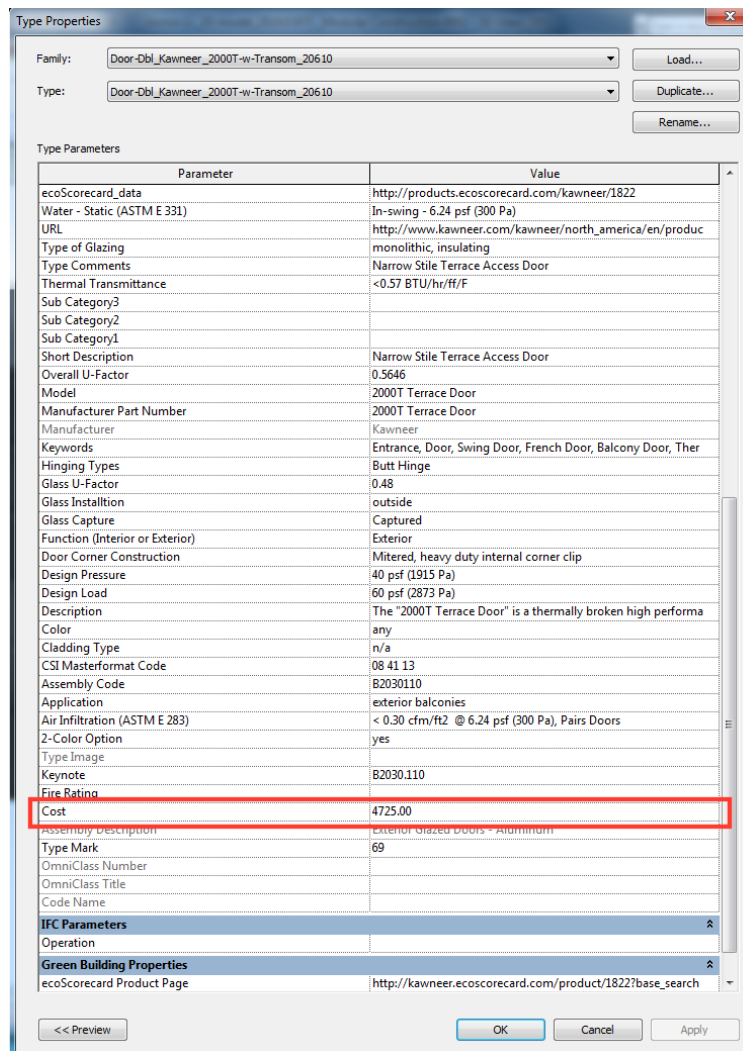


Figure 4.8 Inputting the cost data into families' properties

#### **4.4.2 Plug-in Development**

One of the main contributions of this developed model is the integration of BIM and cost estimation and fulfilling the automatic data extraction from the 3D model to help estimators rapidly obtain an approximation of the construction cost at the conceptual design stage. The BIM tool provides an open and flexible platform, as it holds a different interface that enables users to link it with other software through plug-ins to enhance the collaboration between architectures, engineers, and contractors. In this proposed model, a plug-in, “BIMiT’s Datalink,” is installed into Autodesk Revit, so that data can be easily transferred and extracted from the 3D model by using this plug-in in Revit. As shown in Figure 4.9, this plug-in has seven functions under it. The “Data link”, “Template Editor” and “Merge sheets configuration” are the main functions that will be used in this developed model for automatic data extraction from the 3D model to Excel, and they will be described in detail in Section 4.4.3. The “Update from XLS” function is for two-way data transfer, which means if the data is changed in Excel after exporting from the 3D model, this function can instantly update these changes in the 3D model. For instance, if the cost of one type of component is changed, users can change the cost in Excel and use this function to transfer the new cost data back to Revit.

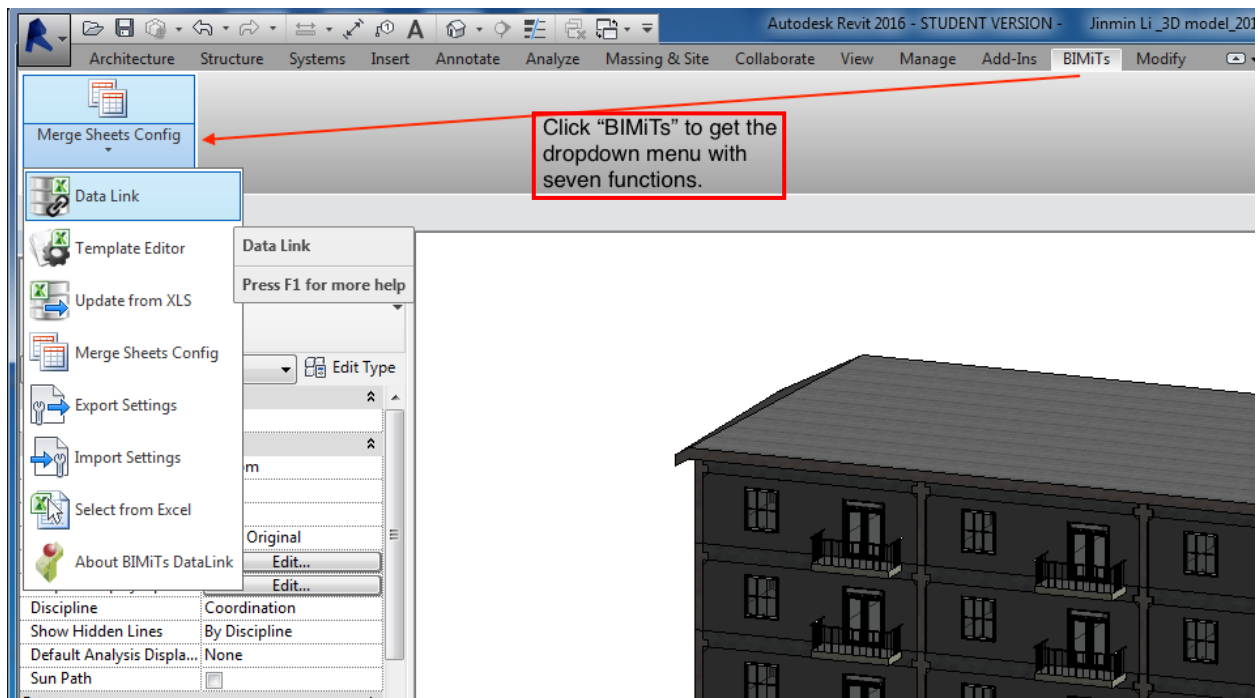


Figure 4.9 The dropdown menu of the BIMiTs plug-in

Thus, this plug-in is the bridge between the 3D BIM model and the cost estimate module, and is also an efficient way of transferring data between Revit and Excel.

#### 4.4.3 Preparation of data extraction

Firstly, the BIMiTs plug-in allows users to customize the kinds of data to be exported. Figure 4.10 shows this process, by activating the “Template Editor” to develop a template for data extraction. In this dialogue box, the left column displays all the categories of items that may be included in the 3D model, from which users can choose what categories they want to export by checking the appropriate check box, and they can choose the parameters that need to be extracted from the middle column. Thus the right column shows the parameters of the selected categories that would be exported. For instance, estimators need to collect all the information about doors used in the building 3D model before estimating the construction cost, thus they can choose the family name, type, width, height, keynote, and cost from the parameter type of doors, and the

category, family name, type, level, TaskID, and LEED points from the instance parameters of doors. Then when pressing the “Apply” button, these selected parameters will be saved and arranged in different columns in Excel worksheets that correspond with the selected categories and indicators. Figure 4.11 shows the finished workbook produced by using the template editor function in the plug-in. It includes all categories that need to be considered in the cost estimate. “T” worksheets display the type parameters, while “I” worksheets display the instance parameter of each element in the 3D model, respectively.

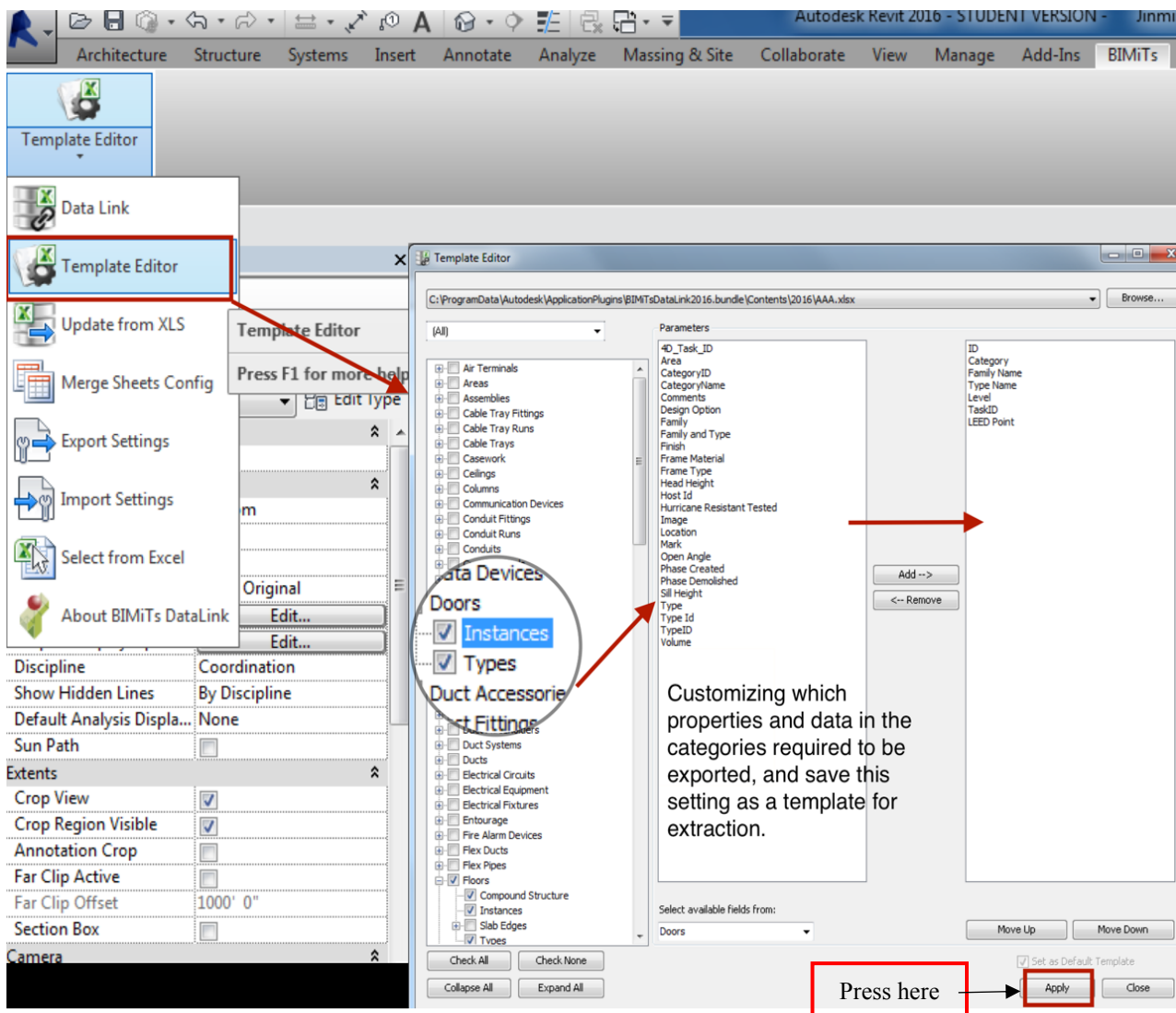


Figure 4.10 Configure the template for data extraction

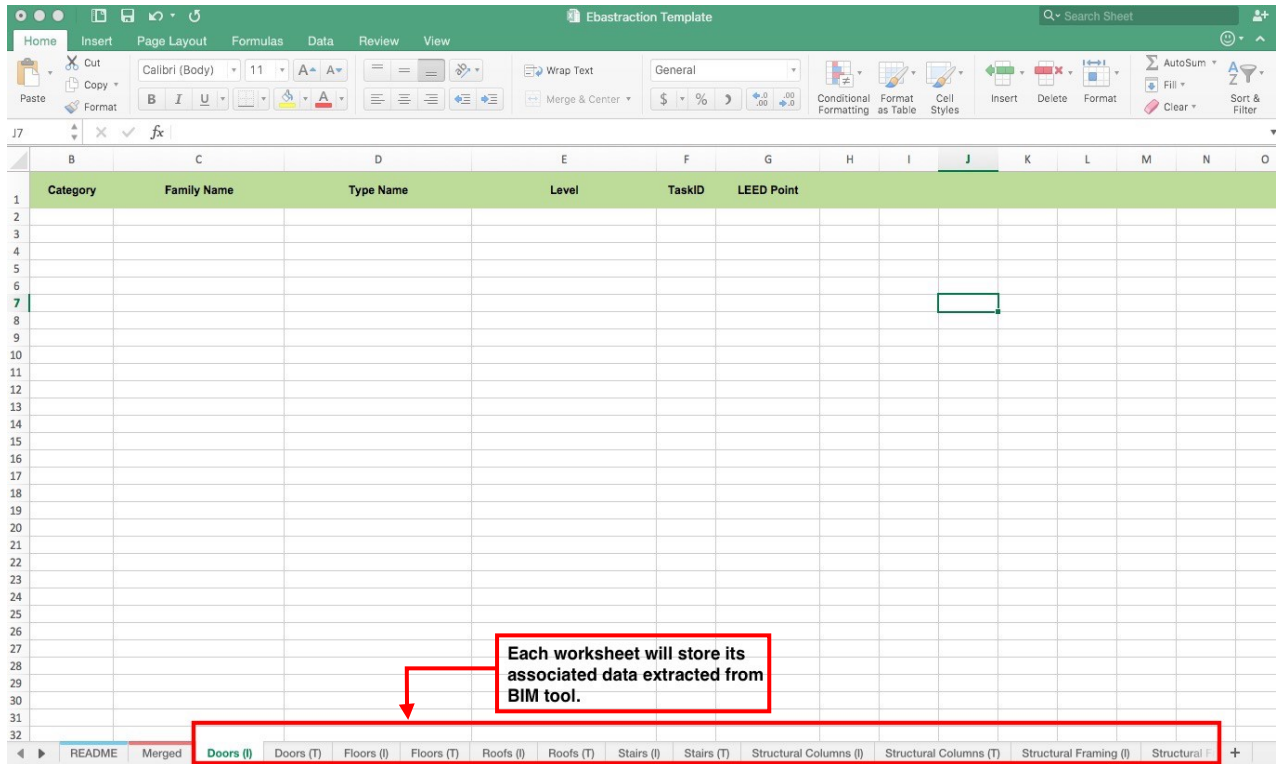


Figure 4.11 The finished template for data exporting

Also, in order to make this a convenient application for users, these worksheets can be worked out more by using formulas in order to efficiently organize the data extracted from the 3D model and to calculate the cost in an automatic way. For instance, as shown in Figure 4.12, in this workbook, four columns are inserted (Unit, Keynote, Unit Cost, and Cost) in each worksheet with an “I” indicator to make it easier to calculate the sub-cost of each item:

- 1) “Unit” is used to store the units of measurement.
- 2) “Keynote” is a type of parameter for identification, and it can be shown as an instance parameter for each element by using the following reference formula. For instance, the following formula is used in the “Floor (I)” worksheet to refer the associate keynote from the “Floor(T)”:

Floors(I)J:  $j=INDEX('Floors (T)!'E:E,MATCH('Floors (I)!'D:D,'Floors (T)!'D:D,0))$ .

- 3) “Unit cost” refers to the “Cost” data in the type parameters.
- 4) “Cost” is the sub-cost that is worked out from multiplying unit cost by quantity for each element in the 3D model.

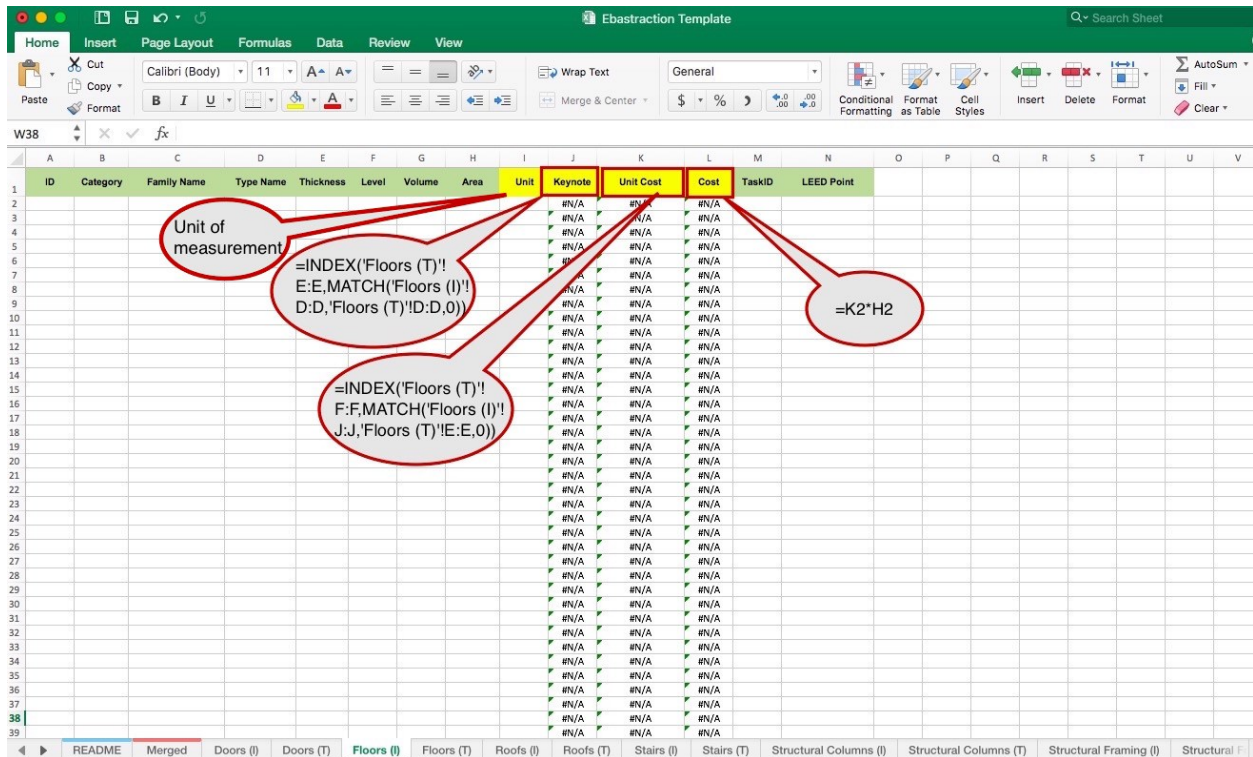


Figure 4.12 Adding new columns in the template workbook for the convenience of the cost estimate

So far, by using the template editor function and inserting necessary formulas to set the parameters in the separate worksheets, it is convenient for estimators to extract the data into the correspondent worksheet and get the construction cost automatically at the same time.

However, sometimes, it is very useful to have all the data in one worksheet, especially when creating a detailed bill of quantities and a time schedule. The plug-in in this proposed model can create such a merged worksheet by making a “copy” of the information from the separate category worksheets. Figure 4.13 presents the process of creating this merged worksheet.

Activate the “Merge sheets Configuration”, and choose the “Add new headers to merged sheet”

to customize the information users want to gather into this worksheet. Since this model is developed to generate quick cost estimation and schedule planning, the level, family, type, keynote, quantity, unit, cost, crew, duration, and TaskID are set as the headers for further estimation and analysis. After headers have been added, they will be immediately shown in the mapping table for users to choose available parameters from the selected category sheet and put them under the appropriate headers in this merged sheet. In this case, all the necessary information from the 3D model can be summarized into this single sheet according to the mapping setting, where this sheet can be considered as the QTO of the proposed project.

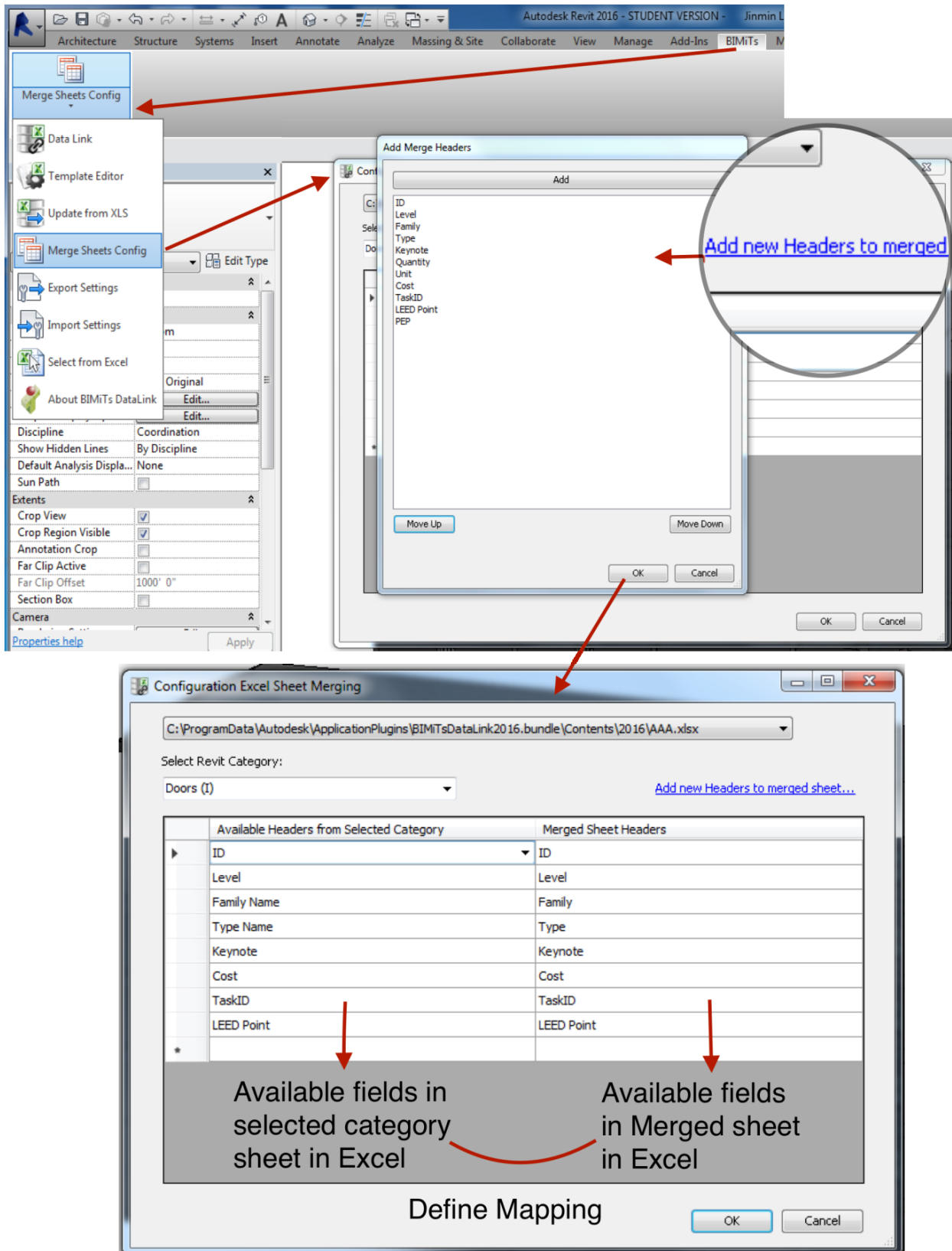


Figure 4.13 The process of creating the merged sheet

Figure 4.14 represents the finished workbook after setting up the separate category worksheets and the merged sheet using the plug-in in Revit. It is now ready for data extraction.

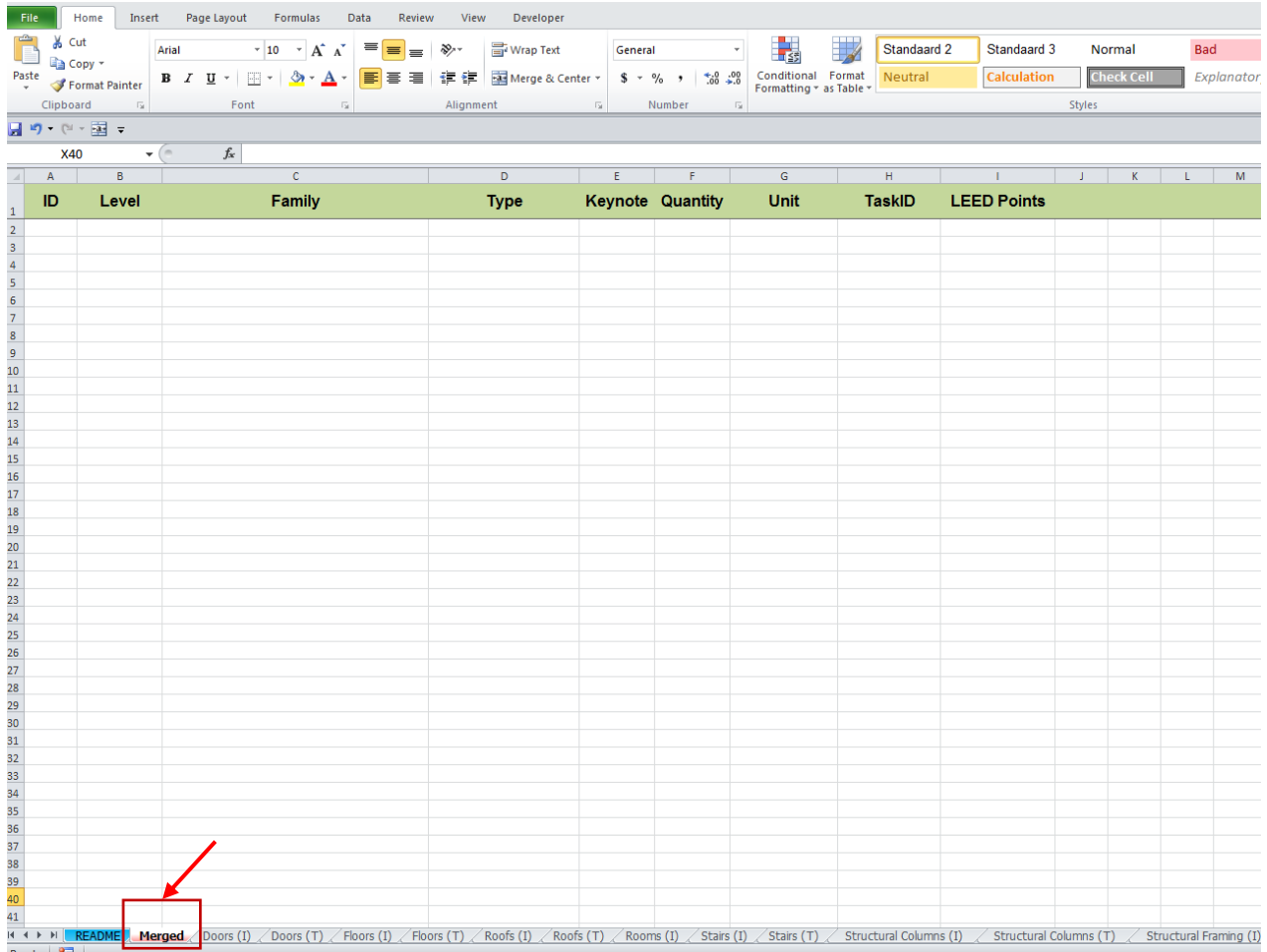


Figure 4.14 Finished merged worksheet of the extraction template

#### 4.4.4 Cost calculation

Through the installation of the plug-in and the setting of the template workbook for data extraction, the data of the 3D model in Revit is ready to be exported. Firstly, the path to save the exported data to should be chosen, then the template file used to which the data is exported should be chosen. After that, the data in Revit can be extracted automatically according to the template.

When the exporting is done, the generated Excel file opens automatically. Figure 4.15 shows an example of the worksheet that displays all types of doors used in a proposed building project and their related data in its 3D model. Figure 4.16 is an example of the “door instance” worksheet that includes all the information about the doors used in the project, including category name, family name, type name, Level, cost, TaskID and LEED points exported from the 3D model in Revit. Meanwhile, the merged sheet automatically summarizes these parameters of each item so that all the basic information for cost estimation and scheduling of a construction project is included in this worksheet.

ID	Family Name	Type Name	Width	Height	Keynote	Cost
182445	Door	Building Door—1800 x 2500mm 2	6.56	8.20	B2030.110	53550
294972	Internal_Door_-_openable_in_3D_13628	760x2000	2.62	6.50	C1020.102	557
304290	Apartment_Bedroom_Door_15894	900mm x 2200mm	2.95	7.22	C1020.102	636
343305	Door-DbI_Kawneer_2000T-w-Transom_206	Door-DbI_Kawneer_2000T-w-Transom_20610	4.92	6.56	B2030.110	4725

Figure 4.15 The data type of the door category from the project

Jinmin Li\_3D model\_2016(0309)\_Modular Construction

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ID	Category	Family Name	Type Name	Level	Keynote	Unit Cost	Cost	TaskID	LEED Point
2E+05	Doors	Entrance Door	building Door---1800 x 2500mm 2	L	B2030.110	53550	53550	L_L	3
3E+05	Doors	Internal_Door_-_openable_in_3	760x2000	L1	C1020.102	557	557	L1_A	3
4E+05	Doors	Internal_Door_-_openable_in_3	760x2000	L1	C1020.102	557	557	L1_A	3
5E+05	Doors	Internal_Door_-_openable_in_3	760x2000	L1	C1020.102	557	557	L1_C	3
6E+05	Doors	Internal_Door_-_openable_in_3	760x2000	L1	C1020.102	557	557	L1_C	3
7E+05	Doors	Internal_Door_-_openable_in_3	760x2000	L1	C1020.102	557	557	L1_E	3
8E+05	Doors	Internal_Door_-_openable_in_3	760x2000	L1	C1020.102	557	557	L1_E	3
9E+05	Doors	Internal_Door_-_openable_in_3	760x2000	L1	C1020.102	557	557	L1_G	3
10E+05	Doors	Internal_Door_-_openable_in_3	760x2000	L1	C1020.102	557	557	L1_L	3
11E+05	Doors	Internal_Door_-_openable_in_3	760x2000	L1	C1020.102	557	557	L1_M	3
12E+05	Doors	Internal_Door_-_openable_in_3	760x2000	L1	C1020.102	557	557	L1_N	3
13E+05	Doors	Door-DbI_Kawneer_2000T-w-Tri	Door-DbI_Kawneer_2000T-w-Transom_206	L1	B2030.110	4725	4725	L1_C	4
14E+05	Doors	Door-DbI_Kawneer_2000T-w-Tri	Door-DbI_Kawneer_2000T-w-Transom_206	L1	B2030.110	4725	4725	L1_A	4
15E+05	Doors	Door-DbI_Kawneer_2000T-w-Tri	Door-DbI_Kawneer_2000T-w-Transom_206	L1	B2030.110	4725	4725	L1_E	4
16E+05	Doors	Door-DbI_Kawneer_2000T-w-Tri	Door-DbI_Kawneer_2000T-w-Transom_206	L1	B2030.110	4725	4725	L1_O	4
17E+05	Doors	Door-DbI_Kawneer_2000T-w-Tri	Door-DbI_Kawneer_2000T-w-Transom_206	L1	B2030.110	4725	4725	L1_M	4
18E+05	Doors	Internal_Door_-_openable_in_3	760x2000	L1	C1020.102	557	557	L1_O	3
19E+05	Doors	Apartment_Bedroom_Door_158	900mm x 2200mm	L1	C1020.102	636	636	L1_A	3
20E+05	Doors	Apartment_Bedroom_Door_158	900mm x 2200mm	L1	C1020.102	636	636	L1_A	3
21E+05	Doors	Apartment_Bedroom_Door_158	900mm x 2200mm	L1	C1020.102	636	636	L1_C	3
22E+05	Doors	Apartment_Bedroom_Door_158	900mm x 2200mm	L1	C1020.102	636	636	L1_C	3
23E+05	Doors	Apartment_Bedroom_Door_158	900mm x 2200mm	L1	C1020.102	636	636	L1_E	3
24E+05	Doors	Apartment_Bedroom_Door_158	900mm x 2200mm	L1	C1020.102	636	636	L1_E	3
25E+05	Doors	Apartment_Bedroom_Door_158	900mm x 2200mm	L1	C1020.102	636	636	L1_G	3
26E+05	Doors	Internal_Door_-_openable_in_3	760x2000	L2	C1020.102	557	557	L2_A	3
27E+05	Doors	Internal_Door_-_openable_in_3	760x2000	L2	C1020.102	557	557	L2_A	3
28E+05	Doors	Internal_Door_-_openable_in_3	760x2000	L2	C1020.102	557	557	L2_C	3
29E+05	Doors	Internal_Door_-_openable_in_3	760x2000	L2	C1020.102	557	557	L2_C	3
30E+05	Doors	Internal_Door_-_openable_in_3	760x2000	L2	C1020.102	557	557	L2_E	3
31E+05	Doors	Internal_Door_-_openable_in_3	760x2000	L2	C1020.102	557	557	L2_E	3
32E+05	Doors	Internal_Door_-_openable_in_3	760x2000	L2	C1020.102	557	557	L2_G	3
33E+05	Doors	Internal_Door_-_openable_in_3	760x2000	L2	C1020.102	557	557	L2_L	3
34E+05	Doors	Internal_Door_-_openable_in_3	760x2000	L2	C1020.102	557	557	L2_M	3
35E+05	Doors	Internal_Door_-_openable_in_3	760x2000	L2	C1020.102	557	557	L2_N	3
36E+05	Doors	Door-DbI_Kawneer_2000T-w-Tri	Door-DbI_Kawneer_2000T-w-Transom_206	L2	B2030.110	4725	4725	L2_C	4
37E+05	Doors	Door-DbI_Kawneer_2000T-w-Tri	Door-DbI_Kawneer_2000T-w-Transom_206	L2	B2030.110	4725	4725	L2_A	4
38E+05	Doors	Door-DbI_Kawneer_2000T-w-Tri	Door-DbI_Kawneer_2000T-w-Transom_206	L2	B2030.110	4725	4725	L2_E	4
39E+05	Doors	Door-DbI_Kawneer_2000T-w-Tri	Door-DbI_Kawneer_2000T-w-Transom_206	L2	B2030.110	4725	4725	L2_M	4
40E+05	Doors	Internal_Door_-_openable_in_3	760x2000	L2	C1020.102	557	557	L2_O	3

Merged Summary Activity Sequence **Doors (I)** Doors (T) Floors (I) Floors (T) Roofs (I) Roofs (T) Stairs (I) Stairs (T) Structural Columns (I) Structural Columns

Figure 4.16 All the exported data about the doors in the project

After collecting the data by automatic extraction from the 3D model, the cost estimator can calculate the construction cost based on this information. Each separate category worksheet includes the unit cost value and quantity of each item, and due to the pre-set formula for cost calculation, the cost of each element can be calculated automatically when exporting the data.

For the cost of traditional construction, it is easy for the estimator to calculate the subtotal of the construction cost for each category by using the “Sum” function to sum up the cost of all elements in the separate category worksheet. Then all the cost subtotal of each category are added up together to obtain the total direct construction cost of the project. Alternatively, the merged sheet is utilized to sum up each of the item cost to get the total direct construction cost. Then, based on the project’s construction location and time, users can adjust the construction cost using Equations 3.3 and 3.4.

For modular construction, considering the benefit of cost reduction of on-site labor and construction waste as discussed in Chapter 3, Equations 3.2 can be used to adjust the direct construction cost to the final value to be as the estimated construction cost for modular construction.

## **4.5 Schedule Planning**

This part mainly introduces another important module in this integrated model, the development of the schedule planning module, which automatically transfers the 3D model data from Excel to Microsoft Project in one “click” to automatically generate the construction schedule.

### **4.5.1 Duration calculation**

As discussed above, in the 3D modelling stage, the instance shared parameter “TaskID” was created to store the construction activity information, and this TaskID information has been

exported automatically to Excel for sorting and summarizing data for schedule planning. Thus, the first step in scheduling is to convert the construction elements into construction activity packages using the TaskID and to estimate the duration of each construction task.

For traditional construction, before sorting the data, the planner needs to estimate the duration of each element of the construction project. Since the developed model utilizes BIMiT's Datalink to finish the Quantity Takeoff of the project, the planner can use the daily output and resources from RS Means to estimate the amount of time required to complete each element. As illustrated in Figure 4.17, the planner inserts three new columns, "Crew", "Daily Output", and "Duration", into every category worksheet. Then the planner inputs the appropriate daily output and crew information in these columns according to RS Means Data and uses Equation 3.5 to calculate the time required to complete each construction element on-site. Thus, once users update the workbook the duration information can be automatically transferred from separate category worksheets to the merged sheet as a convenient way to sort and summarize the construction activity based on TaskID. In this case, planners can sum up the subtotal of both the duration and the construction cost of every task for the proposed project.

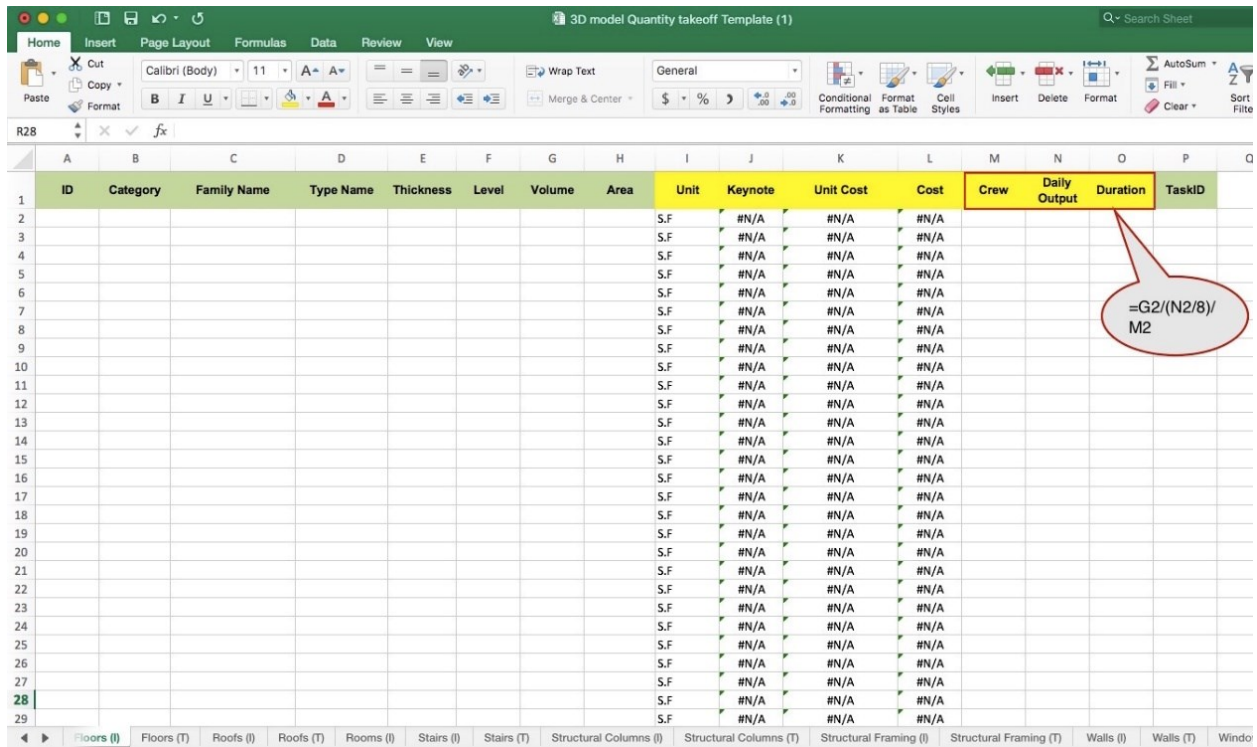


Figure 4.17 Customizing the exported template for the duration calculation

On the other hand, for modular construction, the project duration mainly relies on the installation time of the construction unit. Since every element of the construction unit is assigned the same TaskID in the 3D modelling stage, planners just need to sort the construction elements by their TaskID in the merged sheet, and afterwards assign a regular assembly time and crew size to each construction unit according to the project type and empirical data.

#### 4.5.2 Plug-in development

After calculating the duration and organizing the construction activities based on the construction type in Excel, another plug-in is created to transfer the project's construction duration information to Microsoft Project to accomplish the schedule planning. Microsoft Project has the same interface as Excel, which enables this developed model to use Visual Basic for Application (VBA) to develop a plug-in to automatically transfer the data.

The required functions for this plug-in are:

- 1) Automatically open Microsoft Project by activating the plug-in.
- 2) At the same time, the arranged data, including TaskID, Crew Name, Subtotal cost, Duration, Planned Start Date, and Construction Type, is transferred from Excel to Microsoft Project automatically.
- 3) A Gantt Chart schedule is developed automatically in Microsoft Project.

Based on these requirements, the VBA code in Figure 4.18 is designed to transfer the data to Microsoft Project, and a button is created in Excel for users' convenience to activate this plug-in with just one click. Appendix D shows a sample of the code used in developing this plug-in.

```
Jinmin Li_3D model_2016(0228)_Modular Construction.xlsm - ModularConstruction (Code)
(General) ExportToMsProject

Sub ExportToMsProject()
Dim pjapp As Object
Dim pjProject As MSPProject.Project
Dim strTaskName, strDuration, strStartDate, strEndDate, strResource, strCost, strTaskID, strType As String
Dim newproj
Set pjapp = CreateObject("MSPProject.Application")
If pjapp Is Nothing Then
    MsgBox "MsProject is not installed"
End If
pjapp.Visible = True
Set newproj = pjapp.Projects.Add
newproj.Title = "Test"
Set ActiveProject = newproj

TableEditEx Name:="&Entry", TaskTable:=True, NewFieldName:="COST", Title:="COST", Width:=12, ShowInMenu:=True, ColumnPosition:=-1

TableApply Name:="&Entry"

TableEditEx Name:="&Entry", TaskTable:=True, NewFieldName:="Text1", Title:="Text1", Width:=12, ShowInMenu:=True, ColumnPosition:=-1

TableApply Name:="&Entry"

lastrow = ThisWorkbook.Sheets("Activity Sequence").Cells(Rows.Count, 1).End(xlUp).Row
For i = 2 To lastrow
    strTaskName = Worksheets("Activity Sequence").Range("A" & i)
    strDuration = Worksheets("Activity Sequence").Range("d" & i).Value
    strStartDate = Worksheets("Activity Sequence").Range("e" & i).Value
    strResource = Worksheets("Activity Sequence").Range("b" & i)
    strCost = Worksheets("Activity Sequence").Range("c" & i)
    strTaskID = Worksheets("Activity Sequence").Range("a" & i)
    strType = Worksheets("Activity Sequence").Range("g" & i).Value
    newproj.Tasks.Add strTaskName
    newproj.Tasks(i - 1).Duration = strDuration & "days"
    newproj.Tasks(i - 1).Start = strStartDate
    newproj.Tasks(i - 1).ResourceNames = strResource
    newproj.Tasks(i - 1).Cost = strCost
    newproj.Tasks(i - 1).Text1 = strType
Next
End Sub
```

Figure 4.18 VBA code of the plug-in for exporting data to Microsoft Project

### **4.5.3 Automatically transfer data to Microsoft Project**

The created plug-in is the bridge between cost estimation and schedule planning in this developed model. The data, after organization in Excel, would be transferred to Microsoft Project, thus users can intuitively adjust the construction sequence, interval time, and buffer time between construction activities based on the project's conditions and requirements.

### **4.6 Sustainability evaluation**

Another objective of this developed model is to evaluate the preliminary sustainability performance of the proposed project at the conceptual design stage. As discussed in section 4.3, "LEED Points", as a new attribute of families, has been created in the Revit 3D model, and the potential LEED points of the materials and components can be inserted into it based on the LEED information collected from product suppliers and the USGBC publishers. For instance, as shown in Figure 4.19, the potential LEED points of the material of this type of awning window is stored in the 3D model in Revit. When the 3D model information is extracted into Excel, this LEED information for the materials and components of the proposed project is exported as well, and the LEED points is shown in the column "LEED Points" in the exported workbook as Figure 4.20.

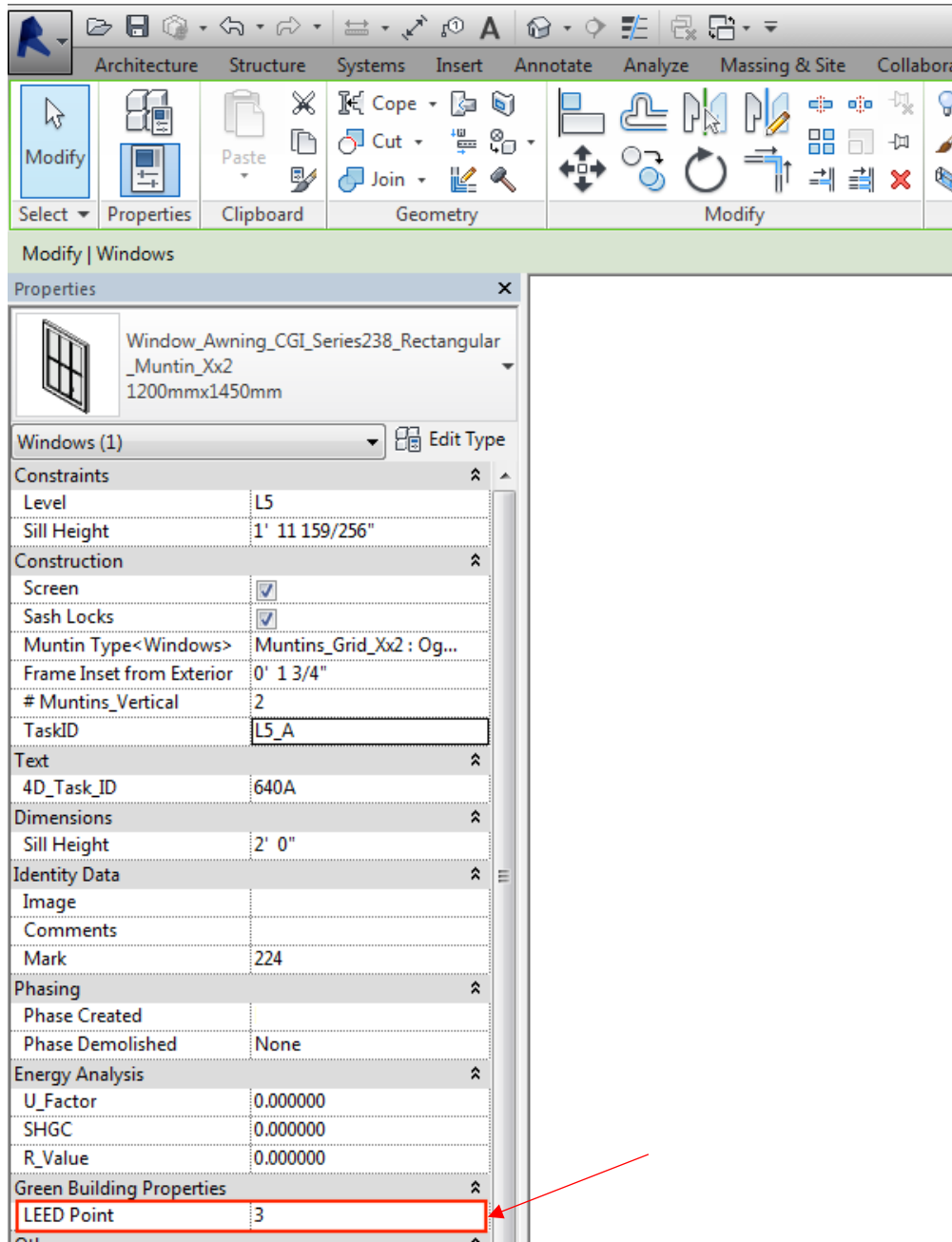


Figure 4.19 Insert the potential LEED points into the window properties

	B	C	D	E	F	G	H	I	J
	Category	Family Name	Type Name	Level	Keynote	Unit Cost	Cost	TaskID	LEED Point
1					#N/A	#N/A	#N/A		
2					#N/A	#N/A	#N/A		
3					#N/A	#N/A	#N/A		
4					#N/A	#N/A	#N/A		
5					#N/A	#N/A	#N/A		
6					#N/A	#N/A	#N/A		
7					#N/A	#N/A	#N/A		
8					#N/A	#N/A	#N/A		
9					#N/A	#N/A	#N/A		
10					#N/A	#N/A	#N/A		
11					#N/A	#N/A	#N/A		
12					#N/A	#N/A	#N/A		
13					#N/A	#N/A	#N/A		
14					#N/A	#N/A	#N/A		
15					#N/A	#N/A	#N/A		
16					#N/A	#N/A	#N/A		
17					#N/A	#N/A	#N/A		
18					#N/A	#N/A	#N/A		
19					#N/A	#N/A	#N/A		
20					#N/A	#N/A	#N/A		
21					#N/A	#N/A	#N/A		
22					#N/A	#N/A	#N/A		
23					#N/A	#N/A	#N/A		
24					#N/A	#N/A	#N/A		
25					#N/A	#N/A	#N/A		
26					#N/A	#N/A	#N/A		
27					#N/A	#N/A	#N/A		
28					#N/A	#N/A	#N/A		
29					#N/A	#N/A	#N/A		
30					#N/A	#N/A	#N/A		
31					#N/A	#N/A	#N/A		
32					#N/A	#N/A	#N/A		
33					#N/A	#N/A	#N/A		
34					#N/A	#N/A	#N/A		
35					#N/A	#N/A	#N/A		
36					#N/A	#N/A	#N/A		
37					#N/A	#N/A	#N/A		
38					#N/A	#N/A	#N/A		
39					#N/A	#N/A	#N/A		
40					#N/A	#N/A	#N/A		
41					#N/A	#N/A	#N/A		

Figure 4.20 The LEED points can be shown in this column after data abstraction

As there are several types of materials and components for one category, the LEED points earned by the materials in one category are varied. In order to obtain the most LEED points earned by this proposed project in the material and resource criterial, we take the maximum value as the approximate number of LEED points for the category. After determining the potential LEED points of each category in the proposed project, they are added up to obtain the potential LEED points that might be earned in the material and resource section if designers used these sustainable materials and components in the proposed building.

#### **4.7 Integration of a 5D module**

Integrating the 3D model with cost estimates and schedule planning in a 5D module is very meaningful for owners and designers as they can predict the proposed project's construction cost and duration at the preliminary stage. Additionally, the integrated model allows engineers to recognize and avoid the potential risks that might occur during the physical construction process through the construction simulation.

This 5D module is developed in another BIM tool, Naviswork, in which architects, estimators and planners can review the integrated model and the sequence of construction for the proposed project. The development process of the 5D module follows these three steps.

1) Transfer the 3D model from Revit to Naviswork:

Data transfer in a BIM platform is convenient and efficient as BIM tools share the same interface and specifications. There are several methods for importing the 3D architectural model from Revit to Naviswork. In order to preserve the data of the 3D model in the transfer process, this developed model chooses to apply the add-ins attached in Revit. As shown in Figure 4.21, the tool "External tool" is used to export the 3D model and save it in an NWC file format. This kind of file can be recognized by Naviswork directly, and it can import the completed 3D model data into Naviswork at the same time.

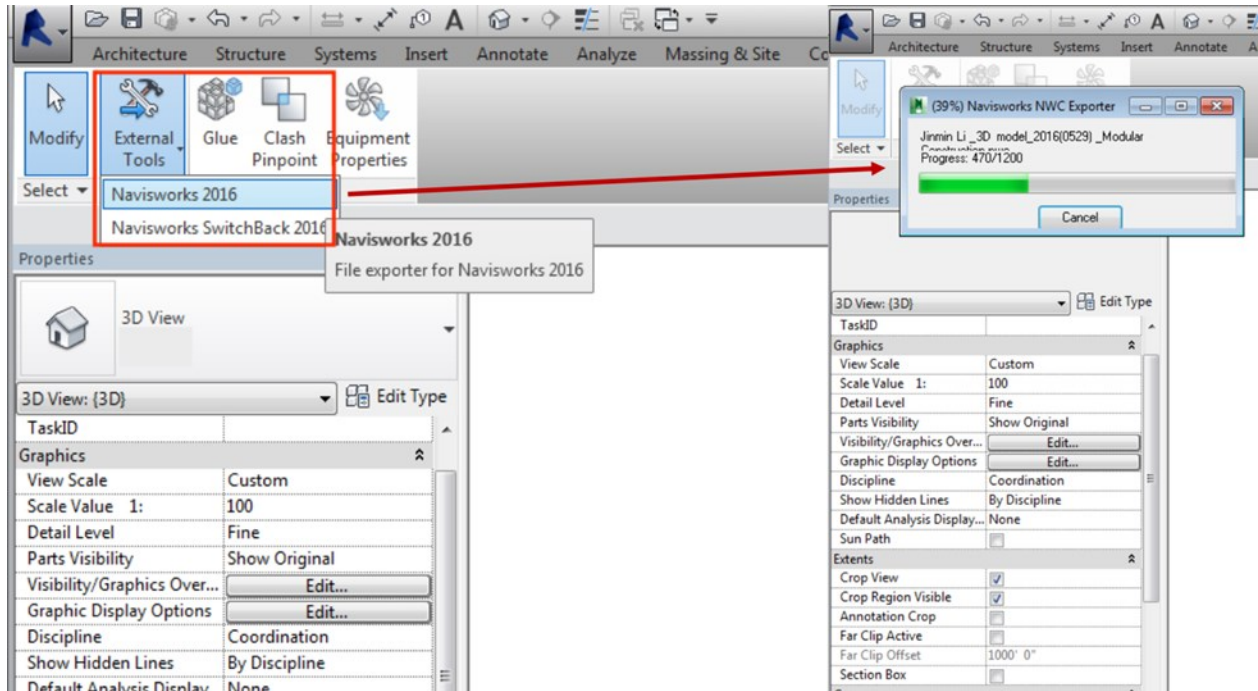


Figure 4.21 Exporting the 3D model from Revit to Naviswork

2) Load the construction cost data and schedule information into Naviswork:

The next step is to load the construction cost data and schedule of the proposed project into Naviswork. As discussed in Section 4.4, the data for the 3D architectural model has been automatically exported to Excel by BIMiTs, and these data are then sorted and organized based on the TaskID for the subtotal cost and duration calculation. After that, these data such as TaskID, subtotal construction cost, duration, and crew resource would be exported to Microsoft Project in one “click.” As shown in Figure 4.22 there is a link between Naviswork and Microsoft Project that users can use to import the data and schedule of the proposed building project, and to map these data to the appropriate set in the next step in Naviswork for simulation.

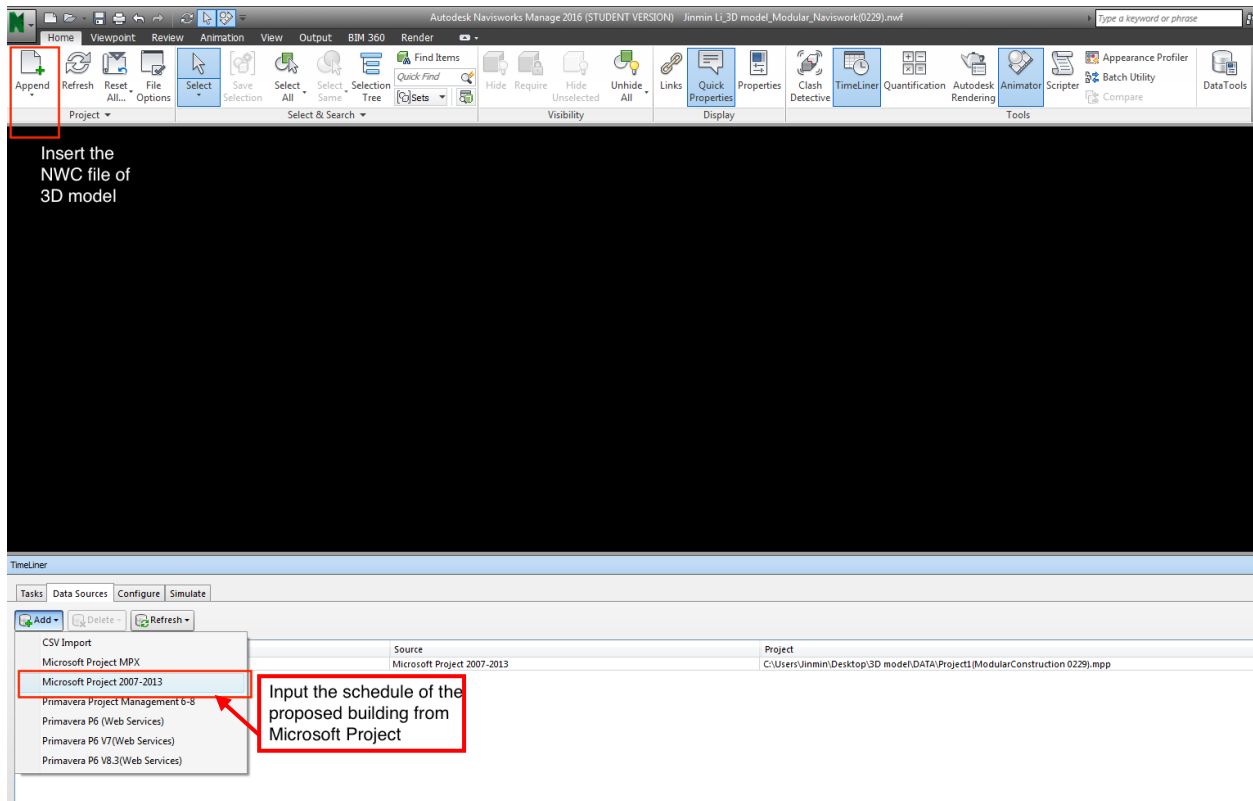


Figure 4.22 Appending the 3D model and linking the appropriate schedule in Naviswork

### 3) Integrating all the data into one 5D model:

After importing the 3D model, construction cost data and schedule of the proposed building into Naviswork, users can merge all these data together into a 5D model. In order to map the construction cost and duration to the corresponding construction activity of a proposed building, the user sorts the elements of the 3D model by the TaskID, by considering each task as a unique “set” in the Naviswork model, and assigns a TaskID to it as the name, which means that a set represents a construction task in Naviswork. Then these sets of the 3D model can be mapped automatically with the appropriate construction subtotal cost and duration in Naviswork. At this time, the 5D integrated model is complete and can be used for construction simulation. This simulation provides owners and engineers with not only the animated construction process, but also the construction cost and accumulated duration of every construction stage.

## 4.8 Summary

This chapter explained the development of the proposed integrated model to improve the reliability and efficiency of cost estimation and schedule planning for construction projects as well as sustainability evaluation at the conceptual design stage. The developed model can be applied to both traditional and modular construction types based on different settings, so that users can have an overview of the cost, duration and sustainability of different alternatives of the proposed projects and can make the right decision in a short time.

The core of the developed model is an automatic data transfer in which BIM enhances the cooperation among the 3D model, the 4D model, and the 5D model. This is accomplished by applying BIMiTs to automatically export the quantity, cost data, family type, material information, TaskID, and LEED points using a customized template. These data can then be organized based on the TaskID in Excel for construction cost estimation and duration calculation before exporting to Microsoft Project for schedule planning by using another plug-in developed in Excel. The 3D architectural model, construction cost data, and schedule can then be integrated into a 5D model to do a construction process simulation. Another contribution of the developed model is a method to import the LEED points into the 3D model and then automatically export them to make a preliminary evaluation of the sustainability of the proposed project according to the LEED v4 rating system.

## **Chapter 5**

### **Model Validation**

This chapter evaluates the workability of the developed model and validates its capabilities of executing the necessary tasks while designing proposed projects at the conceptual stage. The validation is fulfilled by using a proposed hotel project, which currently is under its feasibility study stage in an attempt to be built in 2017 in Ottawa. Its owners and designers want to have an idea about the budget and construction schedule of different alternatives in an efficient and reliable way. This validation will present how the model can shorten the preparation time for cost estimation and scheduling and obtain a preliminary evaluation of the project's sustainability at its initial design stage. At last, this chapter also provides a comparison of the construction cost, project duration, and accumulated LEED points between conventional construction and modular construction.

#### **5.1 Real case project information**

The real project is an express hotel. Here is the basic information for this project:

Project Title:	Green Express Hotel
Gross Square feet:	39,717 square feet
Stories:	6
Height:	72 feet
Location:	1242 Kilborn Place, Ottawa, Ontario, Canada
Planned start of construction date:	2017.05.01

Structure type:

Reinforced Concrete Frame Structure

**5.2 3D architectural modelling**

Based on the requirements, the 3D architectural model of this case hotel project will be developed in Autodesk Revit. In order to create a sustainable building, this 3D model will use the green families collected from suppliers, and most of them would be prefabricated components. Figure 5.1 shows the completed floor plan of the created model and Figure 5.2 illustrates a 3D view of the hotel project.

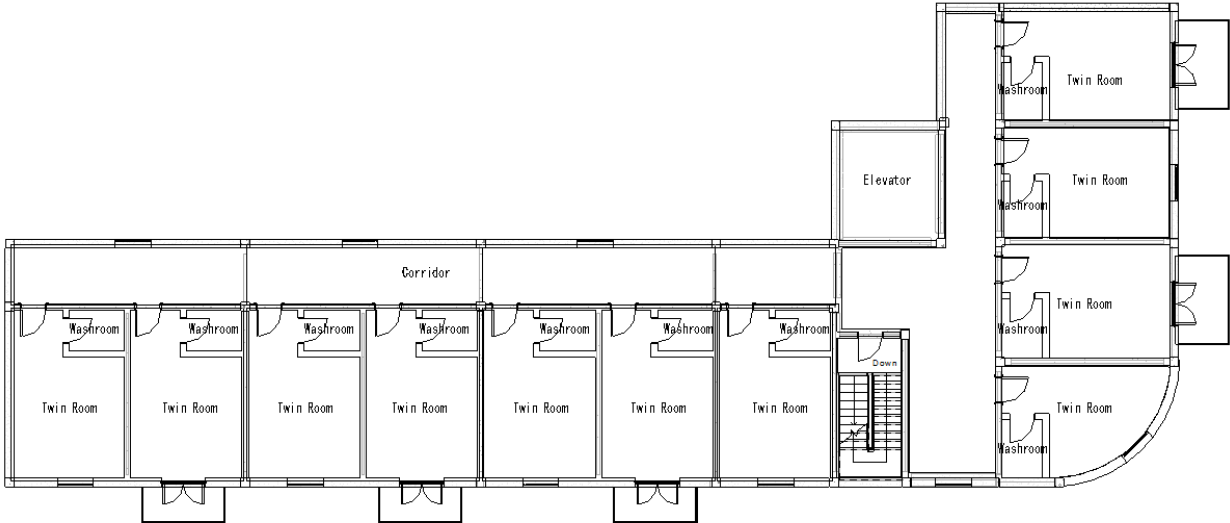


Figure 5.1 Floor plan of the proposed hotel



Figure 5.2 The 3D exterior view of the proposed Express Hotel

After creating the 3D model, the cost data and LEED points are inserted into Revit as seen in Figure 5.3, so that each element in the 3D model has appropriate data related to the construction cost estimate and sustainability evaluation.

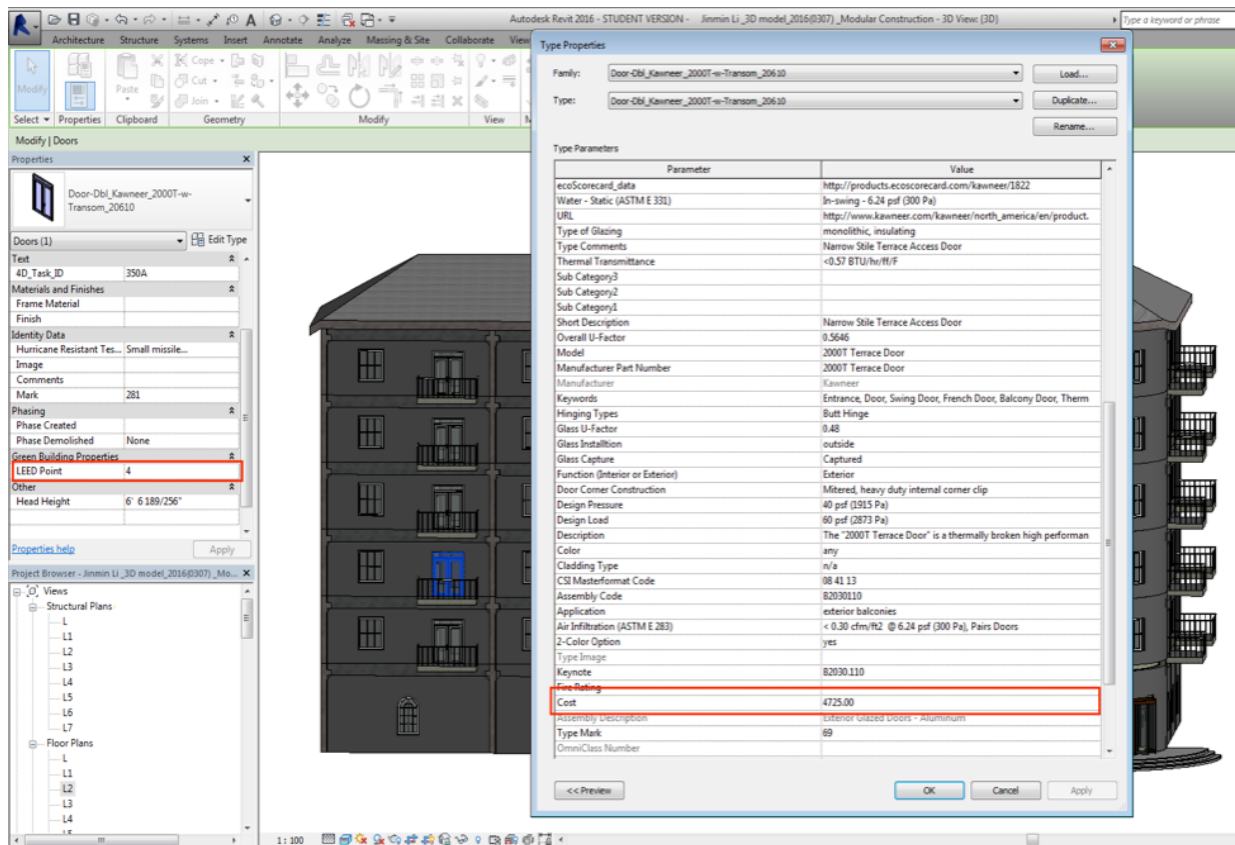


Figure 5.3 Inserting the cost value and LEED points of one type of window into Revit

The elements of the created 3D model are then divided into different work packages and assigned different TaskIDs based on the construction type.

For conventional construction, the hotel construction is divided into six zones, which are: Zone A, Zone B, Zone C, Zone D, Zone E and Zone F as illustrated in Figure 35. According to the typical on-site construction sequence of foundation development, floor, walls, columns, beams, roofs, then doors and windows, a unique task ID is assigned to each construction task. For example, as shown in Figure 5.4, the windows in Zone A of Floor 1 are filtered, and then assigned a task ID of “140A”, and so on. For this TaskID, “1” stands for Level 1; “40” presents the construction sequence of windows installation; and “A” stands for Zone A.

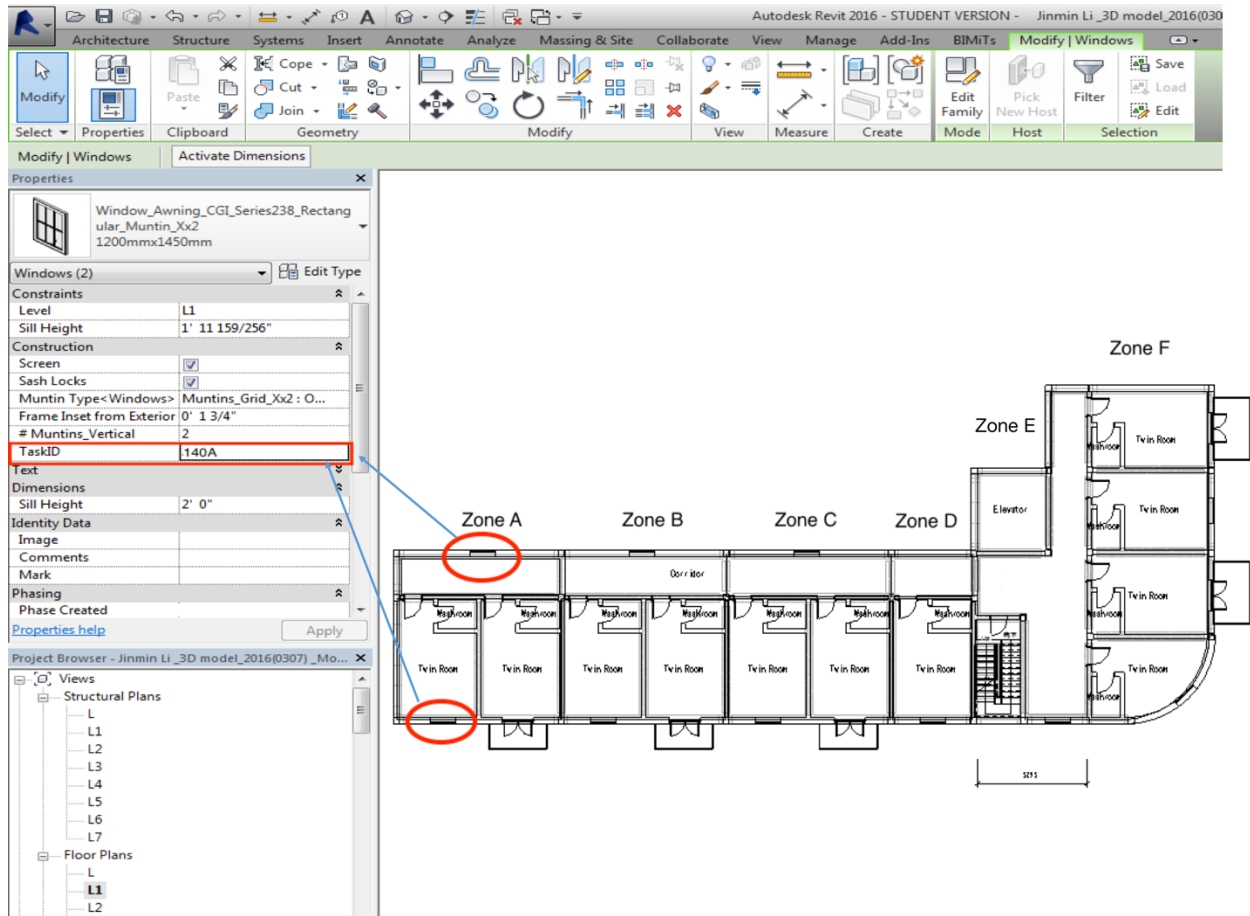


Figure 5.4 Assigning a TaskID to the windows in Zone A at Level 1

For modular construction, this process is relatively simpler. As shown in Figure 5.5, one room is selected as a unit that can be produced in the factory and then be shipped to the construction site for assembly, then assigned a task ID based on the assembly sequence. For instance, the room highlighted can be considered as one unit and assigned the TaskID “L\_A”, in which “L” stands for the ground floor and “A” stands for assembly sequence of this unit.

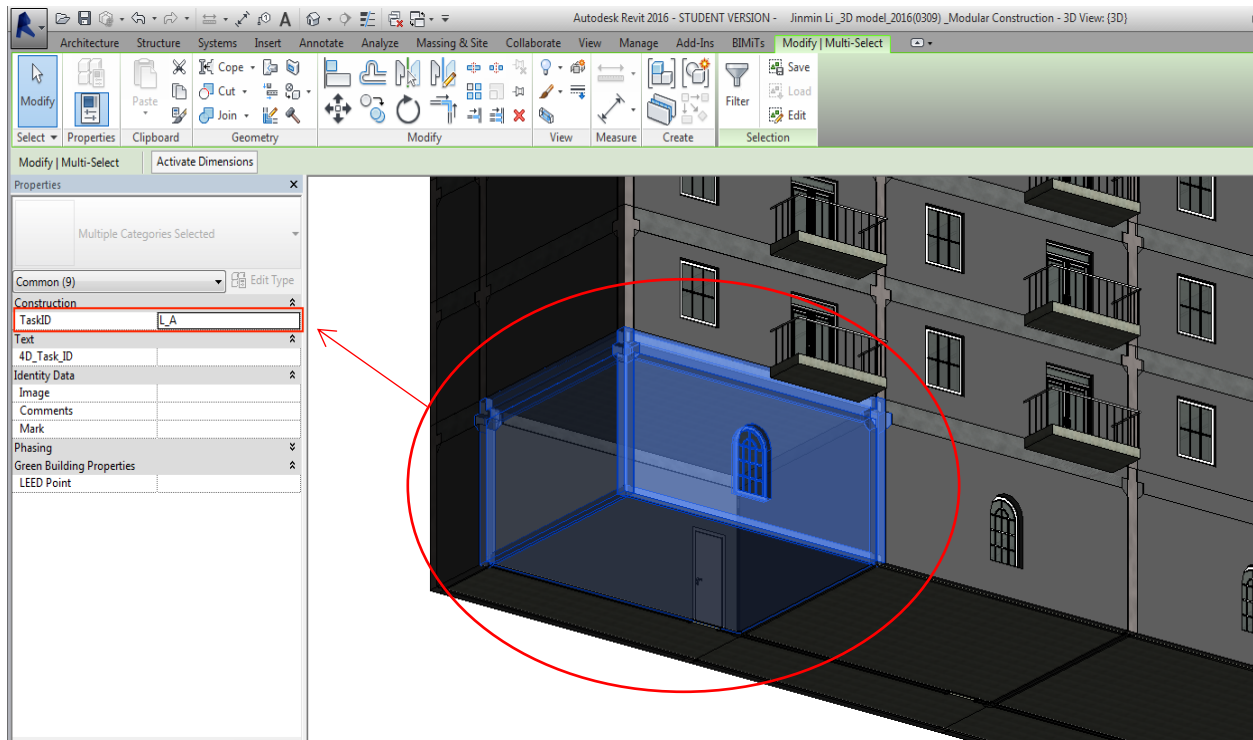


Figure 5.5 Assigning the TaskID “L\_A” to a module on the ground floor

### 5.3 Construction cost estimation for the case project

The 3D model of the express hotel has been built in Revit and the cost data and LEED points have been input into the family properties. At this time users can export these data from Revit to Excel for estimating the construction cost using the following steps:

- 1) For conventional construction:
  - a) Choose the template and export data to Excel

When the 3D model is completed and ready to export, as shown in Figure 5.6, by using the “datalink” in BIMiTs, users can choose the specific template to store the data from 3D BIM model of the projects. Note that users can set different templates for different projects. There are two templates for this hotel project; one is for traditional construction and another is for modular construction.

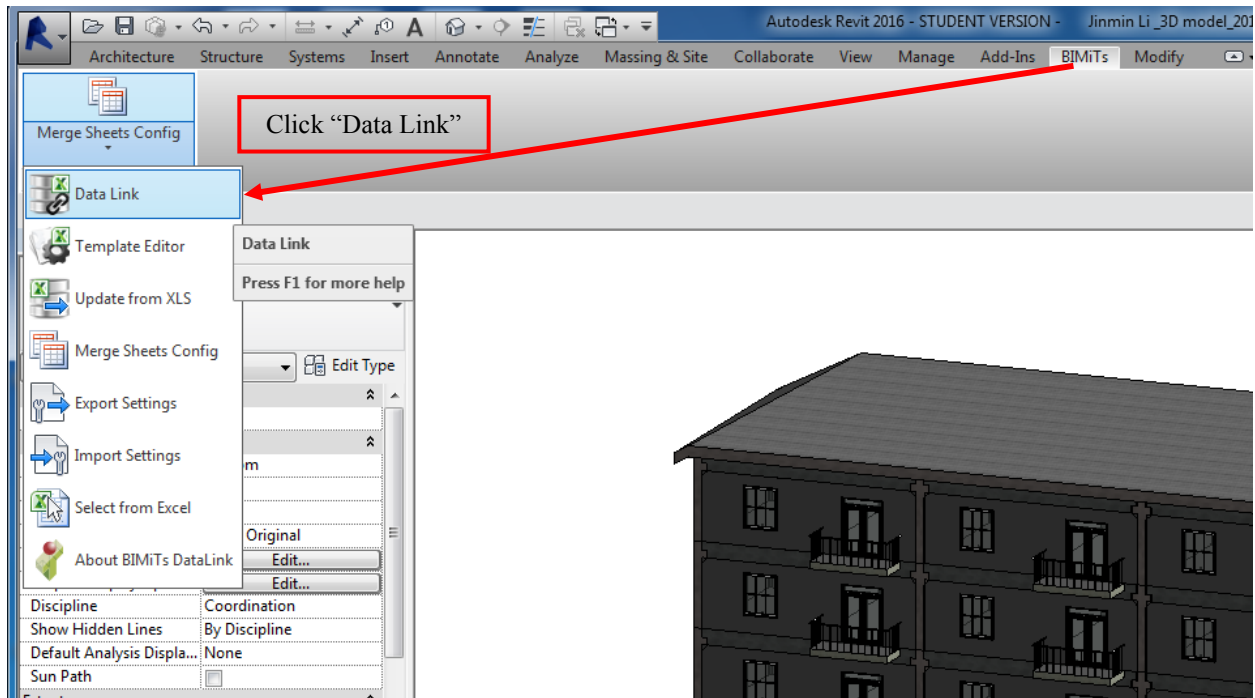


Figure 5.6 Click Data Link for data exporting

After choosing the template for conventional construction, then choose a blank worksheet to save the data from Revit. As shown in Figure 5.7, there is a process bar which appears after the user clicks “OK,” which means that the data is being automatically extracted from the 3D model and exported to the Excel worksheet.

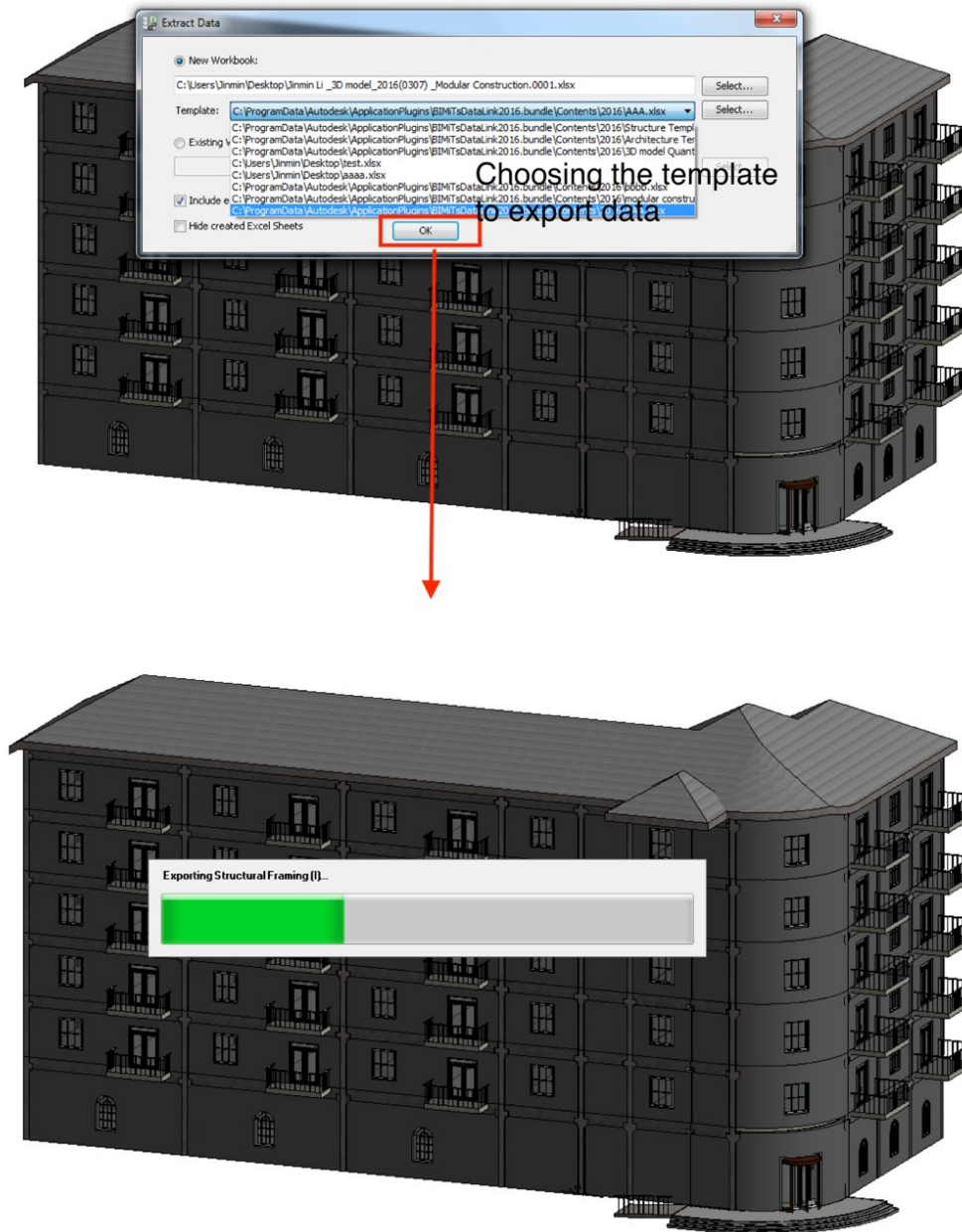


Figure 5.7 Choosing exporting data and extracting data from Revit to Excel

b) Calculate the direct construction cost subtotal of every category

When the process bar finishes running, the workbook will be opened automatically and all data that needs to be extracted has been transferred to this workbook from the 3D model in Revit. This is the automatic QTO process and Appendix B presents a sample of this proposed project's QTO. Figure 5.8 shows an example of the floor category worksheet, in which the columns under

the green titles are automatically extracted from BIM, while the cost of each floor board shown under the column “cost” is the result of multiplying “quantity” by “unit cost” as by the pre-set formula. The function “SUM” is then used to add up all the elements in the floor category to obtain the construction cost subtotal of \$930,677. Each category’s cost subtotal is calculated in this way and all the subtotals are added up to get the total direct construction cost of \$4,908,912.

ID	Category	Family Name	Type Name	Thickness	Level	Volume	Area	Unit	Keynote	Unit Cost	Cost	Cost Subtotal
2	Floors	Floor	Floor Panel 120C	0.82	L1	47.67	58.13	S.F	B2010.102	31.61	1837.33	930677.03
3	Floors	Floor	Floor Panel 120C	0.82	L1	47.67	58.13	S.F	B2010.102	31.61	1837.33	
4	Floors	Floor	Floor Panel 120C	0.82	L3	47.67	58.13	S.F	B2010.102	31.61	1837.33	
5	Floors	Floor	Floor Panel 120C	0.82	L3	47.67	58.13	S.F	B2010.102	31.61	1837.33	
6	Floors	Floor	Floor Panel 120C	0.82	L1	29.65	36.15	S.F	B2010.102	31.61	1142.75	
7	Floors	Floor	Floor Panel 120C	0.82	L1	29.66	36.17	S.F	B2010.102	31.61	1143.23	
8	Floors	Floor	Floor Panel 120C	0.82	L1	29.66	36.17	S.F	B2010.102	31.61	1143.23	
9	Floors	Floor	Floor Panel 120C	0.82	L3	29.66	36.17	S.F	B2010.102	31.61	1143.23	
10	Floors	Floor	Floor Panel 120C	0.82	L3	29.66	36.17	S.F	B2010.102	31.61	1143.23	
11	Floors	Floor	Floor Panel 120C	0.82	L3	29.66	36.17	S.F	B2010.102	31.61	1143.23	
12	Floors	Floor	Floor Panel 120C	0.82	L	408.26	497.75	S.F	B2010.102	31.61	15733.76	
13	Floors	Floor	Floor Panel 120C	0.82	L	408.43	497.96	S.F	B2010.102	31.61	15740.53	
14	Floors	Floor	Floor Panel 120C	0.82	L	408.43	497.96	S.F	B2010.102	31.61	15740.53	
15	Floors	Floor	Floor Panel 120C	0.82	L	201.76	245.98	S.F	B2010.102	31.61	7775.48	
16	Floors	Floor	Floor Panel 120C	0.82	L	144.58	176.27	S.F	B2010.102	31.61	5571.97	
17	Floors	Floor	Floor Panel 120C	0.82	L	143.23	174.63	S.F	B2010.102	31.61	5520.11	
18	Floors	Floor	Floor Panel 120C	0.82	L	143.23	174.63	S.F	B2010.102	31.61	5520.11	
19	Floors	Floor	Floor Panel 120C	0.82	L	70.75	86.26	S.F	B2010.102	31.61	2726.81	
20	Floors	Floor	Floor Panel 120C	0.82	L	1184.15	1443.73	S.F	B2010.102	31.61	45636.27	
21	Floors	Floor	Floor Panel 120C	0.82	L1	408.26	497.75	S.F	B2010.102	31.61	15733.76	
22	Floors	Floor	Floor Panel 120C	0.82	L1	408.43	497.96	S.F	B2010.102	31.61	15740.53	
23	Floors	Floor	Floor Panel 120C	0.82	L1	408.43	497.96	S.F	B2010.102	31.61	15740.53	
24	Floors	Floor	Floor Panel 120C	0.82	L1	201.76	245.98	S.F	B2010.102	31.61	7775.48	
25	Floors	Floor	Floor Panel 120C	0.82	L1	143.23	174.63	S.F	B2010.102	31.61	5520.11	

Figure 5.8 Working out the construction cost subtotal of the floor category

c) Adjust the total direct cost calculation

As the cost data used in this project is from R.S. Means Building Construction Cost Data for year 2013, the total direct construction cost should be adjusted by using the predicted inflation rate of 2.4% for year 2017 (Trading Economics, 2016) and a location factor of 109.2 for the city of Ottawa according to R.S. Means as follows:

$$\text{Construction cost}_{\text{Conventional Construction}} = \$4,908,912 \times (1 + 2.4\%)^4 \times \left(\frac{109.2}{100} \times 100\%\right) = \$5,893,967.16 \quad 5.1$$

2) For modular construction:

The process of cost estimation for modular construction is similar to that of conventional construction. The main difference is that after calculating the total construction cost, this cost would be adjusted by an index. This is because, as discussed above, modular construction can bring benefits such as reducing on-site labour power, producing less construction waste, and so on, to save on the construction budget. According to the result of the survey about “how modular construction can impact the project’s budget” taken by Mc-Graw Hill Construction (2011), we take 6% as the index to adjust the construction cost as follow:

$$\text{Construction Cost}_{\text{Modular Construction}} = \$5,893,967.16 \times (1 - 6\%) = \$5,540,329.13 \quad 5.2$$

## 5.4 Schedule Planning

Considering that the quantity of each category of the 3D model has been extracted from Revit to Excel, the duration of each construction activity can be calculated in the workbook and then exported to Microsoft Project for schedule planning.

1) For conventional construction:

a) Input the daily output and crew information

The first step is to input the daily output and the number of crew into the category worksheet. Figure 5.9 presents the process of inserting the daily output and the crew information in the wall category worksheet. The data of daily output is from RSMeans which is the number of units of a defined construction task can be finished in one eight-hour workday by the designed crew, and the number of crew is assigned by planners based on the available labor resources of the project.

Then, the duration of each construction element can be calculated by the pre-set function and formula in the column titled “duration.”

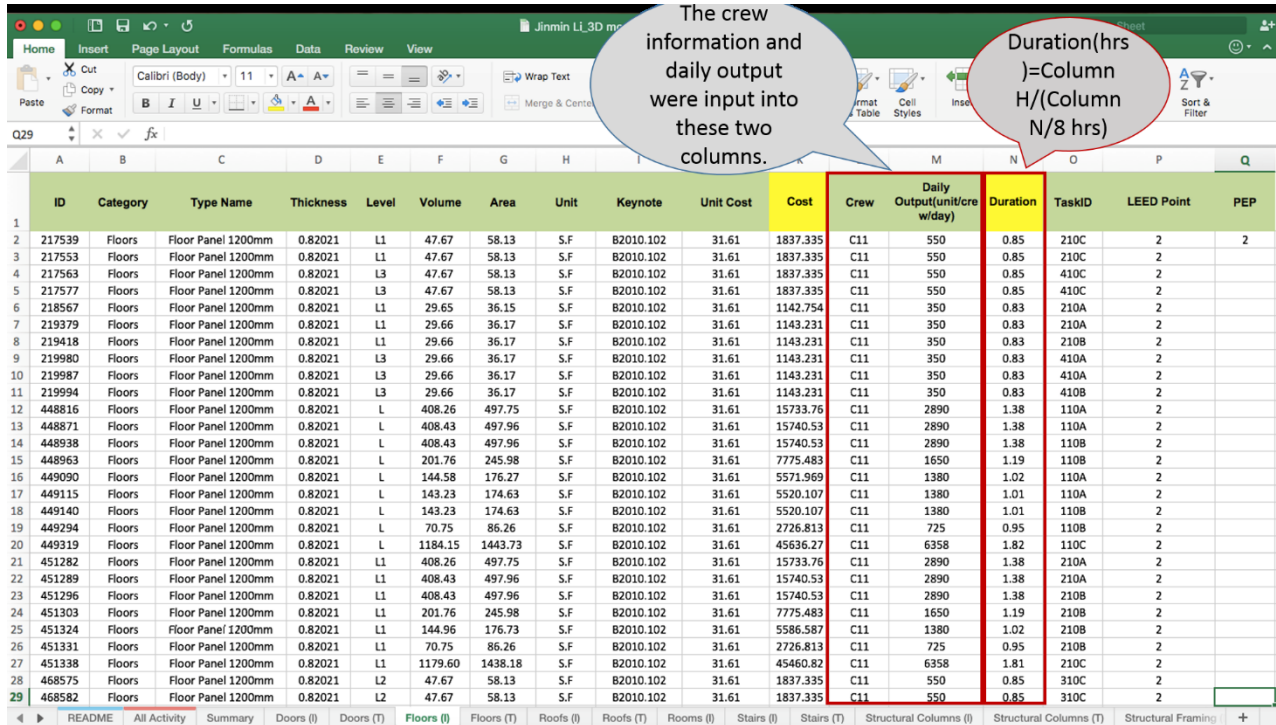


Figure 5.9 Working out the duration of each element in the floor category

b) Organize the data of the construction activities

The workbook is then updated. The data under the columns “daily output,” “crew,” and “duration” of each category worksheet is automatically transferred to the merged worksheet. In order to work out the duration of each task package, the data must be sorted based on the TaskID. Figure 5.10 shows the merged sheet after sorting and summing up the subtotal of duration and construction cost of each construction task. In this way, users can easily know the cost and duration of each construction activity. Appendix E details the process of sorting and organizing in the data in Excel.

Jinmin LT\_3D model Conventional type\_0309

Home Insert Page Layout Formulas Data Review View

Spelling Thesaurus New Comment Delete Previous Next Show/Hide Comment Show All Comments Protect Sheet Protect Workbook Share Workbook Track Changes Restrict Permission

F41 Wall

ID	Level	TaskID	TaskID	Category	Family	Type	Keynote	Quantity	Unit	Crew	Duration(h)	Cost	Subtotal Cost	Duration(d)
448816	L	110A	110A	Floor	Floor	Floor Panel 1200mm	B2010.102	497.75	S.F	C11	1.38	15733.76	42566.37	4.79
448871	L		110A	Floor	Floor	Floor Panel 1200mm	B2010.102	497.96	S.F		1.38	15740.53		
449090	L		110A	Floor	Floor	Floor Panel 1200mm	B2010.102	176.27	S.F		1.02	5571.97		
449115	L	110B	110A	Floor	Floor	Floor Panel 1200mm	B2010.102	174.63	S.F	C11	1.01	5520.11	31762.94	4.54
448938	L		110B	Floor	Floor	Floor Panel 1200mm	B2010.102	497.96	S.F		1.38	15740.53		
448963	L		110B	Floor	Floor	Floor Panel 1200mm	B2010.102	245.98	S.F		1.19	7775.48		
449140	L	110C	110B	Floor	Floor	Floor Panel 1200mm	B2010.102	174.63	S.F	C11	1.01	5520.11	53876.34	3.65
449294	L		110B	Floor	Floor	Floor Panel 1200mm	B2010.102	86.26	S.F		0.95	2726.81		
449319	L		110C	Floor	Floor	Floor Panel 1200mm	B2010.102	1443.73	S.F		1.82	45636.27		
514469	L	120A	110C	Floor	Floor	Floor Panel 1200mm	B2010.102	142.42	S.F	C11	0.89	4501.96	12608.76	6.53
514487	L		110C	Floor	Floor	Floor Panel 1200mm	B2010.102	118.26	S.F		0.95	3738.11		
387509	L		120A	Column	Corner_Precast_Column_with_Corbel_on_Two_Sides_16090	2 Corbie Precast Conmer Column	B1010.207	13.12	L.F.		1.12	2179.13		
393416	L	120B	120A	Column	Corner_Precast_Column_with_Corbel_on_Two_Sides_16090	2 Corbie Precast Conmer Column	B1010.207	13.12	L.F.	E2	1.12	2179.13	12142.72	6.35
394784	L		120A	Column	Precast_Column_with_Corbel_on_Three_Sides_16088	3-Corbel Precastr Column	B1010.207	13.12	L.F.		1.12	2179.13		
395325	L		120A	Column	Precast_Column_with_Corbel_on_Three_Sides_16088	3-Corbel Precastr Column	B1010.207	13.12	L.F.		1.12	2179.13		
398277	L	120C	120A	Column	Precast_Column_with_Corbel_on_Three_Sides_16088	3-Corbel Precastr Column	B1010.207	13.12	L.F.	E2	1.12	2179.13	30612.86	15.68
479617	L		120A	Column	Precast_Column_with_Haunches_2772	4-Corbel Precast Column	B1010.206	9.84	L.F.		0.93	1713.09		
395911	L		120B	Column	Precast_Column_with_Corbel_on_Three_Sides_16088	3-Corbel Precastr Column	B1010.207	13.12	L.F.		1.12	2179.13		
395948	L	130A	120B	Column	Precast_Column_with_Corbel_on_Three_Sides_16088	3-Corbel Precastr Column	B1010.207	13.12	L.F.	E2	1.12	2179.13	12142.72	6.35
398326	L		120B	Column	Precast_Column_with_Corbel_on_Three_Sides_16088	3-Corbel Precastr Column	B1010.207	13.12	L.F.		1.12	2179.13		
398369	L		120B	Column	Precast_Column_with_Corbel_on_Three_Sides_16088	3-Corbel Precastr Column	B1010.207	13.12	L.F.		1.12	2179.13		
479619	L	130A	120B	Column	Precast_Column_with_Haunches_2772	4-Corbel Precast Column	B1010.206	9.84	L.F.	E2	0.93	1713.09	30612.86	15.68
479621	L		120B	Column	Precast_Column_with_Haunches_2772	4-Corbel Precast Column	B1010.206	9.84	L.F.		0.93	1713.09		
393599	L		120C	Column	Corner_Precast_Column_with_Corbel_on_Two_Sides_16090	2 Corbie Precast Conmer Column	B1010.207	13.12	L.F.		1.12	2179.13		
393643	L	130A	120C	Column	Corner_Precast_Column_with_Corbel_on_Two_Sides_16090	2 Corbie Precast Conmer Column	B1010.207	13.12	L.F.	E2	1.12	2179.13	30612.86	15.68
393703	L		120C	Column	Corner_Precast_Column_with_Corbel_on_Two_Sides_16090	2 Corbie Precast Conmer Column	B1010.207	13.12	L.F.		1.12	2179.13		
393739	L		120C	Column	Corner_Precast_Column_with_Corbel_on_Two_Sides_16090	2 Corbie Precast Conmer Column	B1010.207	13.12	L.F.		1.12	2179.13		
393855	L	130A	120C	Column	Corner_Precast_Column_with_Corbel_on_Two_Sides_16090	2 Corbie Precast Conmer Column	B1010.207	13.12	L.F.	E2	1.12	2179.13	30612.86	15.68
394730	L		120C	Column	Corner_Precast_Column_with_Corbel_on_Two_Sides_16090	2 Corbie Precast Conmer Column	B1010.207	13.12	L.F.		1.12	2179.13		
395984	L		120C	Column	Precast_Column_with_Corbel_on_Three_Sides_16088	3-Corbel Precastr Column	B1010.207	13.12	L.F.		1.12	2179.13		
396025	L	130A	120C	Column	Precast_Column_with_Corbel_on_Three_Sides_16088	3-Corbel Precastr Column	B1010.207	13.12	L.F.	E2	1.12	2179.13	30612.86	15.68
396217	L		120C	Column	Precast_Column_with_Corbel_on_Three_Sides_16088	3-Corbel Precastr Column	B1010.207	13.12	L.F.		1.12	2179.13		
396309	L		120C	Column	Precast_Column_with_Corbel_on_Three_Sides_16088	3-Corbel Precastr Column	B1010.207	13.12	L.F.		1.12	2179.13		
396345	L	130A	120C	Column	Precast_Column_with_Haunches_2772	4-Corbel Precast Column	B1010.206	13.12	L.F.	E2	1.12	2284.12	30612.86	15.68
408407	L		120C	Column	Precast_Column_with_Corbel_on_Three_Sides_16088	3-Corbel Precastr Column	B1010.207	13.12	L.F.		1.12	2179.13		
408445	L		120C	Column	Precast_Column_with_Corbel_on_Three_Sides_16088	3-Corbel Precastr Column	B1010.207	13.12	L.F.		1.12	2179.13		
474357	L	130A	120C	Column	Precast_Column_with_Corbel_on_Three_Sides_16088	3-Corbel Precastr Column	B1010.207	13.12	L.F.	E2	1.12	2179.13	30612.86	15.68
415627	L		130A	Wall	Wall	External Wall	B2010.102	268.20	S.F.		1.19	12476.67		
417648	L		130A	Wall	Wall	External Wall	B2010.102	285.37	S.F.		1.23	13275.49		
417817	L	130A	130A	Wall	Wall	External Wall	B2010.102	285.94	S.F.	E2	1.23	13302.08	30612.86	15.68
418027	L		130A	Wall	Wall	External Wall	B2010.102	209.82	S.F.		1.06	9760.62		
418133	L		130A	Wall	Wall	External Wall	B2010.102	88.93	S.F.		0.64	3178.68		

Figure 5.10 Merged sheet of the data from the 3D model

For the convenience of reading and organizing, the columns (TaskID, crew, subtotal cost, subtotal duration) related to schedule planning are copied to a new worksheet as shown in Figure 5.11. Then, the planned starting date is input so that the schedule of each construction task can be worked out.

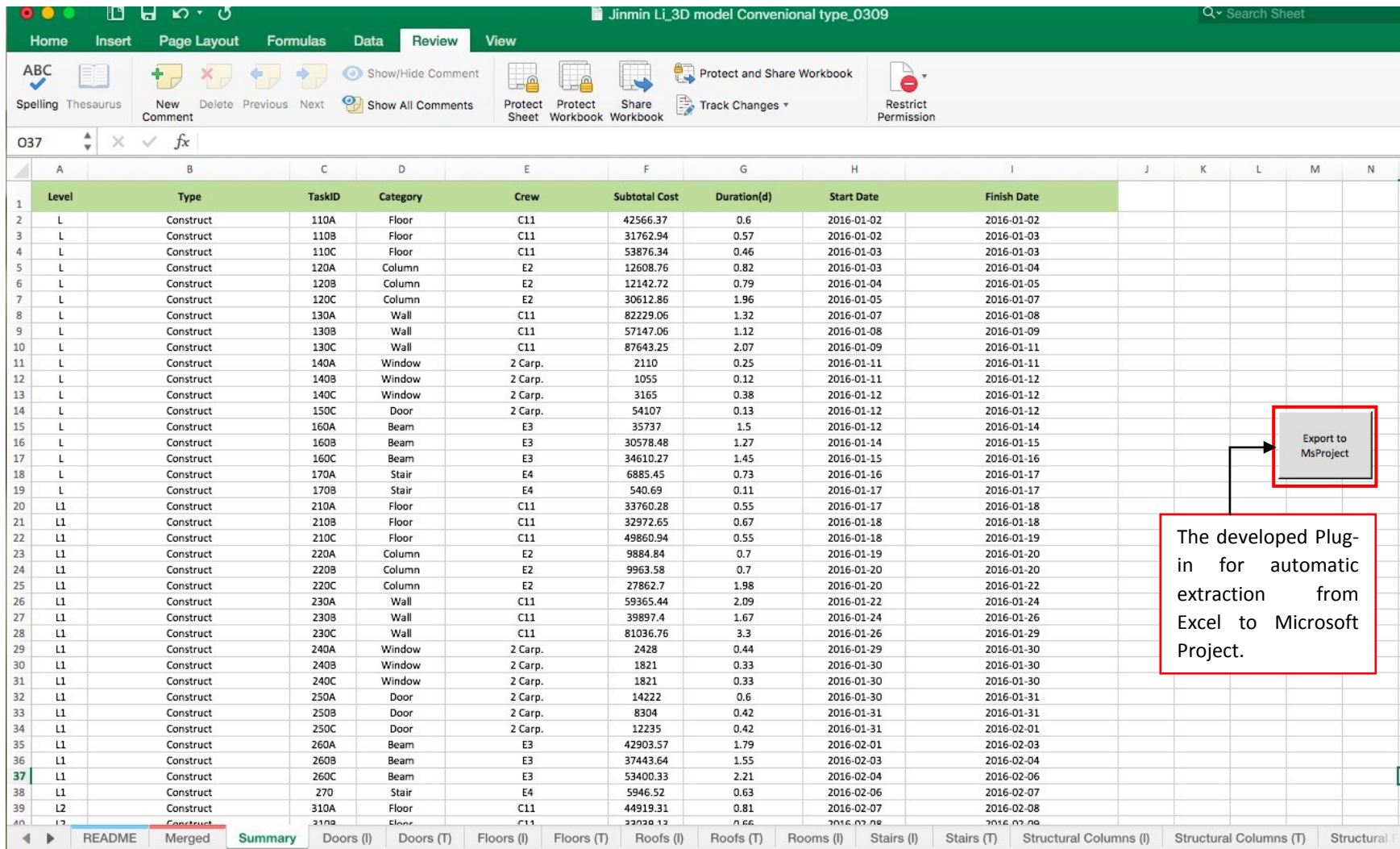


Figure 5.11 The data is organized and ready to export to Microsoft Project (conventional construction)

c) Export data to Microsoft Project

At this time, the duration data and related information of construction activity (such as TaskID, planned starting date, activity duration) has been prepared in Excel and ready to export to Microsoft Project. On clicking the plug-in, Microsoft Project opens and the data is transferred to it automatically. Figure 5.12 illustrates the sample of schedule plan of the hotel project and its Gantt chart. Appendix C shows details about the proposed project’s preliminary schedule. The construction period is 120 workdays. Based on the resource conditions, planners can adjust the activity sequence and the interval time between the adjacent tasks.

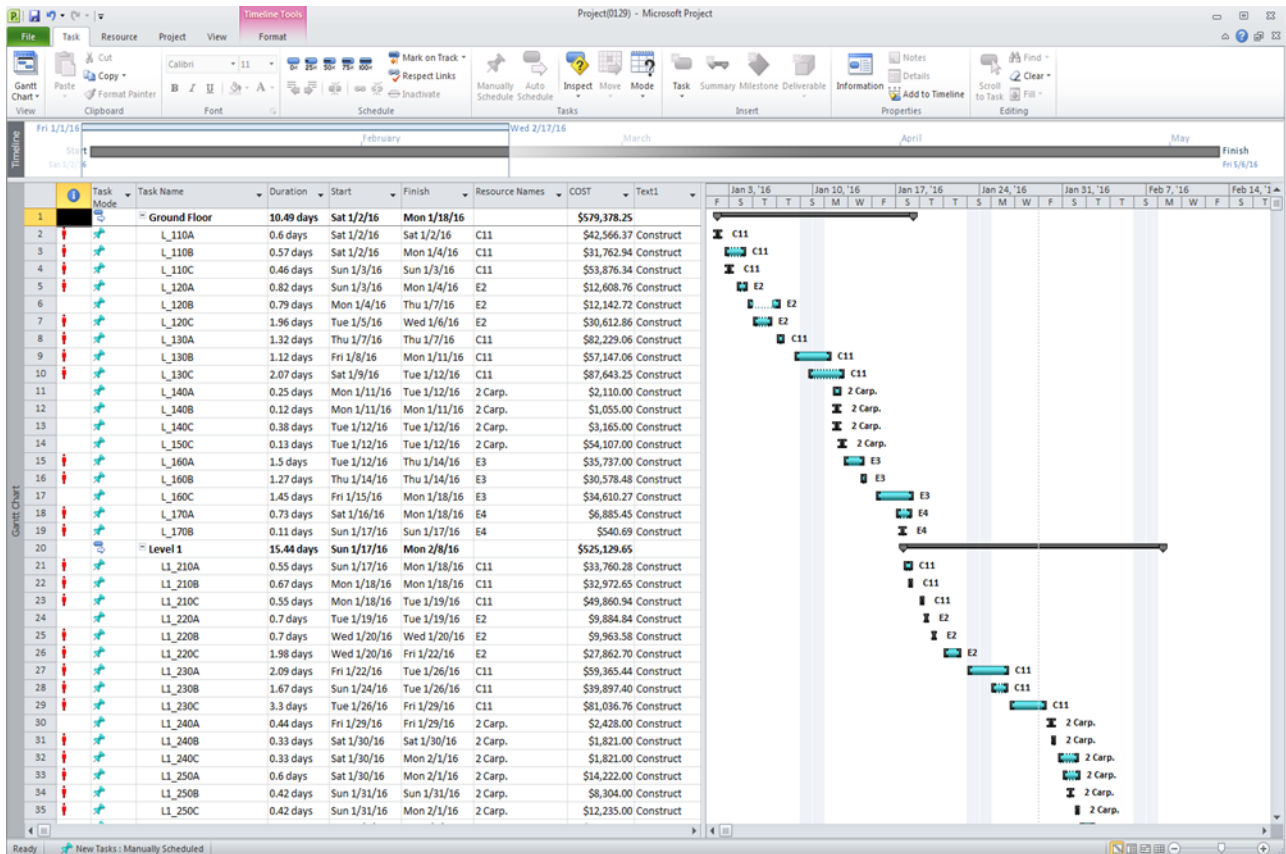


Figure 5.12 The schedule plan for conventional construction of the proposed hotel

2) For modular construction:

Compared with conventional construction, the process of schedule planning for modular construction is simpler. As shown in Figure 5.13, after exporting the data from the 3D model to Excel, the data is sorted and arranged based on the TaskID. According to the data of similar projects and the survey about modular construction taken from Mc-Graw Hill Construction (2011), the installation time of a typical-size unit is approximately 2.6 hours. As each task presents one unit of the hotel project, this installation time is assigned to each task as the duration of that construction task. The data must then be arranged in a new worksheet for the convenience of exporting. The exporting plug-in must be clicked and the TaskID, crew, construction cost subtotal, duration, and start date will be exported directly to Microsoft Project, and the schedule and Gantt chart will automatically open as shown in Figure 5.14 (please refer to Appendix C). The construction duration is 25 workdays if the elected construction method for the proposed project is modular construction.

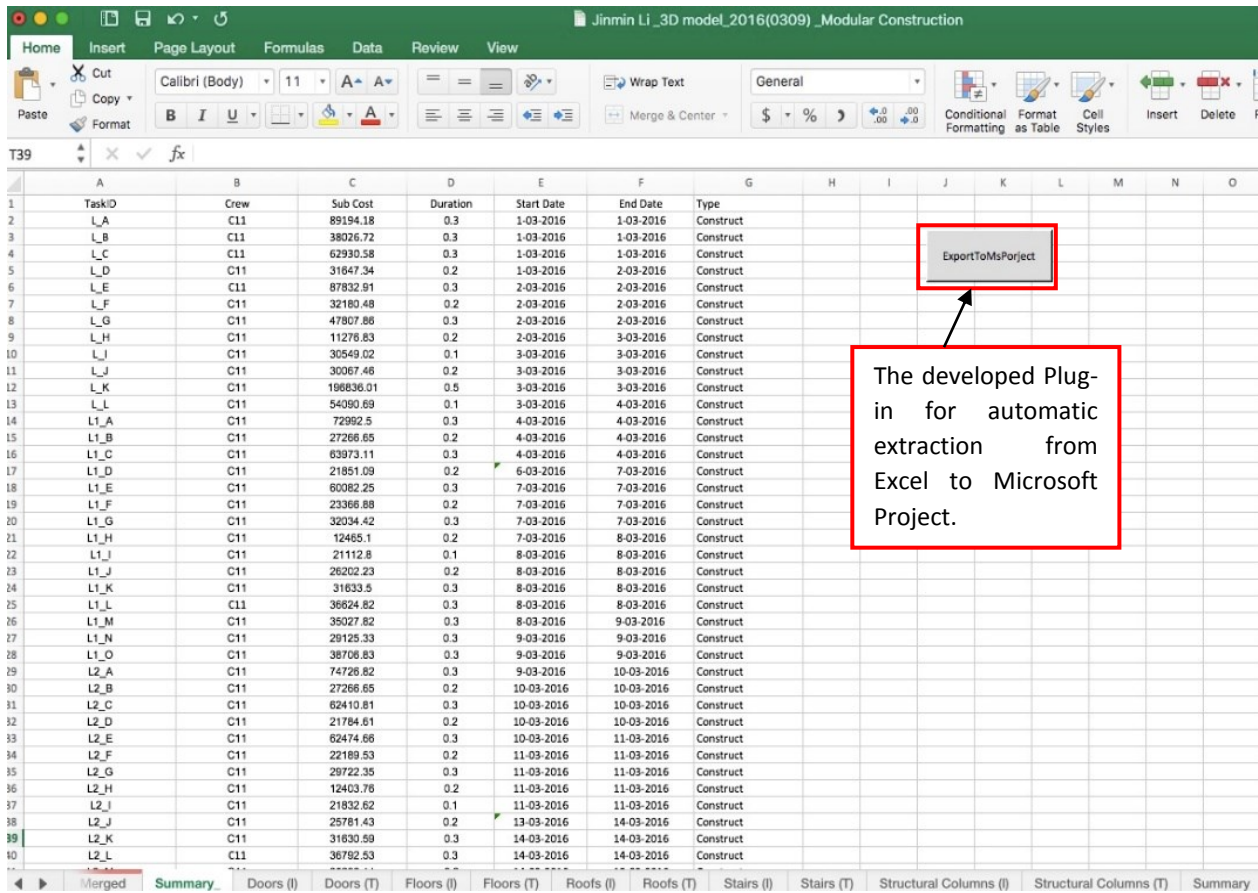


Figure 5.13 The data is organized and ready to export to Microsoft Project (modular construction)

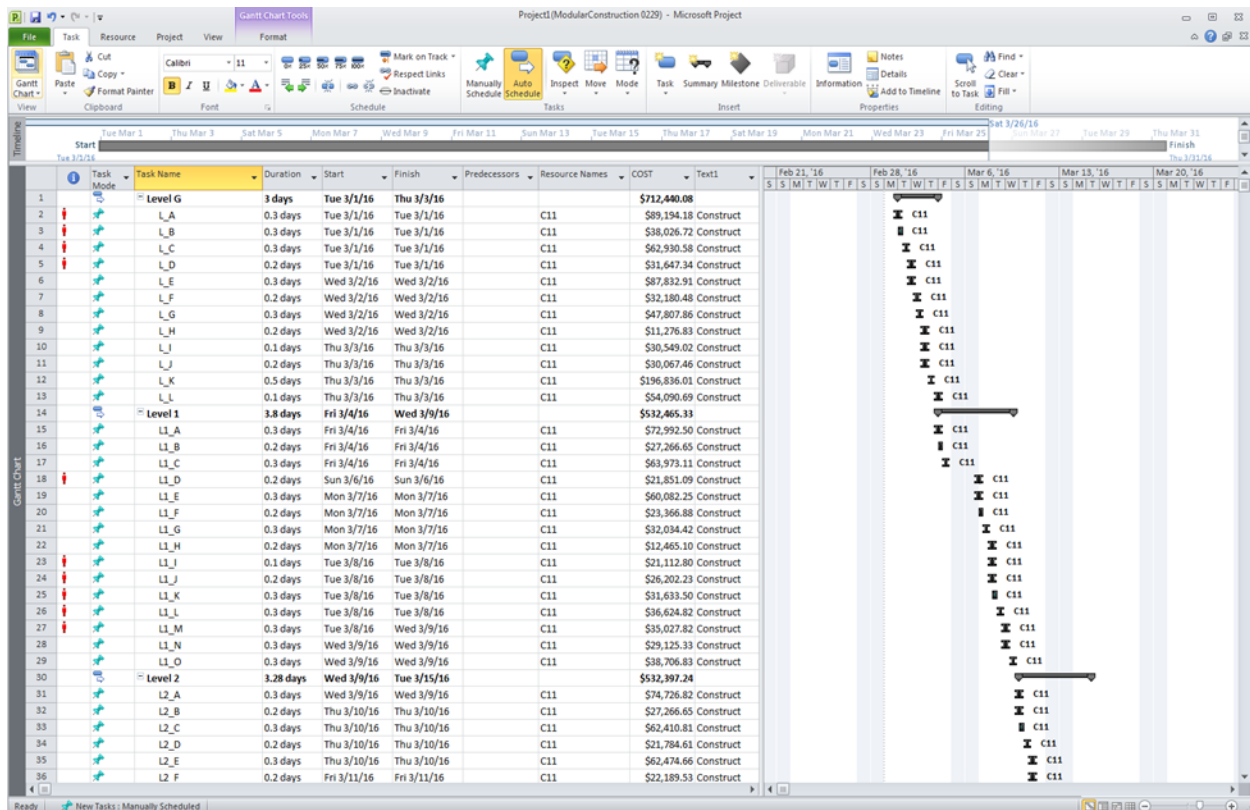


Figure 5.14 The schedule plan for modular construction of the proposed hotel

## 5.5 Sustainability evaluation

When the data is exported to Excel, the LEED points of the materials and components of the project are extracted at the same time. As shown in Figure 5.15, the maximum value of 4 is taken as the potential LEED points (PEP) that may be earned by the materials of the floor category. In this way, the PEP of other categories is collected for the hotel project. As shown in Table 4, the total of the LEED points is 19, which means that if the designer continues to use these materials in the project a total of 19 points on the materials and resources section based on the LEED v4 rating system is earned. It is worth to notice that since this study focuses on the conceptual design stage, this LEED evaluation only considers the sustainable impact with respect to the materials and resources of the components, and this LEED number is not the final sum of the potential points the whole proposed project can earn.

	A	B	C	D	E	F	G	H	I	J	K
1	ID	Category	Family Name	Type Name	Level	Keynote	Unit Cost	Cost	TaskID	LEED Point	PEP
2	182783	Doors	Entrance Door	building Door---1800 x 2500mm 2	L	B2030.110	53550	53550	L_L	3	4
3	332441	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L1	C1020.102	557	557	L1_A	3	
4	332505	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L1	C1020.102	557	557	L1_A	3	
5	332545	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L1	C1020.102	557	557	L1_C	3	
6	332585	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L1	C1020.102	557	557	L1_C	3	
7	332617	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L1	C1020.102	557	557	L1_E	3	
8	332659	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L1	C1020.102	557	557	L1_E	3	
9	332705	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L1	C1020.102	557	557	L1_G	3	
10	332757	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L1	C1020.102	557	557	L1_L	3	
11	332804	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L1	C1020.102	557	557	L1_M	3	
12	332888	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L1	C1020.102	557	557	L1_N	3	
13	452209	Doors	Door-Dbl_Kawneer_2000T-w-Transom_20610	Door-Dbl_Kawneer_2000T-w-Transom_20610	L1	B2030.110	4725	4725	L1_C	4	
14	452210	Doors	Door-Dbl_Kawneer_2000T-w-Transom_20610	Door-Dbl_Kawneer_2000T-w-Transom_20610	L1	B2030.110	4725	4725	L1_A	4	
15	452211	Doors	Door-Dbl_Kawneer_2000T-w-Transom_20610	Door-Dbl_Kawneer_2000T-w-Transom_20610	L1	B2030.110	4725	4725	L1_E	4	
16	452213	Doors	Door-Dbl_Kawneer_2000T-w-Transom_20610	Door-Dbl_Kawneer_2000T-w-Transom_20610	L1	B2030.110	4725	4725	L1_O	4	
17	466664	Doors	Door-Dbl_Kawneer_2000T-w-Transom_20610	Door-Dbl_Kawneer_2000T-w-Transom_20610	L1	B2030.110	4725	4725	L1_M	4	
18	467155	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L1	C1020.102	557	557	L1_O	3	
19	467371	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L1	C1020.102	636	636	L1_A	3	
20	467486	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L1	C1020.102	636	636	L1_A	3	
21	467566	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L1	C1020.102	636	636	L1_C	3	
22	467604	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L1	C1020.102	636	636	L1_C	3	
23	467676	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L1	C1020.102	636	636	L1_E	3	
24	467738	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L1	C1020.102	636	636	L1_E	3	
25	467776	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L1	C1020.102	636	636	L1_G	3	
26	469878	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L2	C1020.102	557	557	L2_A	3	
27	469879	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L2	C1020.102	557	557	L2_A	3	
28	469880	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L2	C1020.102	557	557	L2_C	3	
29	469881	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L2	C1020.102	557	557	L2_C	3	
30	469882	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L2	C1020.102	557	557	L2_E	3	
31	469883	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L2	C1020.102	557	557	L2_E	3	
32	469884	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L2	C1020.102	557	557	L2_G	3	
33	469885	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L2	C1020.102	557	557	L2_L	3	

Take the maximum value.

Figure 5.15 Take the maximum value as the LEED points of the door category

Table 5.1 The potential LEED points of the materials and components of the proposed hotel

Materials and resource	Roof	Floor	Column	Window	Beam	Wall	Door	Stair
Potential LEED point	2	2	2	3	2	1	4	3
Total	19							

## 5.6 5D module of the developed model

By applying the add-in “External tool”, which is attached to the Revit tool, as shown at Figure 5.16, the 3D architectural model of the proposed hotel can be exported and saved in NWC file format. This file can then be opened in Naviswork so that the 3D architectural model and related data are directly transferred to it. At the same time, the construction schedule (for traditional construction or modular construction) of this proposed project can be also linked into Naviswork.

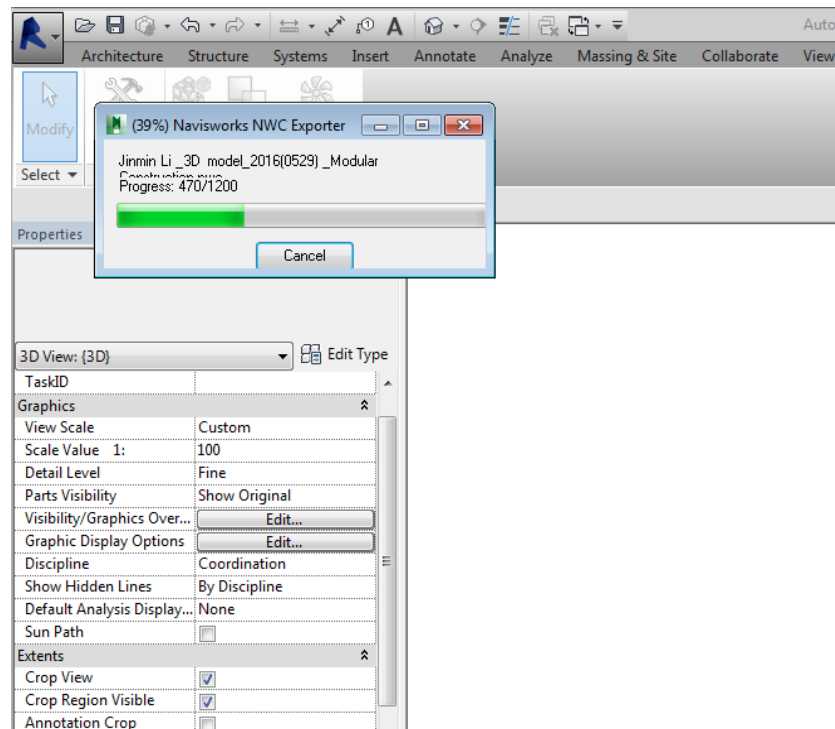


Figure 5.16 The 3D model is exported to the NWC format

The next step is to map the construction tasks in the 3D model with its corresponding tasks information in Naviswork to build the 5D model. As shown in Figure 5.17, the elements with the same TaskID are filtered as a “set”, which can be identified in Naviswok. These sets are named TaskID so that the 3D model “set” can be mapped automatically with its task information matching the same name. Figure 5.18 shows the outcome of this process, where each construction task of the project has its duration data, cost data, construction type, as well as a 3D construction “set.”

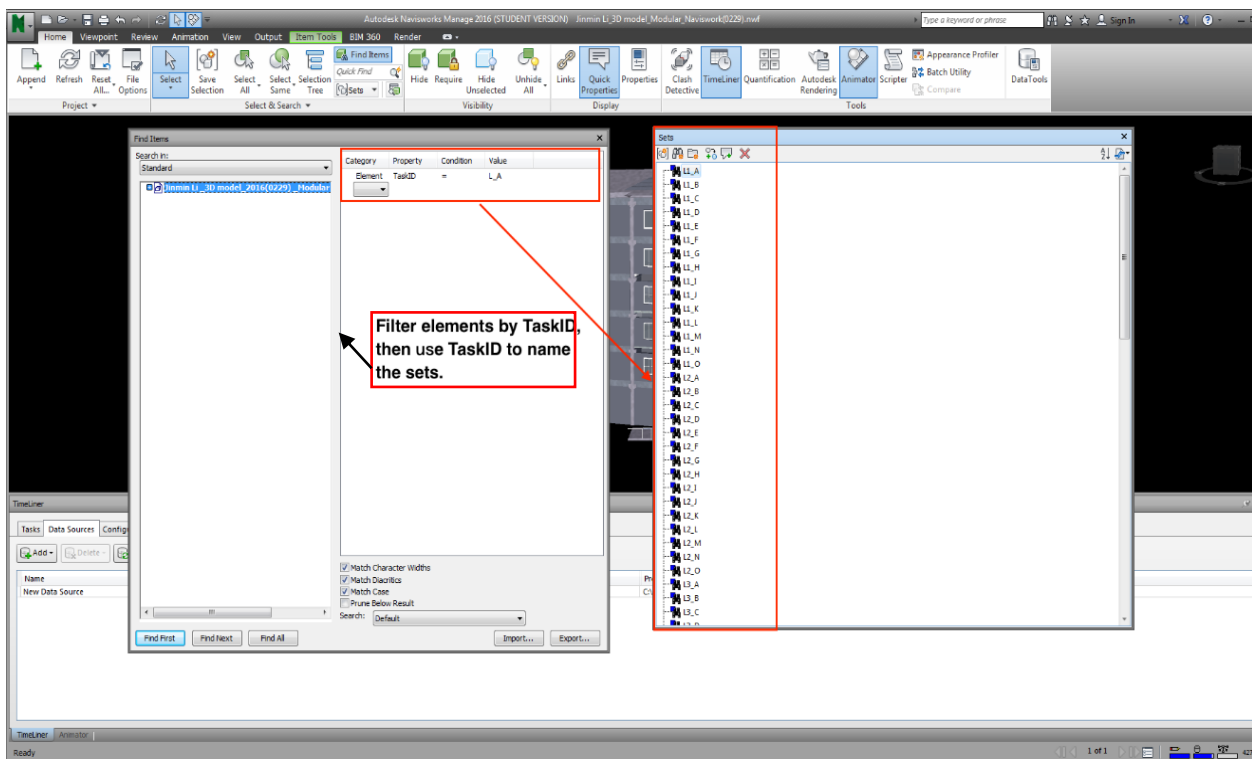


Figure 5.17 Setting the construction activity sets in Naviswork

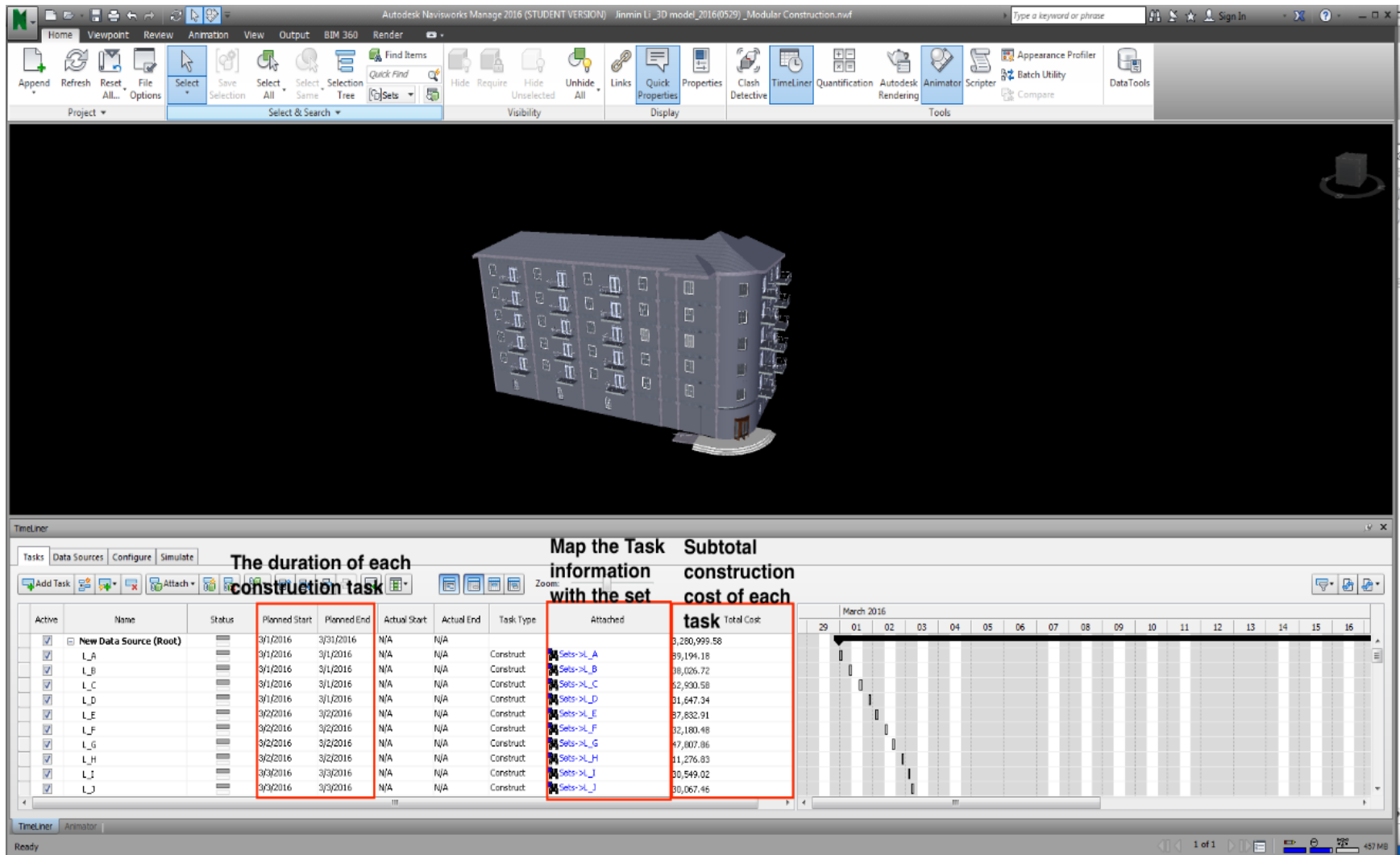


Figure 5.18 The cost data and duration of each construction activity are integrated in Naviswork

Naviswork can then provide a simulation of the construction process for the proposed hotel. Furthermore, the cumulative duration and the construction cost of the corresponding construction stage can be shown in the simulation process so that owners can have an idea on how the hotel will be built and what the construction cost and schedule status will be in different phases.

Figure 5.19 and Figure 5.20 illustrate the simulation process for the conventional construction and modular construction versions of this hotel project, respectively.

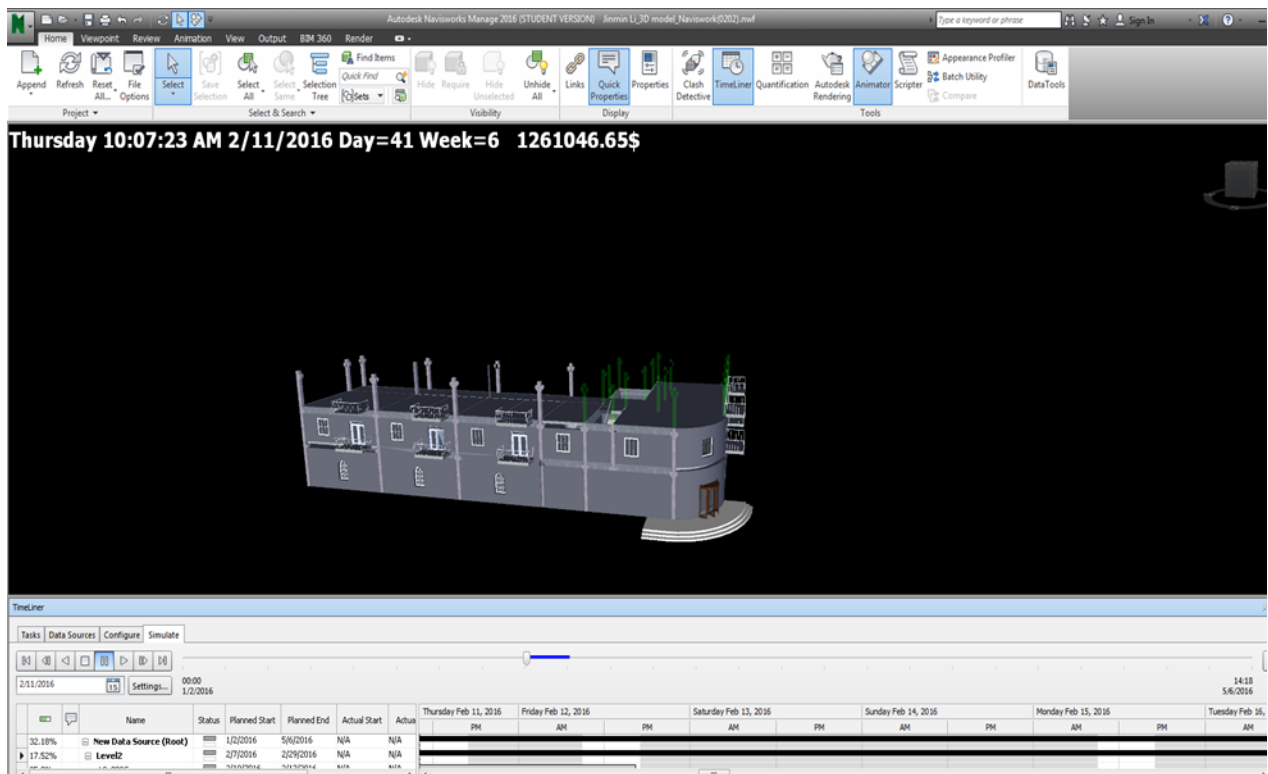


Figure 5.19 Simulation process of conventional construction

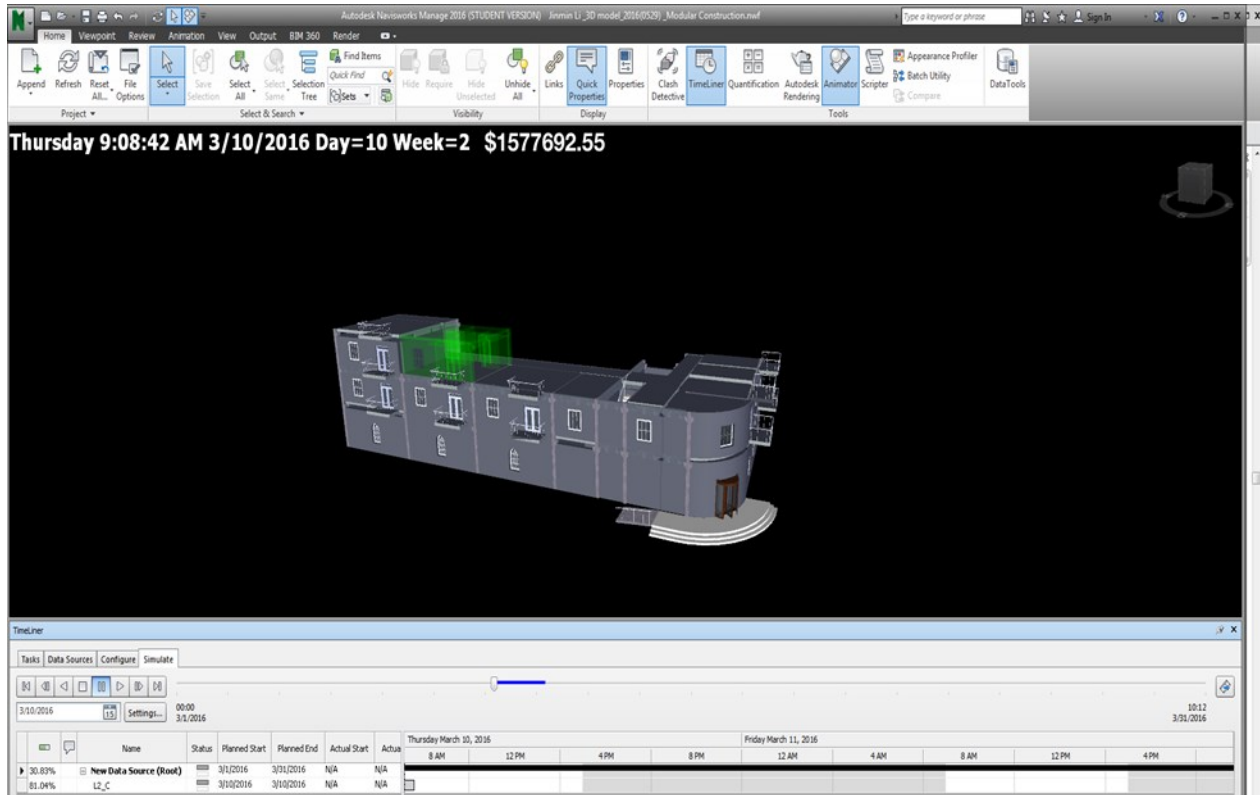


Figure 5.20 Simulation process of modular construction

## 5.7 Analysis and Comparison

The cost data and activity daily output used in this project are from R.S. Means Building Construction Cost 2013 and R.S. Means Green Building Construction Cost 2013. The calculated results from this developed model are adjusted according to the project's location and construction year. Referring to the square foot cost data statistic from R.S. Means 2014, the cost per square foot of 6 stories hotel building is approximate  $\$214.1/\text{ft}^2$ , which means the total construction cost of this building is  $\$9,305,767.3$  after location and time adjustment. There is  $\$3,411,800.14$  difference between the outcome from the proposed model and that from real project values. The most important reason for this difference is because the developed model

does not consider the MEP system estimation, which may cost between 25% - 35% of the total cost of the other divisions. If we consider an additional 30% to the value provided by the model (\$5,893,967.16) to cover the electrical division and another 30% to the new estimated value to cover the mechanical division the total cost would be \$9,960,804.50 which is very close to the calculated value based on \$214.10/ft<sup>2</sup>. Therefore, the outcome from this developed model can be a significant reference to decision makers when calculating the construction cost for projects at their conceptual design stage, especially when it holds several alternatives. On the other hand, the duration of this proposed hotel project is 120 workdays by using conventional construction and 25 days by using modular construction.

Compared with the traditional method of cost estimation and schedule planning, this model allows owners and design professionals to get the approximate direct construction cost and duration of proposed projects at the conceptual phase. Furthermore, this model is flexible for design changes, which means that when designers change the architectural model and data of the project in Revit, the cost data and schedule plan can be easily updated by automatic data transfer. This is especially beneficial for projects, which have several alternatives and public projects with limited preparation time so that owners and decision makers can have reliable information to make decisions in a short period of time at the early stage.

Also, this validation also shows the difference between traditional construction cost and modular construction cost in these respects:

$$\$5,893,967.16 \times (1 - 6\%) = \$5,540,329.13$$

#### 1) Construction cost

If this hotel project applies traditional construction, the estimated construction cost is \$5,893,967.

16. In comparison, the estimated cost is \$5,540,329.13 if this project carries out modular construction. This cost saving is approximately 6% according to the McGraw Hill surveys and is not a large amount. However, the profit margin is slim in the AEC industry due to the labor-intensive and expensive nature of on-site construction, so any relatively small reduction in cost can be critical and beneficial for stakeholders. Moreover, with the advances of BIM and the development of the manufacturing industry, the cost savings of modular construction is increasing.

#### 2) Construction schedule

Reduction in the project schedule is the key productivity benefit of modular construction. The schedule of this project would be 120 workdays if it uses conventional on-site construction, while modular construction would take 25 workdays, which is almost 5 times saving in the duration needed to construct the project. In this proposed hotel, the elements are produced and assembled in a modular unit in factory, and then transported to the construction site. Modular construction can yield time savings through the ability to conduct work simultaneously onsite and offsite, so that this hotel can be brought into operation in a short time and owners can reclaim funds earlier. In addition, the ability to avoid the impact of bad weather can reduce the

construction schedule. Additional time might be spent during the design phase on complex projects; however, the time saved in onsite assembly reduces the overall project schedule. This is why modular construction is particularly applicable in public facilities and disaster relief residences, as well as in buildings whose layouts consist of similar components, such as apartments, hotels and office buildings.

### 3) LEED evaluation

In this study, the developed model is mainly applied at the conceptual design phase when there is not much detailed information for the proposed project, the LEED evaluation only considers the materials and resources of components. Both conventional construction and modular construction have the same LEED points 19 credits in this respect in this project. Since this project is under the feasibility stage and the detail information such as the surrounding environment is not available, the LEED points may be earned by other criteria of LEED v4 is not taken into account in this stage. However, because modular construction can significantly reduce the amount of materials used in construction and the amount of construction onsite waste, making projects greener. Also, modular construction produces less negative impacts on surrounding environments than conventional construction types do. The final LEED points earned by this proposed hotel in modular construction must be bigger than using conventional construction.

## Chapter 6

### Conclusion and future work

#### 6.1 Conclusion

The project preparation stage is a critical stage during its whole life, because it can provide decision makers and engineers with an overview and useful information for the next detailed design stage. This research focused on how to use BIM technology to improve the implementation of cost estimation, schedule planning and sustainability evaluation at the project conceptual stage for both conventional construction and modular construction. To achieve this goal, this research developed a model by following these steps:

- 1) Collecting Revit families, construction costs, schedule data, and LEED information and store them in a database;
- 2) Loading the families into Revit for different types of projects, and then inputting the collected cost data and LEED information into Revit for the comprehensive model development;
- 3) Creating a plug-in in Revit to fulfill the automatic data extraction and QTO from the architectural model to Excel for cost estimation, LEED points calculation, and schedule planning preparation;
- 4) Developing another plug-in for “one-click transfer” that transmits the data from Excel to Microsoft Project for schedule planning;

- 5) Linking the 3D architectural model, cost data, and schedule into Naviswork to develop the 5D model and accomplish the construction simulation.

The features and advantages of the developed model are summarized as follows:

- 1) The data extraction and data transfer in this model is automatic, so users can quickly and easily get the budget, schedule and preliminary sustainability evaluation for different project designs.
- 2) Compared with traditional cost estimation and scheduling, this model provides accurate and reliable QTO by using BIM.
- 3) When the project design changes, the 3D model can be easily modified in Revit, and the cost data and schedule can be updated quickly by refreshing the plug-ins.
- 4) Based on the LEED points of the materials and components collected from USGBC and product suppliers and inputted into Revit, designers can recognize how many LEED points may be earned by using different materials.
- 5) Engineers can realize the potential risk from the construction process simulation so that they can make the proper modification for the project at the detailed design stage.
- 6) This model is flexible and can be used for both conventional construction and modular construction based on different settings.

## **6.2 Research Contribution**

Compared with related studies, this research makes these contributions:

- 1) The development of the BIMiTs plug-in in Revit, which enables users to determine what data they want to export from the 3D model to Excel and finish the QTO automatically. This plug-in greatly shortens the preparation time of cost estimates and schedule plans in an efficient and accurate way.
- 2) The creation of the plug-in between Excel and Microsoft Project. Users can transfer the data extracted from Revit to Microsoft Project by using just one click, which improves the efficiency of scheduling.
- 3) The shared parameters created in Revit. These two shared parameters are used to store the information about LEED points and TaskID respectively, and these two parameters can be exported automatically with other data for schedule planning and sustainability evaluation. Users can use the TaskID to define which construction task the element belongs to, which is the key for using this model in different construction types.
- 4) Building the family database. This database includes more than 300 kinds of Revit families that can be used in different types of construction projects, and most of these families are green families with LEED information.

### **6.3 Limitations of the research**

This research aims at improving the efficiency of the methods used to prepare construction cost and duration estimation by using BIM. However, due to lack of data in specific areas, this research holds the following limitations:

- 1) There are few resources containing cost data for modular construction, and the construction cost of modular construction is an estimated value that can be only used as a reference value at the conceptual stage.
- 2) The 3D building model in this research only considers the basic architectural design and the basic structural components, but not the MEP system. The construction cost obtained from this model cannot stand for the whole construction cost of the project;
- 3) The cost estimation module does not consider profit and overhead fees, so this cost cannot be used for bidding purpose.
- 4) Because the developed model does not consider the MEP installation, the construction schedule obtained from this model may be shorter than that of the actual construction project.

#### **6.4 Recommendation for future work**

This research has described how to integrate BIM with cost estimation, scheduling, and sustainability assessment to offer owners reliable information on the project for decision making at the project conceptual stage. However, there is still some work that can be done to enhance the model in the future:

- 1) Expand the Revit family database and collect more green families so that this model can be used in more types of green buildings;

- 2) Optimize the plug-ins; make them more flexible for two-way data transfer among software;
- 3) Optimize the construction process simulation in Naviswork, such as adding simulation of site preparation and the simulation of lifting units in modular construction;
- 4) Integrate more sustainability analysis systems with BIM, such as sunlight analysis and energy simulation;
- 5) Incorporate risk management with BIM into this model to enhance the cost control and schedule control during the construction process.
- 6) Optimize the LEED points rating system of this developed model to satisfy the requirement of different construction projects.

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## Appendices

# Appendix A

## Sample of the Revit family database

- The Revit family database is collected from various kind of resources. Following is an example of the collection process from SmartBIM Library:

1. Searching the category, such as “Door”

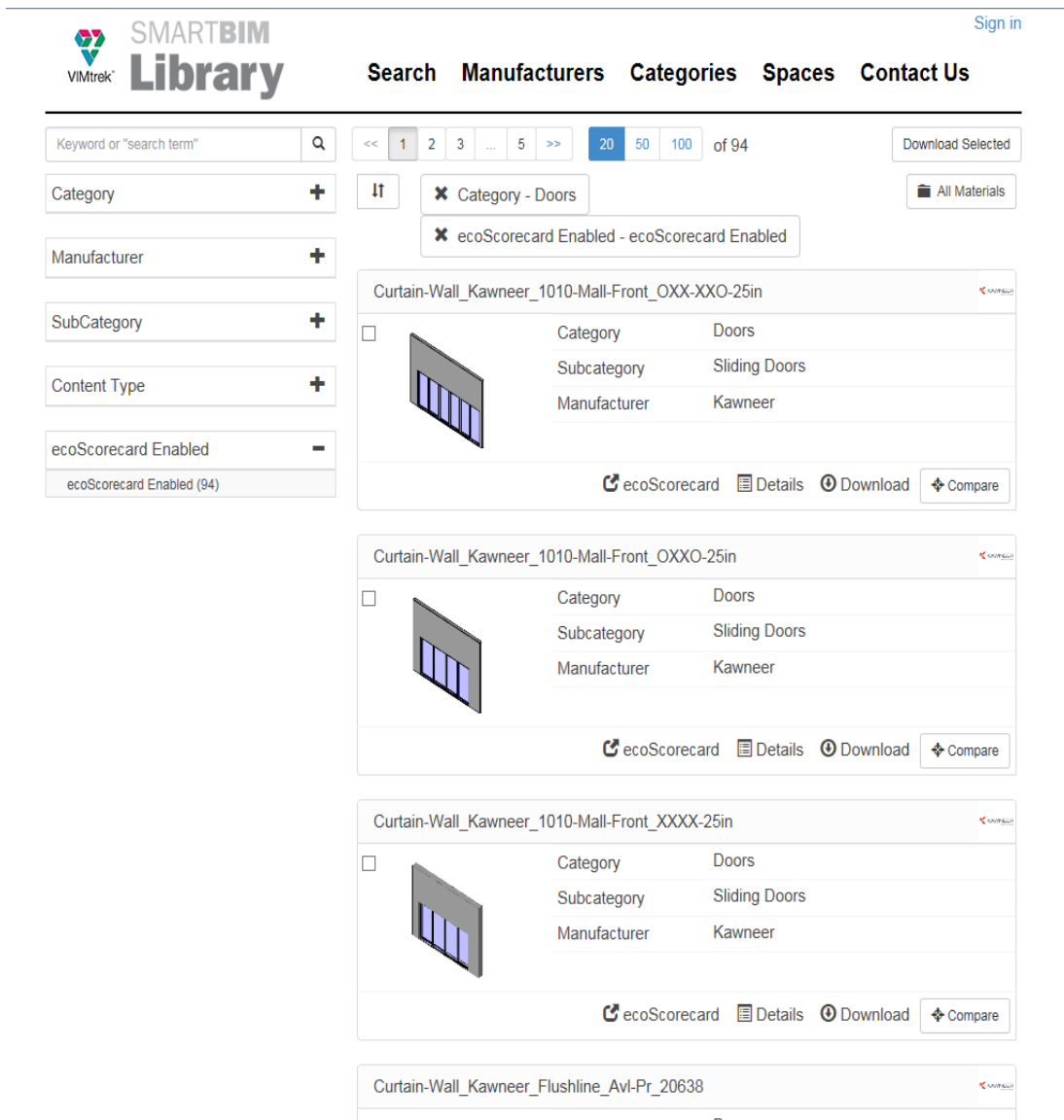


Figure A.1 The sample of Revit family collection

- Users can use the filter to find the types of door that would be used in proposed projects, and then download the family and save it in the pre-set folders. The downloaded Revit family can be saved under both the Masterformat catalogue and UniFormat catalogue. For instance, save the inswing door type in the B2030 folders under the Uniformal catalogue.

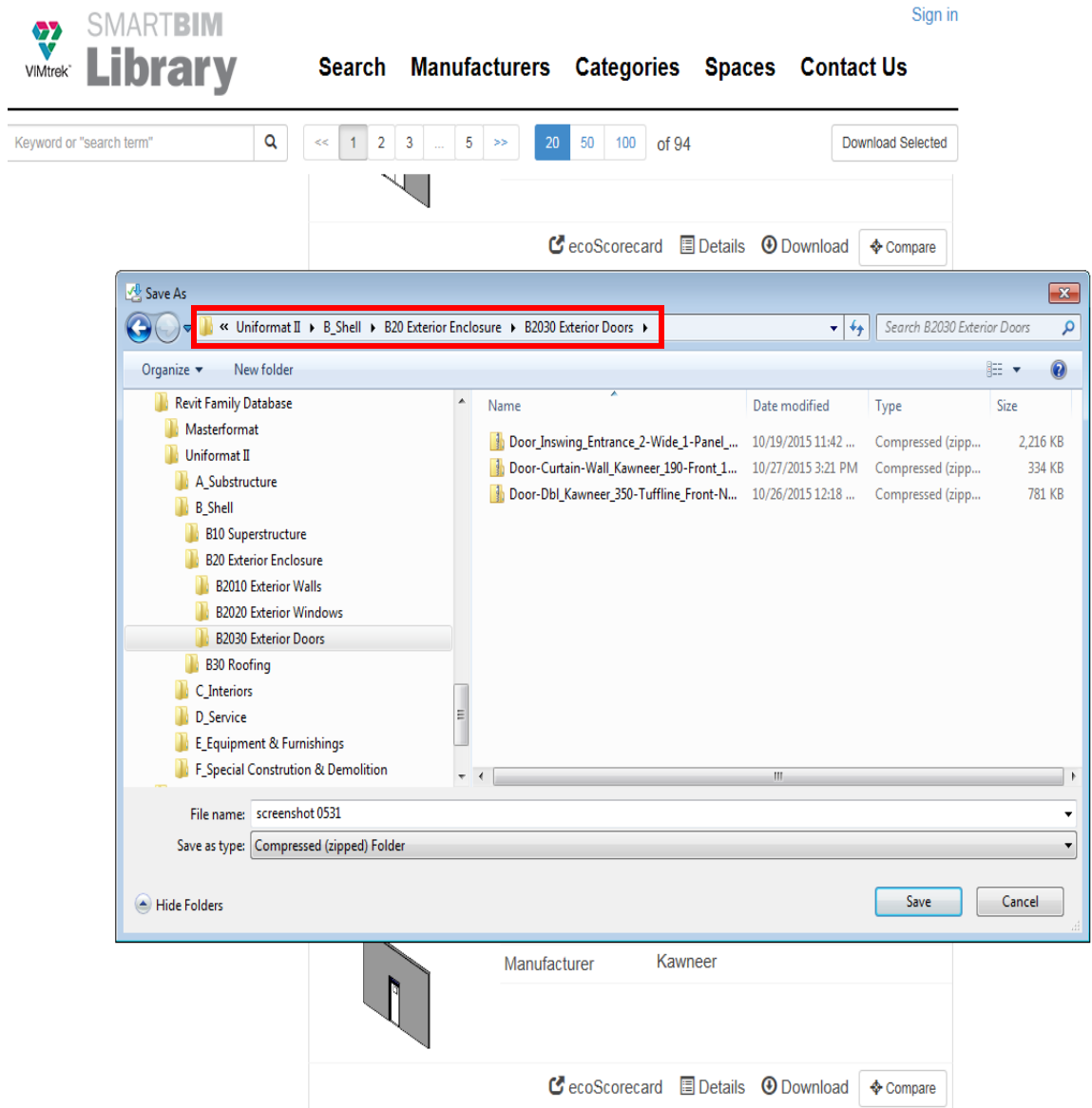


Figure A.2 Storing the family in the external database

3. Following is the sample of the organization of the Revit family database:

-Organized by MasterFormat

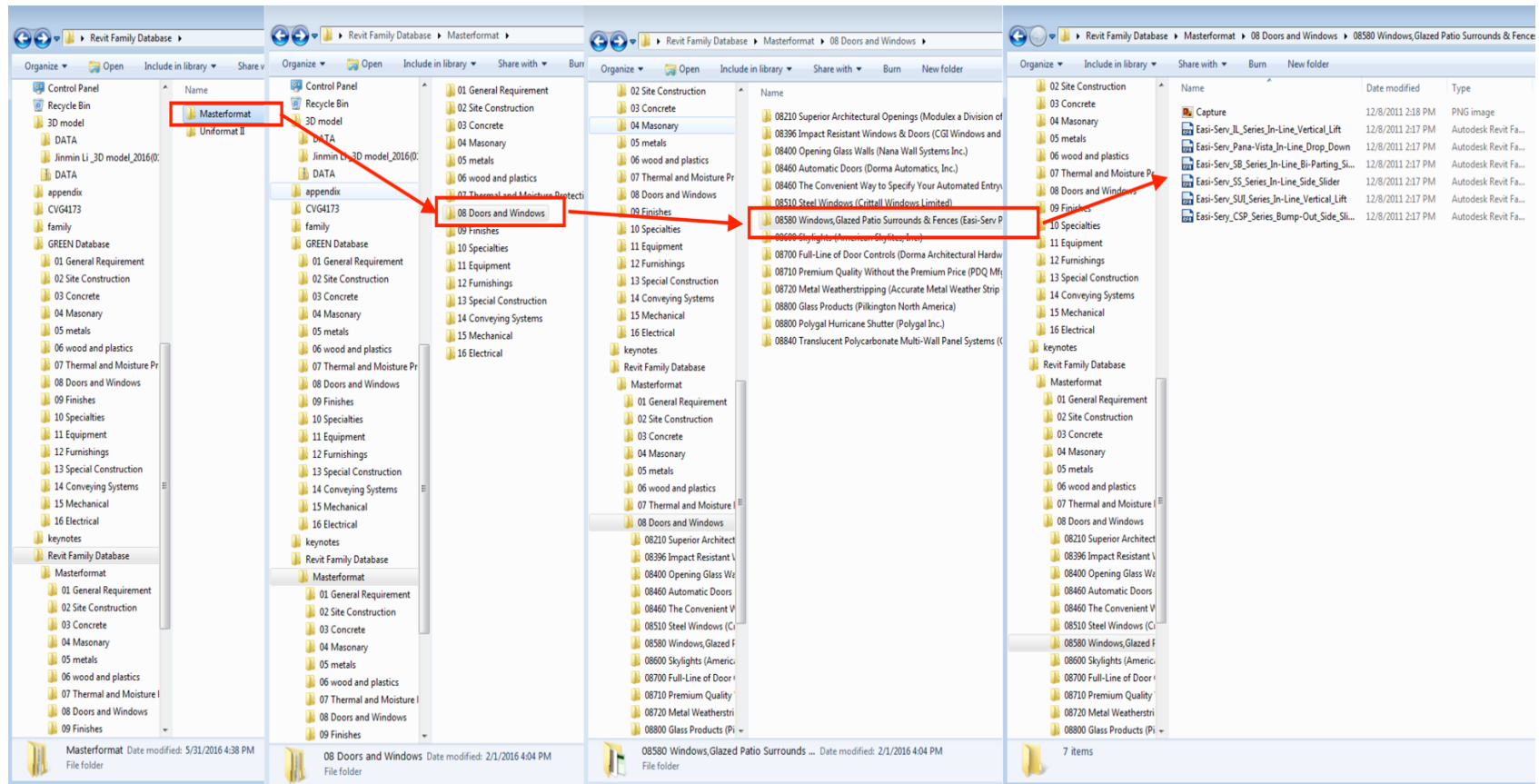


Figure A.3 The MasterFormat organization of the families external database

- Organized by Unitformat

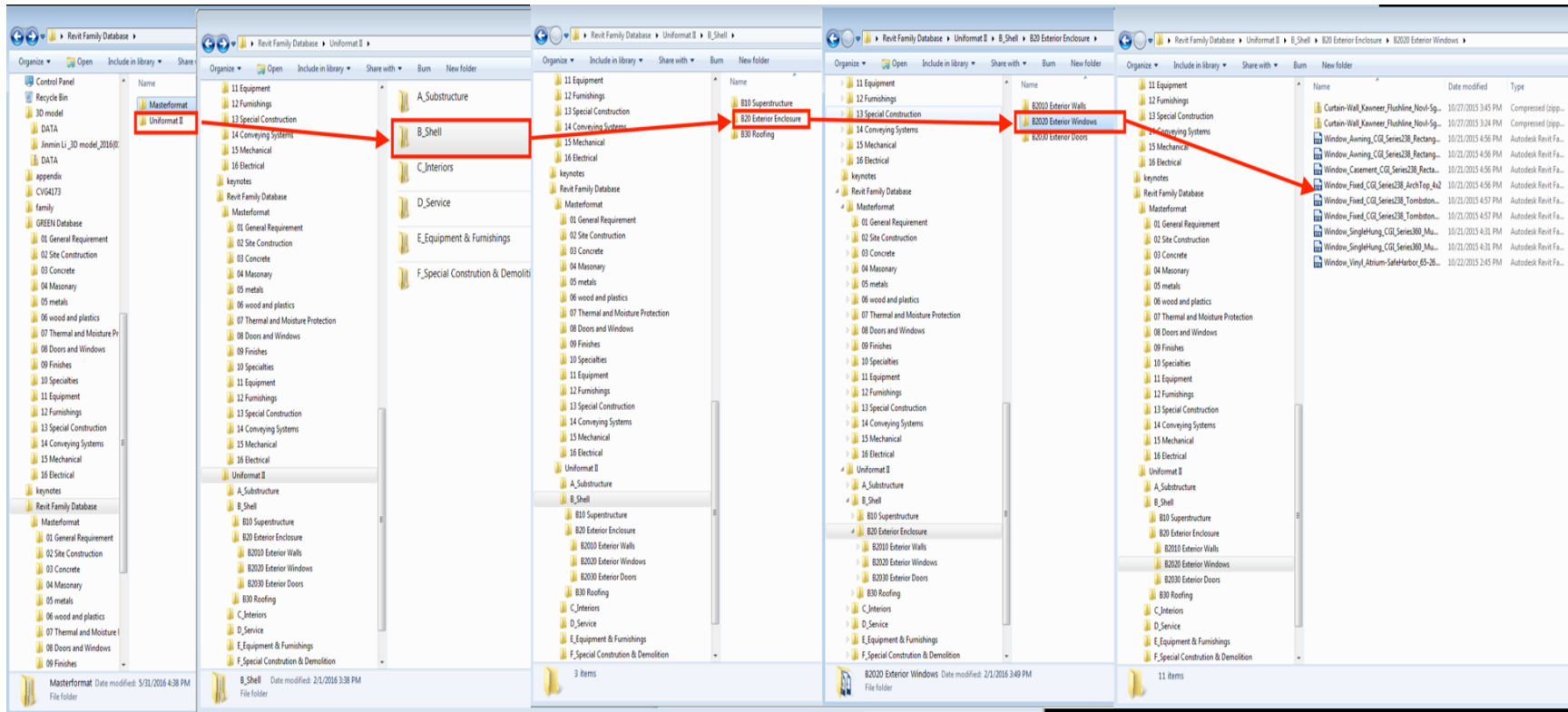


Figure A.4 The UniFormat organization of the families external database

4. The collected Revit family can be loaded directly from the database to Revit.

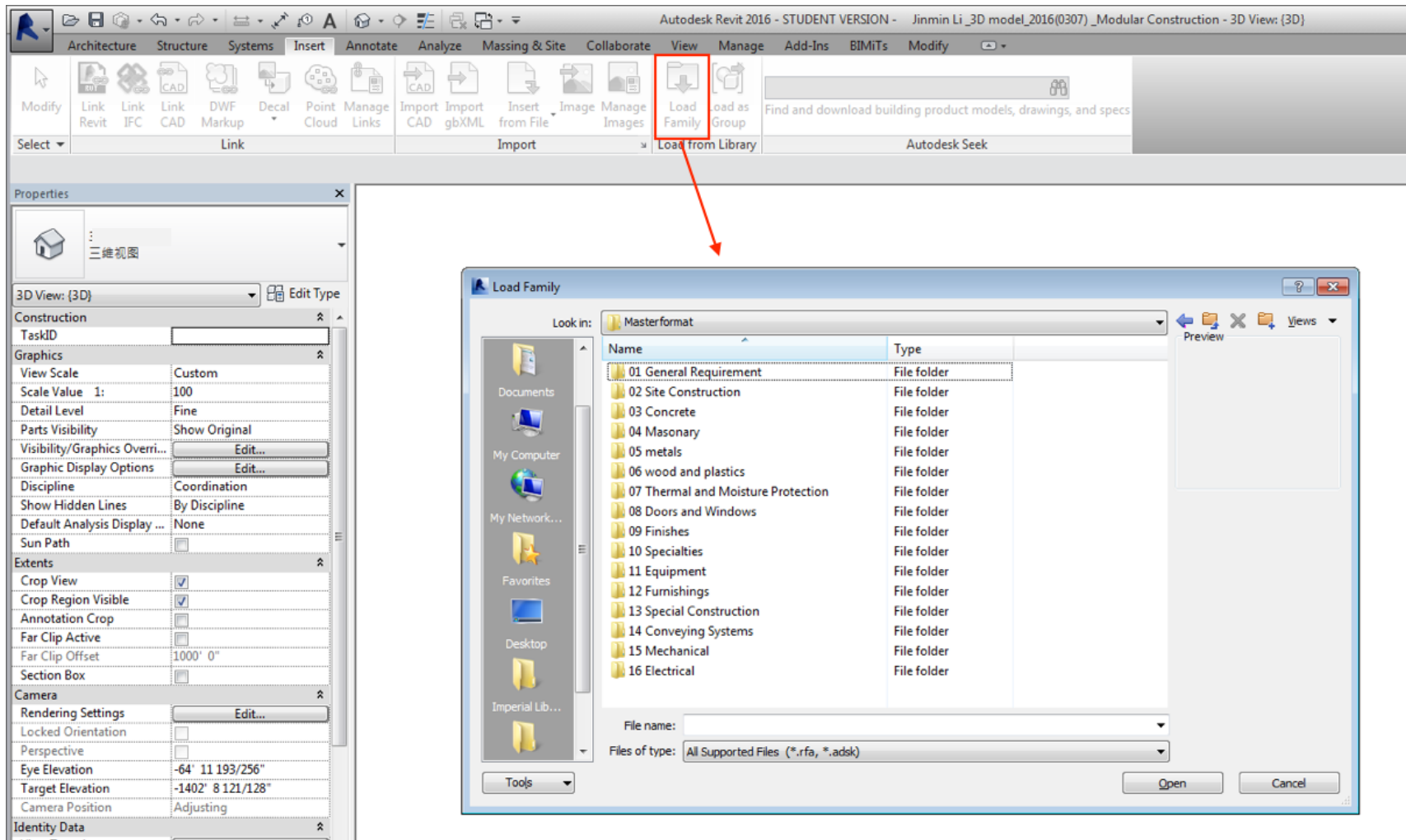


Figure A.5 Loading the external families database into Autodesk Revit

## Appendix B

### Sample of the Quantity Takeoff extracted from the proposed project in Revit

- The QTO and cost data of the door in the proposed hotel project

ID	Category	Family Name	Type Name	Level	Keynote	Unit Cost	Cost	TaskID	LEED Point	PEP
182783	Doors	Entrance Door	building Door---1800 x 2500mm 2	L	B2030.110	53550	53550	L_L	3	4
332441	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L1	C1020.102	557	557	L1_A	3	
332505	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L1	C1020.102	557	557	L1_A	3	
332545	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L1	C1020.102	557	557	L1_C	3	
332585	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L1	C1020.102	557	557	L1_C	3	
332617	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L1	C1020.102	557	557	L1_E	3	
332659	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L1	C1020.102	557	557	L1_E	3	
332705	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L1	C1020.102	557	557	L1_G	3	
332757	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L1	C1020.102	557	557	L1_L	3	
332804	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L1	C1020.102	557	557	L1_M	3	
332888	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L1	C1020.102	557	557	L1_N	3	
452209	Doors	Door-Dbf_Kawneer_2000T-w-Transom_20610	Door-Dbf_Kawneer_2000T-w-Transom_20610	L1	B2030.110	4725	4725	L1_C	4	
452210	Doors	Door-Dbf_Kawneer_2000T-w-Transom_20610	Door-Dbf_Kawneer_2000T-w-Transom_20610	L1	B2030.110	4725	4725	L1_A	4	
452211	Doors	Door-Dbf_Kawneer_2000T-w-Transom_20610	Door-Dbf_Kawneer_2000T-w-Transom_20610	L1	B2030.110	4725	4725	L1_E	4	
452213	Doors	Door-Dbf_Kawneer_2000T-w-Transom_20610	Door-Dbf_Kawneer_2000T-w-Transom_20610	L1	B2030.110	4725	4725	L1_O	4	
466664	Doors	Door-Dbf_Kawneer_2000T-w-Transom_20610	Door-Dbf_Kawneer_2000T-w-Transom_20610	L1	B2030.110	4725	4725	L1_M	4	
467155	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L1	C1020.102	557	557	L1_O	3	
467371	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L1	C1020.102	636	636	L1_A	3	
467486	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L1	C1020.102	636	636	L1_A	3	
467566	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L1	C1020.102	636	636	L1_C	3	
467604	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L1	C1020.102	636	636	L1_C	3	
467676	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L1	C1020.102	636	636	L1_E	3	
467738	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L1	C1020.102	636	636	L1_E	3	
467776	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L1	C1020.102	636	636	L1_G	3	
469878	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L2	C1020.102	557	557	L2_A	3	
469879	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L2	C1020.102	557	557	L2_A	3	
469880	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L2	C1020.102	557	557	L2_C	3	
469881	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L2	C1020.102	557	557	L2_C	3	
469882	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L2	C1020.102	557	557	L2_E	3	
469883	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L2	C1020.102	557	557	L2_E	3	
469884	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L2	C1020.102	557	557	L2_G	3	
469885	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L2	C1020.102	557	557	L2_L	3	
469886	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L2	C1020.102	557	557	L2_M	3	
469887	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L2	C1020.102	557	557	L2_N	3	
469915	Doors	Door-Dbf_Kawneer_2000T-w-Transom_20610	Door-Dbf_Kawneer_2000T-w-Transom_20610	L2	B2030.110	4725	4725	L2_C	4	
469916	Doors	Door-Dbf_Kawneer_2000T-w-Transom_20610	Door-Dbf_Kawneer_2000T-w-Transom_20610	L2	B2030.110	4725	4725	L2_A	4	
469917	Doors	Door-Dbf_Kawneer_2000T-w-Transom_20610	Door-Dbf_Kawneer_2000T-w-Transom_20610	L2	B2030.110	4725	4725	L2_E	4	
469938	Doors	Door-Dbf_Kawneer_2000T-w-Transom_20610	Door-Dbf_Kawneer_2000T-w-Transom_20610	L2	B2030.110	4725	4725	L2_M	4	

Figure B.1 The QTO of the door category of the proposed project

N39										
A	B	C	D	E	F	G	H	I	J	K
39	469938	Doors	Door-Dbl_Kawneer_2000T-w-Transom_20610	Door-Dbl_Kawneer_2000T-w-Transom_20610	L2	B2030.110	4725	4725	L2_M	4
40	469940	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L2	C1020.102	557	557	L2_O	3
41	469942	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L2	C1020.102	636	636	L2_A	3
42	469943	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L2	C1020.102	636	636	L2_A	3
43	469944	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L2	C1020.102	636	636	L2_C	3
44	469945	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L2	C1020.102	636	636	L2_C	3
45	469946	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L2	C1020.102	636	636	L2_E	3
46	469947	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L2	C1020.102	636	636	L2_E	3
47	469948	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L2	C1020.102	636	636	L2_G	3
48	475885	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L3	C1020.102	557	557	L3_A	3
49	475886	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L3	C1020.102	557	557	L3_A	3
50	475887	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L3	C1020.102	557	557	L3_C	3
51	475888	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L3	C1020.102	557	557	L3_C	3
52	475889	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L3	C1020.102	557	557	L3_E	3
53	475890	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L3	C1020.102	557	557	L3_E	3
54	475891	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L3	C1020.102	557	557	L3_G	3
55	475892	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L3	C1020.102	557	557	L3_L	3
56	475893	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L3	C1020.102	557	557	L3_M	3
57	475894	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L3	C1020.102	557	557	L3_N	3
58	475922	Doors	Door-Dbl_Kawneer_2000T-w-Transom_20610	Door-Dbl_Kawneer_2000T-w-Transom_20610	L3	B2030.110	4725	4725	L3_C	4
59	475923	Doors	Door-Dbl_Kawneer_2000T-w-Transom_20610	Door-Dbl_Kawneer_2000T-w-Transom_20610	L3	B2030.110	4725	4725	L3_A	4
60	475924	Doors	Door-Dbl_Kawneer_2000T-w-Transom_20610	Door-Dbl_Kawneer_2000T-w-Transom_20610	L3	B2030.110	4725	4725	L3_E	4
61	475945	Doors	Door-Dbl_Kawneer_2000T-w-Transom_20610	Door-Dbl_Kawneer_2000T-w-Transom_20610	L3	B2030.110	4725	4725	L3_M	4
62	475947	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L3	C1020.102	557	557	L3_O	3
63	475949	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L3	C1020.102	636	636	L3_A	3
64	475950	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L3	C1020.102	636	636	L3_A	3
65	475951	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L3	C1020.102	636	636	L3_C	3
66	475952	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L3	C1020.102	636	636	L3_C	3
67	475953	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L3	C1020.102	636	636	L3_E	3
68	475954	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L3	C1020.102	636	636	L3_E	3
69	475955	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L3	C1020.102	636	636	L3_G	3
70	477554	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L4	C1020.102	557	557	L4_A	3
71	477555	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L4	C1020.102	557	557	L4_A	3
72	477556	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L4	C1020.102	557	557	L4_C	3
73	477557	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L4	C1020.102	557	557	L4_C	3
74	477558	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L4	C1020.102	557	557	L4_E	3
75	477559	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L4	C1020.102	557	557	L4_E	3
76	477560	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L4	C1020.102	557	557	L4_G	3
77	477561	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L4	C1020.102	557	557	L4_L	3
78	477562	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L4	C1020.102	557	557	L4_M	3

Figure B.2 The QTO of the door category of the proposed project (cont.)

	A	B	C	D	E	F	G	H	I	J	K
78	477562	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L4	C1020.102	557	557	L4_M	3	
79	477563	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L4	C1020.102	557	557	L4_N	3	
80	477591	Doors	Door-DbI_Kawneer_2000T-w-Transom_20610	Door-DbI_Kawneer_2000T-w-Transom_20610	L4	B2030.110	4725	4725	L4_C	4	
81	477592	Doors	Door-DbI_Kawneer_2000T-w-Transom_20610	Door-DbI_Kawneer_2000T-w-Transom_20610	L4	B2030.110	4725	4725	L4_A	4	
82	477593	Doors	Door-DbI_Kawneer_2000T-w-Transom_20610	Door-DbI_Kawneer_2000T-w-Transom_20610	L4	B2030.110	4725	4725	L4_E	4	
83	477614	Doors	Door-DbI_Kawneer_2000T-w-Transom_20610	Door-DbI_Kawneer_2000T-w-Transom_20610	L4	B2030.110	4725	4725	L4_M	4	
84	477616	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L4	C1020.102	557	557	L4_O	3	
85	477618	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L4	C1020.102	636	636	L4_A	3	
86	477619	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L4	C1020.102	636	636	L4_A	3	
87	477620	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L4	C1020.102	636	636	L4_C	3	
88	477621	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L4	C1020.102	636	636	L4_C	3	
89	477622	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L4	C1020.102	636	636	L4_E	3	
90	477623	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L4	C1020.102	636	636	L4_E	3	
91	477624	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L4	C1020.102	636	636	L4_G	3	
92	477653	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L5	C1020.102	557	557	L5_A	3	
93	477654	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L5	C1020.102	557	557	L5_A	3	
94	477655	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L5	C1020.102	557	557	L5_C	3	
95	477656	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L5	C1020.102	557	557	L5_C	3	
96	477657	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L5	C1020.102	557	557	L5_E	3	
97	477658	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L5	C1020.102	557	557	L5_E	3	
98	477659	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L5	C1020.102	557	557	L5_G	3	
99	477660	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L5	C1020.102	557	557	L5_L	3	
100	477661	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L5	C1020.102	557	557	L5_M	3	
101	477662	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L5	C1020.102	557	557	L5_N	3	
102	477690	Doors	Door-DbI_Kawneer_2000T-w-Transom_20610	Door-DbI_Kawneer_2000T-w-Transom_20610	L5	B2030.110	4725	4725	L5_C	4	
103	477691	Doors	Door-DbI_Kawneer_2000T-w-Transom_20610	Door-DbI_Kawneer_2000T-w-Transom_20610	L5	B2030.110	4725	4725	L5_A	4	
104	477692	Doors	Door-DbI_Kawneer_2000T-w-Transom_20610	Door-DbI_Kawneer_2000T-w-Transom_20610	L5	B2030.110	4725	4725	L5_E	4	
105	477713	Doors	Door-DbI_Kawneer_2000T-w-Transom_20610	Door-DbI_Kawneer_2000T-w-Transom_20610	L5	B2030.110	4725	4725	L5_M	4	
106	477715	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L5	C1020.102	557	557	L5_O	3	
107	477717	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L5	C1020.102	636	636	L5_A	3	
108	477718	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L5	C1020.102	636	636	L5_A	3	
109	477719	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L5	C1020.102	636	636	L5_C	3	
110	477720	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L5	C1020.102	636	636	L5_C	3	
111	477721	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L5	C1020.102	636	636	L5_E	3	
112	477722	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L5	C1020.102	636	636	L5_E	3	
113	477723	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L5	C1020.102	636	636	L5_G	3	
114	479862	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L	C1020.102	557	557	L_I	3	
115	479956	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L1	C1020.102	557	557	L1_I	3	
116	479960	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L2	C1020.102	557	557	L2_I	3	
117	479964	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L3	C1020.102	557	557	L3_I	3	

Figure B.3 The QTO of the door category of the proposed project (cont.)

117	479964	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L3	C1020.102	557	557	L3_I	3
118	479968	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L4	C1020.102	557	557	L4_I	3
119	479972	Doors	Internal_Door_-_openable_in_3D_13628	760x2000	L5	C1020.102	557	557	L5_I	3
120	497465	Doors	Door-DbI_Kawneer_2000T-w-Transom_20610	Door-DbI_Kawneer_2000T-w-Transom_20610	L2	B2030.110	4725	4725	L2_O	4
121	497469	Doors	Door-DbI_Kawneer_2000T-w-Transom_20610	Door-DbI_Kawneer_2000T-w-Transom_20610	L3	B2030.110	4725	4725	L3_O	4
122	497473	Doors	Door-DbI_Kawneer_2000T-w-Transom_20610	Door-DbI_Kawneer_2000T-w-Transom_20610	L4	B2030.110	4725	4725	L4_O	4
123	497477	Doors	Door-DbI_Kawneer_2000T-w-Transom_20610	Door-DbI_Kawneer_2000T-w-Transom_20610	L5	B2030.110	4725	4725	L5_O	4
124	542862	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L3	C1020.102	636	636	L3_M	3
125	542966	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L3	C1020.102	636	636	L3_L	3
126	542998	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L3	C1020.102	636	636	L3_N	3
127	543058	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L3	C1020.102	636	636	L3_O	3
128	543217	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L1	C1020.102	636	636	L1_M	3
129	543218	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L1	C1020.102	636	636	L1_L	3
130	543219	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L1	C1020.102	636	636	L1_N	3
131	543220	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L1	C1020.102	636	636	L1_O	3
132	543227	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L2	C1020.102	636	636	L2_M	3
133	543228	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L2	C1020.102	636	636	L2_L	3
134	543229	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L2	C1020.102	636	636	L2_N	3
135	543230	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L2	C1020.102	636	636	L2_O	3
136	543237	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L4	C1020.102	636	636	L4_M	3
137	543238	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L4	C1020.102	636	636	L4_L	3
138	543239	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L4	C1020.102	636	636	L4_N	3
139	543240	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L4	C1020.102	636	636	L4_O	3
140	543247	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L5	C1020.102	636	636	L5_M	3
141	543248	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L5	C1020.102	636	636	L5_L	3
142	543249	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L5	C1020.102	636	636	L5_N	3
143	543250	Doors	Apartment_Bedroom_Door_15894	900mm x 2200mm	L5	C1020.102	636	636	L5_O	3
144										
145										
146										
147										
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154										
155										
156										

Figure B.4 The QTO of the door category of the proposed project (cont.)

## Appendix C

### Construction schedule of the proposed hotel project

- Conventional Construction

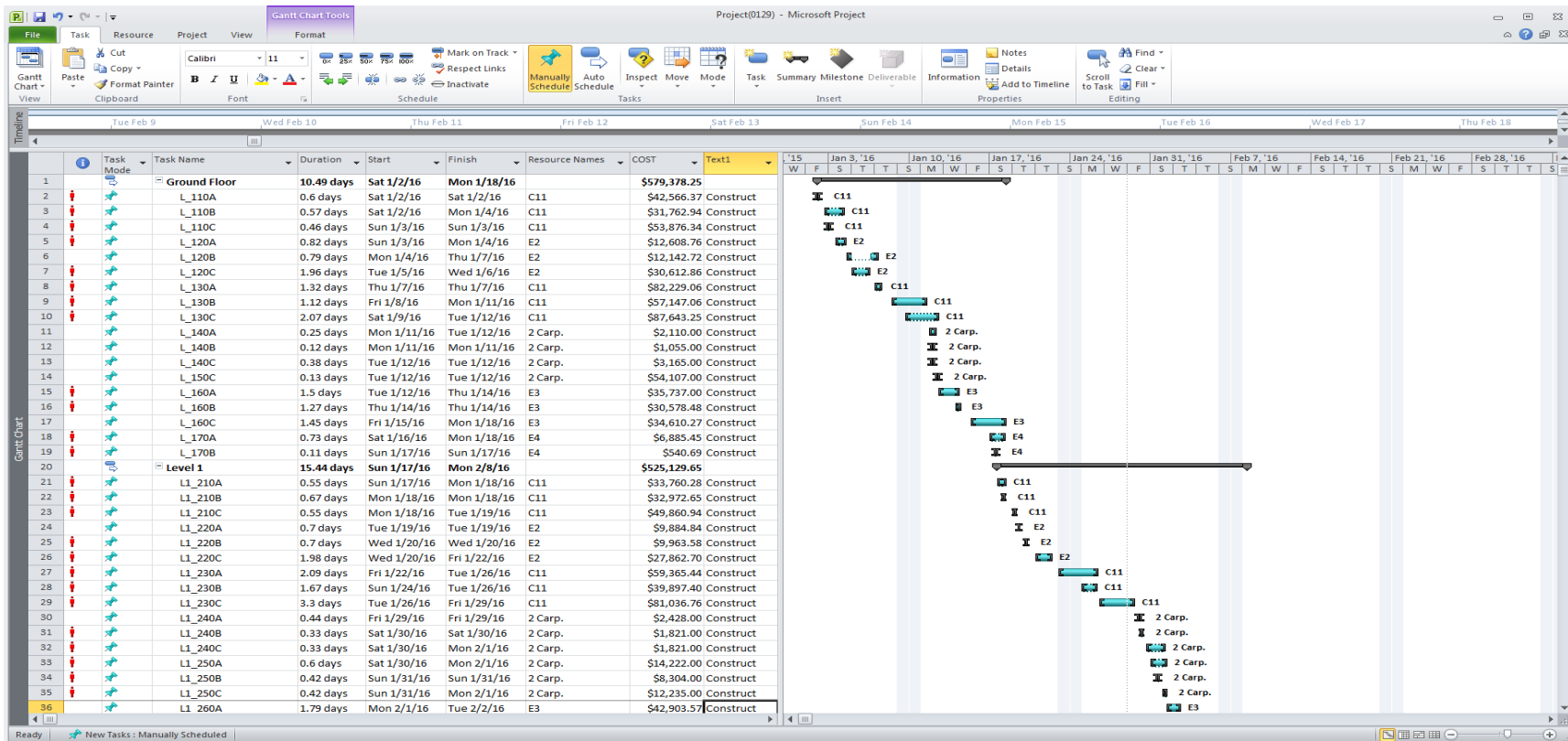


Figure C.1 The construction schedule of conventional construction for the proposed project

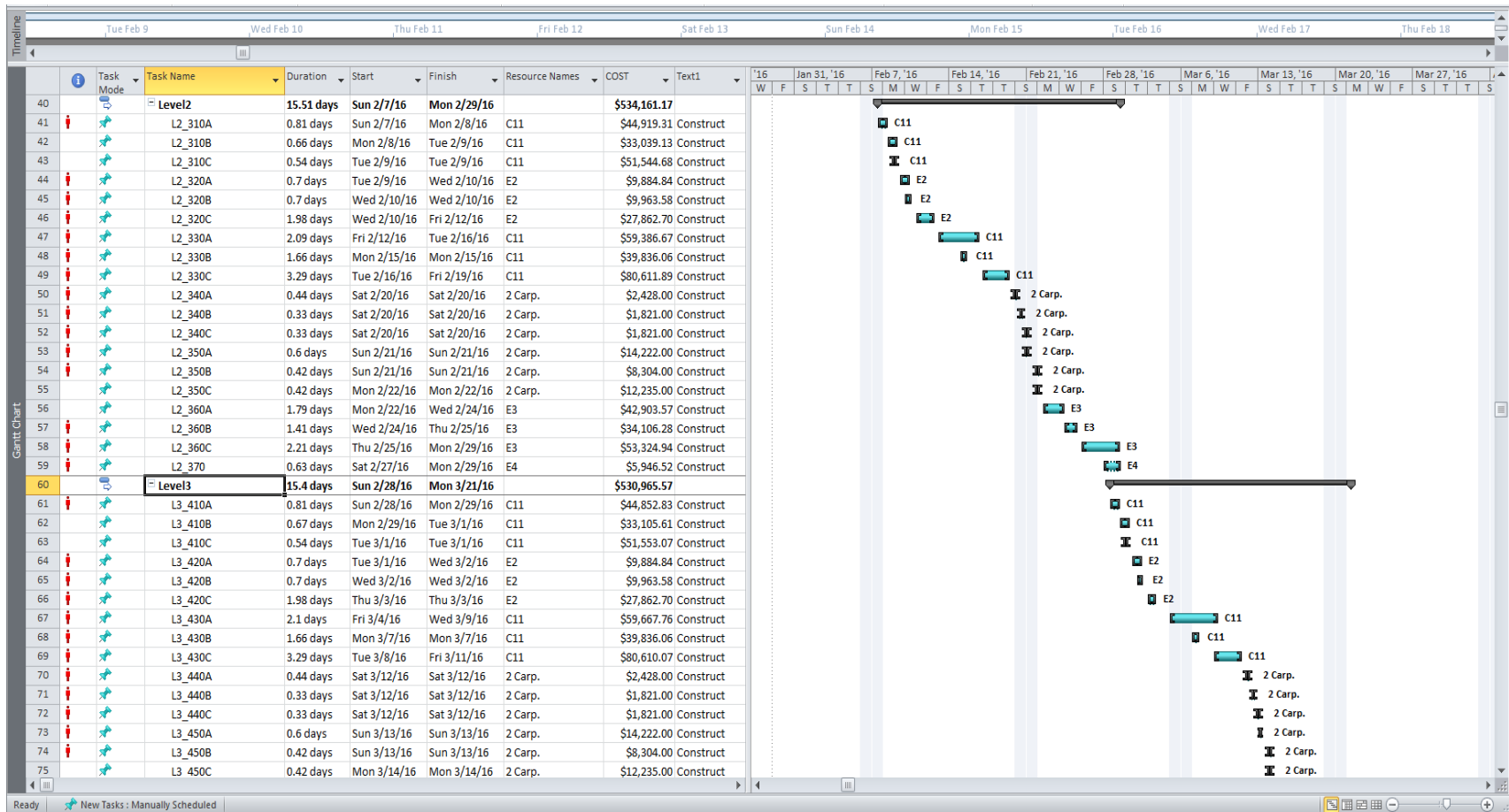


Figure C.2 The construction schedule of conventional construction for the proposed project (cont.)

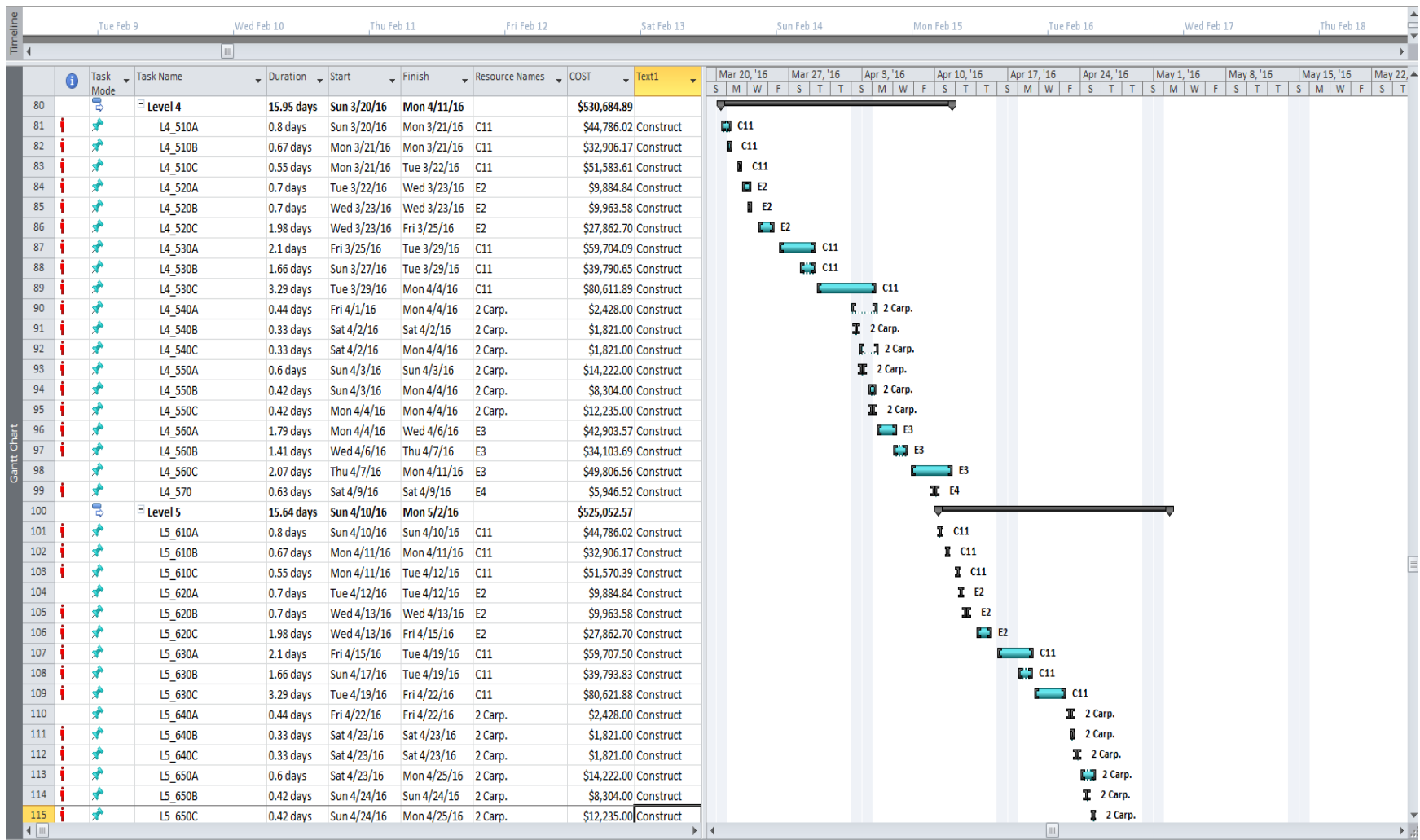


Figure C.3 The construction schedule of conventional construction for the proposed project (cont.)

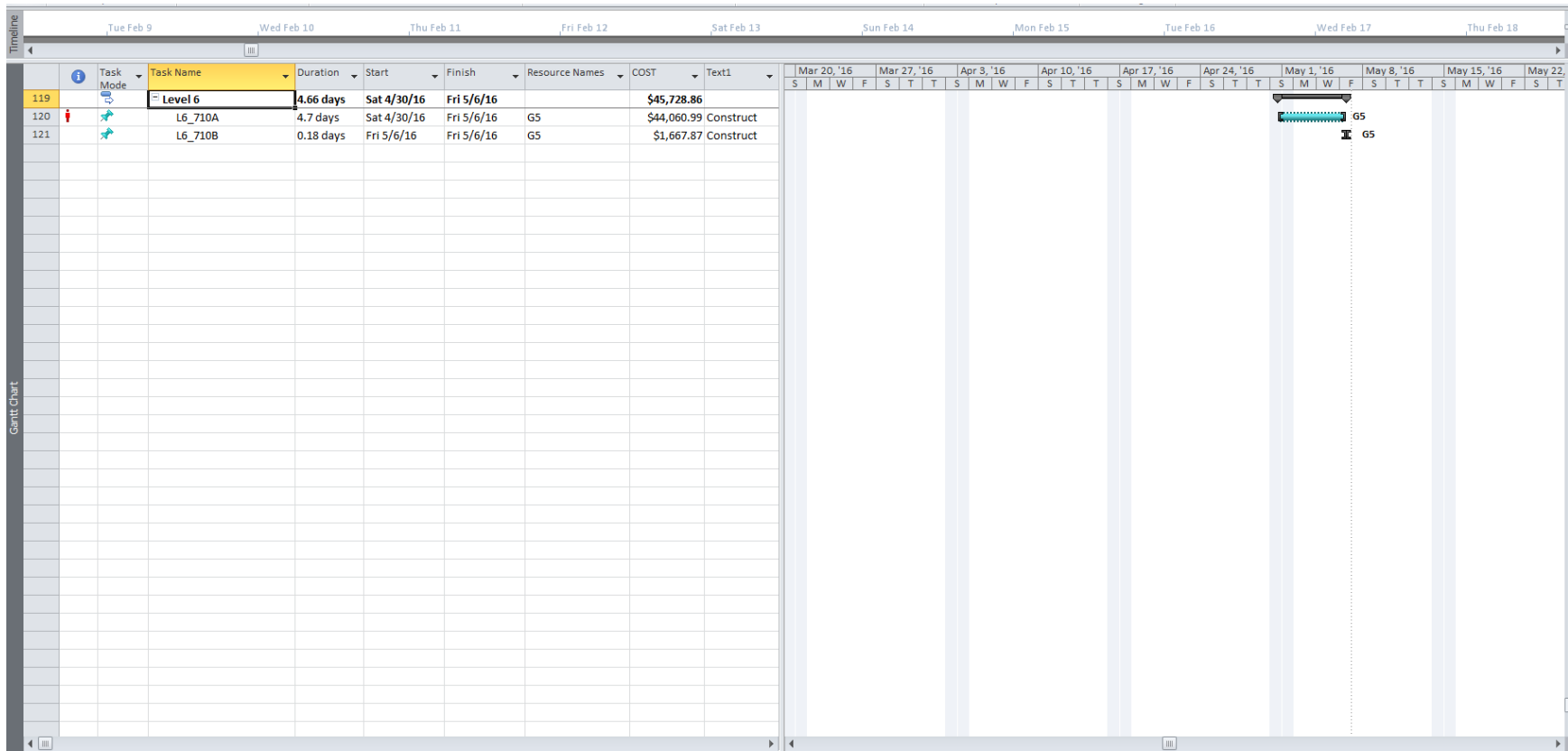


Figure C.4 The construction schedule of conventional construction for the proposed project (cont.)

- Modular Construction

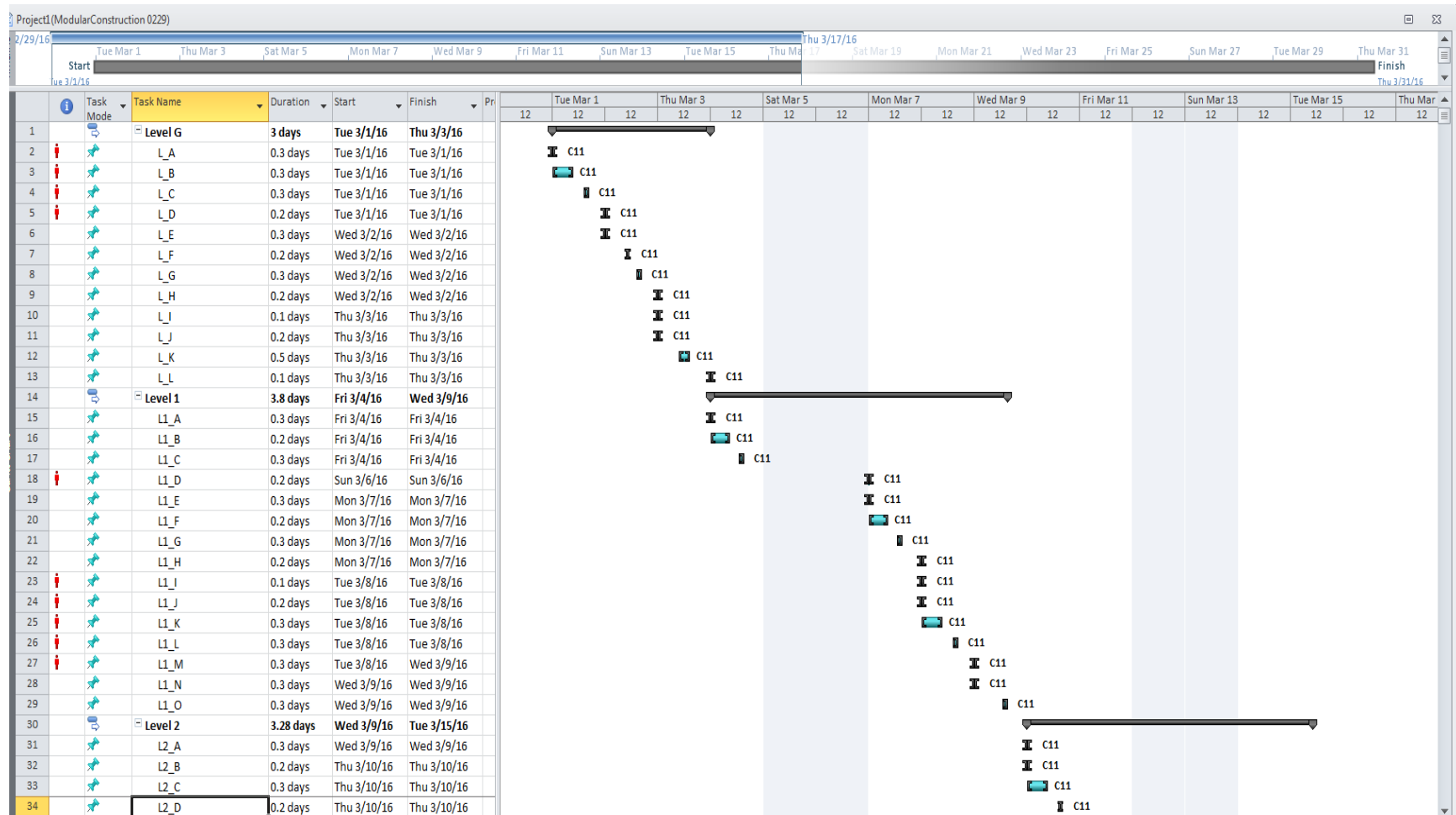


Figure C.5 The construction schedule of modular construction for the proposed project

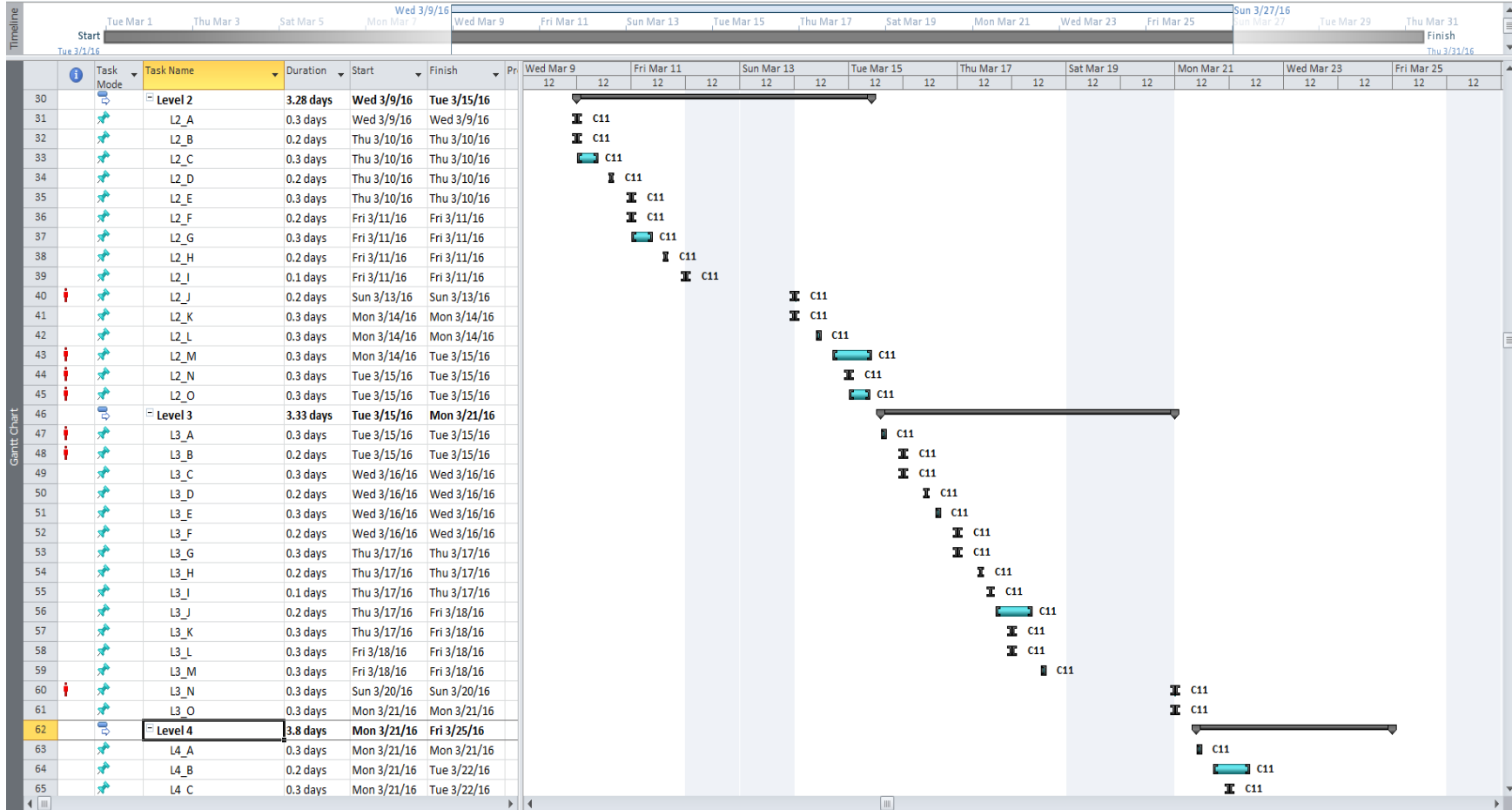


Figure C.6 The construction schedule of modular construction for the proposed project (cont.)

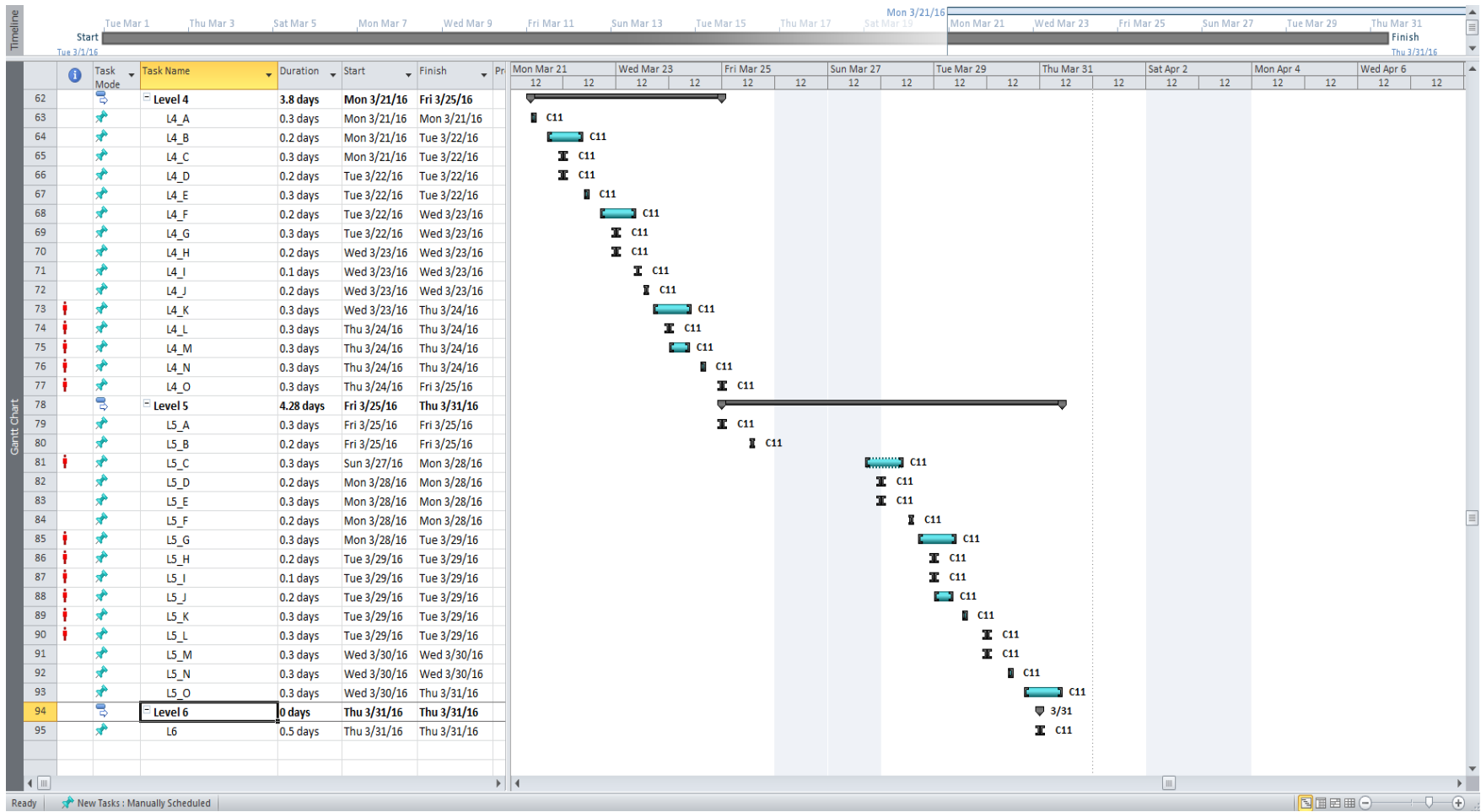


Figure C.7 The construction schedule of modular construction for the proposed project (cont.)

## Appendix D

### Copy of the Code used to develop the plug-in in Microsoft Visual Basic

```
Sub ExportToMsProject()  
  
Dim pjapp As Object  
  
Dim pjProject As MSProject.Project  
  
Dim strTaskName, strDuration, strStartDate, strEndDate, strResource, strCost, strTaskID, strType As  
String  
  
Dim newproj  
  
Set pjapp = CreateObject("MSProject.Application")  
  
If pjapp Is Nothing Then  
  
    MsgBox "MsProject is not installed"  
  
End If  
  
pjapp.Visible = True  
  
Set newproj = pjapp.Projects.Add  
  
newproj.Title = "Test"  
  
Set ActiveProject = newproj
```

TableEditEx Name:="&Entry", TaskTable:=True, NewFieldName:="COST", Title:="COST", Width:=12,

ShowInMenu:=True, ColumnPosition:=-1

TableApply Name:="&Entry"

TableEditEx Name:="&Entry", TaskTable:=True, NewFieldName:="Text1", Title:="Text1", Width:=12,

ShowInMenu:=True, ColumnPosition:=-1

TableApply Name:="&Entry"

lastrow = ThisWorkbook.Sheets("Activity Sequence").Cells(Rows.Count, 1).End(xlUp).Row

For i = 2 To lastrow

strTaskName = Worksheets("Activity Sequence").Range("A" & i)

strDuration = Worksheets("Activity Sequence").Range("d" & i).Value

strStartDate = Worksheets("Activity Sequence").Range("e" & i).Value

strResource = Worksheets("Activity Sequence").Range("b" & i)

strCost = Worksheets("Activity Sequence").Range("c" & i)

strTaskID = Worksheets("Activity Sequence").Range("a" & i)

strType = Worksheets("Activity Sequence").Range("g" & i).Value

newproj.Tasks.Add strTaskName

```
newproj.Tasks(i - 1).Duration = strDuration & "days"
```

```
newproj.Tasks(i - 1).Start = strStartDate
```

```
newproj.Tasks(i - 1).ResourceNames = strResource
```

```
newproj.Tasks(i - 1).Cost = strCost
```

```
newproj.Tasks(i - 1).Text1 = strType
```

```
Next
```

```
End Sub
```

# Appendix E

## Data processing before construction scheduling

The process of organizing and summarizing the data in Excel for schedule planning before exporting it to Microsoft Project:

1. The data extracted automatically from Revit can be sorted based on “Level”, “Category” and “TaskID” by using the “Sort” function as follow:

function as follow:

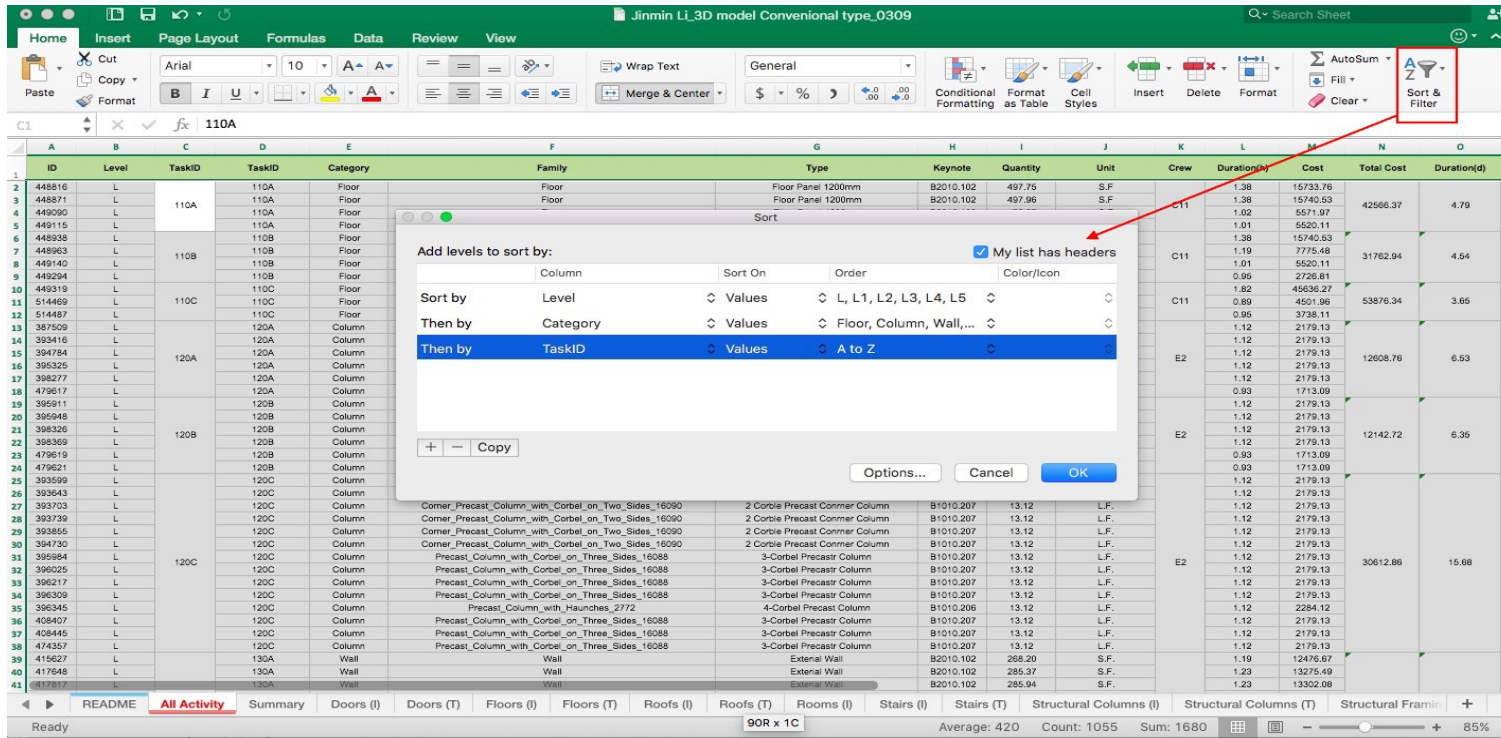


Figure E.1 Sorting the duration data of construction activity by TaskID

Then the cost subtotal and duration subtotal of each construction can be easily calculated after sorting:

ID	Level	Category	TaskID	Family Name	Type	Crew	Cost	Cost Sub	Duration Sub	
1	218567	L1	L_A	Basic Floor	Floor Panel 1200mm	C11	1142.75	89194.17512	0.3	
2	448816	L		Basic Floor	Floor Panel 1200mm		15733.76			
3	451282	L1		Basic Floor	Floor Panel 1200mm		15733.76			
4	387509	L		Corner_Precast_Column_with_Corbel_on_Two_Sides	2 Corble Precast Conrner Column		2179.13			
5	394784	L		Precast_Column_with_Corbel_on_Three_Sides_1608	3-Corbel Precastr Column		2179.13			
6	395325	L		Precast_Column_with_Corbel_on_Three_Sides_1608	3-Corbel Precastr Column		2179.13			
7	479617	L		Precast_Column_with_Haunches_2772	4-Corbel Precast Column		1713.09			
8	400023	L1		Parametric_L_Shaped_Beam_14264	Precast L Shaped Beam 1		2071.67			
9	402591	L1		Parametric_L_Shaped_Beam_14264	Precast L Shaped Beam 4		4275.62			
10	406279	L1		Precast_Inverted_Tee_with_Individually_Adj_Seats	Precast Inverted Tee Beam		5026.25			
11	406411	L1		Precast_Inverted_Tee_with_Individually_Adj_Seats	Precast Inverted Tee Beam		3738.27			
12	415627	L		Basic Wall	Exterial Wall		12476.67			
13	418027	L		Basic Wall	Exterial Wall		9760.62			
14	418450	L		Basic Wall	Interior Wall		5749.70			
15	418902	L		Basic Wall	Interior Wall		4179.60			
16	500843	L		Window	Window_Fixed_CGI_Series238_Tombstone_CustomE		1000mmx1700mm			1055.00
17	449090	L		L_B	Basic Floor		Floor Panel 1200mm			C11
18	533733	L1	Basic Floor		Floor Panel 1200mm	4568.04				
19	393416	L	Corner_Precast_Column_with_Corbel_on_Two_Sides		2 Corble Precast Conrner Column	2179.13				
20	398277	L	Precast_Column_with_Corbel_on_Three_Sides_1608		3-Corbel Precastr Column	2179.13				
21	401500	L1	Parametric_L_Shaped_Beam_14264		Precast L Shaped Beam 2	1172.54				
22	401730	L1	Parametric_L_Shaped_Beam_14264		Precast L Shaped Beam 4	4524.34				
23	406431	L1	Precast_Inverted_Tee_with_Individually_Adj_Seats		Precast Inverted Tee Beam	1350.80				
24	417817	L	Basic Wall		Exterial Wall	13302.08				
25	418133	L	Basic Wall		Exterial Wall	3178.68				
26	219379	L1	Basic Floor		Floor Panel 1200mm	1143.23				
27	448871	L	Basic Floor		Floor Panel 1200mm	15740.53				
28	451289	L1	Basic Floor		Floor Panel 1200mm	15740.53				
29	402456	L1	Parametric_L_Shaped_Beam_14264		Precast L Shaped Beam 4	4275.62				
30	406323	L1	Precast_Inverted_Tee_with_Individually_Adj_Seats		Precast Inverted Tee Beam	5026.25				
31	418524	L	Basic Wall		Interior Wall	5352.11				
32	528299	L	Basic Wall		Exterial Wall	14597.30				
33	528626	L	Window		Window_Fixed_CGI_Series238_Tombstone_CustomE	1000mmx1700mm	1055.00			
34	449115	L	L_C	Basic Floor	Floor Panel 1200mm	C11	5520.11	62930.57657	0.2	
35	533637	L1		Basic Floor	Floor Panel 1200mm		5046.18			
36	398326	L		Precast_Column_with_Corbel_on_Three_Sides_1608	3-Corbel Precastr Column		2179.13			
37	402063	L1		Parametric_L_Shaped_Beam_14264	Precast L Shaped Beam 4		4275.62			
38	406464	L1		Precast_Inverted_Tee_with_Individually_Adj_Seats	Precast Inverted Tee Beam		1350.80			
39	417648	L		Basic Wall	Exterial Wall		13275.49			
40										

Figure E.2 Calculation of cost and duration subtotal after sorting data

2. Create a new worksheet and named “Activity Sequence”, and merge all the data (TaskID, Crew, Cost Subtotal, Duration Subtotal) required for schedule planning in this worksheet, then assign the Start Date to the first activity so that the start date and finish date of other construction activities of the proposed project can be worked out automatically by using the function “F:F=E:E+D:D”

	A	B	C	D	E	F
1	TaskID	Crew	Cost Sub	Duration Sub	Start Date	End Date
2	L_A	C11	89194.18	0.3	1-03-2016	1-03-2016
3	L_B	C11	38026.72	0.3	1-03-2016	1-03-2016
4	L_C	C11	62930.58	0.3	1-03-2016	1-03-2016
5	L_D	C11	31647.34	0.2	1-03-2016	2-03-2016
6	L_E	C11	87832.91	0.3	2-03-2016	2-03-2016
7	L_F	C11	32180.48	0.2	2-03-2016	2-03-2016
8	L_G	C11	47807.86	0.3	2-03-2016	2-03-2016
9	L_H	C11	11276.83	0.2	2-03-2016	3-03-2016
10	L_I	C11	30549.02	0.1	3-03-2016	3-03-2016
11	L_J	C11	30067.46	0.2	3-03-2016	3-03-2016
12	L_K	C11	196836.01	0.5	3-03-2016	3-03-2016
13	L_L	C11	54090.69	0.1	3-03-2016	4-03-2016
14	L1_A	C11	72992.5	0.3	4-03-2016	4-03-2016
15	L1_B	C11	27266.65	0.2	4-03-2016	4-03-2016
16	L1_C	C11	63973.11	0.3	4-03-2016	4-03-2016
17	L1_D	C11	21851.09	0.2	6-03-2016	7-03-2016
18	L1_E	C11	60082.25	0.3	7-03-2016	7-03-2016
19	L1_F	C11	23366.88	0.2	7-03-2016	7-03-2016
20	L1_G	C11	32034.42	0.3	7-03-2016	7-03-2016
21	L1_H	C11	12465.1	0.2	7-03-2016	8-03-2016
22	L1_I	C11	21112.8	0.1	8-03-2016	8-03-2016
23	L1_J	C11	26202.23	0.2	8-03-2016	8-03-2016
24	L1_K	C11	31633.5	0.3	8-03-2016	8-03-2016
25	L1_L	C11	36624.82	0.3	8-03-2016	8-03-2016
26	L1_M	C11	35027.82	0.3	8-03-2016	9-03-2016
27	L1_N	C11	29125.33	0.3	9-03-2016	9-03-2016
28	L1_O	C11	38706.83	0.3	9-03-2016	9-03-2016
29	L2_A	C11	74726.82	0.3	9-03-2016	10-03-2016

Figure E.3 Assigning the start date of the proposed project

3. These data after organized and summarized can be exported automatically from Excel to Microsoft Project by the developed plug-in:

	A	B	C	D	E	F	G	H	I	J
1	TaskID	Crew	Cost Sub	Duration Sub	Start Date	End Date	Type			
2	L_A	C11	89194.18	0.3	1-03-2016	1-03-2016	Construct			
3	L_B	C11	38026.72	0.3	1-03-2016	1-03-2016	Construct			
4	L_C	C11	62930.58	0.3	1-03-2016	1-03-2016	Construct			
5	L_D	C11	31647.34	0.2	1-03-2016	2-03-2016	Construct			
6	L_E	C11	87832.91	0.3	2-03-2016	2-03-2016	Construct			
7	L_F	C11	32180.48	0.2	2-03-2016	2-03-2016	Construct			
8	L_G	C11	47807.86	0.3	2-03-2016	2-03-2016	Construct			
9	L_H	C11	11276.83	0.2	2-03-2016	3-03-2016	Construct			
10	L_I	C11	30549.02	0.1	3-03-2016	3-03-2016	Construct			
11	L_J	C11	30067.46	0.2	3-03-2016	3-03-2016	Construct			
12	L_K	C11	196836.01	0.5	3-03-2016	3-03-2016	Construct			
13	L_L	C11	54090.69	0.1	3-03-2016	4-03-2016	Construct			
14	L1_A	C11	72992.5	0.3	4-03-2016	4-03-2016	Construct			
15	L1_B	C11	27266.65	0.2	4-03-2016	4-03-2016	Construct			
16	L1_C	C11	63973.11	0.3	4-03-2016	4-03-2016	Construct			
17	L1_D	C11	21851.09	0.2	6-03-2016	7-03-2016	Construct			
18	L1_E	C11	60082.25	0.3	7-03-2016	7-03-2016	Construct			
19	L1_F	C11	23366.88	0.2	7-03-2016	7-03-2016	Construct			
20	L1_G	C11	32034.42	0.3	7-03-2016	7-03-2016	Construct			
21	L1_H	C11	12465.1	0.2	7-03-2016	8-03-2016	Construct			
22	L1_I	C11	21112.8	0.1	8-03-2016	8-03-2016	Construct			
23	L1_J	C11	26202.23	0.2	8-03-2016	8-03-2016	Construct			
24	L1_K	C11	31633.5	0.3	8-03-2016	8-03-2016	Construct			
25	L1_L	C11	36624.82	0.3	8-03-2016	8-03-2016	Construct			
26	L1_M	C11	35027.82	0.3	8-03-2016	9-03-2016	Construct			
27	L1_N	C11	29125.33	0.3	9-03-2016	9-03-2016	Construct			
28	L1_O	C11	38706.83	0.3	9-03-2016	9-03-2016	Construct			
29	L2_A	C11	74726.82	0.3	9-03-2016	10-03-2016	Construct			

Figure E.4 The data for scheduling is ready to export to MsProject by using the plug-in