A BIM-DATABASE-INTEGRATED SYSTEM FOR EVALUATING BUILDING LIFE-CYCLE COSTS USING A MULTI-PARAMETRIC MODEL

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ระบบซึ่งบูรณาการการจำลองสารสนเทศอาคารและฐานข้อมูลสำหรับประเมินต้นทุนวงจรชีวิตอาคาร
โดยอาศัยแบบจำลองแบบหลายพารามิเตอร์

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ฮาง ธีรุ เล : ระบบซึ่งบูรณาการการจำลองสารสนเทศอาคารและฐานข้อมูลสำหรับประเมินต้นทุนวงจรชีวิตอาคารโดยอาศัยแบบจำลองแบบหลายพารามิเตอร์. (A BIM-DATABASE-INTEGRATED SYSTEM FOR EVALUATING BUILDING LIFE-CYCLE COSTS USING A MULTI-PARAMETRIC MODEL) อ.ที่ปรึกษาหลัก : วีระศักดิ์ ลิขิตเรืองศิลป์, อ.ที่ปรึกษาร่วม : โนบุโยชิ ยาบุกิ

การวิเคราะห์ต้นทุนวงจรชีวิต (life-cycle cost analysis หรือ LCCA) ได้กลายมาเป็นข้อกำหนดที่สำคัญสำหรับการจัดจ้างอย่างยั่งยืน (sustainable procurement) สำหรับโครงการก่อสร้างมากมาย วิธีการวิเคราะห์ต้นทุนวงจรชีวิตอาคารที่มีอยู่มีความสลับซับซ้อนเป็นอย่างมากและจำเป็นต้องใช้เวลายาวนานเนื่องจากต้องทำงานที่ซ้ำ ๆ กัน ข้อมูลซึ่งจำเป็นที่มากมายมหาศาล ข้อมูลนำเข้ากระจัดกระจาย รวมถึงระเบียบข้อกำหนดอันหลากหลาย สาเหตุเหล่านี้นำไปสู่ต้นทุนวงจรชีวิตที่ไม่ถูกต้อง การจำลองสารสนเทศอาคาร (building information modeling หรือ BIM) เป็นเทคโนโลยีสารสนเทศสมัยใหม่ซึ่งสามารถกำจัดอุปสรรคจากการวิเคราะห์ต้นทุนวงจรชีวิตอาคารที่มีอยู่ได้ งานวิจัยนี้ได้พัฒนาระบบซึ่งบูรณาการการจำลองสารสนเทศอาคารและฐานข้อมูลสำหรับประเมินต้นทุนวงจรชีวิตอาคารโดยอาศัยแบบจำลองแบบหลายพารามิเตอร์ (BIM-BLCC) ระบบนี้ประกอบด้วย 4 มอดูล (1) มอดูลจัดการฐานข้อมูลเชิงสัมพันธ์ (relational database management module) จะรวบรวมและจัดข้อมูลข้อมูลที่จำเป็นสำหรับแบบจำลอง BIM (2) มอดูลซึ่งบูรณาการกับ BIM เพื่อการสร้างภาพนามธรรม (visualized BIM-integrated module) จะสร้างภาพนามธรรมแบบสามมิติร่วมกับการวิเคราะห์ต้นทุนวงจรชีวิต และช่วยในการคำนวณที่สลับซับซ้อน เช่น สัมประสิทธิ์อุณหภูมิ (thermal coefficient) เพื่อประมาณต้นทุนพลังงาน (3) มอดูลการประมาณแบบหลายพารามิเตอร์ (multi-parametric estimation module) จะคำนวณหมวดต้นทุนทั้งหมดของต้นทุนวงจรชีวิตอาคารแบบอัตโนมัติโดยอาศัยการจำลองสถานการณ์แบบหลายพารามิเตอร์ (multi-parametric simulation) (4) มอดูลรายงานผลซึ่งบูรณาการกับ BIM (BIM-integrated report module) จะรายงานผลการวิเคราะห์จากแบบจำลองแบบหลายพารามิเตอร์ในรูปแบบของ spreadsheet ประสิทธิภาพและการปฏิบัติได้จริงของระบบ BIM-BLCC ได้ถูกทวนสอบโดยการประยุกต์ใช้กับอาคารสำนักงานจริง ผลจากการคำนวณด้วยมือได้ถูกเปรียบเทียบกับผลลัพธ์จากระบบ BIM-BLCC ซึ่งพบว่าค่าทั้งสองมีความใกล้เคียงกัน นอกจากนั้นผลลัพธ์จากระบบยังได้ถูกทวนสอบโดยผู้เชี่ยวชาญอีกด้วย เราจึงสามารถสรุปได้ว่าระบบ BIM-BLCC นี้สามารถถูกใช้โดยผู้ร่วมโครงการเพื่อประเมินต้นทุนวงจรชีวิตอาคารในโครงการก่อสร้างอาคารจริงได้อย่างมีประสิทธิภาพ

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Hang Thi Thu Le : A BIM-DATABASE-INTEGRATED SYSTEM FOR EVALUATING BUILDING LIFE-CYCLE COSTS USING A MULTI-PARAMETRIC MODEL. Advisor: Assoc. Prof. VEERASAK LIKHITRUANGSILP, Ph.D. Co-advisor: Prof. Nobuyoshi Yabuki, Ph.D.

Life-cycle cost analysis (LCCA) has become an essential requirement of the sustainable procurement for many construction projects. Conventional building LCCA methods are extremely complex and time-consuming due to repetitive works, numerous required data, scattered data inputs, and various regulatory requirements, which subsequently lead to inaccurate building life-cycle costs (LCC). Building information modeling (BIM) offers a revolutionary information technology, which can overcome the asperities of the conventional building LCCA. This research develops the BIM-database-integrated system for evaluating building life-cycle costs using a multi-parametric model (BIM-BLCC). The BIM-BLCC consists of four interrelated modules. The relational database management module collects and organizes the required data for the BIM model. The visualized BIM-integrated module generates 3D visualization along with the LCCA and facilitates complex calculations such as the thermal coefficients for estimating the energy cost. The multi-parametric estimation module automatically calculates all cost categories of the building LCC through multi-parametric simulation. The BIM-integrated report module reports the analysis results from the multi-parametric model in the form of spreadsheets. The efficacy and practicality of the BIM-BLCC were verified through applying it to an actual office building. The manual calculation was conducted and its results were compared with those provided by the BIM-BLCC. Based on the similar results from both approaches and the experts' verification, it can be concluded that the BIM-BLCC can be efficiently used by the project participants to evaluate the building LCC in actual building projects.

Field of Study:	Civil Engineering	Student's Signature ....
Academic Year:	2018	Advisor's Signature ....
		Co-advisor's Signature ....

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CHAPTER 1
INTRODUCTION

1.1 General overview

Buildings serve many important functions in human life, especially providing space for work, education, living, as well as other public and private uses. Building construction is one of the most important sectors of the construction industry in many developing countries. Buildings also have a vital impact on the environment and occupants' health. According to the U.S. Green Building Council (2015), buildings in the U.S. were responsible for 41 percentage of the total U.S. energy expenditure. Electricity consumption inside the buildings represented 73 percentage of the total energy expenditure. Moreover, they also created 38 percentage of the total U.S. carbon dioxide emanation and contributed to 250 million tons of construction and demolition waste in the States (USGBC, 2015). In fact, the building industry is one of the most significant consumers of natural resources, which accounts for a large percentage of the greenhouse gas emissions that affect climate change.

Decreasing the impact of building on the environment can be achieved by embedding of the life-cycle cost analysis (LCCA) into the procurement system to promote more sustainable buildings for future generations.

Sustainability is currently acknowledged by many developed and developing countries worldwide. Achieving sustainability encompasses three main pillars: environment, society, and economy. The LCCA is an effective economic approach to assess the sustainability of a building project. The awareness of a better value of money by LCC is beyond the initial price alone. Many countries such as the U.S.A., Japan, and the European Council have added the LCCA as a key provision in the context of the procurement system to promote sustainable growth. Different from the conventional system, the sustainable approach concerns not only economic but also environmental issues. It is designed to highlight the characteristics of a building project that can minimize the environmental impact during a project's life span. There have been many project cases that represent the advantages of sustainable procurement in construction projects. For example, the City of Regensburg found that the use of green public procurement saved 10 million EUR on energy and water costs over a 15-year period (Kohler, 2016). The Dutch Ministry of Infrastructure and Environment reported that three million tons of carbon dioxide would be saved in the Netherlands and 10 percent of energy consumption could be reduced in case that all Dutch public authorities applied the national sustainable public procurement benchmark (Berry, 2011).

The endorsement of building information modeling (BIM) in the construction industry has been rising year-by-year. This is because BIM is acknowledged as a supporting technology to reduce waste, increase productivity, improve environmental impacts, and decrease the total cost of occupancy of a building project. According to the United Kingdom Cabinet Office (2011) BIM level 2 was mandated on public projects with the initial capital cost of over 5 million GBP by 2016. The Netherlands, Denmark, Finland, and Norway also mandated BIM for the public sector procurement to support the sustainable growth (Kohler, 2016). The Chinese government strongly encouraged the introduction and adoption of BIM technologies in the architecture, construction, and engineering (AEC) industry (Herr and Fischer, 2018). In the US, the number of projects adopting BIM was only 28 percent in 2007, but reached 71 percent in 2012 and continued growing (Skanska, 2012). This means that BIM has now become a mainstream of the construction industry. In Southeast Asia, Singapore is a leader of BIM implementation. Many strategies have been proposed to encourage BIM use in the construction industry. For example, the government of Singapore has established a construction productivity and capability capital of 250 million USD for BIM use. The CORENET e-plan test tool has been developed to support BIM use (Smith, 2014).

1.2 Problem statement

The life-cycle cost analysis (LCCA) is an effective economic assessment tool that provides a detailed account for all costs related to construction, operation, maintenance, and disposal of a building project over a defined period of time. Although the LCCA is now a criterion in many national policies such as the 2014 Public Sector

Directive of the European Council, the three guidelines for procurement consisting of the Life Cycle Costing Procurement Guide, the Life Cycle Costs in Equipment Procurement - Casebook, and the Life Cycle Cost Guide for System Acquisitions of the United States, as well as the current National Code of the United States. In addition, the results from the Perera survey on the use of the LCCA in sustainable public procurement in 28 countries showed that many countries such as the U.S.A., Japan, Switzerland, and Norway had applied the LCCA as part of green and sustainable procurement policies. Many countries are conducting some forms of the LCCA in the procurement of new energy-efficient buildings including Sweden, New Zealand, Germany, the United Kingdom, Denmark, the Netherlands, France, Australia, Korea, and Austria. Many other countries have experimented the use of the LCCA in the commissioning of profitable energy buildings including Canada, Chile, South Africa, Argentina, Costa Rica, Mexico, Italy, Spain, India, Singapore, Portugal, China, and Brazil. Meanwhile, other countries were at the beginning stage of using the LCCA in their sustainable procurement policy, including Vietnam, Botswana, Senegal, Mauritius, Ghana, and Indonesia (Perera, 2009).

In practice, the evaluation of the building LCCA is still limited because of the unavailability of required data, the time restraints and costs to invest and maintain the predicting system, as well as the uncertainty caused by human error and mistakes in inputting data manually. Table 1.1 shows the limited use of the building LCCA as a tool for early stage evaluation of projects in the United Kingdom (Higham et al., 2015). The accuracy of LCC is massively dependent on the availability of data in construction, maintenance, and operation, in conjunction with general information related to the value of money. However, quantity surveyors (QSs) usually face difficulties while collecting required data. Boussabaine and Kirkham (2017) pointed out that it is challenging for project managers to perform the building LCCA because it is difficult to obtain appropriate, accurate, and consistent data for a building in the early design phase.

Table 1.1 Frequency of the LCCA by project types

Project categories	Rarely (%)	Sometimes (%)	Often (%)	Always (%)
Housing	55	9	27	9
Health	48	5	26	21
Education	57	14	7	22
Industrial	78	11	11	0
Commercial	77	15	8	0
Highway infrastructure	50	13	25	12
Other	22	22	33	22

According to Emblemsvåg (2003) and Bull (2003), the building LCCA is accurate only wherever the collected data are sincere. However, data collection for the evaluating process is difficult because a large number of documents are usually stored under paper files. Other research works also identified the quality of the data available to execute the evaluation of a potential building project's as a critical problem affecting the use of the building LCCA in practice (M. Kishk, Laing, R., and Edge, M., 2006). The uncertainty concerning the variables has a decisive role in the accuracy of the estimation, so the elimination of uncertain data is necessary for the building LCCA models (Flanagan, 1989). Assaf (2002) pointed out that designers usually face difficulties of collecting and analyzing data, especially for operation and maintenance costs such as data for regular repair services, predictive maintenance, and energy costs.

The building sector consumes almost 50 percent of the total energy per year. Most of this amount occurs during the life cycle period (Kansal, 2010). Since, the cost of energy plays a significant role in long-term exploitation costs, the building LCCA is an important tool for alleviating the adverse impact of buildings on the environment and enhancing energy efficiency. However, the difficulties of data acquisition limit its implementation, especially energy cost estimation. Some research work points out that most building LCCA tools often do not consider energy costs as a cost category (Gluch and Baumann, 2004; Langdon, 2007; and Tsai et al., 2014).

A commercial spreadsheet software has been developed by Microsoft Excel for calculating the LCC (e.g., ACEIT, BLCC, CAMSLCC, EDCAS, and CASA). These commercial applications often use conventional 2D CAD drawings to perform the building LCCA. However, they cannot promote the use of the LCCA in practice. Kishk et al. (2003) pointed out important reasons the building LCCA is rarely performed in practice. First, for most existing building LCCA tools, required information must be input manually, and they can perform only a single calculation. Thus, it usually takes a long time to perform several LCCA for all building elements. Second, the installation and maintenance costs of the systems are usually high. Dhillon (1989) showed that the software cost accounts for a large proportion of the total computer system expense, which consists of two distinct categories: development cost and maintenance cost. The average percentage of the development expenditure is 36.5 percent of the total software cost, and the average percentage of the maintenance is 63.5 percentage of the total software cost. Third, the results obtained from the software are often controlled by its regulatory requirements. Thus, the analysis cannot be modified to local standards. In addition, the existing tools use the parametric method to estimate expenses, which are difficult to perform in the early design stage due to the lack of information and data (Mason, 1997).

Building information modeling (BIM) is a revolutionary technology that has been adopted by the AEC to transform the conventional construction industry to the digital one. Many research have confirmed the advantages of BIM in the construction management area. BIM helps designers create virtual modules of digitally constructed buildings. These modules allow owners to visualize their buildings before they are built. BIM allows multi-punitive information to be contained through one module. It also incorporates the sustainability assessment to the design process (Autodesk, 2005). BIM can enhance the accuracy of quantity takeoff as compared with those by manual calculation. Shen (2010) confirmed that the BIM-based design module yields more efficient and accurate construction cost. Sabol (2008) pointed out that BIM estimates exactly what is in the model, which means that there is no variation between what has been computed and what is required. Natephra (2018) found that the BIM database can store the thermal properties of material’s so it can reduce time calculating the heat transfer coefficient and the solar heat gain coefficient of the energy cost. BIM has also been used to evaluate the energy consummation of buildings' during the design process (Che, 2010). BIM was integrated to design decision-making (Schlueter, 2009), and to a decision-making tool in selecting sustainable materials for building projects (Jalaei, 2015).

Although BIM provides various advantages to construction management, BIM tools for 5D cost management are still limited. Goucher (2012) stated that the cost database and the unit of calculation are usually based on historic standards, which are not applicable to BIM items. Thus, the current cost estimating cannot be performed without a critical change from the cost per standard method to the cost per BIM items. Sabol (2017) pointed out that there are two barriers for implementing BIM for cost management. First, the model properties in BIM authoring programs do not conform with the cost management methodology. Thus, it is difficult to create a formal cost plan with the BIM design tool per the standard method of calculation. Second, the 5D quantity surveying cannot find the BIM tool that is sufficient for cost plan modeling because the data structure of the BIM model is not appropriate with the elemental or trade code structure required by classification structures. Shen (2010) reported that the current BIM tools are not genetically wealthy enough to cover all data in overall construction process and job conditions.

A number of research have investigated the sustainability of building projects through evaluating the LCC. Moussatche (2001) performed the service whole cost analysis for evaluating the materials of interior floor of the educational project in the State of Florida based on 50-year service life. Castro-Lacouture (2009) proposed a mixed optimistic model to assist decision-makers in selecting of the appropriate materials for the desired environmental goals. Kim (2013) proposed a method for predicting maintenance and operation costs for a hospital project using Monte Carlo simulation. This proposed system uses a long normal distribution to define the minimum and maximum values. Although BIM research works have been increasing in both academics and industry, there has been limited studies on the BIM implementation for the building LCCA. Fu (2007) pointed out that without standards guiding BIM elements, models cannot directly relate to the elemental building classification on cost databases. Thus, it is necessary to integrating BIM platforms to the building LCCA process. Shen (2010) found that the present model properties are not genetically rich enough to contain all data of construction phases and job conditions. Goucher (2012) pointed out that the existing BIM tools did not have enough capability to accommodate the required data for carrying out the building LCCA. In fact, there are a few required data of BIM objects to evaluate a building LCCA such as construction unit price, annual service unit price, expected service life, and thermal parameters to estimate the energy cost. In addition, the problem concerning interoperability is a major barrier of BIM adoption for the building LCCA. Fischer (2004) as well as Grilo (2010) argued that it is ineffective to input data in commercial software due to the lack of interoperability between different software and types of data format. Hjelseth (2017) identified that the lack of integration among the standards and methods of calculation, the collaborative people, and the interoperable technology were the most critical factors that limit the use of BIM for the building LCCA. Olatunji (2011) found that interoperability is a major problem for BIM adoption in the construction industry. Laakso (2012) also stated that information exchange is essential for cost consultants because without complete interoperability, the missing data will disrupt in the estimating process.

A visual programming interface has been developed for BIM authoring programs, which allows users to extend the capacity of present BIM tools for the building LCCA by using the graphical algorithm. Visual script is a programming language that is easy to write and understand for cost managers who are usually nonprogrammers. Thus, it will be beneficial if the building LCCA is integrated with BIM authoring programming with the visual programming interface, database management system, and spreadsheet programming.

1.3 Research objective

The main objective of this dissertation is to develop a BIM-database-integrated system for evaluating building life-cycle costs using a multi-parametric model (BIM-BLCC). The proposed system focuses on the economic evaluation for supporting the sustainable procurement of building projects. It integrates the functionalities of BIM authoring programming, the database management system, visual programming, and spreadsheet programming. The system consists of four main modules:

(1) *The relational database management module* provides the necessary data for the BIM model. The data in this database are analyzed following the assembly format, which is appropriate for the element objects. The raw data were collected from similar past projects and other reliable data sources.

(2) *The visualized BIM-integrated module* provides 3D model visualization for the BIM-BLCC, which supports the calculation of the heat transfer coefficient and the solar heat gain coefficient for predicting the energy cost based on the structural design of element models.

(3) *The multi-parametric estimation module* automatically calculates all cost coefficients for the building LCCA through a multi-parametric model.

(4) *The BIM-integrated report module* reports the results of the building LCCA from the multi-parametric model in the form of spreadsheet reports.

1.4 Scope of research

The scope of this research is as follows:

1) The cost categories computed by the proposed system encompass the construction cost, maintenance cost, operation cost, and salvage value. Other cost categories were not included in the system.

2) The proposed system entails the architectural system of a building project, which is considered the largest portion for a building LCC. Other systems of the building such as the structural, mechanical, electrical, and plumbing systems are not within the scope of this research.

3) The system adopted the same discount rate to compute the time value of money for all cost categories.

4) The system focuses on the detailed building LCCA performed during the procurement phase.

5) Most of the data were collected from similar past projects in Thailand, the published data from the Assemblies Costs within RSMeans data 2018 43rd

annual edition (Phelan, 2018), and the Life cycle costing for design professionals (Kirk, S., J., and Dell'Isola, A., J., 1995), the 1989 ASHRAE handbook fundamentals (Robert, 1989), the internal Revit material library, and the records of the Royal Thai Meteorological Department of 2017.

1.5 Research steps

The concept of the building LCCA is used as the fundamental for developing the called the BIM-BLCC. The selection of BIM and big data in the construction industry also constitutes the foundation to design the system architecture. The system is primarily based on four main modules, which are interrelated to perform their functions. This research consists of seven steps.

(1) Do literature review

The first step is to review proper literature, including the advantages of BIM for construction management, the building LCCA in practical sustainable procurement, database management systems in construction management, cost categories for the building LCCA, sustainable procurement, visual programming, required data, data organizations. The literature was collected from books, journals, proceedings, reports, standards, and guidelines. The research problem was stated and critical research gaps were identified.

(2) Establish the system framework and its components

Based on the reviewed knowledge in Step 1, the conceptual framework of the proposed system was established. The components of each module were then structured.

(3) Identify the system platform

All potential system platforms were thoroughly examined. Through the system requirements, expert interviews, and the attributes of the potential platforms, the most suitable platform was adopted to develop the proposed system.

(4) Develop the system

The system architecture of the BIM-BLCC was created from the conceptual framework and requirements, which were established in Step 2. The four modules of the BIM-BLCC were developed using the adopted platforms; and then integrated into a unified system

(5) Collect data for the proposed system

In this step, raw data was collected and used as inputs of the proposed system. Because BIM models cannot accommodate all of required data for all element model to evaluate the building LCCA, some parts of building element data was stored in the relational LCC database. Other data were supported through BIM authoring programming.

(6) Apply the proposed system to the case study

The proposed system was applied to a 6-story office building for examining its practicality. The system results were compared with manual calculations to verify their accuracy.

(7) Draw conclusion

Per the application in Step 6, the system performances were analyzed and assessed. Finally, the research conclusion, limitation, and suggestion were discussed.

1.6 Structure of dissertation

The dissertation consist of nine chapters, the summary of which is as follows.

Chapter 1 presents the background, problem statement, research objective, scope of research, research steps, and structure of dissertation.

Chapter 2 presents the results for our literature review including the overview of the building LCCA, cost categories of a building LCCA, mathematical approaches for the building LCCA, the building LCCA stipulated in sustainable procurement system, building information modeling in construction management, database management system in construction management, interoperability, and visual programming interface.

Chapter 3 discusses the research methodology used to develop the proposed system. It contains system requirements, system architecture and modules, definition of potential platforms for the proposed system, data collection, system verification and validation.

Chapter 4 presents the development of the relational database management module of the BIM-BLCC, which consists of the characteristics of the relational LCC database, the schema of relational LCC database, and data organization.

Chapter 5 discusses the development of the visualized BIM-integrated module of the proposed system. It includes the introduction of the workflow for developing the visualized BIM-integrated module, the level of development (LOD) of the BIM model for evaluating the building LCCA, the required parameters for element properties for the building LCCA, and the process of extracting added parameters for the 3D BIM model.

Chapter 6 presents the development of the multi-parametric estimation module of the BIM-BLCC. The chapter contains the introduction of the workflow for developing the multi-parametric estimation module, the formulations for calculating cost categories of the building LCCA, the selection of assumption for the building LCCA, and the development of multi-parametric estimation module.

Chapter 7 discusses the BIM-integrated report module of the BIM-BLCC. In this chapter, we present the introduction of the workflow for developing the BIM-integrated report module, the development of the spreadsheet workbook, and the process for exporting results from multi-parametric model to the spreadsheet workbook by using visual programming interface.

Chapter 8 presents the system verification and validation. We discuss the concept of system verification and validation, the characteristics of the case study building project, the process of applying the BIM-BLCC to the case study building project, results and discussions, and the evaluation of the BIM-BLCC application by the interview with experts.

Chapter 9 presents the conclusions, research outcomes, the limitations of this research, the recommendations for future research to improve the BIM-BLCC, and the future works.

CHAPTER 2
LITERATURE REVIEW

The chapter reviews relevant knowledge related to this research and gaps of previous research. This chapter is divided into nine section. The first section is the overview of the building LCCA. The second section presented cost categories for the building LCCA. The third section reviews mathematical approaches for the building LCCA. The four section presents the LCCA stipulated in sustainable procurement system. The five section presents building information modeling for construction management. The six section presents database management system. The seven section presents interoperability of BIM platforms. The final section presents visual programming interface.

2.1 Overview of the building life-cycle cost analysis (LCCA)

The building life-cycle cost analysis (LCCA) is an economic approach for project evaluation that considers all significant costs arising from constructing, operating, maintaining, and ultimately disposing of a building.

Flanagan (1989) defined that there are some terminology that were and are using to call a life-cycle cost (LCC) such as “cost in use”, “life cycle cost”, “whole life costing”, and “whole life appraisal”. The terminology of LCC has change over the years. According to BS ISO 15686-5 (ISO, 2017), the definition of each term was described based on the costs that were included in the analysis of each term. The term “life-cycle cost” is usually used today which contains consideration of the cost benefits and consummation of project over its life cycle. The term “life-cycle cost” was used as a cradle to grave way that analyzes the direct monetary costs of a valid facility.

Jrade (2012) defined that the LCCA is a technology of economic evaluation of all costs related to constructing, operating, and maintaining a building project over a defined period of time. Another definition identified the LCCA was a mathematical method used to support a decision and was often employed when deliberating on a selection of alternative (Bull, 2003). Dale (2003) defined that the LCCA was a technology used to determine a decision and was usually employed when considering on a selection of options. It was an auditable financial ranking tool for commonly exclusive alternatives which can be used to promote the desirable and eliminate the undesirable in a financial environment. Farr (2011) defined the LCCA is the total ownership cost of a project over its useful life. The LCCA considers all predicted costs associated with a construction project throughout its life including the total of the direct, indirect, recurring, nonrecurring, and other related costs in design, construction, operation, maintenance, and disposal stages of a project over its life cycle. The LCCA is a worthwhile technique that is used for estimating and assessing the cost performance of constructed assets. The LCCA is considered in the assessment of design decisions to achieve long-term value of money. It is one framework of analysis for determining whether a project meets the user's requirements (ISO, 2017).

National Institute of Standards and Technology proposed a list of ten key steps in the LCCA process following (Fuller, 1996):

- Step 1: Identify problem and objective
- Step 2: Define feasible alternatives
- Step 3: Identify assumed parameters
- Step 4: Construct costs and times of appearance for each alternative
- Step 5: Compute present value of future costs
- Step 6: Compare the LCCA for each alternative
- Step 7: Compute priority conditions
- Step 8: Evaluate uncertainty of input data
- Step 9: Consider supplementary costs which cannot be estimated
- Step 10: Make decision

Farr (2011) also proposed seven steps of a simple process for developing the LCCA model, as shown in Figure 2.1.

There are many research about the LCCA in the fields of construction projects, facility management, and infrastructure. Smith, M., Whitelegg, J., and Williams, N. (1997) proposed the LCCA application for assessing the costs and benefits of selecting environment friendly construction practices for social rented housing in Scotland. Life-cycle assessment (LCA) and the LCCA are applied two building: a conventional building and an environmentally responsible building for the costs and benefits assessment.

Khanduri (1996) developed a quantitative LCC model and tool for the evaluation of the financial feasibility of office building projects at the early design stage. This model takes care most of necessary data and financial factors that are required to decide the life cycle costs of the proposed building at the feasibility stage with minimum input. The proposed model calculated the life cycle costs following three factors including present worth, annual worth, and savings-to-investment ratio. Sterner (2000) implicate the expansion of the LCCA use for government, developer, and professionals in Swedish caused by increasing the perspective of the LCCA useful of cost reductions in the operation and maintenance phase. According to Bull (2003), the LCCA was used as an engineering tool for supporting decision-making in design and procurement of construction process. It can also use a decision support system for construction management that overcomes many deficiencies of conventional cost accounting and provide useful cost insights in construction management. Furthermore, the LCCA can been considered as a design and technological tool for environmental objectives.

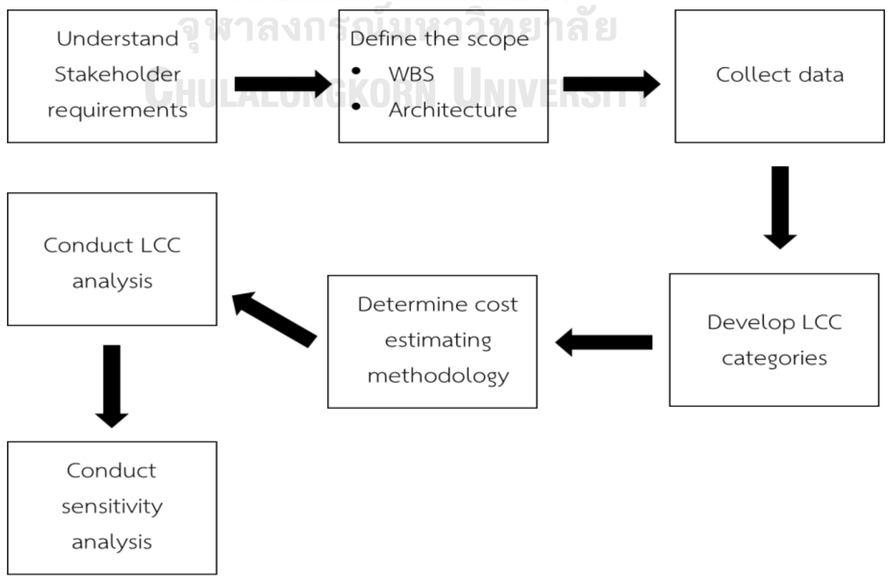


Figure 2.1 Process for developing the LCCA model

Kirk, S., J., and Dell'Isola, A., J. (1995) also presents the use of the LCCA throughout project stages. At the conceptual stage, the LCCA was applied as a component of an investment assessment. This is a systematic approach to determine capital investment regarding proposed projects. At the design stage, the LCCA was applied to evaluate the different options in the design in order to consider the economic impact throughout the project life. Cycle. At the construction stage, the LCCA was concern in three cases. First, the contractor was allowed the selected materials or components that conform to the specification but will nonetheless have an impact upon the LCCA of projects. Second, the contractor should consider the LCCA when they determinate to the buy, lease, or rent of the construction facilities and equipment. Third, the project managers are able to provide a professional input to the inspection of the design whether it involved sufficiently early in the project life cycle. They may be able to define the LCCA application of the design in the context of construction and in the way that the project will be assembled on construction site. During the project use and occupation period, the LCCA is able to show that it can help to improve efficiency of the life quality and the better environmental controls that will outweigh the maintenance costs within the defined period. The LCCA is an proper technique to be used in the energy measurement. A reduction in energy consumption has been encouraged, due to the rising costs of oil supplies, the finite availability of such fossil fuels, and now what has become commonly known as the 'greenhouse effect'. The energy assessment required a detailed research of assumptions, reporting of outputs, tariff documentation, and appropriate monitoring systems.

Fretty (2003) argued that the building LCCA is really the only approach to estimate the exact cost of primary purchase decisions. The implementation of the building LCCA can drastically reduce maintenance costs. However, the facility managers must apply accurate and update cost and information to achieved with the building LCCA.

Suttell (2002) concluded that the building LCCA helps building owners and designers to evaluate agreements among construction and operation costs of a building project. The users can get an understandable picture of how well your building reaches its purpose through economic evaluation, customer satisfactory surveys, and operational benchmarks.

The implementation of the LCCA in the building industry is still limited because of the lack of standards and the different required data that affect the reliability of the building LCCA results. According to a government policy issued by the Building Research Establishment of 1998, there were four main barriers to performing the building LCCA

- The lack of standard formats for performing the building LCCA
- The difficulty in integrating platforms for sharing data
- The inconsistency of data collection. There are so many types of data that require for implementing the building LCCA from different project participants. And the reliability of data will affect to the consequence of the building LCCA.
- The obligation for an individually maintained database on implementation and cost of the building LCCA.

2.2 Cost categories of the building LCCA

The purpose of the building LCCA in this research is to make economic evaluation for a tender evaluation process. Scope of each analysis depends on the identified list of costs over life of a building. For example, Kirk, S., J., and Dell'Isola, A., J. (1995) suggested the list of cost categories of the building LCCA consist of:

- Construction costs including cost, fees, and other initial costs for constructing a building project
- One time costs including replacement cost, salvage value, and other one-time costs
- Annual costs including operation cost, maintenance cost, financial cost, taxes, insurance, security, and other annual costs
- Functional costs including staffing, materials, denial of use, and other functional costs

BS ISO 15686-5:2017 proposed the hierarchical organization for cost categories of the building LCCA throughout four phases of a building life cycle consist of construction, operation, maintenance, and end of life stage, as shown in Figures 2.2.

2.2.1 Construction phase

Construction costs include costs related to fees for project design and engineering, temporary works, and statutory consents that was used for site clearance; construction of asset including infrastructure, fixtures, commissioning, valuation and handover; taxes on construction goods and services, and other project contingencies. Compared with other stages, cost categories of the construction stage are relatively clear and visible because they occur relatively close to the present time. However, the findings of Ashworth found that the contractor cost estimation were only accurate to about 13% (Ashworth, 1993).

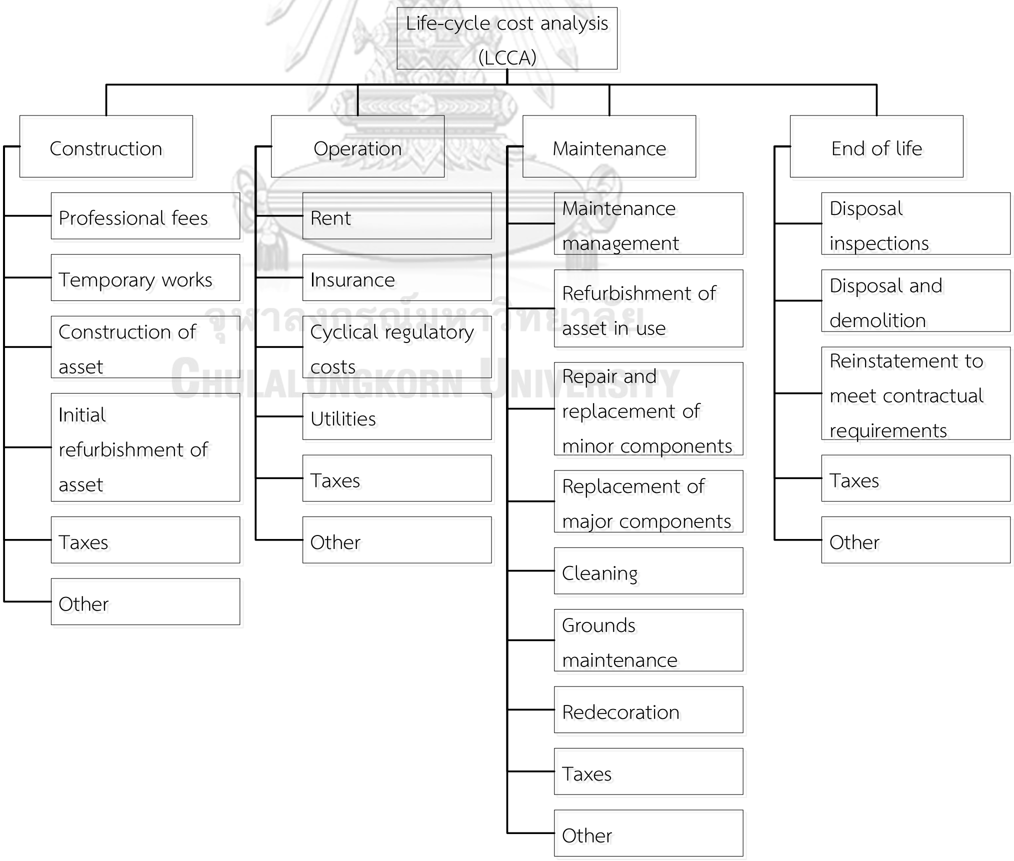


Figure 2.2 Scope of cost categories for the building LCCA

2.2.2 Operation phase

The operating and maintaining stages are often the longest period in the building life-span. However, they are often neglected in building procurement system. The costs of operation and maintenance activities usually appear repeatedly. They are probably to represent a large percent of the total building LCCs.

Operation costs include rent fees, insurance of the building occupiers or owners, circular regulatory costs that used for fire system or enter inspections, utilities including fuel for heating, cooling, watering, power, lighting, and sewerage costs, taxes for local fees, or environmental changes, and other allowance for future conformity with regulatory adjustments.

The energy cost usually takes up the greatest share of the operation cost. Building consumes the energy through heating, cooling, lighting system influenced by the employment and hours of weather conditions, the building design, building systems operations, the performance level required by owners, the insulation arrangement, the energy demands, energy prices and efficiencies of the energy consuming systems in the building. The energy of a building design takes into account building energy losses that take place during an examined period following heat transfer throughout convention, conduction and radiation. They occur periodically and may often be viewed as a yearly recurring cost. For the sustainability, the building users are usually expected to decrease the annually energy utilization for the long time operational cost of a building. Computing annual amounts of energy demanded for a building performance can be based on technological specifications, energy estimating mathematical statements, or on digital simulations. Energy expenditure amounts should be calculated for each type of energy consumed by the building. The users should examine even if you need hourly, monthly, and annual energy expenditure data and regularly energy demand data for selecting the sustainable computer simulation program for computing energy costs. Estimating building energy consumption is usually performed by the energy engineering throughout some specialized digital application such as Energy Plus, BLAST, Green Building Studio, eQuest, or DOE-2.1E. The most difficulties for software application is data collection because most of data input are often not ready for use until later phase in the design process.

The heating load is a significant factor for building energy calculation. The heating load calculation for the energy design of buildings uses the transfer function method (TFM) based on the 1989 ASHRAE handbook fundamentals.

(5) Heat gain through exterior wall and roof is estimated as follows

$$q = U \times A \times \Delta Toi \qquad (1)$$

(6) Heat gain through fenestration is computed as follows

$$q = [(U \times A \times \Delta Toi) + (A \times SC \times SHGC)] \qquad (2)$$

(7) Heat gain through exterior wall and roof is measured as follows

$$q = U \times A \times \Delta Tai \qquad (3)$$

where *U, A, ΔToi, SHGC, SC, ΔTai* are coefficient of heat transfer, total area of surface, design temperature difference of exterior surface, solar heat gain coefficient, shading coefficient, and design temperature difference of interior surface of the building structure, respectively.

Chirarattananon (2010) also proposed the equation to estimate the whole building energy requirement of a new building design as following

$$E_{pa} = \sum_{i=1}^{n}\Big[\frac{A_{wi}(OTTV_i)}{COP_i} + \frac{A_{ri}(OTTV_i)}{COP_i} + A_i\Big\{\frac{C_l(LCD_i)+C_e(EQD_i)+130C_o(OCCU_i)+24C_V(VENT_i)}{COP_i}\Big\}\Big]n_h + \sum_{i=1}^{n} A_i(LCD_i + EQD_i)n_h$$

where *RTTV, OTTV,* EQD_i, LCD_i, $OCCU_i$, $VENT_i$, A_{wi}, A_{ri}, A_i, C_l, C_e, C_o, C_v, COP_i, n_h are roof thermal transfer value, overall thermal transfer value, equipment power density of zone i, lighting power density of zone I, occupants in zone i, ventilation rate of zone I, area of external wall of air-conditioned zone i, floor area of zone I, area of roof over air-conditioned zone i, the values of coefficients of thermal energy contribution to the load of the air-conditioning systems by equipment, occupants, lighting, and ventilation, coefficient of performance of an air-conditioning system, number of hours of occupancy in zone I, respectively.

Vechaphutti (1987) also suggested a method to calculate the heat gain through building wrapping including heat conduction over opaque walls and roofs, heat conduction over glass windows, and solar radiation over glass windows

$$q=(A_W)(U_W)(TD_{eq})+(U_f)(A_f)(VT)+(A_f)(SC)(SF)$$

where q, A_w, U_w, TD_{eq}, A_f, ΔT, SC, U_f, and SF are heat gain over building envelope, area of opaque area, thermal transmittance of opaque wall, equivalent temperature difference, area of fenestration, temperature difference between exterior and interior design condition, fenestration shading coefficient, fenestration thermal transmittance, and solar factor, respectively.

2.2.3 Maintenance phase

Maintenance costs are the cost of preserving the building in well-being repair and functioning condition. They costs include maintenance management fees such as periodic inspections, design of maintenance activities, manage of planned service contracts, provide of the handover, validation, commissioning repair, replacement of small components or areas, adapt and refurbish of facilities identified by replaced policies of system, dimension and amount of area, terms in arrangement consisting of regular cleaning service, policies for facilities management, regulatory design terms, area of maintenance, seasonal, regular, or special decoration, changes for operation and maintenance services.

A simple relational database stores the average value of annual maintenance cost per unit of building projects. The raw data consist of material cost per unit, labor cost per unit, and equipment per unit. Ashworth (1993) presented many factors impacting to maintenance costs of facilities consisting of the size, entities available, and address of buildings. The building life can be extended from 20 to 50 or more years. Thus, the expenditure for operating and maintaining services are often equal or exceed the capital cost.

According to Al-Hajj (1999), the research of maintenance cost is an fundamental part of the comprehensive building LCCA of any building project. The building owner always expect the costs of repair and maintenance work. Maintenance cost are often difficult to estimate because the building owner's desired quality standard of the maintenance works differ from building to building. It depends on the ability of the building owner to perform maintenance works.

2.2.4 End of life

The yields of end of building life-span include the cost for supervisions in anticipation of demolition and disposal for recovery for energy, and demolishing raw material, waste, site cleanup, reinstatement to meet contractual requirements, or taxes on goods and services. The salvage value is the profits of the project at the end of the analyzed period that earned from sell the building components. The salvage value is computed as another income rather than the expenditure of the facilities.

2.2.5 Time value of money

The building LCCA requires all cost categories that are computed based on the consideration of the value of money following time to make sure that the costs appear during the various phases of a year that repeatedly at the same time each year.

Interest rate is a simple cost rate of money that you must pay based on amount of money borrowed from bank, or the cost that the investors borrow from the bank or other financial organizations. It is usually described on the basic value. That interest rate has application in the modern enterprise. It is advantageous for establishing the concept of the value of money over the time. The discounting operations are usually used in the building LCCA to be divided into four discount factors (NIST, 2004).

(1) Single current factor is applied to estimate the current value, CV, of a future amount of money appearing at the last moment of year t, Ft, given a discount rate, d.

$$CV = F_t \times \frac{1}{(1+d)^t}$$

(2) Uniform current factor is applied to estimate the current value of a list amounts of money, A_o, that return per annum over a period of n years, given d

$$CV = A_o \times \sum_{t=1}^{n} \frac{1}{(1+d)^t}$$

(3) Uniform current factor adjusted for cost acceleration factor is used to estimate the CV appearing annual amounts that change from year at a constant acceleration rate, e, over n years, given d. The acceleration rate can be negative or positive.

$$CV = A_o \times \frac{(1+e)}{(d-e)} \times [1-(\frac{1+e}{1+d})^n]$$

(4) Energy current factor is applied to estimate the CV of each year energy costs over n years, which are assumed to adjust annually at a no fixed acceleration rate.

Before establishing a discount rate, several factors need be considered (Kirk, S., J., and Dell'Isola, A., J., 1995):

- Whether the project is to be financed through hired money or from initial expense
- Whether the prospective return needs to be greater than the cost of borrowed money to justify the risks to the owners associated with fixed obligations to pay interest and repay principal at stated dates
- Whether the client is a governmental organization or individual industry
- The return rate of the construction industry

2.3 Mathematical approaches for the building LCCA

There are five mathematical approaches that are commonly used to help decision makers determine the financial worth of their investment in building sector, consist of simple payback (SPB), net present value (NPV), discounted payback (DPB), adjusted rate of return (ARR), and equivalent annual cost (EAC) (Bull, 2003).

2.3.1 Simple payback (SPB) method

Simple payback is a simple approach of cost estimation that is identified as the period taken for turn back on an investment to pay back the investment. SPB does not apply discounted rate in the estimated process. It also neglect any adjustments in prices, especially energy acceleration rate during the payback time. SPB is not a valid method for selecting project alternatives. The equation of simple payback is showed below

$$PB = \frac{I}{R}$$

where PB is payback time (years), I is money invested, and R is money returned from investment.

2.3.2 Discount payback (DPB) method

Discount payback is a method of estimating the payback time for a project because it requires that cost flow appearing each year be adjusted to current value before summing them as savings. In case the DPB is lower than the service time used in the analysis, the project is customarily cost productive. The payback criterion typically applied is often applied to choose the shorter period of the preferred time of building projects.

2.3.3 Adjusted rate of return (ARR) method

Adjusted rate of return is a method to estimate the percentage benefits of each year return from the investment through the analyzed period. It is related to the effectiveness of the money investment. In using ARR, the initial money is balanced against income to acquire the zero value of a NPV. The preferred alternative has the maximum ARR. The discount rate necessary is the ARR. ARR is commonly considered to be a high accurate method of the rate of return on an initial investment and high consistency with the general LCC tool. Besides that, the calculator can estimate ARR by using a simple mathematical equation, it can be calculated directly by using a simple mathematical formulation. The equation of adjusted rate of return is showed below

$$ARR = (1+r)x(SIR)^{\frac{1}{N}} - 1$$

where N and r are the number of years and the reinvestment rate in the analyzed period. The calculation of ARR needs to consider the SIR for a construction project be calculated first.

2.3.4 Net present value (NPV) method

Net present value (NPV) is a method to evaluate the cash flow of building project that have some related options. This method defined the total money investment that needs to be spent now will be met at future period. The best selection should be the one has the minimum NPV. The equation is to compute the net present value as

$$NPV = \sum_{t=0}^{T} \frac{C_t}{(1+r)^t}$$

where r is the discount rate, C is the estimated cost in year t, , and T is the analyzed years.

NPV is a fundamental criterion for evaluating an investment and comparing investment alternatives. It gives the present value of all future cash flows. If NPV has positive, the investment can be obtained. If NPV has negative, the investment alternatives could be tried. Therefore, the key for investors is how to maximize the NPV. The investors can contribute to the maximization of the NPV by minimizing the total capital cost and the future cost associated with the physical systems of a building.

2.3.5 Equivalent annual cost (EAC) method

EAC is a method to consider a one time value of current value. The uniform equivalent money of each year is adjusted to many costs of an option. The EAC does not present an actual value that will appear annually; however, it is present an average value of cost. The best selection should have the minimum the value of EAC.

2.4 Life-cycle cost analysis (LCCA) stipulated in sustainable procurement system

The building construction has highly impact to sustainable development. Because it provides the environmental life for people, social, organization, and nations. According to the description of ISO 15392:2008, there are three aspects for assessing the sustainability of a building project consist of economic, environmental, or social performance. Most of methods for assessing the sustainability of buildings are focused on the environmental and social performance of buildings. Economic sustainability is rarely considered in the analysis that makes it significant to develop for the sustainability in building construction (ISO, 2008).

Traditional procurement system considered three key criteria consist of time, cost, and quality for planning and assessing project performance in the construction industry, whereas a project meet the completion date; cost more than the client can pay, and quality meet project needs. Because of rising the awareness of the environment and social welfare. The economic, environmental, and social, criterion are added to public procurement to support for the sustainable growth.

According to (Berry, 2011), sustainable procurement is tool to be applied to help the long time benefits for economic, society, and environment. There are four main objectives of sustainable procurement including (1) to reduce the pessimistic impacts of services, activities, and works across their life, (2) to minimize demand for resources, (3) to make sure the balance in contract cost that must meet the human rights, minimum ethical, and employment standards, (4) to improve the equality and diversity among local suppliers or woman payment. Sustainable procurement need to train and provide to the construction participants to reduce the pessimistic impacts and to increase the beneficial outcomes for three pillars. In addition, Riley (2013) defined that sustainable procurement is not just focused on acquiring buildings and infrastructure. It must also be considered that construction avoidance could often be the most sustainable and efficient process. According BS 8903 (2010), green procurement is a process by which companies achieve the benefits not only economic on a whole project life but also the minimum damage to environment and the maximum value to society for their works, services, or products.

In the United States (U.S.), the term “life-cycle cost” first is reported in a list of three documents for procurement that were issues by the U. S. Department of Defense including Life Cycle Costing Procurement Guide, Life Cycle Costing in Equipment Procurement Casebook, and Life Cycle Costing Guide for System Acquisitions. For building projects, the highlight of LCC is represented in the Section 8254, the U.S. Code, part B Federal Energy Management, subchapter III Federal Energy Initiative, chapter 91 National Energy Conservation Policy, the title 42 of the Public Health and Welfare. Section 8254 (a) states that “establish practical and effective present value methods for estimating and comparing life-cycle cost for Federal buildings”. Section 8254 (b) states that “The design of new Federal buildings, and the application of energy conservation measures to existing Federal buildings, shall be made using life cycle cost methods and procedures established under subsection (a) of this section”. Section 8254 (c) states that “The Secretary shall make available information to the public on the use of life cycle cost method in the construction of buildings, structures, and facilities in all segments of the economy” (Code, 2018).

In European, the 2014 Public Sector Directive is established to emphasis the LCC criterion in tender evaluation in a public project. Article 67 (1) states that “contracting authorities shall base the award of public contracts on the most economically advantageous tender”. The definition of the most economically advantageous tender is explained farther in Article 67 (2): “The most economical advantageous tender from the point of view of the contracting authority shall be identified on the basis of price or cost, using a cost-effectiveness approach, such as life-cycle costing…”. The detailed LCCA in the content of Article 68 represents “life-cycle cost shall to the extent relevant cover parts or all of the following costs over the life cycle of a product, service, or works”. The contracting authorities evaluate the costs using the LCCA approach, they shall indicate in the documents of procurement that data to be supported by the contractors and the method which the tender will use to calculate the total cost on the basic of those data. In addition, the Directive also mentioned that it is the mandatory by a legislative organization of the Union to the contractors who need to calculate the life-cycle cost using any common method (European, 2014).

The results of Perera survey about International Institute for Sustainable Development made an inquiry the LCCA in sustainable public procurement in twenty-eight countries showed that:

- The Norway, Japan, U.S.A., and Switzerland applied the LCCA as an essential requirements of green procurement policies.
- New Zealand, Austria, UK, Germany, Sweden, Denmark, The Netherlands, France, Korea, and Australia reported to be used the LCCA in some forms of procurement for new buildings to support the efficient energy.
- Brazil, Costa Rica, Mexico, Portugal, Italy, Singapore, India, Spain, Argentina, Africa, South Africa, Chile, and Canada reported to have used with the LCCA in the commissioning stage to support the efficient energy in building projects.
- Indonesia, Senegal, Botswana, Mauritius, and Vietnam are at the beginning stage for applying the LCCA in green procurement policies (Perera, 2009).

The early standard for sustainable procurement is BS 8903 Principles and framework for procuring sustainably that was issued in August 2010. BS 8903 provided guidance to many organizations (e.g. private, public, or industry organizations) on selecting and integrating green procurement principles and practices. This standard can assist the owners in optimizing its competitiveness, highlight tendering, engage the owner apply the LCCA in a contractual manner.

The traditional procurement approaches often make decision based on the lowest construction costs that assigns the small value compared to operating and maintaining costs of a project life. The results are the owners and operators usually born the highest of cost of inadequate interoperability. There is very ineffective way. The LCCA is a concept developed to increase the effectiveness of cost savings during the project life span. It is also a supported decision tool in environmental management because

- Cost analysis is often a more reliable that any physical analysis
- Cost analysis supports an effective measure compare with other measures
- The result of cost savings is easy to promote and accept by the people who are not the knowledge in the field of environmental management.

2.5 Building information modeling (BIM) in construction management

2.5.1 Definition of BIM

There are various descriptions of BIM such as the United States National Building Information Model Standard Project Committee (NIBS) defined BIM is a digital technology of functional and physical characteristics of a construction project. BIM was defined as an existing tool to exchange data from the beginning to the end of phase of a construction project. NIBS noted that the BIM is applied to present a construction product such as a building or a work through an action of drawing a 3D model including the technologies used and the processes of specialist companies creating the virtual model, or a system that increase quality and efficiency for construction activities (NIBS, 2017). According to Volk (2014), BIM was descripted as the tool to improve the design decision making, to increase coordination, to increase the consistency od data, to improve the productivity of works, to simulate building performance, to estimate construction cost, and to improve construction planning. A survey was conducted in the Czech Republic to evaluate the understanding of BIM definition from expert public, the result showed that there was no astronomically agreed the description of BIM (Matějka, 2017).

2.5.2 BIM implementation in construction management

The construction industry participants indicated that the advantages of BIM can improve the current difficulties in construction management.

The 3D visualized model is created by the BIM authoring programming at the early design phase can manage the design changes. When the project participants are issued changes to the building design, the BIM technology help to guarantee the consistency of drawings that create by the design modification (Eastman, C., Jeong, Y., S., Sacks, R., and Kaner, I., 2009). Thus, BIM helps to save time consuming for the design process. Likhitruangsilp (2018) proposed a new methodology to evaluate the impact of changes in construction. BIM can used for building quantity take-off to improve the accuracy of construction cost estimation. Following the result contained within the model, the owners are can make better decision under BIM uses compare with the traditional 2D CAD technology. Muzvimwe (2011) stated that the value of the cost management service will increase when the cost manager use BIM to analyze the information generated by the model and manage various design. BIM model can be connected with other building energy performance tools to allow the owner evaluate the energy consumption at the beginning phase of the construction process that traditional 2D tools cannot do. The approach to connect the BIM model with other tools or modern technologies to improve the quality of construction activities (Eastman, C., Teicholz, P., Sacks, R., and Liston, K., 2011). BIM is not only created the visualized model from the design ideas of the owners or architectures, it is but also support the collaboration and communication among building participants (Bennett, 2008). BIM provides many advantage for the project design stage, especially for the capacity to improve the visualization of 3D design. In addition, with the connected capacity of the BIM technology, BIM helps to improve the sustainability for design decisions in construction (Eastman, C., Teicholz, P., Sacks, R., and Liston, K., 2011).

Revit software is one of popular tools in BIM that was used to help architect, engineer, and contractor increase their productivity. BIM technology can help to check and balance the quantity through 4D and 5D capabilities of the procurement phase. According to Bradshaw (2004), an architectural and planning company which was using Revit for several years in Georgia. There was the different times spend on the design process when working on Revit and AutoCAD. The result of their research showed that using Revit spend about 1,141 hours instead of 1,824 hours spend working on CAD, as shown in Table 2.1 (Althobaiti, 2009). Especially, they also save time in the construction documents and information. Therefore, Revit has been used at Georgia since 2004 and now it is used almost for all new projects.

Table 2.1 Time spent on Revit Architecture versus AutoCAD adopted

Project phase	CAD (Hours)	Revit (Hours)	Hours saved	Time savings
Schematic design	190	90	100	53%
Design development	436	220	216	50%
Procurement	1,023	815	208	20%
Checking and coordination	175	16	159	91%
Totals	1,824	1,141	683	

In the construction stage, 4D BIM provides the simulation of the construction process day by day and convenience to improve the safeties, conflicts, site layout problems in construction management that are not available from paper bid document. In addition, BIM supports the accuracy of 3D model for the design and material management. It is also decrease cost and support better coordination at the construction site (Eastman, C., Teicholz, P., Sacks, R., and Liston, K., 2011). BIM assisted the contractor reduce material waste on construction site and increase the effective of construction material use (Eastman, C., Teicholz, P., Sacks, R., and Liston, K., 2008). The contractors can easily understand the site layout with 3D visualization. They also reduce conflicts and increase material management by using BIM. Thus, BIM is considered as a significant tool for construction managers (Eastman, C., Jeong, Y., S., Sacks, R., and Kaner, I., 2009).

In the operation and maintenance stage, the BIM technology support the accuracy of information for as-built phase for all system work after the building is complete. This information will be used for operating building projects in future phases (Sabol, 2017). In fact, once the building module was created, the information input for cost estimating, construction planning can be saved for future facility management.

2.5.3 BIM for sustainability

Today both building owners and architects, designers, constructors have increasingly perception about the benefits of sustainable buildings such as decreasing carbon dioxide emission, make less energy expenditure, decreasing material waste, and improving work productivity. More projects have been constructed over recent years which contribute to the sustainability throughout improving the building energy performance. The results from the studies of Krygiel revealed that green buildings can save 30 percentage of energy consumption, a 35 percent reduction of carbon on average, from a 30 to 50 percent savings in potable water use, and from a 50 to 97 percent reduction in landfilled wastes (Krygiel, E. and Nies, B., 2008).

BIM technology provided a new way for the sustainability throughout the capacity for making faster decision, the consistency of design information, the better management of construction documents, the capacity to select the sustainable design of building projects, and the ability to perform building energy analysis by 3D simulation (Autodesk, 2010). Hardin (2015) described three dimension of the sustainability with BIM including (1) BIM use for selecting sustainable construction material, (2) BIM use for managing construction site, and BIM use for building performance analysis. Krygiel, E. and Nies, B. (2008) identified different strategies of BIM use to achieve the sustainable policies of the building projects. All of them are categorized in building components and systems. For example, the building orientation in sustainable design that is defined as the way a building is placed on a site relative to the sun path throughout the year. Orientation can be applied to cooling, heating, ventilation, lighting system for the sustainability. To find the adjustment of the model environment in BIM, it requires the data about the longitude and latitude address(Eastman, C., Teicholz, P., Sacks, R., and Liston, K., 2011).

For the building performance, the BIM technology helps the designer define the exactly location of construction projects. It also helps to choose the correct building mass by comparing various massing configurations to decrease the total energy expenditure. To implement, the building energy analysis, the 3D BIM models need to be exported to other building analyzed software to it run the simulations. The optimum design strategy will be chosen (Eastman, C., Jeong, Y., S., Sacks, R., and Kaner, I., 2009). The other advantage of BIM involves building form that is day lighting optimization. Based on the results of building simulations, the building designers can select the optimal design for their building projects. One more benefit of BIM use involves the water harvesting. Understanding the impacts of climate can help to reduce the use of water in daily lives that is away to optimize the building form. By using the following three separate tools including 3D design models, internet to look up rainfall data, and a spreadsheet, we can collect and analyze information for sustainable design decision. The advantage involves a building energy demands. The optimization of energy performance depends on proper building orientation, using a flexible building massing, and the use of day lighting. To establish energy model, we need to have the BIM model, a building energy analysis tool, and the assistance of a energy engineering. The use of the BIM model can help to save time for the analysis process, and support better optimization for building design. To optimize the use of inexhaustible energy, the BIM helps to calculate the potential energy return and the feasibility of all building system. To select the optimal building materials, the building owners need to set up the criterion for their project materials. The selected materials should be friendly with environment throughout its life span. Although a number of current BIM tool support the material thermal library, the results of energy analysis still cannot reliability (Vangimalla, 2011). In addition, some difficulties in the exported process from the BIM authoring software to building energy analysis tool is also problem for the development of sustainable construction (Laakso, 2012). Therefore, future research are still need more the tools for supporting the sustainability by integrating BIM technology.

Although the number of research investigate BIM are increasing. There are limited research focus on the integration BIM with the LCCA for the sustainability. Yang and Wang (2013) proposed a framework to use the output of the BIM-integrated life-cycle assessment (LCA) model to calculate the LCC in residential buildings. Abanda (2016) investigated a methodology to assess the effect of the mass on the building energy expenditure using the BIM technology. The results from a case study pointed out that the good building design can save the energy cost during building life span especially for the total electrical consumption. Kehily D. (2016) presented a methodology to embed LCCs in the current BIM tool for cost estimation (CostX). Marzouk (2018) proposed a framework to integrate the BIM authoring software with the genetic algorithm, and Monte-Calrlo simulation in performing a stochastic LCC model for buildings. Fu (2007) developed a new tool for estimating the LCCs based on industry foundation classes. Nour (2012) reported a BIM approach for optimizing the whole cost of a building life. To solve the current problems of the existing BIM tools for energy analysis in terms of interoperability and quality of the results.

2.6 Database management system (DBMS)

The database management system (DBMS) is a technology which is used to manage the data in its warehouse and to manage a database structure. DBMS is a efficiently technology to manage data for the AEC industry (Holness, 2006). A DBMS can provide some advantages for stakeholders in the construction project (Coronel, 2016) including

- Create an environment to project parties can access to more data and quickly respond to changes during the project life cycle.
- Improve data security by providing the password for the database users
- Integrate data of project parties. It helps to see changes in one activity affect to other activities.
- Reduce data inconsistence when exchanging data for different purposes.
- Improve data quality throughout the systematic system

The structure of database often wrote by data scientist who are an in programming language such as Visual Basic, Structure Query Language (SQL), or C#. A good database design will bring the facilitation for managing data and generate the accuracy of information that can lead to successful decision making (Eken, 2015).

In the context of data management in construction management, Rujirayanyong (2006) proposed a project-oriented data warehouse to store types of information: contracts, materials, estimates, and performance for medium and large contractors. This proposed data warehouse consists of four activities: accessing data, storing data servers, supplying data area, and keeping data sources. Another research has been done by Park (2013) proposed a sewer data warehouse to improve data management for sewer infrastructures. This database was connected with the decision supporting systems for determine the appropriate supervision and recurrence systems of pipelines. BIM is an accomplished technology to solve with data problem in construction management (IFCwiki, 2008a). BIM provides the advantage for data exchange among the project participants through a digital technology that can replace the conventional approach for data management in the paper formats (Goedert, 2008).

2.7 Interoperability

Interoperability is described the capacity to integrate more than two platforms for various objectives. This technology will help the designers to reduce the duplicate information and manage data changes. To support to the LCCA, we need data exchange between different platforms, therefore data exchange is essential to the cost estimating consultant. There were four methods that are used to change the data between BIM platforms

(1) Link two BIM platforms directly: In this way, we will use the potential interfaces to link two BIM tools such as Component Object Model (COM) or Open Database Connection (ODBC). These interface are often designed for two software companies. The information on the BIM model is shared between two platforms using these interfaces (Eastman, C., Teicholz, P., Sacks, R., and Liston, K., 2011).

(2) Exchange proprietary using file format: In this way, the file formats are created by the software organization for specific purposes, thus this exchange format may only be adaptable with its tool (Eastman, C., Teicholz, P., Sacks, R., and Liston, K., 2011).

(3) Exchange data by public level format: In this way, the exchanging models are created based on the public level format. For example, Industry Foundation Classes (IFCwiki) model is supporting many BIM software tools (Wikipedia, 2019). The IFC are becoming the widely international standard for data exchange in the construction industry (NIBS, 2017).

(4) Exchange data through Extensible Markup Language (XMP): In this way, we will designed a markup language to transport and store data between different platform. This language was mostly used for small business that do not have enough data for exchanging process (Eastman, C., Jeong, Y., S., Sacks, R., and Kaner, I., 2009).

2.8 Visual programming interface

Visual programming interface has been grown up for the BIM authoring software such as Autodesk Revit. It is a software application that can stand alone or sit as a plugin into other application such as Revit. According to Boeykens (2009), the application of visual technology can improve the disadvantages of traditions coding technology. One example of visual technology is Dynamo that is developed for extending the capacity of the BIM authoring software. Dynamo allows the users to extend BIM capacity by building and running the graphical algorithms within the native software by connecting nodes together to form an overall program. The node is a small part of program. The BIM users can easily access the element properties and then extract customize specific parameter for their demand using visual programming interface.

Dynamo is an easy programming language to understand for cost managers who are usually nonprogrammers. Some research represented integrating BIM platforms to develop the automatic systems in construction management area using visual programming interface. For example, Likhitruangsilp et al. (2018) integrated Autodesk Revit Architecture, Excel spreadsheet, Visual Basic for Application, and Revit Dynamo (as a visual programming interface) to develop a new tool for evaluating the impacts of changes in construction through BIM integration. This dissertation presents a methodology to develop a BIM-database-integrated system for evaluating building LCC using a multi-parametric model by integrating BIM authoring programming, database management system, visual programming interface, and spreadsheet system.

2.9 Summary

From the literate review, it was found that the implementation of the building LCCA are not high in the real construction industry although it was stipulated in the building procurement system and was also encouraged by many government. That is why many experts and previous research offered to develop the building LCCA tools to solve the problem. With the information from BIM, database management system, the LCCA process, visual programming interface, this research proposed to develop the building LCCA tool throughout integrating potential BIM platforms.

CHAPTER 3
RESEARCH METHODOLOGY

This chapter presents the details of the seven steps to develop the proposed BIM-BLCC. The system contains four main modules: (1) the relational database management module, (2) the visualized BIM-integrated module, (3) the multi-parametric estimation module, and (4) the BIM-integrated report module. The chapter summarizes the input, process, output, and adaptation of the research platforms.

3.1 Overview of the research methodology

Before discussing the details of each research step, we would like to present a brief overview of the methodology, as shown in Figure 3.1. The first step is to comprehensively review literature in the related fields. This is to identify the problem statement, gaps of related research, BIM advantages for the building LCCA, and system requirements. The second step is to establish the system framework and its components. Then, we designed the system platform to develop the BIM-BLCC from the system requirements, expert interviews, and attributes of potential platforms. Four platforms were selected to develop the proposed system: the BIM authoring programming, the database management system, the spreadsheet system, and the visual programming interface. The fourth step is to develop the contents of the BIM-BLCC. This system was based on the conceptual framework and system requirements. The major outputs of this step are of the system architecture and the four modules, namely, the relational database management module, the visualized BIM-integrated module, the multi-parametric estimation module, and the BIM-integrated report module. The fifth step is to collect input data for the system from historical projects, relevant books, and the support of internal Revit database. The sixth step is to apply the proposed system to an actual building project to evaluate the practically of the proposed system. In addition, the manual calculation was performed to verify the results from the BIM-BLCC. The last step is to draw conclusions, discuss the limitations of the BIM-BLCC, and provide suggestions for future research.

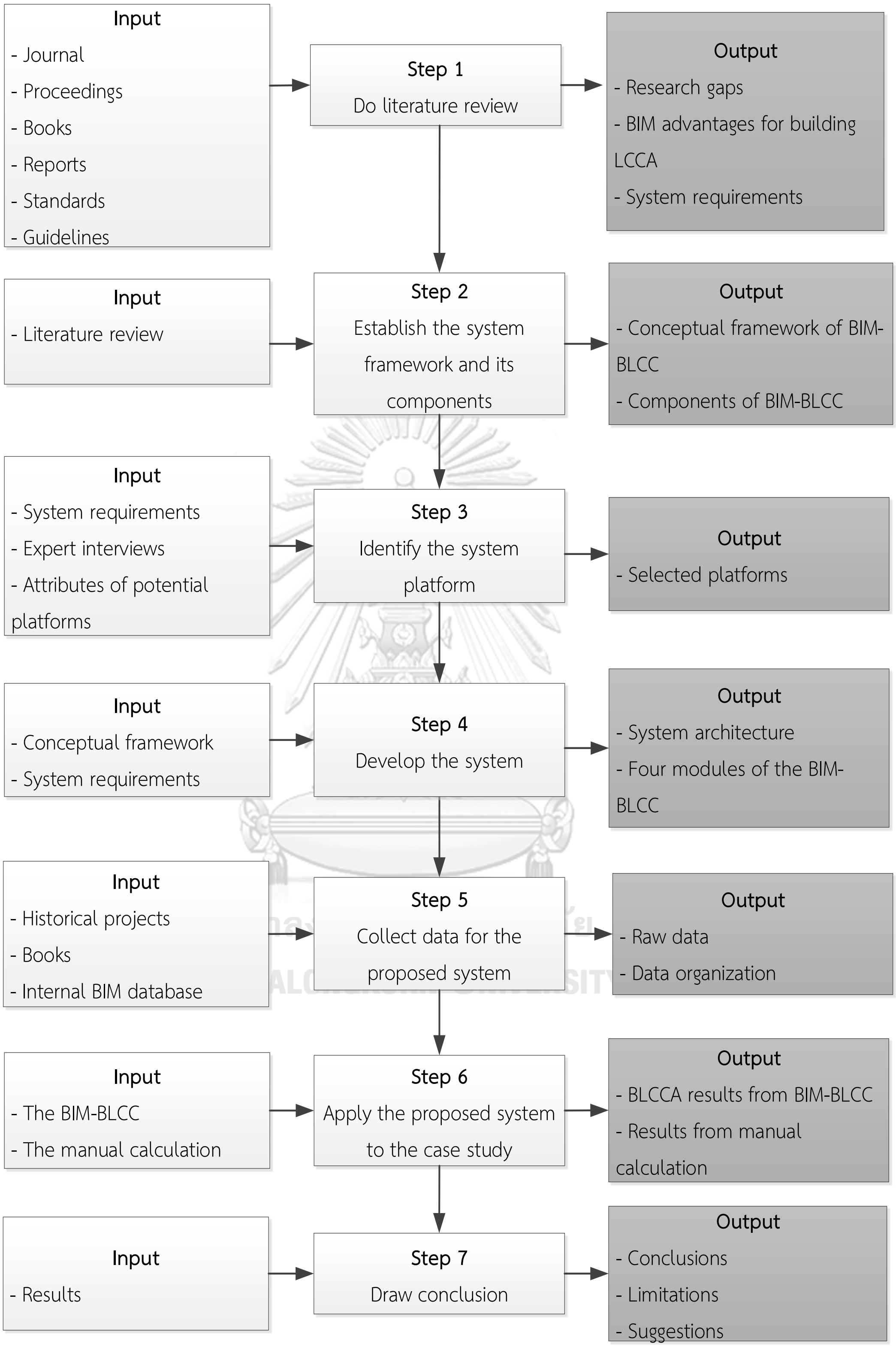


Figure 3.1 Workflow of the research methodology

3.2 Reviewing relevant literature

Relevant literature gathered from academic journal papers, conference papers, books, reports, standards, and guidelines related to the building LCCA and BIM implementation were comprehensively reviewed. Herein, we focused on:

- The building LCCA practice, the causal, and the impact
- LCCA stipulated in sustainable procurement system
- Existing system for the building LCCA
- BIM benefits and uses
- Current BIM implementation for the building LCCA
- Benefits and uses of database management systems in construction

From the comprehensive literature review, we can identify research gaps, advantages of BIM for the building LCCA, and the requirements for developing the proposed system.

The system requirements were established according to the literature review presented in Chapter 2 along with the characteristics to be considered in a practical system. Before embarking on the development of the BIM-BLCC, the basic requirements were designed to achieve the following characteristics:

- Easily visualize and evaluate the building LCCA
- Can store a large volume of data in order to satisfy the requirements of data for the building LCCA
- Be flexible on updating the data when necessary
- Be flexible on adjusting the assumptions based on the practical conditions of the building projects
- Allow for future expansion and enhancement

3.3 Establishing the system framework and its components

The outputs of this step are the conceptual framework of the BIM-BLCC and its components. According to Levy and Ellis (2006), each research step needed to consist of three main parts: input, process, and output. The function of the input part is to find the relevant literature for the process step. The function of the process part is to summarize and demonstrate information from the literature, identify important knowledge from the literature, and evaluate opinions or knowledge based on the literature. The function of the output part is to report the results from the process step into an academic form.

3.4 Identifying the system platform

An important step of the system development is the selection of appropriate platforms for the BIM-BLCC. Many governments were and are mandating the use of BIM for different publically funded projects. For example, the UK government mandated all public projects of 5 million GPB and more must implement the level 2 BIM by 2016. The Spanish government mandated the use of BIM by 2018. The French government mandated the use of BIM by 2016. The Italian government mandated the use of BIM for all public projects costing five million Euros and more. The Danish government mandated the use of BIM on all works exceeding 5 million Kroner. Other countries such as Norway, Finland, Germany, and the US Army also mandate the use of BIM for their typical construction projects (RIBA, 2017; Paul, 2018).

Autodesk Revit is a popular BIM authoring program that is mentioned in many research (Krygiel, Read, and Vandezande, 2010). It is primarily used to design various elements of the 3D building models in this research. We also investigated its flexibility to add in information and extract information from the models. In addition, the thermal parameters was examined to assure the estimation of energy costs for the building LCCA. Thus, in this research we decided to adopt Revit as a BIM authoring program to support the development of the proposed BIM-BLCC.

The database management system (DBMS) is an effective tool to manage a large volume of various data types in the construction industry (Li, Moselhi, and Alkass, 2006). Microsoft Access is a relational database management that stores data in interrelated tables. In this research, we examined its capacity to carry out some specific tasks, for which spreadsheet software cannot handle such as storing a large volume of records, updating and modifying a complete set of records at one time, and querying records that are distributed among multiple tables. In addition, this research also examined the integration of Microsoft Access with 3D BIM models for providing the required data.

Spreadsheet software is a widely used tool to perform calculations for cost quantification in construction management (Kehily D., 2016). We investigated an effective spreadsheet system (Microsoft Excel) to connect it with Microsoft Access. The tabulation interface also is also designed to store the analysis results.

Dynamo is a visual programming language, which is extended for Autodesk Revit. It allows users to extend Revit's capacity by using the graphical algorithm editor (Boeykens, 2009). In this research, we investigated its capacity to read geometric and non-geometric data from the Revit database through the direct relation between its graphical programming and Revit. The automatic quantity takeoff was examined through the development of Python scripts. Dynamo was adopted as an integrating tool for Autodesk Revit, Microsoft Access, and Microsoft Excel by engaging visual programming. The code was packaged into nodes, which can be used easily by users and arrange the process as needed.

This research adopted various supporting tools to develop the BIM-BLCC. First, the relational database management module was developed with Microsoft Access to store organized data for the BIM model. Second, the BIM model was designed though Autodesk Revit to allow the visualization of buildings. Third, a direct link between Autodesk Revit and Microsoft Access was established though Microsoft Excel and Dynamo visual programming for extracting the required data for the BIM model. Fourth, Dynamo programming with Python scripts were coded to perform the required data extraction and automatic multi-parametric model for the building LCCA. Fifth, the Dynamo programming was written to export the relevant results to the workbook into Microsoft Excel.

3.5 Developing the system

According to Jaakkola (2010), an important role of the system architecture is to communicate among software, establish the requirement of the system components and interfaces, and take advantages in software development. The role of the system architecture in this thesis is elaborated in the structure of the thesis. Table 3.1 shows the function of the flowchart nodes, which were used in developing the system architecture.

The proposed system is developed based on the practical building LCCA process. The developing process was divided into four main implementation phases. The first was to develop the relational database management module for organizing required data of the building LCCA. The second was to create the visualized BIM-integrated module for visualizing practical building projects. The third was to develop the multi-parametric estimation module to carry out the evaluation process. The fourth was develop the BIM-integrated report module to illustrate the building LCCA results. Figure 3.2 illustrates the architecture of the BIM-BLCC in the form of a matrix that describes the various platforms and modules as well as summarizes the detailed steps entailed in each module.

Table 3.1 Flowchart nodes in the system architecture

Nodes	Name	Function
	Action	To show the context of a single step being performed
	Input/ Output	To show the input or output for each module
	Arrow	To represent the connection between two action nodes, or the relation between an input/output to an action.

The development of the relational database management module of the BIM-BLCC entails four steps. First, the structure of the database is designed by using the database management system. The required raw data are then collected from relevant data sources. The details of this step are discussed in Chapter 4. The raw data are analyzed and become the required data, which will be an input of the database tables. The required data are prepared based on the Uniformat in the spreadsheet system. Finally, the required data are input into the database tables of the relational database of the BIM-BLCC.

The development of the visualized BIM-integrated module of the BIM-BLCC consists of five steps. In the first step, a 3D BIM is created for building projects using the BIM authoring programming. Then, we query the data for all element types of the 3D BIM model using the structure query language (SQL) into the database management system. Next, the results are exported to the spreadsheet file. In this third step, we integrate the 3D BIM model with the spreadsheet file using visual programming interface. The required data are extracted to the element properties of the 3D BIM model. Finally, the output is the completed 3D BIM model with the required data for the building LCCA.

The multi-parametric estimation module of the BIM-BLCC is developed by the following six steps. First, the required data are extracted from the element properties of the BIM model using the visual programming interface. Second, the assumed parameters are extracted from the spreadsheet report using the visual programming interface. Third, all element types of the 3D BIM model are selected using the visual programming interface. Fourth, the formulation is introduced for calculating the cost categories of the building LCCA. Finally, we perform the simulation of the multi-parametric model for the building LCCA.

The BIM-integrated report module of the BIM-BLCC is developed by the following three steps. First, the spreadsheet report is created. It contains the values of assumed parameters and the building LCCA results in the spreadsheet system. Second, the assumed parameters are input into the spreadsheet report. Third, the results of the multi-parametric model are exported to the spreadsheet report using the visual programming interface.

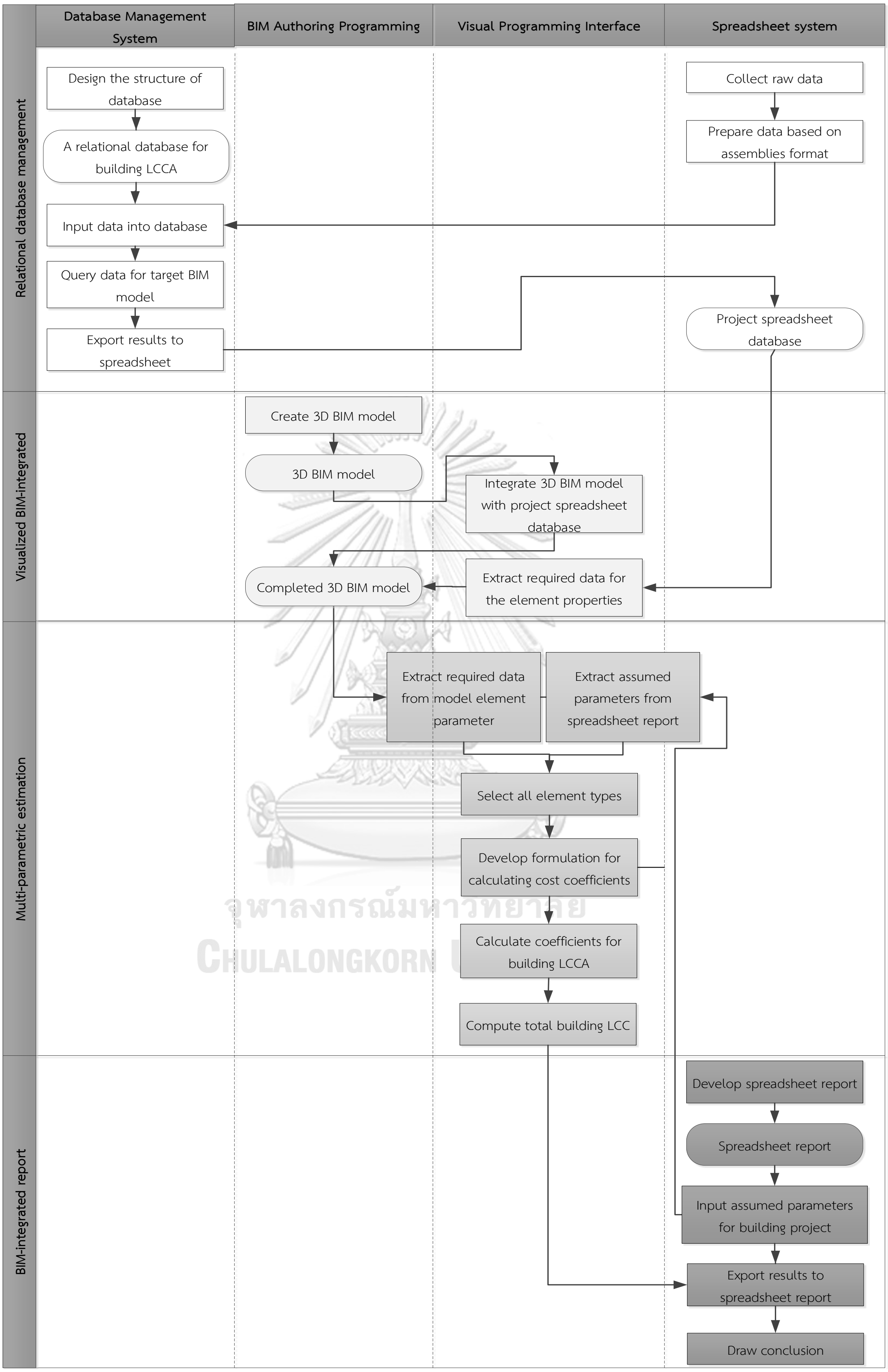


Figure 3.2 System architecture of the BIM-BLCC

3.6 Collecting data for the proposed system

Data collection was designed based on the system requirements that must be achieved in performing the building LCCA. The proposed system requires two types of data: (1) the parameter data for each building element model and (2) the assumed parameters for each building project.

The parameter data consist of the construction unit price, expected service life, annual service unit price, and energy unit price of building element types. In this research, the raw data for calculating the construction unit price were collected from two data sources. The first source was historical building projects. These data consist of material unit cost, labor unit cost, and equipment unit cost for constructing building projects. Herein, the data were based on the Uniformat. The second, source was "Assemblies Costs with RSMeans data 2018, 43rd annual edition" published by Gordian RSMeans data. Gordian was one of the leaders in facility and construction cost data, software, and expertise for all phases of building life cycle including planning, design, procurement, construction, and operation (Phelan, 2018). To establish this database, the RSMeans data engineers invested over 22,000 hours in cost research annually and applied real-world construction experience to identify and quantify new building products and methodologies, adjust productivity rates, and adjust costs to local market conditions across the nation. This is an important book that contains valuable data in respect to industry-standard material, labor, and equipment cost information databases for contractors, facility owners and managers, architects, engineers, and anyone else, who require the latest localized construction cost information. The expected service life and the annual service unit price were collected from "Life Cycle Costing for Design Professionals"; by Kirk, S., J., and Dell'Isola, A., J. (1995) and published by McGraw-Hill. The data in this book were organized in the Uniformat for accounting for the life-cycle cost of building elements. The raw data were analyzed by Microsoft Excel before inputting into the relational database. The thermal data for calculating energy costs were collected from two main data sources. The first source was the internal Revit material library. For creating the 3D BIM model, the internal Revit material library assisted the quantity surveyors in calculating the heat transfer coefficient and the solar heat gain coefficient based on the design characteristic and the material selection for building model elements. The Revit material library is a significant data solution for calculating the energy cost. The second source was data records from the ASHRAE Thailand chapter; by Vechaphutti (1987).

The assumed parameters consist of the analyzed period, discount rate, electrical unit price, hourly usage per year, design temperature difference of exterior surfaces, and design temperature difference of interior surfaces. For the analysis period, according to Kirk, S., J., and Dell'Isola, A., J. (1995), if the building life is perpetual, the period of 25 to 40 years is long enough to anticipate future costs for economic purposes because it captures most significant costs. In this research, the discount rate will be used to calculate the maintenance present worth factor, energy present worth factor, and salvage present worth factor. The electrical unit price and hourly usage per year were based on the average value of the last two years. The design temperature difference of exterior surfaces and design temperature difference of interior surfaces were gathered from the ASHRAE Thailand chapter and the “1989 ASHRAE handbook fundamentals” book, by Robert (1989). All assumed parameters will be input into the spreadsheet file before extracting for the multi-parametric model of the BIM-BLCC.

3.7 Applying the proposed system to the case study

In order to evaluate the practicality of the BIM-BLCC, it was applied to an actual building project by the following four main steps. First, we created a 3D BIM model of the building project case study. Second, the required data were extracted from the 3D BIM model. Third, we run simulation on the multi-parametric model for the building LCCA. Finally, the results were reported in the spreadsheet file. Chapter 8 discusses the details of the system application.

In order to ensure the accuracy of the BIM-BLCC, we also performed manual calculation of the building LCCA for the same actual case study building. The results from this manual calculation were then compared with those from the system to verify the system’s accuracy. A calculator and Microsoft Excel were used as tools for this step. It is expected that the results from both approaches would not be different. The similar results from the two methods indicate that the proposed system is acceptable.

3.8 Drawing conclusions

Based on the system's results, the conclusions were drawn and the limitations were discussed. Furthermore, the suggestions for future research were also provided. All of these contents are presented in Chapter 9.

3.9 Summary

The BIM-BLCC is a computerized system, which is developed based on the synthesis of the building LCCA practice, the capabilities of the BIM authoring programming, the database management system, the spreadsheet system, and the visual programming interface. The system can address four main limitations of the existing building LCCA tools: (1) data management and collection, (2) time requirements for performing many repetitive works of the building LCCA, (3) expenses on acquiring and maintaining commercial systems, and (4) the inaccuracy of results due to the regulatory requirements. The BIM-BLCC consists of four main interconnected modules: (1) the relational database management module, (2) the visualized BIM-integrated module, (3) the multi-parametric estimation module, and (4) the BIM-integrated report module.

To accomplish the research objectives, seven steps of the research methodology are performed: (1) do literature review, (2) establish the system framework and its components, (3) identify the system platform, (4) develop the system, (5) collect data for the proposed system, (6) apply the proposed system to an actual case study building, and (7) draw conclusions and discuss system limitations. The system development is primarily based on the principles of the building LCCA. The system components are developed based on the relevant attributes of various platforms and system requirements.

CHAPTER 4
RELATIONAL DATABASE MANAGEMENT MODULE

This chapter presents the development of the relational database management module, which is the first module of the BIM-BLCC. The main functions of this module are data collection, data organization, and data storage, all of which will be subsequently used by the other modules, as will be presented Chapters 5, 6, and 7. In this chapter, we will discuss the conceptual structure of database for the building LCCA, the data organization, and the completed data warehouse for this research.

4.1 Introduction

The building LCCA requires various data throughout each building element life such as material, equipment, labor, operation, repair, replace, and disposal. These data need to be appropriately organized so that they can be easily accessed. A database management system is a digital solution for the data storage. A database is an organization that is designed to manage a large volume of information, store data in a logical structure that allows users to easily manage and retrieve data when necessary. By comparing with a spreadsheet, a database can achieve some specify purposes that a spreadsheet cannot do so. For example, a database can record a large volume of information that complies with particular criteria. A database can update and modify a complete set of records simultaneously and can extract values from multiple database tables. The proposed module thus adopts a database management system to store all necessary information for the building LCCA.

The relational LCC database is designed based on the assembly format, which consists of three sub-modules: (1) database conceptual design, (2) data organization, and (3) data storage. The main role of the relational LCC database is a central data warehouse to accommodate the required data for the 3D BIM models. The relational LCC database development encompasses four main steps, as shown in Figure 4.1. The first step is to investigate the main characteristics of the database of the proposed system, which are the type of database and the format of data. A relational database schema aims to achieve simplicity and to gain efficiency for data queries. Microsoft Access is used for creating the relational database management system due to its capacities and simplicity. The second step is to design the schema of database, the schema of database tables, and the relation among database tables. A database table is a data container, and the data in table is organized into rows (called records) and columns (called fields). The third step is to collect raw data from relevant data sources and organize data based on the data format identified in the first step. Microsoft Excel is a tool for preparing data. The fourth step is to input the data to the database tables.

4.2 Characteristics of the relational database management for the BIM-BLCC

This section presents the format of data and the relevant type of database which are selected for the BIM-BLCC based on the system requirements presented in Chapter 3. The format of data is defined by the characteristics of the 3D BIM model that is created by Autodesk Revit. The Uniformat of Revit supports the construction of workflows through identifying, classifying, and quantifying unique element combinations in the model. Revit provides a set of tools that enables the architecture model of all the elements were designed. The Uniformat simplifies the estimating process of construction works. Users can easily manage the changes of the element models. Thus, the Uniformat is selected to organize the cost data for the proposed system.

The type of database is defined by the characteristics of three logical types of database: (1) the hierarchical database, (2) the network database, and (3) the relational database. The hierarchical database is the collection of records on one-to-one relation, which means that each element of this type of database is subordinate to just another element, which is called the root. The root is always at the top of the hierarchy. Unlike the hierarchical database, each record in the network database can be subordinate to many other records. It is the collection of records on one-to-many relations. The relational database organizes its information in records and fields called tables. A table consists of a number of rows, and; each row contains the same number of columns. This type of database provides Structured Query Language (SQL), which is a database computer language designed for managing data in the relational database management system. This research selects the relational database for the data storage of the BIM-BLCC. Microsoft Access is a database management platform for creating the relational database of the BIM-BLCC.

4.3 Structure of the relational database

The building LCCA requires various data from many sources. The integration of these data with the BIM model benefits for the cost estimating process. The relational database stores all required data for the BIM-BLCC. The building LCCA of a building element is the sum of cost categories such as the construction cost, the maintenance cost, the operation cost, and the salvage value of that model element. Figure 4.2 illustrates the workflow for developing the structure of the relational database in Microsoft Access.

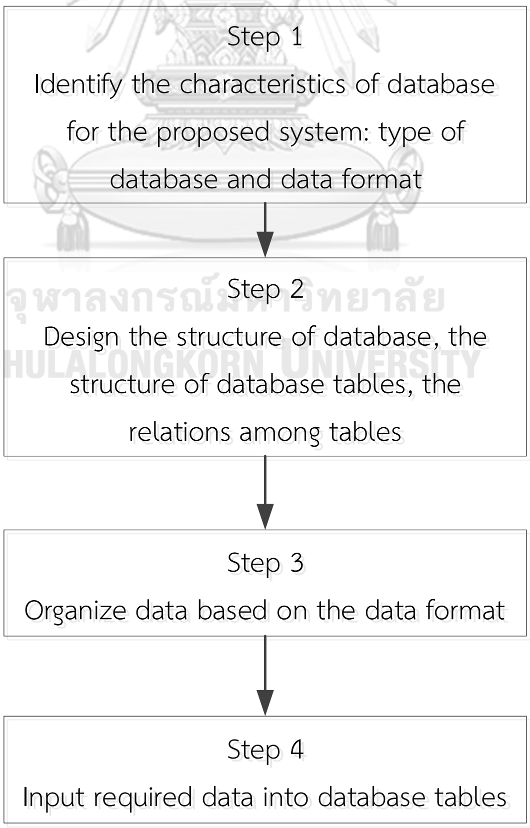


Figure 4.1 Workflow for developing the relational database management module

Creating the relational database of the BIM-BLCC requires design of the structure of the database, the database table, and the relation among database tables. For designing the structure of the database, three steps must be performed to create the relational database via Microsoft Access, as shown in Figure 4.2.

- Step 1: Click on the Blank Desktop Database template icon
- Step 2: Type the database name in the file name textbox
- Step 3: Click on create button

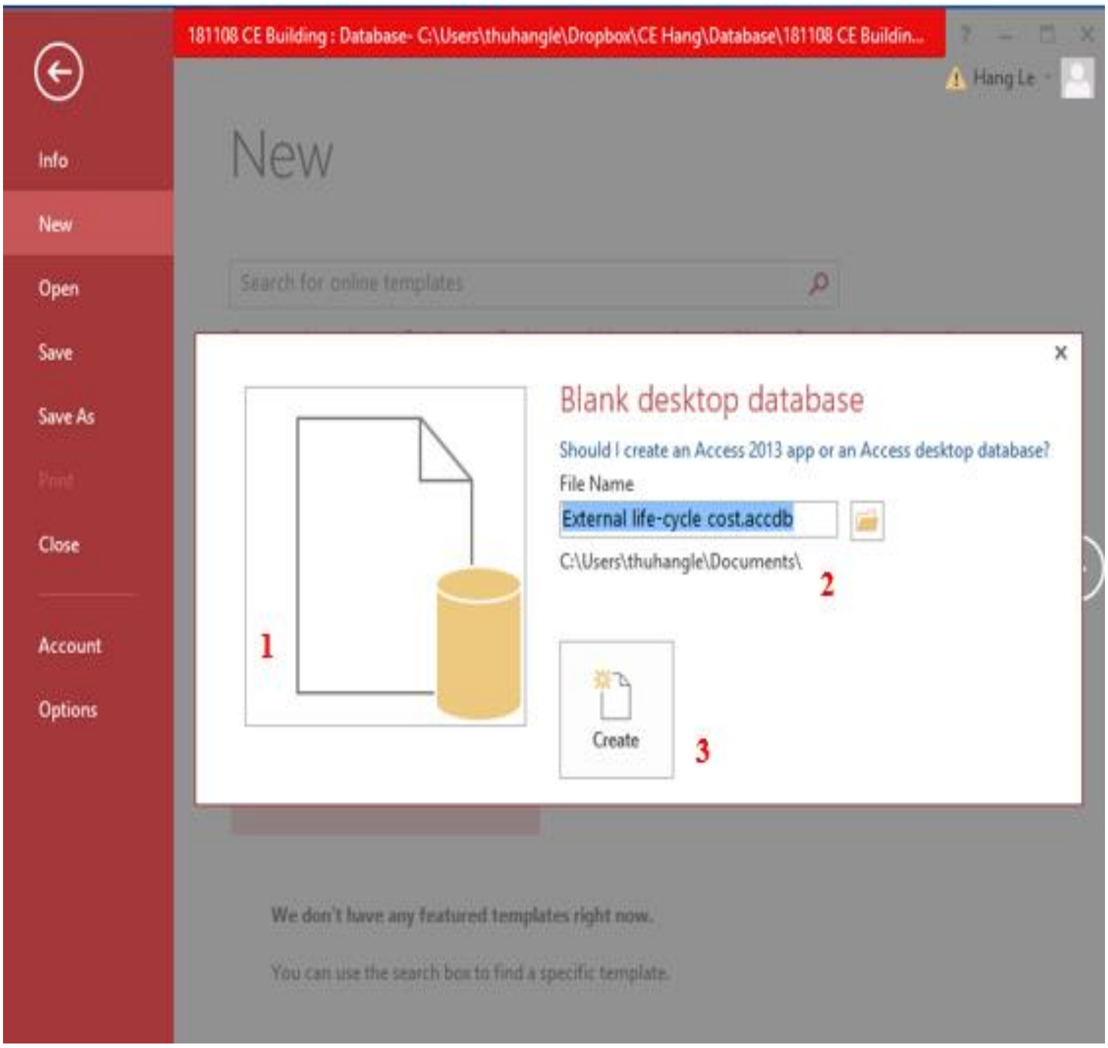


Figure 4.2 Workflow of developing the structure of the relational database in Microsoft Access

For designing the database table, seven steps to create a table in design view for the BIM-BLCC with Microsoft Access are shown in Figure 4.3

- Step 1: Click the “CREATE” tab
- Step 2: Click the “Table Design” symbol under the table group.
- Step 3: Enter the desired table name and click “OK” to save that table
- Step 4: Determine which fields are needed for each table
- Step 5: Enter field names that can be from 1 to 64 characters in length, the type of data of each field such as “Short Text”; “Long Text”; “Number”; “Date/Time”; “Currency”; “AutoNumber”; “Yes/No”; “OLE Object”; “Hyperlink”; “Attachment”; “Calculated”; “Lookup Wizard”; properties, and descriptions
- Step 6: Choose the table’s primary key
- Step 7: Save the table’s design

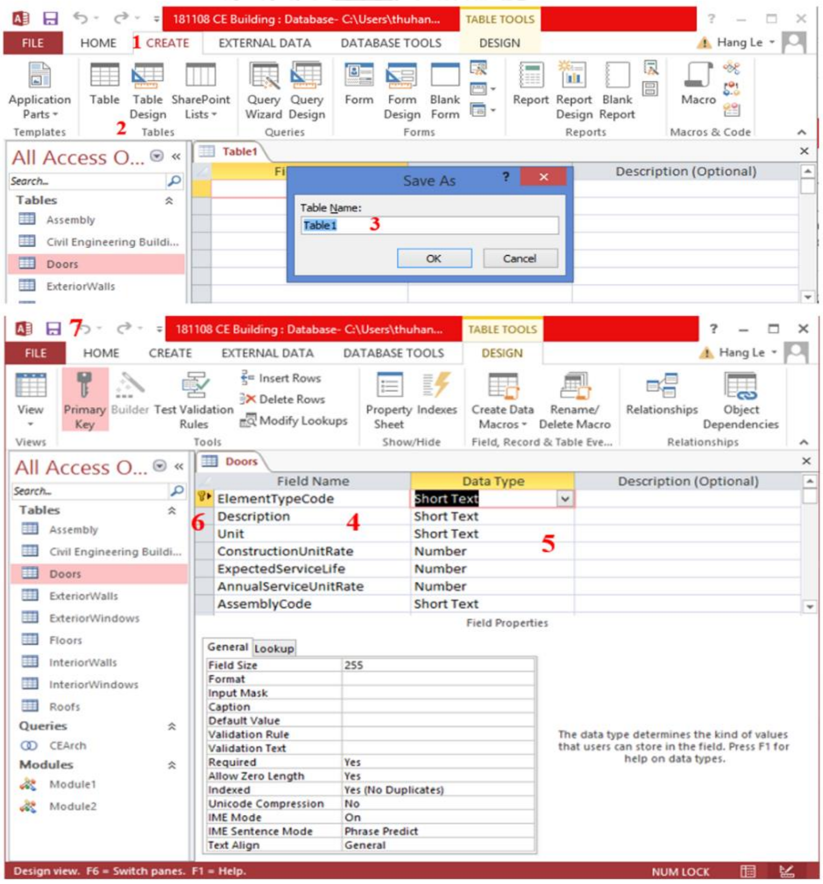


Figure 4.3 Workflow for creating a database table in design view

Designing the relation among database tables encompasses linking two or more tables for exchanging data. The relation of database tables allows users to draw up a query for extracting the required data. Three basic types of relations between two tables on a relational database are one-to-one, one-to-many, and many-to-many. In this research, one-to-many relation is selected to link the tables in this database. Figure 4.4 displays eight steps to link any two tables with one-to-many relation by Microsoft Access

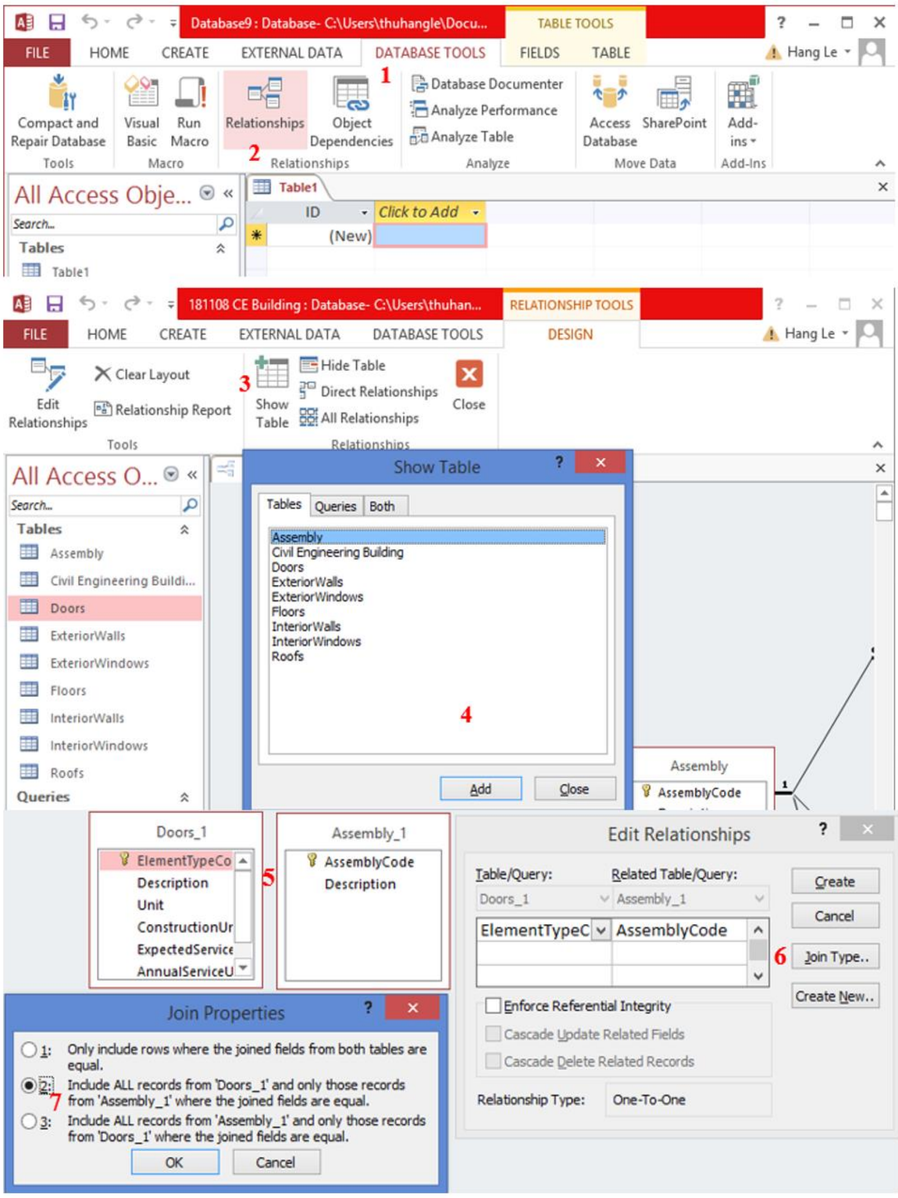


Figure 4.4 Workflow for designing the relation among database tables

- Step 1: Click the “DATABASE TOOLS” tab
- Step 2: Click the “Relationships” icon under the relationship group
- Step 3: Click “Show Table” then this prompts the show table dialogue box
- Step 4: Select the tables and click “Add” button. Then click “Close”, as shown in Figure 4.4
- Step 5: Click and drag the join field with primary key in the first table to join field without primary key of the second table.
- Step 6: Click on “Join Type” in the edit relationship dialogue box
- Step 7: Select the second option, which shows include all records from table 1 and only those records from table 2 where the joined fields are equal. Then click OK

4.4 Data organization

In the proposed system, seven data types need to be record for each building element type of the BIM model: (1) element type code, (2) description, (3) unit, (4) construction unit rate, (5) expected service life, (6) annual service unit rate, and (7) assembly code. Raw data are collected from three main data sources. The first source is the historical data of similar previous projects. The second source is “Assemblies Cost with RSMeans data 2018, 43rd annual edition” by Gordian RSMeans data. Both provide the raw data for calculating the construction unit rate of building element types such as the exterior wall types, the interior wall types, the door types, the exterior window types, the interior window types, the floor types, and the roof types. The raw data consist of the material unit cost, labor unit cost, and equipment unit cost that used to build the building element types. The last source is “Life cycle costing for design professionals” by Kirk, S., J., and Dell'Isola, A., J. (1995). The data provided by this source are the expected service life and the annual service unit rate of the building element type. The data is prepared in Microsoft Excel before inputting to the relational database.

BIM presents information of a building project in the form of 3D graphical representation of elements. To develop a consistent relational database, this research adopts the Uniformat as the standard format of the BIM-BLCC. Although there is no universally accepted standard for the hierarchical coding structure for BIM models, the Uniformat is adopted because it has been widely used for almost 3D building projects (CSI, 2016). The purpose of using the Uniformat is to ensure the consistency in the economic evaluation of the building projects in all stages of their life cycle: design, construction, operation, maintenance, and disposal. The code of each building element type entails four levels. The Uniformat is the arrangement of construction information based on the physical parts of a facility which are called systems and assemblies.

The assembly format is an efficient tool for organizing construction cost estimating. It is often used during the early of design development to compare the cost impact of various design alternatives in the total building cost. In addition, the assembly format also provides a fast and reasonably accurate way to develop construction costs (Phelan, 2018). Thus, this research adopts the assembly format as a standard format to organize the data based on the Uniformat for classifying the building elements.

An example element type code “B2010151” of red ceramic tile 4x8 wall W66 represents a typical exterior wall type, as shown in Figure 4.5. “B” indicates that the major group element (level 1) of this element type is shell. “B20” indicates that the group element (level 2) of this element type is exterior enclosure. “B2010” indicates that the individual element (level 3) of this element type is exterior walls. “B2010151” indicates that the detailed elements (level 4) of this element types is red ceramic tile 4x8 wall W66. The Uniformat provides a standardized format for collecting and analyzing historical data to use in estimating new building projects. It also facilitates communications and collections among members of a project team regarding the scope of work, and establishes a consistent database for the building LCCA.

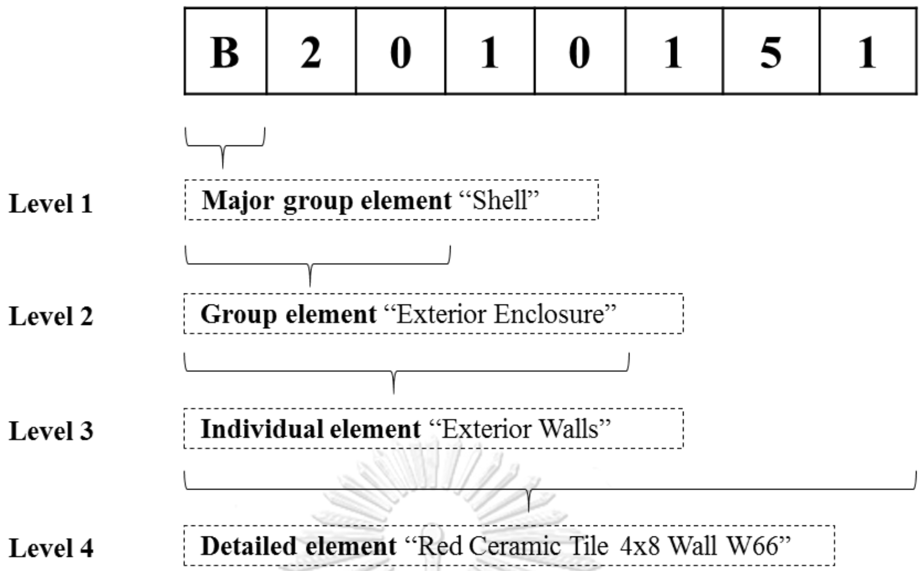


Figure 4.5 Hierarchical coding structure of a typical exterior wall type

Table 4.1 presents a sample list of the wall types, which are prepared in Microsoft Excel. The raw data required for each wall types are: (1) element type code, (2) description, (3) unit, (4) material unit cost, (5) labor unit cost for estimating construction unit rate of each wall type, (6) the expected service life, (7) percent replaced, (8) description, (9) material unit cost, (10) labor unit cost, and (11) equipment unit cost for estimating annual service unit rate of all material layers built the unit of each wall type. The structure of material for each wall type includes one structure material layer and two finished material layers.

Table 4.2 presents a sample list of the window types, which is prepared in Microsoft Excel. The raw data are: (1) element type code, (2) description, (3) unit, (4) unit, (5) material unit cost, (6) labor unit cost for estimating the cost per window set or the cost per square meter (SQM) window, (7) expected service life, (8) percent replaced, (9) description for window maintenance, (10) material unit cost, (11) labor unit cost, and (12) equipment unit cost for estimating annual unit rate per set window or annual unit rate per SQM window. The structure of the window type is selected based on the Revit material family.

Table 4.1 A sample list of the wall types in Microsoft Excel

Element Type Code	Description	Unit	Construction: Material Unit Cost (Baht)	Construction: Labor Unit Cost (Baht)	Construction: Unit Rate (Baht)	Expected Service Life (Years)	Percent Replaced (%)	Maintenance: Description	Maintenance: Material Unit Cost (Baht)	Maintenance: Labor Unit Cost (Baht)	Maintenance: Equipment Unit Cost (Baht)	Maintenance: Annual Service Unit Rate (Baht)
B2010151	**Red ceramic tile 4x8 wall W66**	**SQM**	**780**	**305**	**1,085**	**75**	**100%**	Repointing joints (4.0 min every 15 years)	**2.04**	**0.68**	**0.034**	**2.75**
	Interior red ceramic tile 4x8 W6	*SQM*	*500*	*150*	*650*							
	Brick wall	*SQM*	*230*	*120*	*350*							
	Internal plaster	*SQM*	*50*	*35*	*85*							
B2010152	**Cladding alu wall W2**	**SQM**	**2,630**	**1,170**	**3,800**	**75**	**100%**	Minor repair, cleaning (2 min. ev	**2.72**	**0.34**	**0.034**	**3.09**
	Brick wall	*SQM*	*230*	*120*	*350*							
	Exterior cladding alu wall W2	*SQM*	*2,400*	*1,050*	*3,450*							
C1010111	**Brick wall W11**	**SQM**	**330**	**190**	**520**	**75**	**100%**	Minor repair (1.0 min every 10 years)	**5.44**	**1.36**	**0.714**	**7.51**
	Brick wall W1	SQM	230	120	350							
	Paint wall W11	SQM	100	70	170			High use areas: Paint - 2 coats (1.0 min every 2 years)	4.42	1.02	0.68	6.12
C1010131	**Cladding tile 12x12 wall W33**	**SQM**	**830**	**420**	**1,250**	**75**	**100%**	Repointing joints (4.0 min every 15 years)	**90.78**	**4.42**	**0.748**	**95.95**
	Brick wall	SQM	230	120	350							
	Tile wall W33	SQM	600	300	900			High use areas: 2 coats - Damp cleaning daily (0.06 min per day) - Minor repair yearly	88.74	3.74	0.714	93.19
C1010141	**Reinforced concrete wall W44**	**SQM**	**0**	**0**	**0**	**100**	**100%**					
	Reinforced concrete wall	SQM	0	0	0							
	Paint wall W44	SQM	100	70	170			High use areas: Paint - 2 coats (1.0 min every 2 years)	4.42	1.02	0.68	6.12
C1010151	**Gypsum wall W55**	**SQM**	**450**	**220**	**670**	**35**	**100%**	_Minor repair, cleaning (2 min. every 6 years) _High use areas: Paint 2 coats (1.0 min every 2 years)	**5.44**	**1.36**	**0.714**	**7.51**
	Gypsum wall with steel frame	*SQM*	*350*	*150*	*500*							
	Paint wall W55 Left paint W5 Right paint W5	SQM	100	70	170			High use areas: Paint - 2 coats (1.0 min every 2 years)	4.42	1.02	0.68	6.12

Table 4.2 A sample list of the window types in Microsoft Excel

Element Type Code	Description	Unit	Area (SQM)	Construction: Material Unit Cost (Baht)	Construction: Labor Unit Cost (Baht)	Construction: Cost per Set (Baht)	Construction: Cost per Area (Baht)	Expected Service Life (Years)	Percent Replaced	Maintenance: Description	Maintenance: Material Unit Cost (Baht)	Maintenance: Labor Unit Cost (Baht)	Maintenance: Equipment Unit Cost (Baht)	Maintenance: Annual Unit Rate per SQM (Baht)	Maintenance: Annual Unit Rate per SET (Baht)
B2020111	Exterior metal-glazed window W1'	SET	7.41	11,115	5,928	17,043	2,300	40	100%	_Wash and squeegee dry both sides of glass (0.18 min/week) _Repair glazing, frame and hardware	2.02	2.03	0.051	139.43	1,033.21
B2020112	Exterior metal-glazed window W1"	SET	3.71	5,558	2,964	8,522	2,300	40	100%	_Wash and squeegee dry both sides of glass (0.18 min/week) _Repair glazing, frame and hardware	2.02	2.03	0.051	139.43	516.60
B2020113	Exterior metal-glazed window W1"'	SET	3.71	11,115	5,928	17,043	4,600	40	100%	_Wash and squeegee dry both sides of glass (0.18 min/week) _Repair glazing, frame and hardware	2.02	2.03	0.051	139.43	516.60
B2020114	Exterior metal-glazed window W1" "	SET	7.41	11,115	5,928	17,043	2,300	40	100%	_Wash and squeegee dry both sides of glass (0.18 min/week) _Repair glazing, frame and hardware	2.02	2.03	0.051	139.43	1,033.21
B2020115	Exterior metal-glazed window W1" " '	SET	7.41	11,115	5,928	17,043	2,300	40	100%	_Wash and squeegee dry both sides of glass (0.18 min/week) _Repair glazing, frame and hardware	2.02	2.03	0.051	139.43	1,033.21
B2020211	Exterior frosted glazed window W2	SET	5.46	18,900	8,100	27,000	4,947	40	100%	_Wash and squeegee dry both sides of glass (0.18 min/week) _Repair glazing, frame and hardware	2.02	2.03	0.051	139.43	760.96
B2020311	Exterior glazed window W2'	SET	4.28	14,814	6,349	21,163	4,948	40	100%	_Wash and squeegee dry both sides of glass (0.18 min/week) _Repair glazing, frame and hardware	2.02	2.03	0.051	139.43	596.43
B2020312	Exterior glazed window W3	SET	3.07	9,450	4,050	13,500	4,399	40	100%	_Wash and squeegee dry both sides of glass (0.18 min/week) _Repair glazing, frame and hardware	2.02	2.03	0.051	139.43	427.92
B2020313	Exterior glazed window W3'	SET	2.39	7,367	3,157	10,524	4,399	40	100%	_Wash and squeegee dry both sides of glass (0.18 min/week) _Repair glazing, frame and hardware	2.02	2.03	0.051	139.43	333.60
B2020116	Exterior metal-glazed window W4'	SET	11.21	16,815	11,210	28,025	2,500	40	100%	_Wash and squeegee dry both sides of glass (0.18 min/week) _Repair glazing, frame and hardware	2.02	2.03	0.051	139.43	1,563.06

Table 4.3 A sample list of the door types in Microsoft Excel

Element Type Code	Description	Unit	Area (SQM)	Construction: Material Unit Cost (Baht)	Construction: Labor Unit Cost (Baht)	Construction: Unit Rate per Set (Baht)	Construction: Unit Rate per SQM (Baht)	Maintenance: Expected Service Life (Years)	Maintenance: Percent Replaced	Maintenance: Description	Maintenance: Material Unit Cost (Baht)	Maintenance: Labor Unit Cost (Baht)	Maintenance: Equipment Unit Cost (Baht)	Maintenance: Annual Unit Rate per SQM (Baht)	Maintenance: Annual Unit Rate per SET (Baht)
B2030121	Exterior metal-glazed double door D1	SET	13.3	*35,000*	*15,000*	50,000	3,759	40	100%	_Damp clean both sides (.12 min/quarter) _Repair door, frame, hardware	0.18	0.06	0.03	9.18	122.09
C1020111	Interior metal-glazed doubled door D2	SET	6.555	*19,600*	*8,400*	28,000	4,272	30	100%	_Damp clean both sides (.12 min/quarter) _Repair door, frame, hardware	0.16	0.05	0.01	7.48	49.03
C1020112	Interior metal-glazed single door D3	SET	2.5	*8,400*	*3,600*	12,000	4,800	30	100%	_Damp clean both sides (.12 min/quarter) _Repair door, frame, hardware	0.16	0.05	0.01	7.48	18.70
B2030122	Exterior metal single door D4	SET	2.15	*20,000*	*5,000*	25,000	11,628	40	100%	_Damp clean both sides (.12 min/quarter) _Repair door, frame, hardware	0.18	0.06	0.03	9.18	19.74
C1020121	Interior wood single door D5	SET	1.935	*8,400*	*3,600*	12,000	6,202	30	100%	_Damp clean both sides (.12 min/quarter) _Repair door, frame, hardware _Painting 2 coats (1.0 every 6 years)	0.21	0.07	0.021	10.234	19.80
C1020131	Interior plastic single door D6	SET	1.72	*4,522*	*3,002*	7,524	4,375	30	100%	_Damp clean both sides (.12 min/quarter) _Repair door, frame, hardware _Painting 2 coats (1.0 every 6 years)	0.21	0.07	0.021	10.234	17.60

Table 4.3 shows a sample list of the door types, which are prepared in Microsoft Excel. Each door type requires the element type code, description, unit, area of unit, material unit cost, labor unit cost for estimating the cost per door set or the cost per SQM door, expected service life, percent replaced, description for door maintenance, material unit cost, labor unit cost, equipment unit cost for estimating annual unit rate per set door or annual unit rate per SQM door. The material of each door type is supported from the Revit material family.

Table 4.4 A sample list of the floor types in Microsoft Excel

Element Type Code	Description	Unit	Construction: Material Unit Cost (Baht)	Construction: Labor Unit Cost (Baht)	Construction: Unit Rate (Baht)	Maintenance: Expected Service Life (Years)	Maintenance: Percent Replaced	Maintenance: Description	Maintenance: Material Unit Cost (Baht)	Maintenance: Labor Unit Cost (Baht)	Maintenance: Equipment Unit Cost (Baht)	Maintenance: Annual Unit Rate per SQM (Baht)
C3020411	*Gray stone floor F1*	*SQM*			*1436.31*	*50*	*100%*	*Cleaning, waxing 0.2 min every month)*	*13.6*	*3.74*	*0.68*	*18.02*
	Gray stone		*250*	*150*	400							
	CIP floor PS 125mm				1036.31							
C3020421	Black stone floor F1/1	SQM	*250*	*150*	400	50	100%	Cleaning, waxing 0.2 min every month)	13.6	3.74	0.68	18.02
C3020431	*Gray tile floor F2*	*SQM*			*1321.22*	*50*	*100%*	*Cleaning, waxing 0.2 min every month)*	*13.6*	*3.74*	*0.68*	*18.02*
	Gray stone		300	200	500							
	Composite floor HC 0.12 - CIP 0.05m				821.22							
C3020441	*Ceramic tile floor F3*	*SQM*			*1222.07*	*50*	*100%*	*Cleaning, waxing 0.2 min every month)*	*13.6*	*3.74*	*0.68*	*18.02*
	Ceramic tile		300	120	420							
	CIP floor S2 125mm				802.07							
C3020451	Concrete floor with waterproofing F4	SQM			1765.37	50						18.02
	Waterproofing F4		*50*	*50*	136	50	100%	Cleaning, waxing 0.2 min every month)	13.6	3.74	0.68	18.02
	Compressor concrete floor 0.25m				1629.37							
C3020461	*White-gray terrazzo floor F5*	*SQM*			*2179.37*	*50*	*100%*	*Cleaning, waxing 0.2 min every month)*	*13.6*	*3.74*	*0.68*	*18.02*
	White-gray terrazzo floor				550							
	Compressor concrete floor 0.25m				1629.37							
C3020471	*Concrete floor F6*	*SQM*			*798.1494*	*50*	*100%*	*Cleaning, waxing 0.2 min every month)*	*13.6*	*3.74*	*0.68*	*18.02*
	CIP floor S1 125mm				798.1494							
C3020432	*Gray tile floor F2'*	*SQM*			*2129.37*	*50*	*100%*	*Cleaning, waxing 0.2 min every month)*	*13.6*	*3.74*	*0.68*	*18.02*
	Gray stone		300	200	500							
	Compressor concrete floor 0.25m				1629.37							
C3020412	*Gray stone floor F1'*	*SQM*			*2029.37*	*50*	*100%*	*Cleaning, waxing 0.2 min every month)*	*13.6*	*3.74*	*0.68*	*18.02*
	Gray stone		*250*	*150*	400							
	Compressor concrete floor 0.25m				1629.37							
C3020472	*Concrete floor F6'*	*SQM*			*1464.1196*	*50*	*100%*	*Cleaning, waxing 0.2 min every month)*	*13.6*	*3.74*	*0.68*	*18.02*
	Compressor concrete floor 0.2m				1464.12							

Table 4.5 A sample list of the roof types in Microsoft Excel

Element Type Code	Description	Unit	Construction: Material Unit Cost (Baht)	Construction: Labor Unit Cost (Baht)	Construction: Unit Rate (Baht)	Maintenance: Expected Service Life (Years)	Maintenance: Percent Replaced	Maintenance: Description	Maintenance: Material Unit Cost (Baht)	Maintenance: Labor Unit Cost (Baht)	Maintenance: Equipment Unit Cost (Baht)	Maintenance: Annual Unit Rate per SQM (Baht)
C3020452	*Concrete roof with waterproofing F4*	*SQM*			*1765.37*	*50*		Cleaning, waxing 0.2 min every month)	*13.6*	*3.74*	*0.68*	*18.02*
	Waterproofing surface		*50*	*86*	136		100%					
	Compressor concrete floor 0.25m				1629.37							
C3020431	*Gray tile roof F2'*	*SQM*			*2129.37*	*50*		Cleaning, waxing 0.2 min every month)	*13.6*	*3.74*	*0.68*	*18.02*
	Tile surface		*300*	*200*	500		100%					
	Compressor concrete floor 0.25m				1629.37							
C3020471	*Concrete roof F6'*	*SQM*			*1765.37*	*50*	*100%*	Cleaning, waxing 0.2 min every month)	*13.6*	*3.74*	*0.68*	*18.02*
	Waterproofing surface		*50*	*86*	136		100%					
	Compressor concrete floor 0.25m				1629.37							
C3020451	*Membrane roofing*	*SQM*			*1765.37*	*50*		Cleaning, waxing 0.2 min every month)	*13.6*	*3.74*	*0.68*	*18.02*
	Waterproofing surface		*50*	*86*	136		100%					
	Compressor concrete floor 0.25m				1629.37							

Table 4.4 displays a sample list of floor types, which are prepared in Microsoft Excel. Each floor type contains the element type code, description of material, unit, material unit cost, labor unit cost for estimating the cost per SQM floor, expected service life, percent replaced, description for floor maintenance activities, material unit cost, labor unit cost, equipment unit cost for estimating annual unit rate per SQM floor.

Table 4.5 illustrates a sample list of roof types, which are prepared in Microsoft Excel. Each roof type entails the element type code, description of structural and finished material layers, unit, material unit cost, labor unit cost for estimating the cost per SQM roof, expected service life, percent replaced, description for roof maintenance activities, material unit cost, labor unit cost, equipment unit cost for estimating annual unit rate per SQM roof.

4.5 Results

Figure 4.6 shows the structure of the relational database of the BIM-BLCC. Eight tables are created to store all required data for the BIM-BLCC: (1) ExteriorWalls, (2) ExteriorWindows, (3) Floors, (4) Roofs, (5) InteriorWalls, (6) InteriorWindows, (7) Doors, and (8) Assembly. The description attribute is used to describe the name of type within the field.

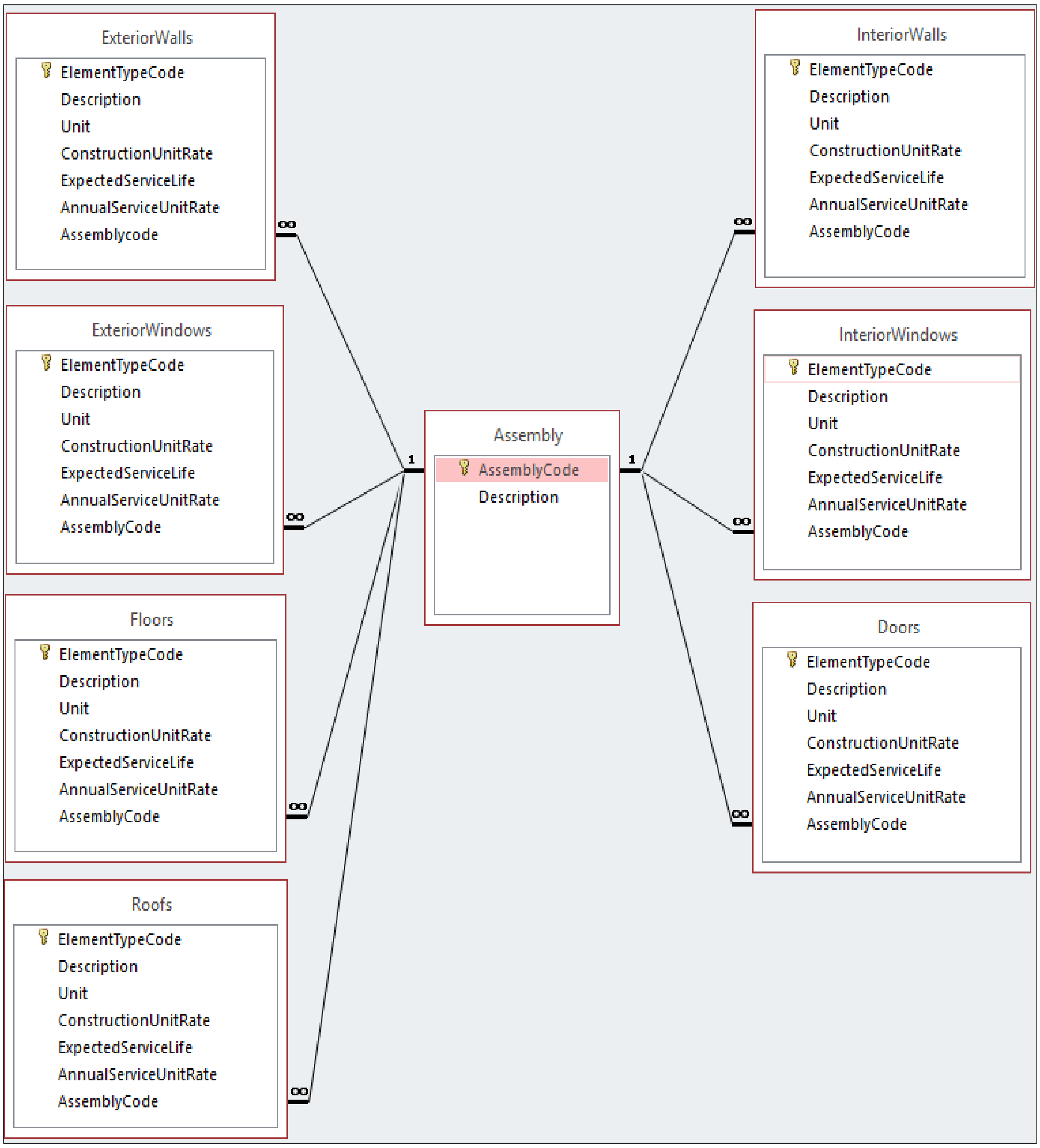
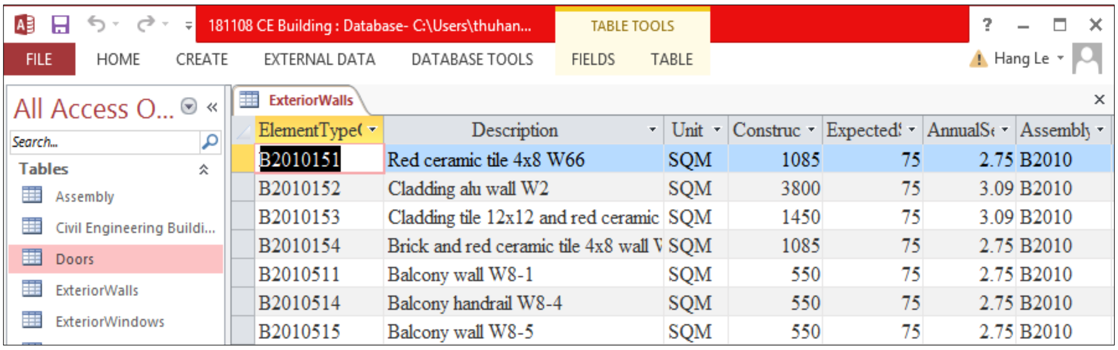


Figure 4.6 Structure of the relational database of the BIM-BLCC

For the ExteriorWalls table, seven fields are created to store the required data, namely, the element type code, description, unit, construction unit rate, expected service life, annual service unit rate, and assembly code. The element type code field stores the unique code of each exterior wall type, which helps identify an exterior wall type easier than using its name. The type of valid data to be recorded in this field is short text that stores up to 255 characters of texts, numbers, and symbols. The description field stores the name attribute of each exterior wall type. The type of valid data to be recorded in this field is also a short text. The unit field stores the calculating unit of each exterior wall type. The square meter is selected as a calculating unit for all the exterior wall types of the relational database. The type of data to be recorded in this field is short text. The construction unit rate field is used to describe the value of the construction cost unit of each exterior wall type. The type of valid data to be recorded in this field is the numbers that store the results of the processed data in mathematical calculations from the data organization section. The expected service life field stores a number of useful years of each exterior wall type. The type of data to be recorded in this field is the number. The annual service unit rate field stores the value of the annual service unit rate for each exterior wall type. The type of valid data to be recorded in this field is the number. The assembly code field stores the code of the building structure that the exterior wall type belongs. This code is developed based on level 3 of the Uniformat classification system of building elements. The primary key of this table is the element type code. This code is uniquely assigned to each exterior wall type to help identify an exterior wall type easier than using its name and to avoid any duplication of data in a field. A link is created between the ExteriorWalls table and the Assembly table in order to share data between both tables. The assembly code field is selected as a join field between two tables. The one-to-many relation is used for joining tables through the assembly code field. Figure 4.7 shows a sample list of exterior wall type stores in this table.



ElementType(	Description	Unit	Construc	Expected!	AnnualS	Assembly
B2010151	Red ceramic tile 4x8 W66	SQM	1085	75	2.75	B2010
B2010152	Cladding alu wall W2	SQM	3800	75	3.09	B2010
B2010153	Cladding tile 12x12 and red ceramic	SQM	1450	75	3.09	B2010
B2010154	Brick and red ceramic tile 4x8 wall V	SQM	1085	75	2.75	B2010
B2010511	Balcony wall W8-1	SQM	550	75	2.75	B2010
B2010514	Balcony handrail W8-4	SQM	550	75	2.75	B2010
B2010515	Balcony wall W8-5	SQM	550	75	2.75	B2010

Figure 4.7 A sample data list of the ExteriorWalls table

For the other database tables consist of the ExteriorWindows table, the Floors table, the Roofs table, the Doors table, the InteriorWindows table, and the InteriorWalls table, seven fields are created to contain information of each table, namely, the element type code, description, unit, construction unit rate, expected service life, annual service unit rate, and assembly code. The details of each table are shown in the Appendix B.

For the assembly table, two fields are introduced to contain information of this table: the assembly code and description. The assembly code field stores the code of the building structure that is developed based on the level 3 of the Uniformat classification system of building elements. The assembly code is uniquely assigned to each building structure (e.g., the exterior wall and the exterior window). This is to identify a building structure easier than using its name. The primary key of this table is the assembly code field. The type of data to be recorded in this field is the short text. The description field stores the name of building structure. The type of data to be recorded in this field is also the short text. Seven links are created between the assembly table and other tables of the relational LCC database for sharing data. The one-to-many relation is used for joining the tables. Figure 4.8 shows a sample list of data stored in this table.

4.6 Summary

This chapter discusses a methodology for developing a database for the proposed system consists of the database requirements, the database schema, the data organization, and the structure of the tables in the relational LCC database and their relations. Among various database models, the relational database model is adopted to develop the relational LCC database. The proposed database comprises eight database tables to storing the processed data for the building structure: the Assembly, Doors, ExteriorWalls, ExteriorWindows, Floors, InteriorWalls, InteriorWindows, and Roofs table. The one-to-many relation is selected for joining two tables in this database. The developed database is used to store necessary data for the 3D BIM model of the BIM-BLCC.

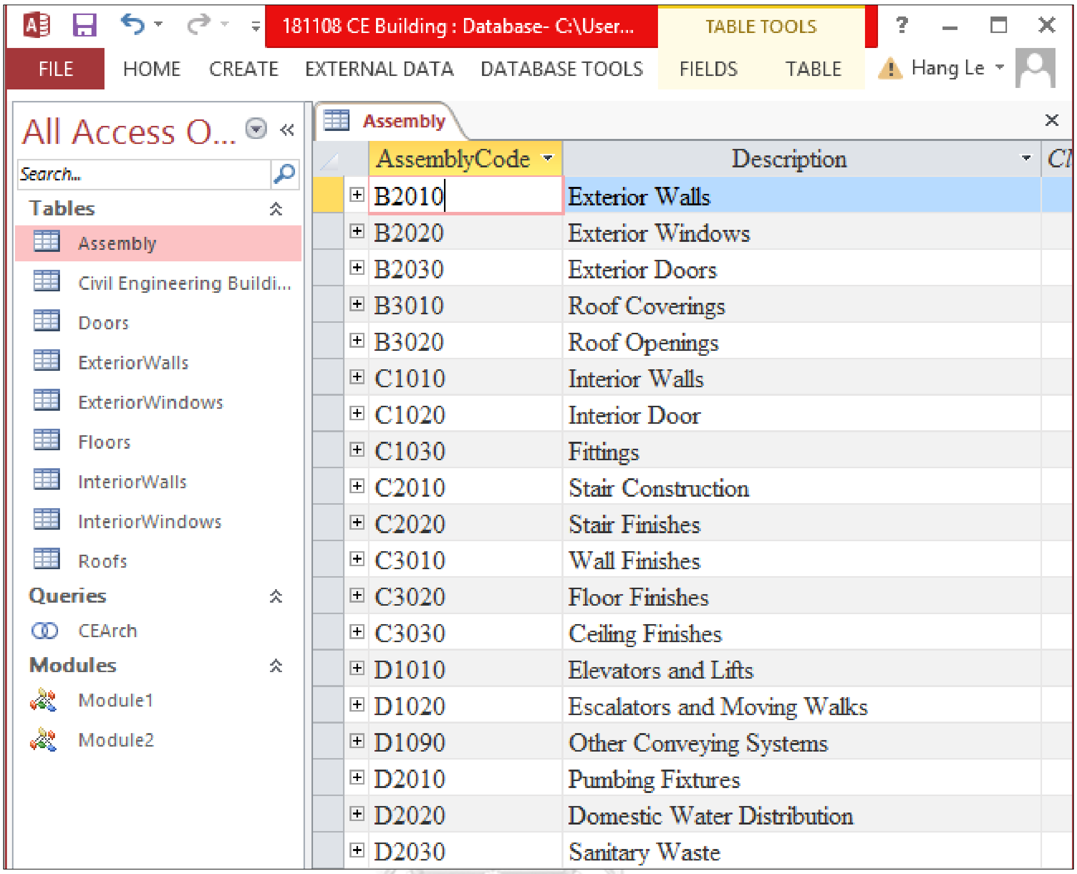


Figure 4.8 A sample data list of the Assembly table

CHAPTER 5
VISUALIZED BIM-INTEGRATED MODULE

This chapter presents the development of the visualized BIM-integrated module of the BIM-BLCC. Autodesk Revit is selected as a platform for authoring the 3D BIM model. The contents of this chapter consist of the requirements of the level of development (LOD) for the 3D BIM model, the required data of various element models of the 3D model, and the methodology to extract the required data from the relational database management module to the 3D BIM model using an integrated system among the BIM authoring programming, the database management system, the visual programming interface, and the spreadsheet system.

5.1 Introduction

Performing the building LCCA requires various information, in which is inherent from the design to disposal phases of construction projects. A major challenge is how to gather all the required data form all project participants. BIM has become a popular information technology in the architecture, engineering, and construction (AEC) industry. BIM is a database structure, object-oriented, and parametric digital representation of a facility. BIM can improve communication among project participants in construction projects. However, the current BIM tools cannot accommodate all required data for performing the building LCCA. To address this problem, the BIM model needs to incorporate more parameters such as construction unit rate, service unit cost, expected service rate, energy unit cost for each building element. Furthermore, there is no standard or guideline that relates BIM element models to the elemental building classification on the cost database. Thus, this chapter proposes a new methodology for developing the 3D BIM model for performing the building LCCA, which consists of six steps, as shown in Figure 5.1. The first step is to identify the level of development (LOD) of the building structures such as floor, exterior wall, roof, exterior window, door, interior wall, and interior window. The second step is to create the conceptual 3D BIM model using BIM authoring software.

In this research, Autodesk Revit Architecture is used for creating the 3D BIM model. Revit provides a comprehensive BIM model with high visualized quality and better document coordination. The third step is to identify the data for each element model. Users can add more parameters to the element properties for different purposes at any time. The fourth step is to integrate the conceptual 3D BIM model with the visual programming interface by using graphical scripts. The fifth step is to integrate the relational LCC database with the visual programming interface by using the spreadsheet software and graphical scripts. The sixth step is to extract the required parameters for the element properties. The outcome of this module is the completed 3D BIM model of the BIM-database-integrated system for evaluating the building LCC using a multi-parametric model.

5.2 Level of development (LOD) of the BIM model

There are no standards for LOD of the BIM model for the building LCCA. This research proposed the LOD 300 for different element models of building projects to fit with the requirements for the building LCCA at the procurement phase. Before creating the 3D objects of BIM model, the designers need to identify the non-geometry information of each object such as length, width, height, and thinness. Table 5.1 displays the LOD definitions of the BIM element model for the building LCCA.

As shown in Table 5.1, each floor element model represented both geometry and non-geometry data. Geometry data are length, height, and thickness of material layers of the floor element model. Non-geometry data are element type code, construction unit rate, annual service unit rate, and expected service life of the floor element model. Each exterior window element represented the thickness, length, and height for its geometry data. Non-geometry data are element type code, construction unit rate, annual service unit rate, expected service life, heat transfer coefficient, and solar heat gain coefficient. The type of glass should be represented to define the heat transfer coefficient and the solar heat gain coefficient of each exterior window element.

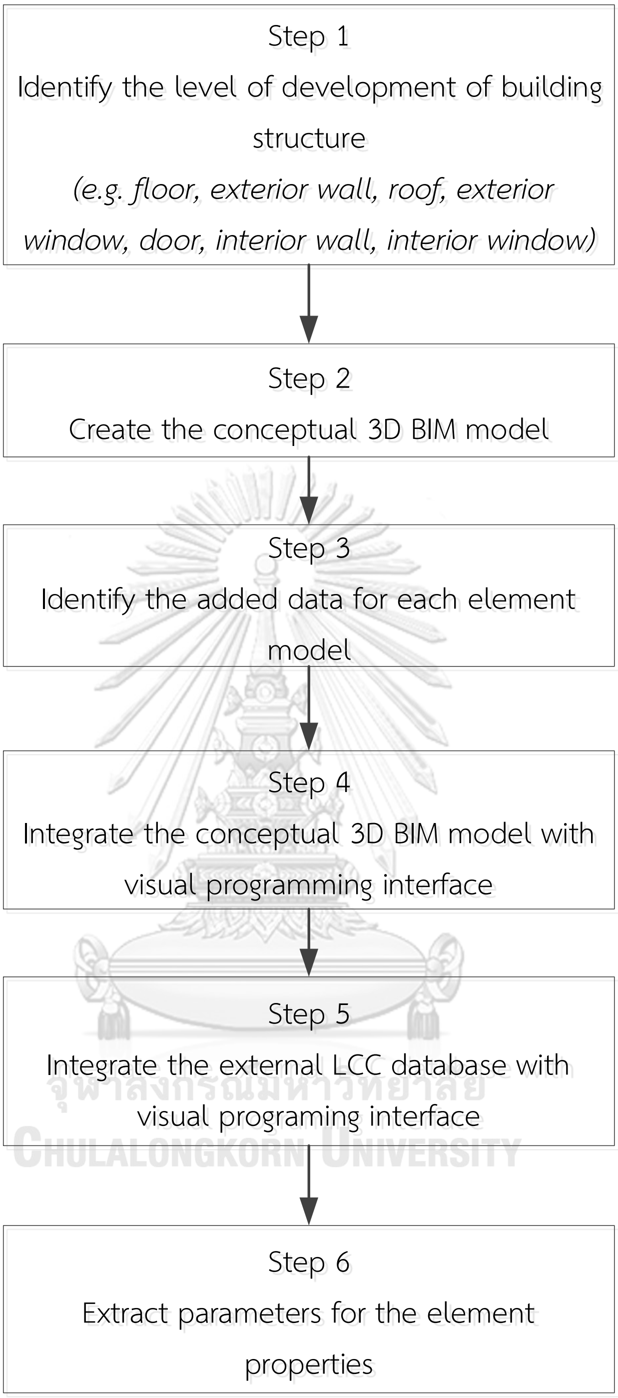
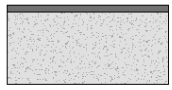
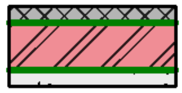
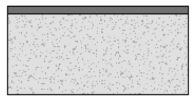
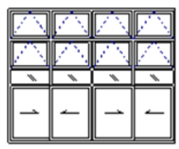
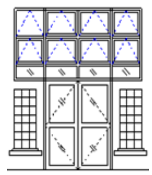
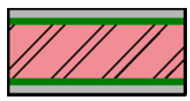
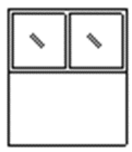


Figure 5.1 Workflow of developing the visualized BIM-integrated module of the BIM-BLCC

Table 5.1 LOD definition for the BIM model of the BIM-BLCC

Category	Model content requirements for building LCCA	LOD	Graphical illustration
Floor	_ Geometry (length, height, thick of material layers) _ Non-Geometry (element type code, construction unit rate, annual service unit rate, expected service life)	300	
Exterior wall	_ Geometry (length, height, thick of material layers) _ Non-Geometry (element type code, construction unit rate, annual service unit rate, expected service life, heat transfer coefficient, equivalent temperature difference)	300	
Roof	_ Geometry (length, height, thick of material layers) _ Non-Geometry (element type code, construction unit rate, annual service unit rate, expected service life, heat transfer coefficient, equivalent temperature difference)	300	
Exterior window	_ Geometry (length, height, thick of material) _ Non-Geometry (element type code, construction unit rate, annual service unit rate, expected service life, heat transfer coefficient, solar heat gain coefficient)	300	
Door	_ Geometry (length, height, thick of material layers) _ Non-Geometry (element type code, construction unit rate, annual service unit rate, expected service life)	300	
Interior wall	_ Geometry (length, height, thick of material layers) _ Non-Geometry (element type code, construction unit rate, annual service unit rate, expected service life)	300	
Interior window	_ Geometry (length, height, thick of material layers) _ Non-Geometry (element type code, construction unit rate, annual service unit rate, expected service life)	300	

Each exterior wall element model needed contain both geometry and non-geometry data. Geometry data are its thickness, length, and width. Non-geometry data consist of element type code, construction unit rate, annual service unit rate, expected service life, heat transfer coefficient, and equivalent temperature difference. The type and thickness of material layers should be represented to define the heat transfer coefficient for each exterior wall element.

Each roof element model contained both geometry and non-geometry data. Geometry data are thickness, length, and global width of the roof element model. Non-geometry data are element type code, construction unit rate, annual service unit rate, expected service life, heat transfer coefficient, and equivalent temperature difference of the roof element model. The type and thickness of material layers should be represented to define the heat transfer coefficient for each roof element model.

Each door element model represented its thickness, length, and global width for geometry data. Non-geometry data are element type code, construction unit rate, annual service unit rate, and expected service life of the door element model. The type and thickness of material layers should be represented to define the heat transfer coefficient for each door element.

Each interior wall element model contained both geometry and non-geometry data. Geometry data are thickness, length, and width of the interior wall element model. Non-geometry data are element type code, construction unit rate, annual service unit rate, and expected service life of the interior wall element model. The type and thickness of material layers should be represented to define the heat transfer coefficient for each interior wall element model.

Each interior window model needed to contain the same geometry and non-geometry data with the interior wall element model.

5.3 Parametric requirements of various building elements of the BIM model

The current BIM authoring software do not have the capabilities to accommodate the data for the building LCCA. To carry out the building LCCA, the BIM objects need to be added more parameters to their properties. The added data is extracted from two main data sources. The first data source is from the relational database of the BIM-BLCC that is developed from the previous chapter. The data consist of the element type code, the construction unit rate, the expected service life, the annual service unit price of each building element type. The second data source is from the internal database by the Revit material library. The data consist of the coefficient of heat transfer, the average equivalent temperature difference, and the solar heat gain coefficient for each building element type.

5.4 Integration of the BIM model and the relational database

5.4.1 Union query statement for extracting the required data from the relational database

Query is an essential part of database application that support for the users extract the required data from multiple tables of the relational database based on a specified criteria. The relational database of the BIM-BLCC contains many building element types in a table. Each 3D BIM model need to retrieve only the data of its building element types. To implement a task manually would take much of your time, but the users can achieve it within few minutes by using the structure query language (SQL) in Microsoft Access.

The SQL is a simple computer language that is used to retrieve data from relational database management system like Microsoft Access. SQL environment is an advance view that allows you to type SQL statements directly for query. There are six steps to access the SQL view in Microsoft Access to type a union query for extracting data for the 3D BIM model, as shown in Figure 5.2.

- Step 1: Click “Create” tap to create new query
- Step 2: Click “Query Design” located in the queries group under the create tab
- Step 3: Close the show table dialogue box that is opened after performing the step 2 without selecting any table by clicking “Close” button.
- Step 4: Click “Union” icon located in the query type group under the design tab. Microsoft Access will display the SQL view where you can directly type your SQL statements.
- Step 5: Type SQL statements for an union query
- Step 6: Click “Run” command located near the view menu in the results group to run the query.

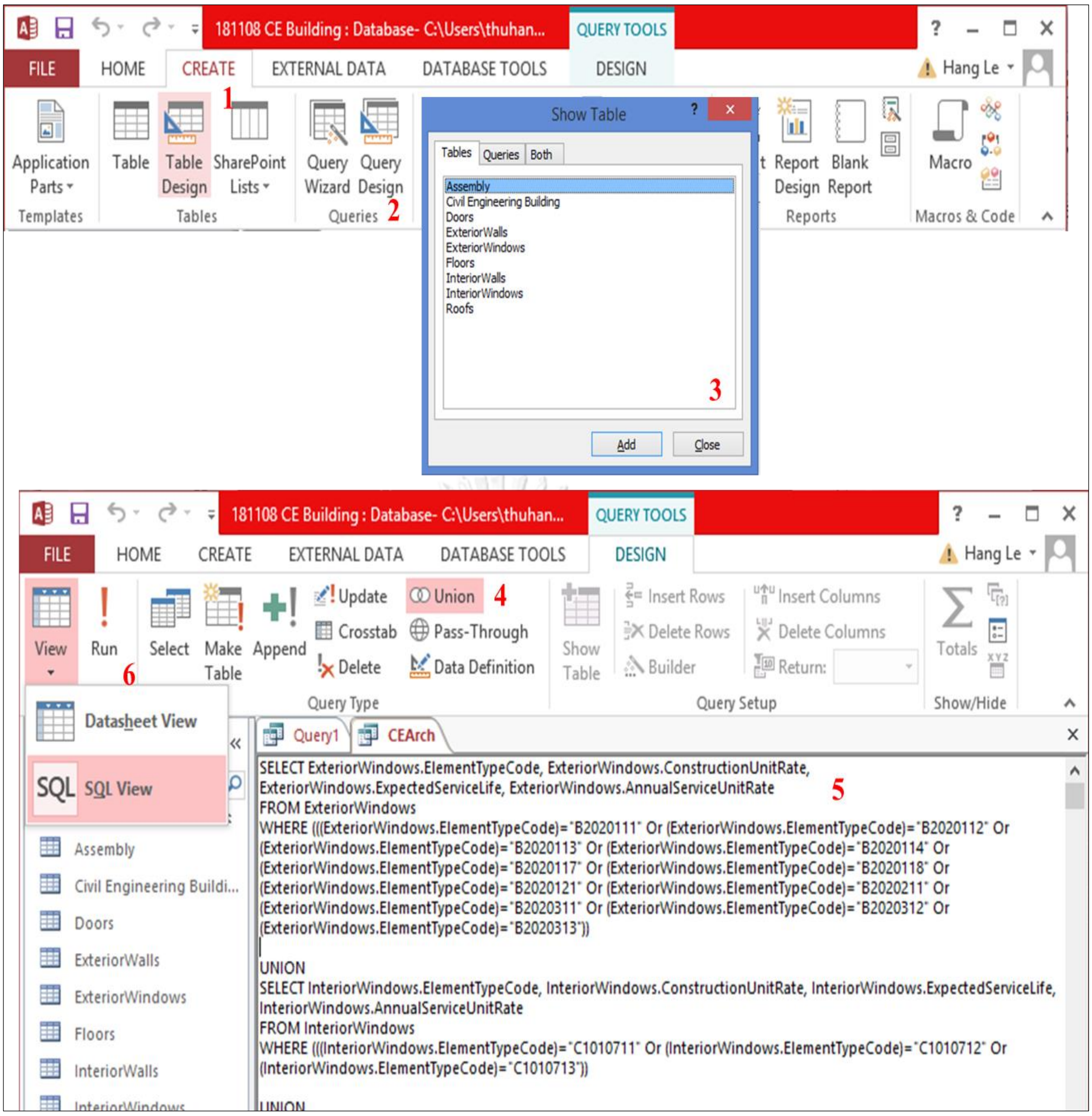


Figure 5.2 Workflow of the SQL view for extracting the required data from the relational database of the BIM-BLCC

The union query is built when the users joins two or more related tables together. The select statements that you combine in a union query must have the same number of output fields in the same order and with the compatible data types. There are two methods of creating union queries in Microsoft Access consist of (1) combining two select queries previously created in design view and (2) creating the union query directly in SQL view. In this research, the second method is selected due to the user has not created the previous select queries. The SQL statements for a union query that combine seven SELECT queries is presented appendix.

The first SELECT query statement for the UNION query, we selected element type code field, construction unit rate field, expected service life field, annual service unit rate field of the ExteriorWindows table. The SELECT statement is always used with a FROM clause. The FROM clause in this select query identifies the name of the ExteriorWindows table that contain the fields listed in the preceding SELECT clause, separating the field names with a comma and a space. The enter key is used to create a new line for a FROM clause. The WHERE clause in this SELECT statement to specify a criteria for element type code field from ExteriorWindows table in the preceding FROM clause. To add additional criteria for the SELECT statement, we use the OR keyword at the end of the WHERE clause. The enter key is used to create a new line for a WHERE clause.

The second SELECT query statement for the UNION query, we selected element type code field, construction unit rate field, expected service life field, annual service unit rate field of the InteriorWindows table. The FROM clause in this select query identifies the name of the InteriorWindows table that contain the fields listed in the preceding SELECT clause, separating the field names with a comma and a space. The WHERE clause in this SELECT statement to specify a criteria for element type code field from InteriorWindows table in the preceding FROM clause. To add additional criteria for the SELECT statement for the interior windows, we use the OR keyword at the end of the WHERE clause. The UNION operator is used to merge the SELECT query for the exterior windows with the SELECT query for the interior windows to produce one read-only dataset.

The third SELECT query statement for the UNION query, we selected element type code field, construction unit rate field, expected service life field, annual service unit rate field of the Doors table. The FROM clause in this select query identifies the name of the Doors table that contain the fields listed in the preceding SELECT clause, separating the field names with a comma and a space. The WHERE clause in this SELECT statement to specify a criteria for element type code field from Doors table in the preceding FROM clause. To add additional criteria for the SELECT statement for the doors, we use the OR keyword at the end of the WHERE clause. The UNION operator is used to merge the SELECT query for the door, with the SELECT query for the interior windows, and with the SELECT query for the exterior windows to produce one read-only dataset.

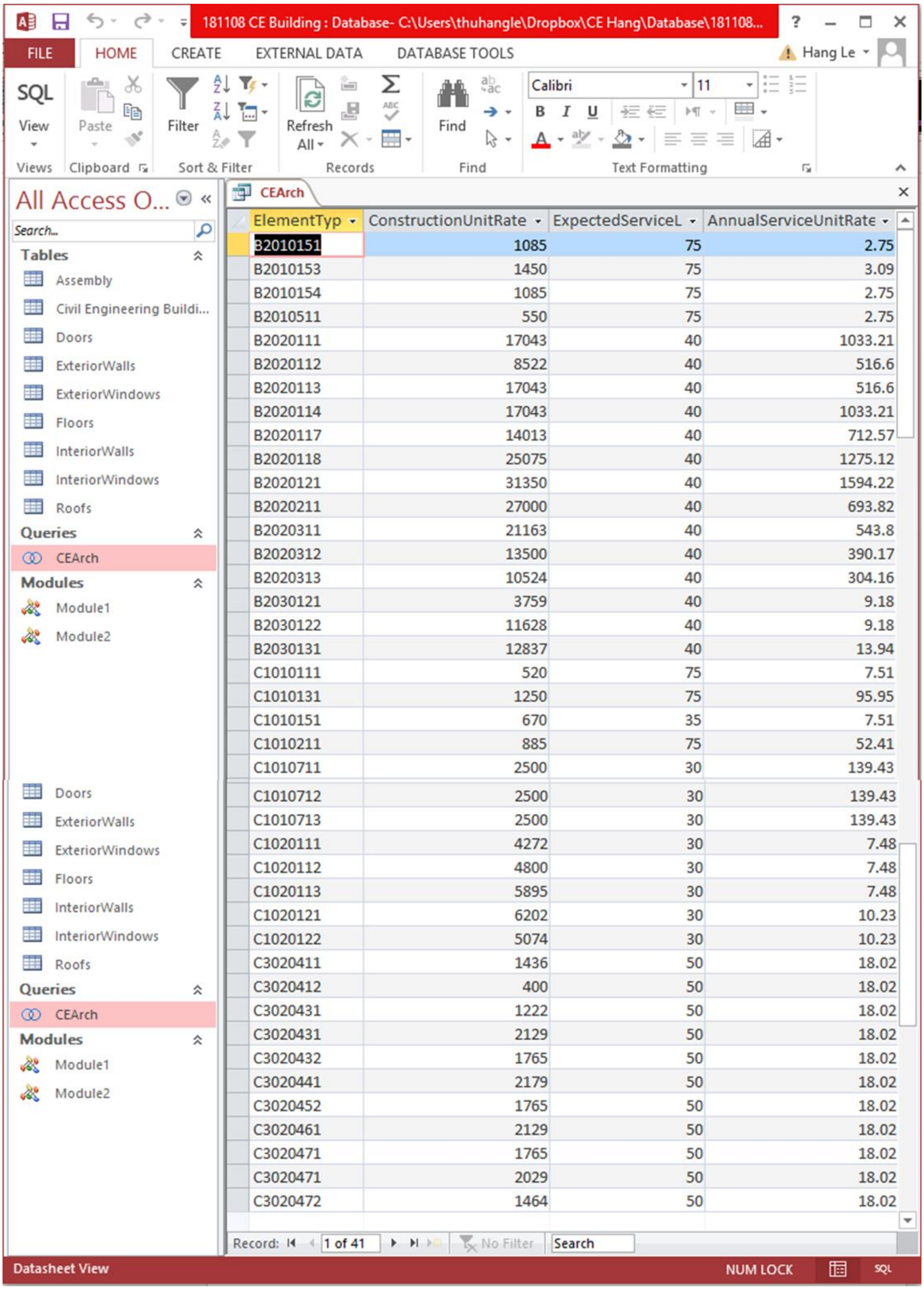
The fourth SELECT query statement for the UNION query, we selected element type code field, construction unit rate field, expected service life field, annual service unit rate field of the ExteriorWalls table. The FROM clause in this select query identifies the name of the ExteriorWalls table that contain the fields listed in the preceding SELECT clause, separating the field names with a comma and a space. The WHERE clause in this SELECT statement to specify a criteria for element type code field from ExteriorWalls table in the preceding FROM clause. To add additional criteria for the SELECT statement for the exterior walls, we use the OR keyword at the end of the WHERE clause. The UNION operator is used to merge the SELECT query for the exterior walls, with the SELECT query for the doors, with the SELECT query for the interior windows, and with the SELECT query for the exterior windows to produce one read-only dataset.

The fifth SELECT query statement for the UNION query, we selected element type code field, construction unit rate field, expected service life field, annual service unit rate field of the InteriorWalls table. The FROM clause in this select query identifies the name of the InteriorWalls table that contain the fields listed in the preceding SELECT clause, separating the field names with a comma and a space. The WHERE clause in this SELECT statement to specify a criteria for element type code field from InteriorWalls table in the preceding FROM clause. To add additional criteria for the SELECT statement for the interior walls, we use the OR keyword at the end of the WHERE clause. The UNION operator is used to merge the SELECT query for the interior walls, with the SELECT query for the exterior walls, with the SELECT query for the doors, with the SELECT query for the interior windows, and with the SELECT query for the exterior windows to produce one read-only dataset.

The sixth SELECT query statement for the UNION query, we selected element type code field, construction unit rate field, expected service life field, annual service unit rate field of the Floors table. The FROM clause in this select query identifies the name of the Floors table that contain the fields listed in the preceding SELECT clause, separating the field names with a comma and a space. The WHERE clause in this SELECT statement to specify a criteria for element type code field from Floors table in the preceding FROM clause. To add additional criteria for the SELECT statement for the floors, we use the OR keyword at the end of the WHERE clause. The UNION operator is used to merge the SELECT query for the floors, with the SELECT query for the interior walls, with the SELECT query for the exterior walls, with the SELECT query for the doors, with the SELECT query for the interior windows, and with the SELECT query for the exterior windows to produce one read-only dataset.

The seventh SELECT query statement for the UNION query, we selected element type code field, construction unit rate field, expected service life field, annual service unit rate field of the Roofs table. The FROM clause in this select query identifies the name of the Roofs table that contain the fields listed in the preceding SELECT clause, separating the field names with a comma and a space. The WHERE clause in this SELECT statement to specify a criteria for element type code field from Roofs table in the preceding FROM clause. To add additional criteria for the SELECT statement for the roofs, we use the OR keyword at the end of the WHERE clause. The UNION operator is used to merge the SELECT query for the roofs, with the SELECT query for the floors, with the SELECT query for the interior walls, with the SELECT query for the exterior walls, with the SELECT query for the doors, with the SELECT query for the interior windows, and with the SELECT query for the exterior windows to produce one read-only dataset. A semi-colon is type at this SELECT query statement to indicate the end of the UNION query.

After clicking the Run! Icon that is located beside view drop down menu in the results group under the design tab. The result appears in a datasheet view. An example of the dataset is directly create by using a union query in Microsoft Access, as shown in Figure 5.3.



ElementTyp	ConstructionUnitRate	ExpectedServiceL	AnnualServiceUnitRate
B2010151	1085	75	2.75
B2010153	1450	75	3.09
B2010154	1085	75	2.75
B2010511	550	75	2.75
B2020111	17043	40	1033.21
B2020112	8522	40	516.6
B2020113	17043	40	516.6
B2020114	17043	40	1033.21
B2020117	14013	40	712.57
B2020118	25075	40	1275.12
B2020121	31350	40	1594.22
B2020211	27000	40	693.82
B2020311	21163	40	543.8
B2020312	13500	40	390.17
B2020313	10524	40	304.16
B2030121	3759	40	9.18
B2030122	11628	40	9.18
B2030131	12837	40	13.94
C1010111	520	75	7.51
C1010131	1250	75	95.95
C1010151	670	35	7.51
C1010211	885	75	52.41
C1010711	2500	30	139.43
C1010712	2500	30	139.43
C1010713	2500	30	139.43
C1020111	4272	30	7.48
C1020112	4800	30	7.48
C1020113	5895	30	7.48
C1020121	6202	30	10.23
C1020122	5074	30	10.23
C3020411	1436	50	18.02
C3020412	400	50	18.02
C3020431	1222	50	18.02
C3020431	2129	50	18.02
C3020432	1765	50	18.02
C3020441	2179	50	18.02
C3020452	1765	50	18.02
C3020461	2129	50	18.02
C3020471	1765	50	18.02
C3020471	2029	50	18.02
C3020472	1464	50	18.02

Figure 5.3 Example of a dataset is queried using the SQL union statement

5.4.2 Results for applying the union query statement

To work with the data of the relational database in the BIM authoring programing, we need to perform the second phase of integration the 3D BIM model with the relational database is the exporting of the queried dataset to Microsoft Excel. There are eight steps to export a queried dataset to a spreadsheet file, as shown in Figure 5.4. An example result was shown in Figure 5.5.

- Step 1: Click the RELATIONAL DATA tab
- Step 2 Click the Excel icon under the export group
- Step 3: This prompts the Export - Excel Spreadsheet dialogue box. Click the Browse button beside the File name box to select the destination for the data you want to export. The destination location is the place where the exported data will be stored.
- Step 4: Select Excel Workbook for the file format.
- Step 5: Check the setting Export data with formatting and layout checkbox to preserve most formatting and layout information when exporting a union query. This prompts the Open the destination file after the export operation is complete check box. Click this checkbox to view the results of the export operation.
- Step 6: Click OK to perform the export. Ignore the other checkbox which is grayed out. The output is a sample list of data in the spreadsheet file, as shown in Figure 5.5
- Step 7: Check the Save export steps
- Step 8: Click the Save Export button in the Export - Excel Spreadsheet dialogue box. By saving your export setting, you can quickly export the same union query later on.

5.4.3 Data acquisition for the BIM model using visual programing interface

The 3D BIM model do not have enough the required data to carry out the building LCCA. Therefore, the integration of BIM model and the relational database of the BIM-BLCC is necessary to extract the required data for the BIM model.

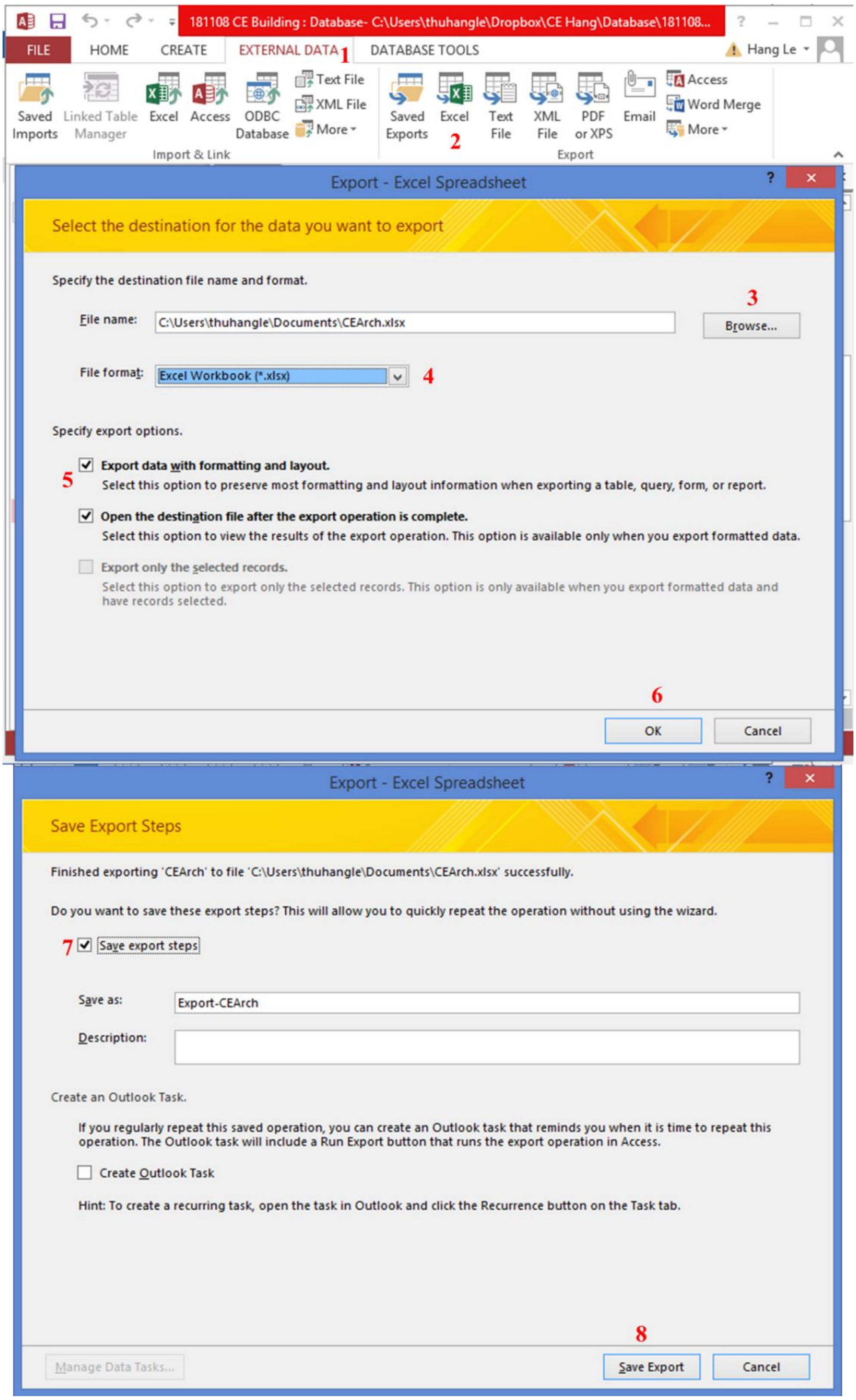
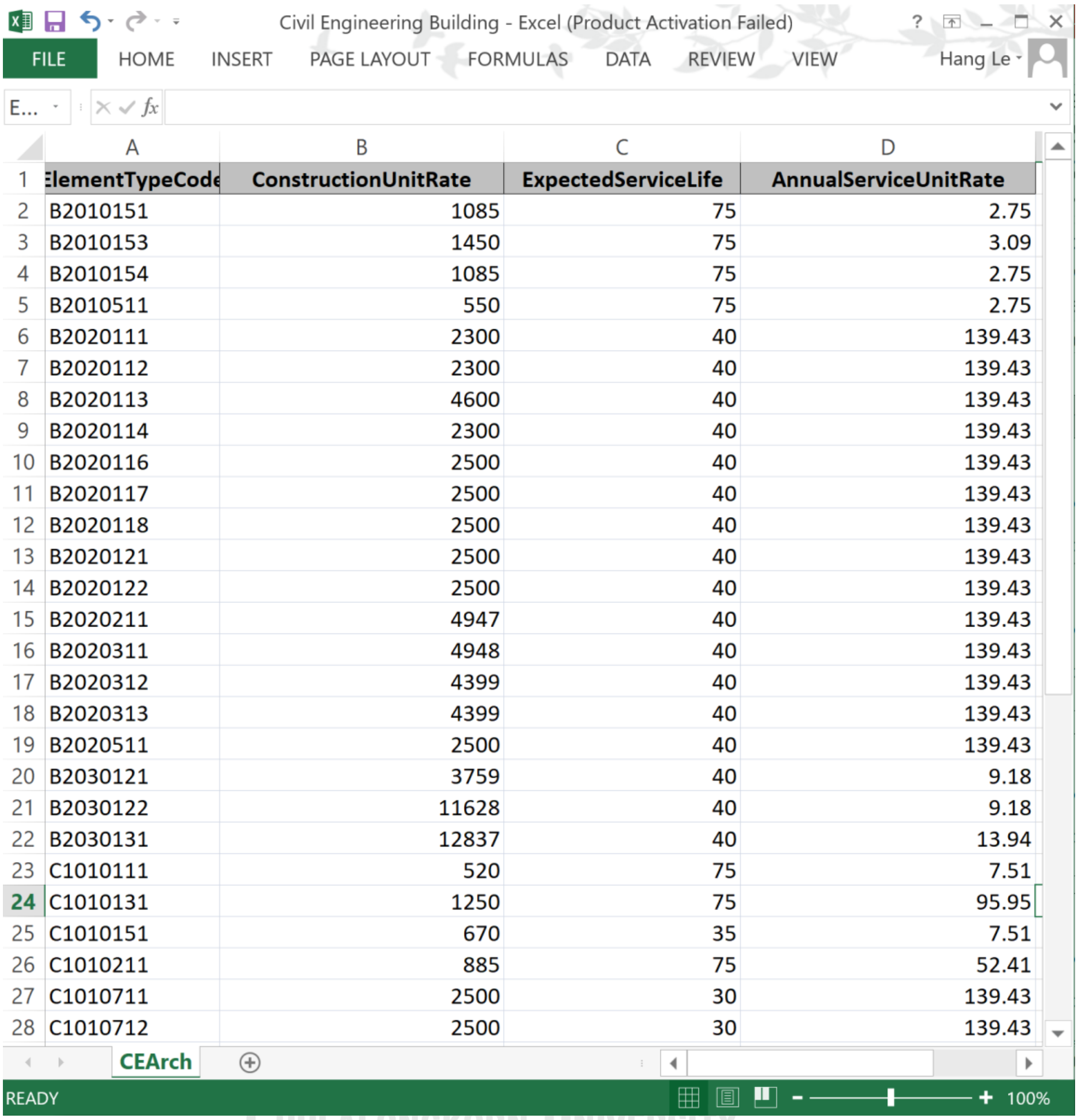


Figure 5.4 Workflow for exporting a union query to the spreadsheet file



	A	B	C	D
1	ElementTypeCode	ConstructionUnitRate	ExpectedServiceLife	AnnualServiceUnitRate
2	B2010151	1085	75	2.75
3	B2010153	1450	75	3.09
4	B2010154	1085	75	2.75
5	B2010511	550	75	2.75
6	B2020111	2300	40	139.43
7	B2020112	2300	40	139.43
8	B2020113	4600	40	139.43
9	B2020114	2300	40	139.43
10	B2020116	2500	40	139.43
11	B2020117	2500	40	139.43
12	B2020118	2500	40	139.43
13	B2020121	2500	40	139.43
14	B2020122	2500	40	139.43
15	B2020211	4947	40	139.43
16	B2020311	4948	40	139.43
17	B2020312	4399	40	139.43
18	B2020313	4399	40	139.43
19	B2020511	2500	40	139.43
20	B2030121	3759	40	9.18
21	B2030122	11628	40	9.18
22	B2030131	12837	40	13.94
23	C1010111	520	75	7.51
24	C1010131	1250	75	95.95
25	C1010151	670	35	7.51
26	C1010211	885	75	52.41
27	C1010711	2500	30	139.43
28	C1010712	2500	30	139.43

Figure 5.5 Sample of a data list into the spreadsheet file

The most difficulty of the QSs is how to integrate the BIM model and the spreadsheet file to perform the data retrieval process because they are non-programmers. To solve this problem, this chapter proposed an automatic methodology for extracting the required data from the spreadsheet file for the 3D BIM model by using visual programming interface. The integrated process is developed throughout two main phases. Phase 1 links the spreadsheet file into visual environment by visual scripts. Phase 2 extracts the required data for the 3D BIM model by visual scripts.

The workflow for integrating the spreadsheet file into visual environment, as shown in Figure 5.6, which consists of three steps. Step 1 identifies the spreadsheet file that obtains the appropriate data for the 3D BIM model in Microsoft Excel. There are two Dynamo node, which are used to carry out this job consist of *File Path* node and *File.FromPath* node. Step 2 identifies the sheet name in the spreadsheet file that obtained the needed data using *Code Block* node. This node is written by Python scripts to access the target sheet. Step 3 displays all data lists of the selected sheet that is entered based on the row format of Microsoft Excel using *Excel.ReadFromFile* node. These data is read as the strings in visual programming interface.

The workflow for extracting the required data for the 3D BIM model by visual scripts consists of four steps. Step 1 selects the building element types of the 3D BIM model. Step 2 identifies the required data that need to be extracted the value from the type properties. The names of the required data were added to the type properties of the 3D BIM model in Revit through 11 sub-steps, as shown in Figure 5.7. Step 3 selects the required data from the relevant data lists. Step 4 extracts the value of the required data of the selected building element type of the BIM model.

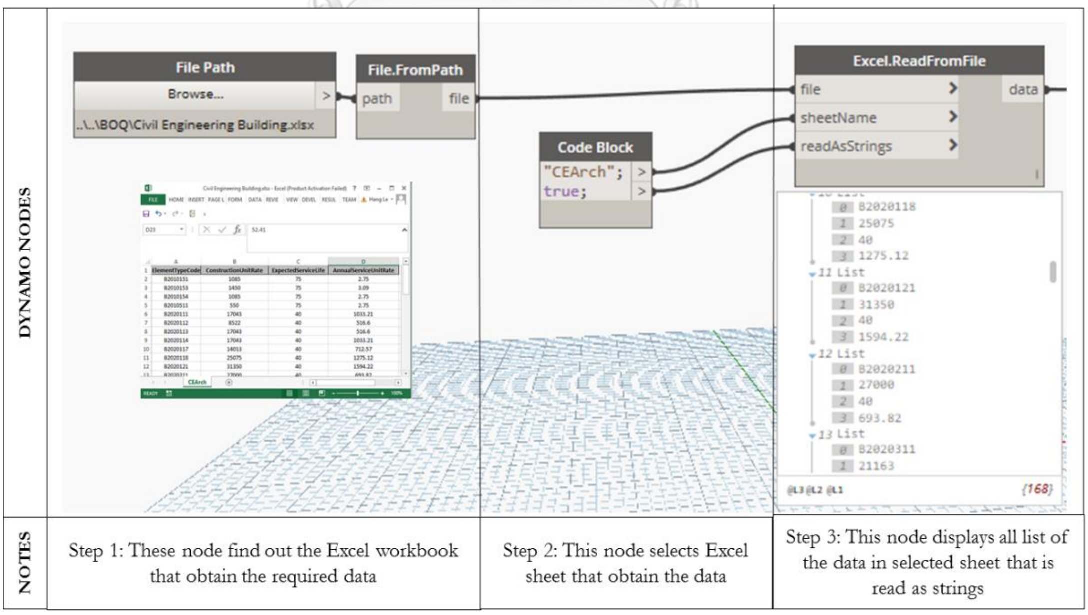


Figure 5.6 Workflow for integrating the spreadsheet file into visual environment using visual scripts

The workflow for adding the names of the required to the type properties in Revit, as shown in Figure 5.7 consists of eleven steps.

- Sub-step 1: Open the conceptual 3D BIM model of the building projects in Revit
- Sub-step 2: Click the Manage tab
- Sub-step 3: Click the Project Parameters icon
- Sub-step 4: This prompts the project parameters dialogue box. Click Add button to add the parameters to elements in this project.
- Sub-step 5: This prompts the parameter properties dialogue box. Type parameter name.
- Sub-step 6: Check the Type parameter. In case the parameter value need to be modify, the new parameters will be applied to all elements of the family type.
- Sub-step 7: Drop down the Type of Parameter box and select the Number type for the value of this parameters.
- Sub-step 8: Drop down the Group parameter under and select the Identity Data group for this parameter.
- Sub-step 9: Check the categories that is selected to add the new parameter
- Sub-step 10: Click OK to complete the adding process. Then repeat sub-step 4, 5, 6, 7, 8, 9, and 10 for construction unit rate parameter, element type code parameter, and service life parameter.
- Sub-step 11: When finished all additional parameters, click OK to save the new properties for element type.

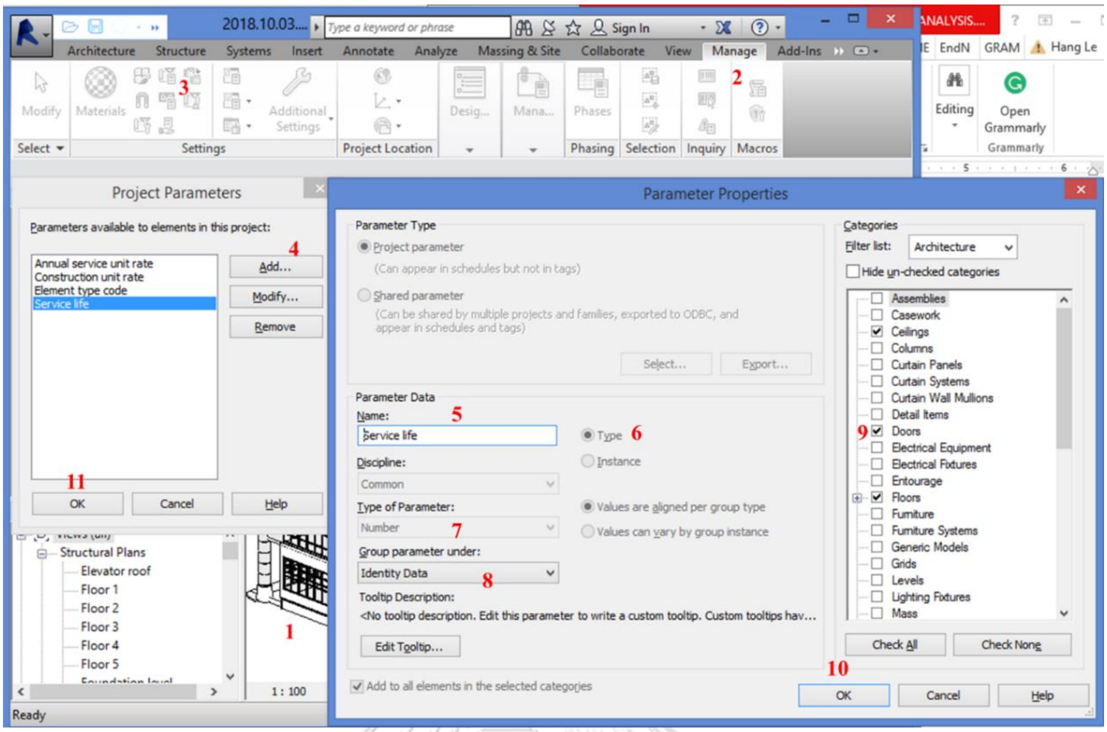


Figure 5.7 Workflow of adding the new parameters to type properties

For the exterior window, an example of the acquiring value of required data for a selected type using Dynamo scripts is described through four steps, as shown in Figure 5.8. Step 1 selects the exterior window type using *Family Types* node. Step 2 identifies the name of parameters that need to be extract the value using two *Code Block* nodes. Code Block node is written by Python script to access the system of 3D BIM model. Step 3 extracts the relevant value for exterior window type parameters. This step is performed through six sub-steps. Sub-step 1 identifies the location of the relevant data list using a *Code Block* node. Sub-step 2 gets all the value of selected list using a *Code Block* node. Sub-step 3 identifies the location of relevant data using a *Code Block* node. Sub-step 4 gets the relevant value for required parameters consist of element type code, construction unit rate, service life, annual service unit rate using four *List.GetItemAtIndex* nodes. Sub-step 5 groups the value of construction unit rate, service life, and annual service unit rate into a list. Sub-step 6 transforms the value of list from string to number using *List.Create* node. Step 4 assigns the value to the element type parameters using two *Element.SetParameterByName* nodes.

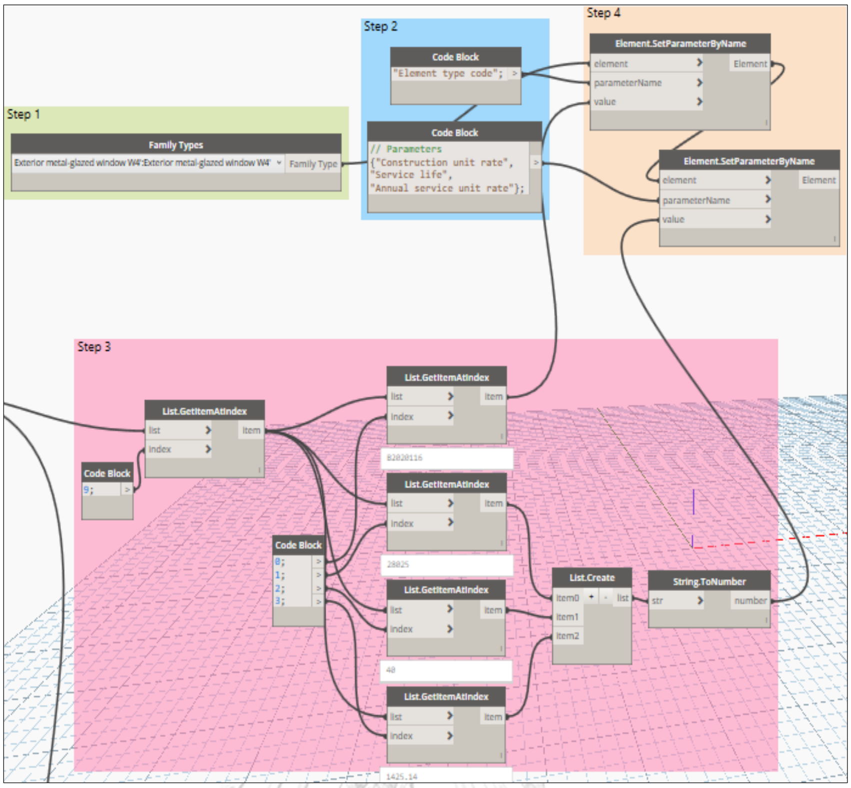


Figure 5.8 Example for acquiring the required data of an exterior window type

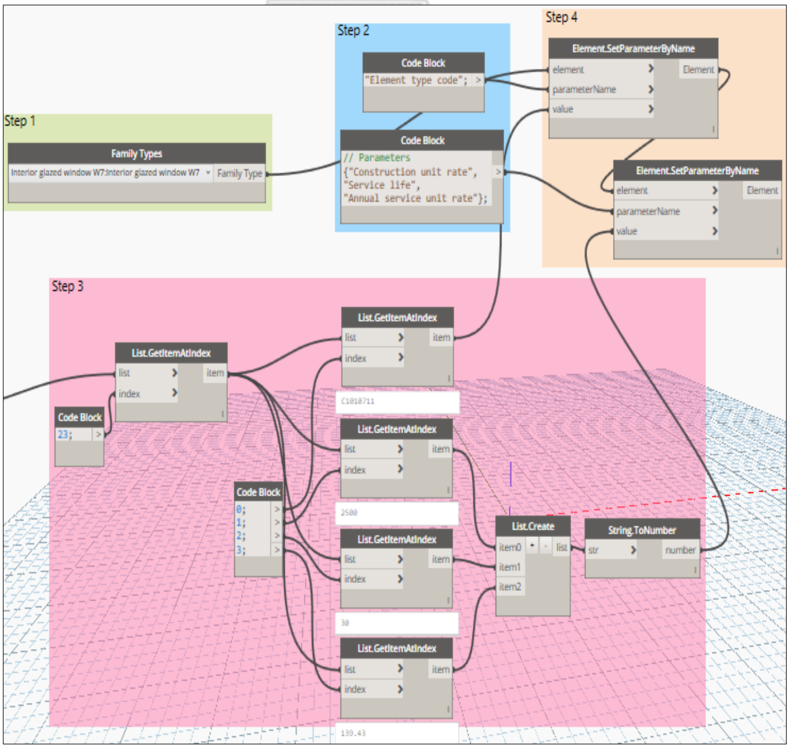


Figure 5.9 Example of acquiring the required data for an interior window type

Four steps of the acquiring value of the required data for a selected exterior wall type using Dynamo scripts, as shown in Figure 5.10. Step 1 selects the exterior wall type using *Wall Types* node. Step 2 identifies the name of parameters that need to be extract the value using two *Code Block* nodes. Step 3 extracts the relevant value for exterior wall type parameters through six sub-steps. Sub-step 1 identifies the location of the relevant data list using a *Code Block* node. Sub-step 2 gets all the value of selected list using a *Code Block* node. Sub-step 3 identifies the location of relevant data using a *Code Block* node. Sub-step 4 gets the relevant value for required parameters consist of element type code, construction unit rate, service life, annual service unit rate using four *List.GetItemAtIndex* nodes. Sub-step 5 groups the value of construction unit rate, service life, and annual service unit rate into a list. Sub-step 6 transforms the value of list from string to number using *List.Create* node. Step 4 assigns the value to the exterior wall type parameters using two *Element.SetParameterByName* nodes.

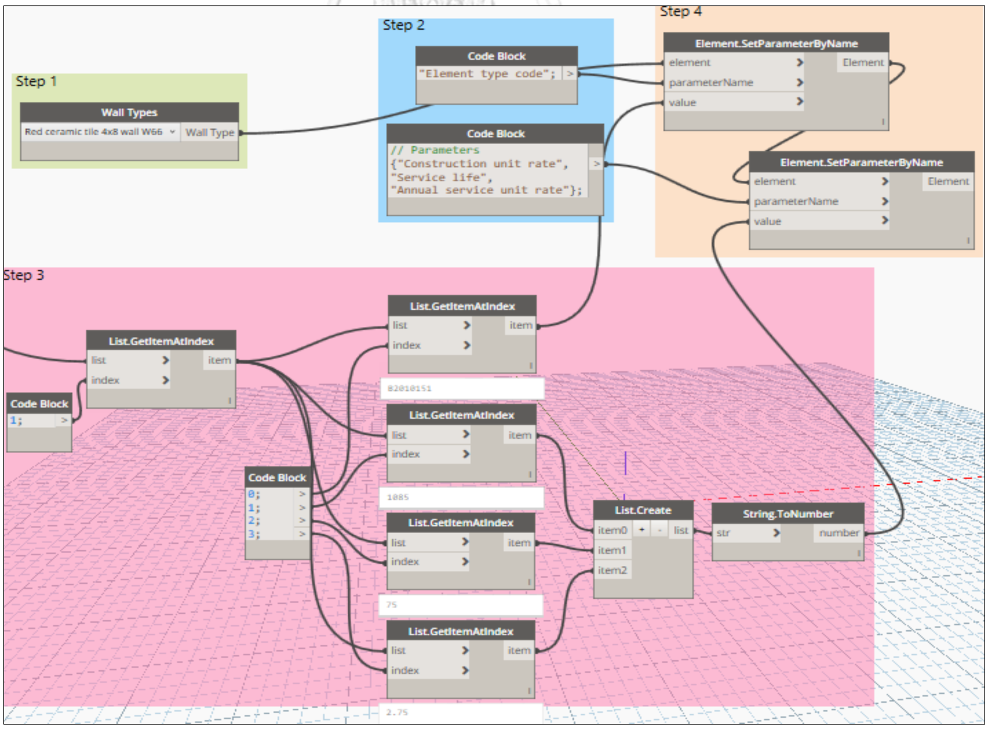


Figure 5.10 Example for acquiring the required data of an exterior wall type

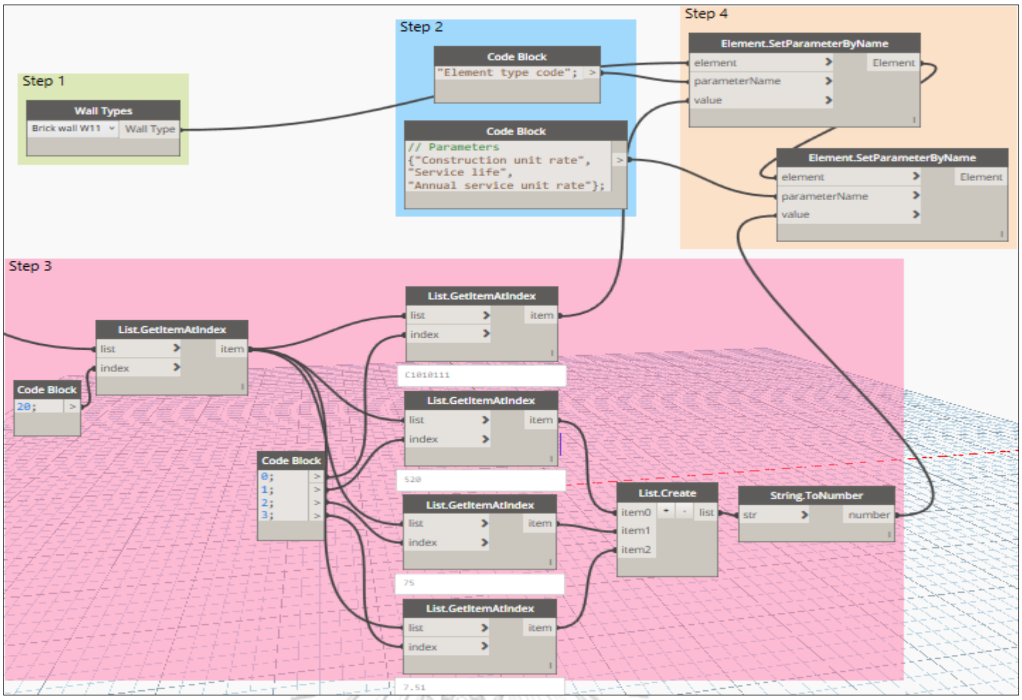


Figure 5.11 Example for acquiring the required data of an interior wall type

For the interior wall, Figure 5.11 presents four steps to acquire value of the required data for a interior wall type using Dynamo scripts as the same with the.

Figure 5.2 presents four steps to acquire the value of the required data for a selected door type using Dynamo scripts. Step 1 selects the door type using *Family Types* node. Step 2 identifies the name of parameters that need to be extract the value for selected door type using two *Code Block* nodes. Step 3 extracts the relevant value for door type parameters through six sub-steps. Sub-step 1 identifies the location of the relevant data list using a *Code Block* node. Sub-step 2 gets all the value of selected list using a *Code Block* node. Sub-step 3 identifies the location of relevant data using a *Code Block* node. Sub-step 4 gets the relevant value for required parameters consist of element type code, construction unit rate, service life, annual service unit rate using four *List.GetItemAtIndex* nodes. Sub-step 5 groups the value of construction unit rate, service life, and annual service unit rate into a list. Sub-step 6 transforms the value of list from string to number using *List.Create* node. Step 4 assigns the value to the door type parameters using two *Element.SetParameterByName* nodes.

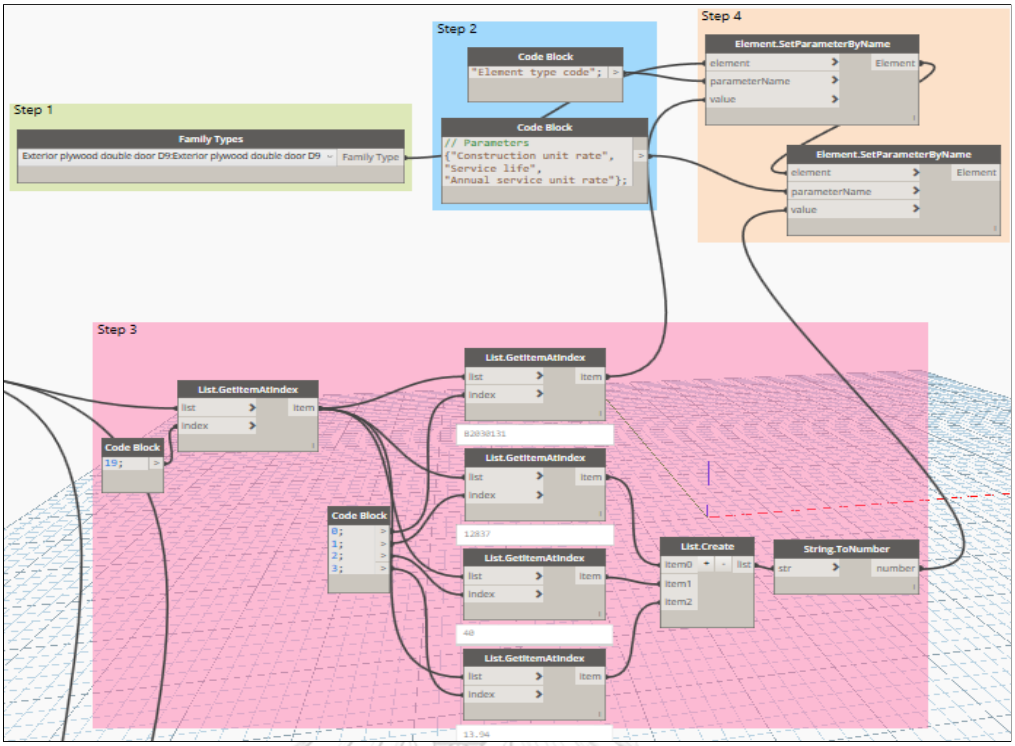


Figure 5.12 Example for acquiring the required data of a door type

For the floor, example of the acquiring value of the required data for a selected type by using Dynamo scripts is described through four steps, as shown in Figure 5.13. Step 1 selects the floor type using *Floor Types* node. Step 2 identifies the name of parameters that need to be extract the value for select floor type using two *Code Block* nodes. Step 3 extracts the relevant value for door type parameters through six sub-steps. Sub-step 1 identifies the location of the relevant data list using a *Code Block* node. Sub-step 2 gets all the value of selected list using a *Code Block* node. Sub-step 3 identifies the location of relevant data using a *Code Block* node. Sub-step 4 gets the relevant value for required parameters consist of element type code, construction unit rate, service life, annual service unit rate using four *List.GetItemAtIndex* nodes. Sub-step 5 groups the value of construction unit rate, service life, and annual service unit rate into a list. Sub-step 6 transforms the value of list from string to number using *List.Create* node. Step 4 assigns the value to the element type parameters using two *Element.SetParameterByName* nodes.

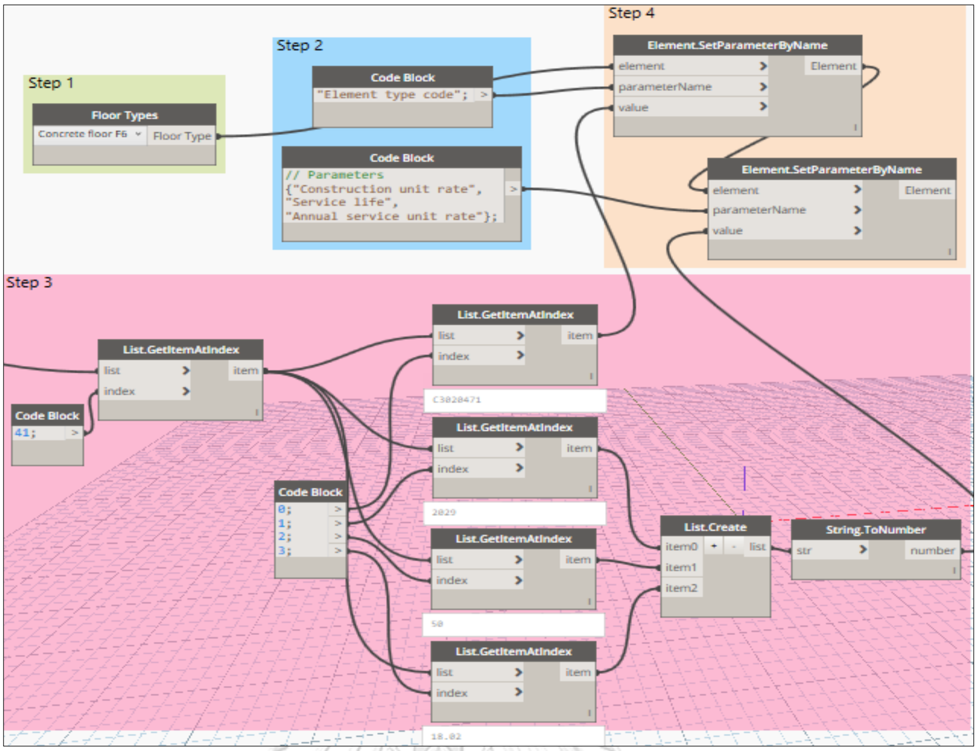


Figure 5.13 Example for acquiring the required data of a floor type

For the roof, Figure 5.14 presented an example of the acquiring value of the required data for a selected roof type using Dynamo scripts is described through four steps as the same with the floor type.

5.5 Summary

This chapter proposed a methodology for developing the BIM model for the building LCCA that consists of three parts: the LOD of the 3D BIM model, the required data of element models of the BIM model, and the integration between the 3D BIM model with the relational database for extracting the required data. Among the various BIM authoring programing, Autodesk Revit is adopted to develop the 3D BIM model for the building projects due to the popular and powerful design platform for professionals in architecture, structural engineering, construction, and MEP. Dynamo is a potential visual programming interface, which is adopted to develop the automatic integrated model between the BIM authoring programming and the spreadsheet system for extracting the required data to the BIM model. Dynamo allows the QSs who are nonprogrammers to extend the capacities of the current BIM tools to link with other platforms. Finally, the function of the visualized BIM-integrated module is the design authoring, data supporting, and data storage for the BIM-BLCC.

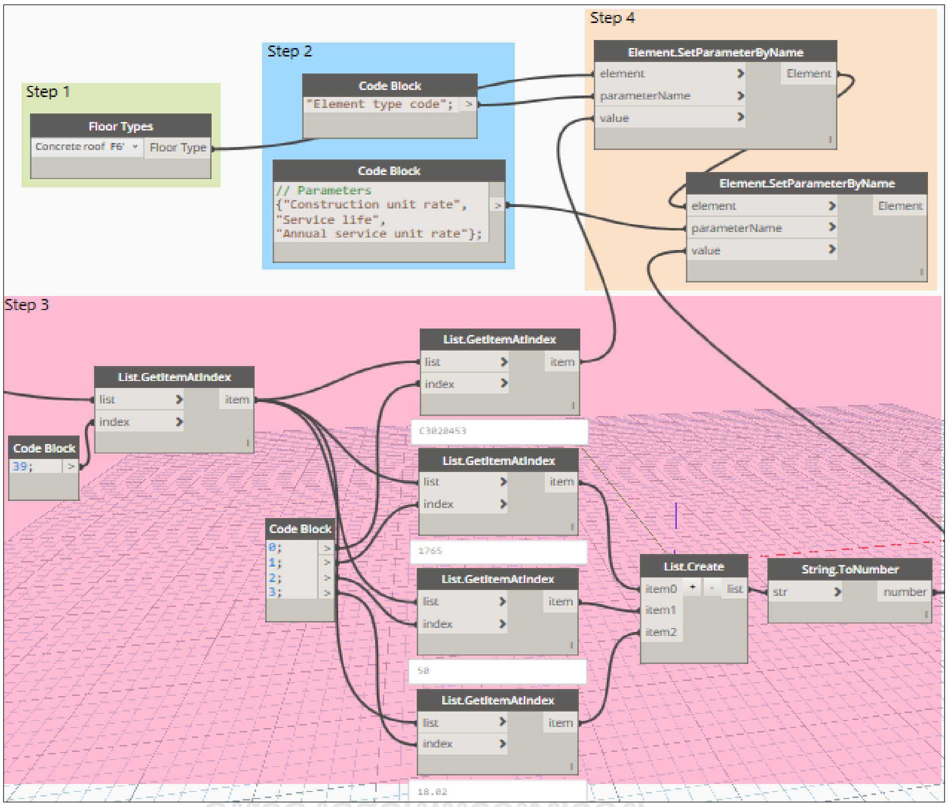


Figure 5.14 Example for acquiring the required data for a roof type

CHAPTER 6
MULTI-PARAMETRIC ESTIMATION MODULE

This chapter is the development of the multi-parametric estimation module of the BIM-BLCC. The function of this module is to evaluate LCC for all the building elements of the 3D model. The mathematical models for computing cost categories of the building LCCA were developed in detail. For this chapter, the introduction was presented at the first part. Then, the formulations for calculating cost categories of a BIM-BLCC was presented. The assumed parameters were presented at the continued part. Final, an automatic multi-parametric model was developed into visual programing interface. The required data of building elements were retrieved from the visualized BIM-integrated module. Besides, the assumed parameters were retrieved from the spreadsheet workbook for evaluating the building LCCA.

6.1 Introduction

Life-cycle cost (LCC) is an essential criterion to improve the contractor selection procedures for the sustainable growth. In this research, the economic analysis is adopted as a dynamic method that is used to carry out the building LCCA. The net present value (NPV) is a very common technique that used for the financial evaluation of a building project.

Building information modeling (BIM) is a modern technology that provides some advantages for the building LCCA. BIM allows for many data to be superimposed through one element model. In addition, BIM quantifies exactly what is in the model that mean there is no different between what has been designed and what is measured. Multiple references pointed out that most of the building LCCA research do not often consider building energy usage that are limited the usability of the building LCCA as sustainability based research (Gluch, 2004). The use of BIM authoring programing and its visual programing interface to support the access and extraction of required parameters regarding the thermal properties of building element type to estimate the energy cost for the building projects. In this chapter, the multi-parametric estimation module was developed based on the integration of BIM module that was developed in the chapter 5, visual programming interface, and spreadsheet system. The process of developing the multi-parametric estimation module passed to five main steps, as shown in Figure 6.1. The first step identifies cost categories of the building LCCA and the formulation for calculating these cost categories. The formulation of the energy cost is built based on 1989 Fundamentals ASHRAE handbook edited by Robert A. Parsons. This book is adopted for developing the formulation of cost categories into the building LCCA because of comparing with other edition, this edition has expanded the chapters on the cooling and heating load calculation manual that provide significant information to construct the formulations for this module. The second step establishes the assumptions for the building LCCA. The third step integrates the spreadsheet workbook with visual programming interface. The fourth step integrates the 3D BIM model with visual programming interface. Microsoft Excel, Dynamo, and Revit Architecture are adopted as the potential platforms to develop the multi-parametric estimation module. The fifth step performs the multi-parametric estimation by using Dynamo scripts.

6.2 Formulations for calculating cost categories of the BIM-BLCC

The definition of the cost categories is necessary for the Quantity Surveyors (QSs) to carry out the building LCCA. There are various ways to define the cost categories of the building LCCA. According to BS ISO 15686-5:2017, the cost categories should be classify in four main phases of a building life consist of construction phase, operation phase, maintenance phase, and disposal phase. In this research, the formulation for calculating the total LCC of a building element type such as a floor type, an exterior wall type, a roof type, an exterior window type, a door type, an interior wall, or an interior window ($C_{Life\text{-}Cycle}$) as following the Equation 1.

$$C_{Life\_cycle} = C_{Construction} + \frac{(1+i)^{n}-1}{i(1+i)^{n}} C_{Maintenance} + \frac{(1+i)^{n}-1}{i(1+i)^{n}} C_{Operation} - \frac{1}{(1+i)^{n}} C_{Salvage} \quad (1)$$

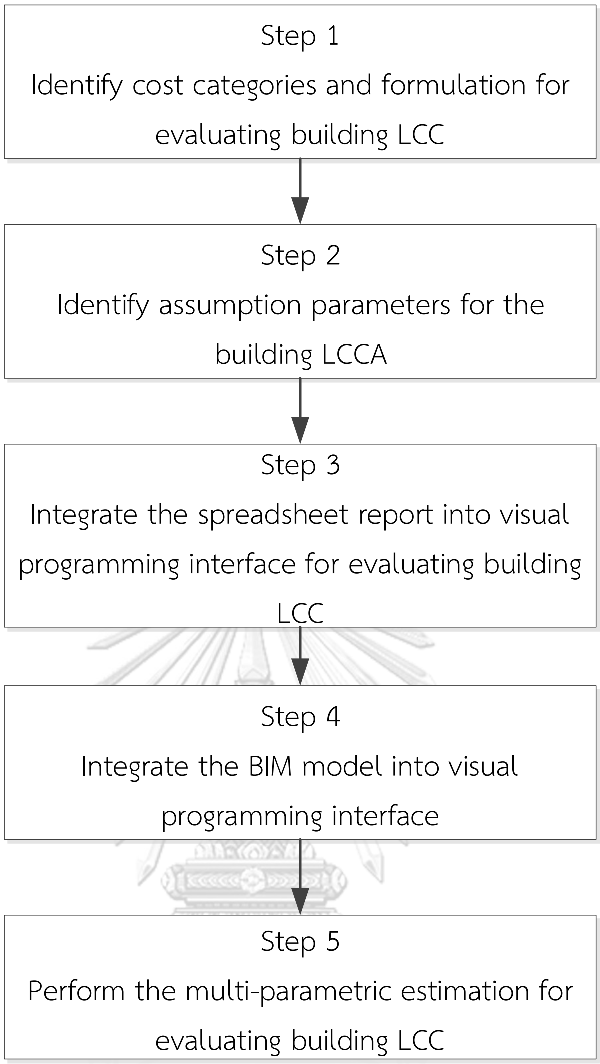


Figure 6.1 Workflow of the development of the multi-parametric estimation module

where C_{Life_cycle}, $C_{Construction}$, $C_{Maintenance}$, $C_{Operation}$ $C_{Salvage}$ are the total life-cycle cost, construction cost, maintenance cost, operation cost, and salvage cost of a floor type, an exterior wall type, a roof type, an exterior window type, a door type, an interior wall, or an interior window type, respectively; i is the discount rate of money, and n is the period of analysis.

6.2.1 Formulation for calculating construction cost

The construction costs related to the costs of material, labor, and equipment to construct the all building element types. These costs are obvious compared with other cost categories of the building LCCA. For the multi-parametric estimation module, the construction cost of a floor type, an exterior wall type, a roof type, an exterior window type, a door type, an interior wall, an interior window ($C_{Construction}$) is computed as follow in Equation 2.

$$C_{Construction} = C_{ConstructionUnitRate} \times A_S \qquad (2)$$

where $C_{ConstructionUnitRate}$ and A_S are the construction unit price of an element type (e.g. a floor type, an exterior wall type, a roof type, an exterior window type, a door type, an interior wall, an interior wall) and the total area of surface of that element type, respectively.

6.2.2 Formulation for calculating maintenance cost

The maintenance costs related to the costs of regular care, repair, and replacement of a building element type. In this paper, the maintenance cost is considered an annual service cost of a floor type, an exterior wall type, a roof type, an exterior window type, a door type, an interior wall, an interior window ($C_{Maintenance}$) is computed as follow in Equation 3.

$$C_{Construction} = C_{ConstructionUnitRate} \times A_S \qquad (3)$$

where $C_{AnnualServiceUnitRate}$ and A_S are the annual service unit price of element type (e.g. a floor type, an exterior wall type, a roof type, an exterior window type, a door type, an interior wall, an interior wall) and the total area of surface of that type, respectively.

6.2.3 Formulation for calculating operation cost

The operation costs encompass all cost for service activities of the building projects under the considered condition. The energy cost usually takes up the greatest share of the operation cost. The amount of energy consumption for a building depends heavily on the using hours of building system operations, weather conditions, the performance level required by building owners, as well as the building design and insulation provisions. Therefore, the operation cost is considered as the energy costs of a building element types. Equation 4 is established to compute the energy cost of an exterior wall type ($C_{Operation}$).

$$C_{Operation} = C_{EnergyUnitRate} \times \left[\left(U_{ew} \times A_{ew} \times TD_{eq} \right) \times H \right] \quad (4)$$

where U_{ew} *and* A_{ew} are the coefficient of heat transfer, the total area of surface of an exterior wall type, respectively; $C_{EnergyUnitRate}$, TD_{eq}, and H are the energy unit price, the equivalent temperature difference, and the hourly usage per year of the typical building project, respectively.

Equation 5 is established to compute the energy cost of a roof type ($C_{Operation}$).

$$C_{Operation} = C_{EnergyUnitRate} \times \left[\left(U_{ew} \times A_{ew} \times TD_{eq} \right) \times H \right] \quad (5)$$

where U_r *and* A_r are the coefficient of heat transfer, the total area of surface of a roof type, respectively; $C_{EnergyUnitRate}$, TD_{eq}, and H are the energy unit price, the equivalent temperature difference, and the hourly usage per year of the typical building project, respectively.

Equation 6 is established to compute the energy cost of an exterior window type ($C_{Operation}$).

$$C_{Operation} = C_{EnergyUnitRate} \times \left[\left(U_{eg} \times A_{eg} \times \Delta T \right) + \left(A_{eg} \times SC_{eg} \times SF_{eg} \right) \right] \times H \quad (6)$$

where U_{eg}, A_{eg}, SC_{eg}, SF_{eg} are the coefficient of heat transfer, the total area of surface, the shading coefficient, the solar shading factor of an exterior window type, respectively; $C_{EnergyUnitRate}$, ΔT, and H are the energy unit price, the temperature difference for glazed windows, and the hourly usage per year of the typical building project, respectively.

Equation 7 is established to compute the energy cost of a skylight glazing type ($C_{Operation}$).

$$C_{Operation} = C_{EnergyUnitRate} \times \left[\left(U_S \times A_S \times \Delta T \right) + \left(A_S \times SC_S \times SF_S \right) \right] \times H \quad (7)$$

where U_s, A_s, SC_s, SF_s are the coefficient of heat transfer, the total area of surface, the shading coefficient, the solar shading factor of a skylight glazing type, respectively; $C_{EnergyUnitRate}$, ΔT, and H are the energy unit price, the temperature difference for glazed skylight, and the hourly usage per year of the typical building project, respectively. Equations 4, 5, 6, and 7 are established according to Transfer Function Method into the *1989 ASHRAE Handbook Fundamentals* published by Robert A. P, the building energy code of Thailand (Chirarattananon, S., et al., 2010; Vechaphutti, T., 1987), the building energy code of Singapore (Chou, 1988).

6.2.4 Formulation for calculating salvage value

Each building element has a unique expected service life. Once it reaches such expected life, the building element will lose its technical capacity, reliability, and quality due to natural ageing and use. The salvage cost is the value of a building element type at the end of the service life. It is calculated as the difference of the resale value of that building element type. In this paper, the salvage value of a floor type, an exterior wall type, a roof type, an exterior window type, a door type, an interior wall, or an interior window ($C_{Salvage}$) is computed as follow in Equation 7.

$$C_{Salvage} = C_{Construction} - \left[\frac{T_A}{T_L} \times C_{Construction} \right] \qquad (7)$$

where $C_{Construction}$ and T_L are the total construction cost and the expected service life of a floor type, an exterior wall type, a roof type, an exterior window type, a door type, an interior wall, or an interior window, respectively; T_A is the analyzed period of the typical building project, in this research the value of the analyzed period of the typical building project is equal the value of the period of analysis in the Equation 1.

6.3 The assumed parameters for multi-parametric estimation module

There are nine assumption parametric need to be defined before carrying out a multi-parametric estimation for forecasting building LCC consist of the economic or analyzed period of a building project, the discount rate for calculating the maintenance present worth factor, the energy present worth factor, and the salvage present worth factor, the electrical unit price, the hourly usage per year of the building, the temperature difference between glazing surface and air, the design temperature difference, unconditioned area to room, the average solar shading factor for wall, the average solar shading factor for roof, and the solar heat gain of reference glass.

The cost categories occur at different phases of a building project in order that the costs must be discount to their present value before they are combined into the LCCA for a building element type. The discount rate is used to discount future cash flows to present value is based on the time value of money. The discount rate is usually determined by the minimum acceptable rate of return for investments. The selection of the appropriate discount rate is vary significantly from project to project. However, according to the National Energy Conservation Policy Act, the discount rate to be used for energy conservation in federal buildings and facilities is established by Department of Energy (DOE) is seven percentage each year. In this research, the discount rate is used to compute the value of maintenance present worth factor, the energy present worth factor, and the salvage present worth factor for calculating the building LCCA. For the analyzed period, the owner, not the designer must establish this time frame. If the building life is considered as being forever, 25 to 40 years is long enough to anticipate future costs for economic purposes to capture the most significant costs (Kirk and Dell'Isola, 1995). In this research, the time frame can be flexible change for the proposed system under analysis. The electrical unit rate is adopted based on the median values of information published in the two years 2017 and 2018. The hourly usage per year is taken from the median value of data records of the time use of the last year. For the temperature difference between glazing surface and air, the design temperature difference, unconditioned area to room, the average solar shading factor for wall, the average solar shading factor for roof, and the solar heat gain for reference glass, the data are taken from the median value of the weather records of the Royal Thai Meteorological Department in last year. All the assumptions can be flexible change based in the practical building project. Then the assumptions were recorded to the Excel spreadsheet template to integrate with visual programming interface for performing the multi-parametric estimation for the building LCCA.

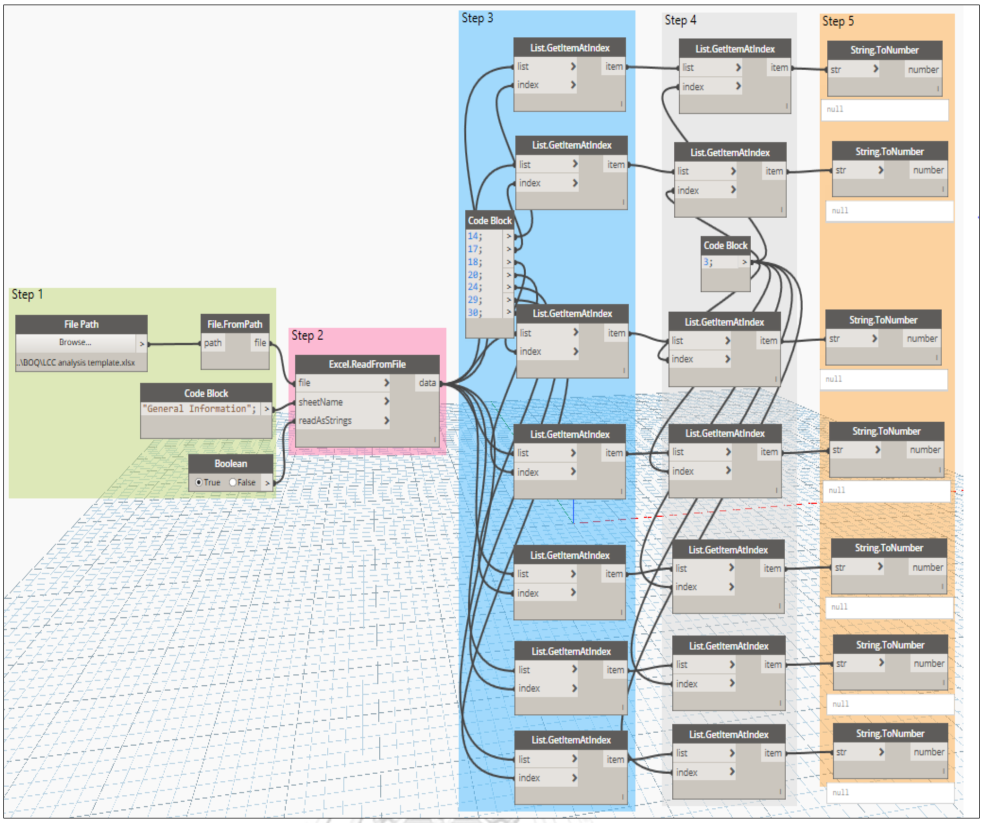


Figure 6.2 Workflow for acquiring the assumed parameters

6.4 Development of multi-parametric estimation module

6.4.1 Acquisition of the assumed parameters using visual programming

To retrieve the value of assumed parameters from the Excel spreadsheet template to carry out the building LCCA, the visualized BIM-database-integrated system for analyzing building life-cycle costs using a multi-parametric model proposed an automatic method to integrating the spreadsheet system with visual programming interface by using Dynamo nodes, as shown in Figure 6.2.

The workflow for integrating the Excel spreadsheet template with visual programming interface to acquire the assumed parameters consist of five main steps. The first step selects the Excel sheet that contains the value of assumptions, and then read data in selected sheet as strings. There is a group of Dynamo nodes are used to carry out this process consist of *File Path*, *File.FromPath*, *Code Block*, and *Boolean* node. *File Path* and *File.FromPath* nodes are used to find the path to come the target

Excel file on the spreadsheet system that contain information that need to be extract for the building LCCA. *Code Block* node is written by Python script to access the sheet name that contain the value of the assumptions. *Boolean* node is used to read all of the data into the selected Excel sheet as strings even if they are numbers. A string is usually a bit of text you want to display to someone or export out of the program you are writing. *Boolean* node is used to represent the two values True and False for an evaluating test. The second step read all the data of the selected Excel sheet as the lists of data by using *Excel.ReadFromFile* node. The third step is to filter the target lists that contain the needed value by using a group of seven *List.GetItemAtIndex* nodes and one *Code Block* node. *Code Block* node is used to identify the number of the target lists that contain the needed value from all the data lists of the selected Excel sheet. Seven *List.GetItemAtIndex* nodes are used to get all index of each selected lists. The fourth step is to filter the target index from each selected list by using a group of seven *List.GetItemAtIndex* nodes and one *Code Block* node. *Code Block* node is used to identify the number of the target index. Seven L*ist.GetItemAtIndex* nodes are used to get the needed index. The fifth step transforms the value of extracted index from strings to numbers by using seven *String.ToNumber* nodes.

6.4.2 Acquisition of required data from the BIM model

Based on the required data from the formulation for calculating the cost categories of the building LCCA, this section illustrates an automatic method to extract various required data from the BIM model for multi-parametric estimation module consist of the total surface area, the construction unit cost, the annual service unit rate, the heat transfer coefficient, the shading coefficient, the solar heat gain coefficient, and the expected service life of a different building element type by using Dynamo scripting.

The workflow for acquiring the required parameters for an exterior wall type includes seven main steps, as shown in Figure 6.3. The first step selects an exterior wall type by using *Wall.Types* node. The second step gets the total surface area of the selected exterior wall type by using a group of Dynamo node consist of *Get.AllElementsOfType*, *Code Block*, *Element.GetParameterValueByName*, and

Math.Sum node. The current Dynamo programming do not have the node that is written to collect all elements of a type in order that *Get.AllElementsOfType* node is developed by Python scripts to perform this function. *Code Block* node is used to call the name of required parameter that is the area. *Element.GetParameterValueByName* node is used to collect the area value of all elements of wall type. *Math.Sum* node is used to compute the sum of the surface area of the selected type. The third step extracts the value of the construction unit rate of the selected exterior wall type by using *String* and *Element.GetParameterValueByName* node. *String* node is used to call the name of construction unit rate parameter. *Element.GetParameterValueByName* node is used to get the value of that parameter of the selected wall type. The fourth step extracts the value of the annual service unit rate of the selected exterior wall type by using *String* and *Element.GetParameterValueByName* node. The fifth step extracts the value of the heat transfer coefficient of the selected exterior wall type by using *String* node and *Element.GetParameterValueByName* node. The sixth step extracts the value of the service life of the selected exterior wall type by using *String* node and *Element.GetParameterValueByName* node. The seventh step extracted the value of the average equivalent temperature difference of the selected exterior wall type by using *String* node and *Element.GetParameterValueByName* node.

The workflow for acquiring the required parameters for an exterior window type includes seven main steps, as shown in Figure 6.4. The first step selects an exterior window type by using *Family Types* node. The second step gets the total surface area of the selected exterior wall type by using a group of Dynamo node consist of *Get.AllElementsOfType* node, *Code Block* node, *Element.GetParameterValueByName* node, and *Math.Sum* node. The current Dynamo programming do not have the node that is written to collect all elements of an exterior window type in order that *Get.AllElementsOfType* node is developed by Python scripts to perform this function. *Code Block* node is used to call the name of the area parameter of the selected exterior window type. *Element.GetParameterValueByName* node is used to collect the area value of all elements of window type. *Math.Sum* node is used to compute the sum of the surface area of the selected exterior window type. The third step extracts the value of the construction unit rate of the selected exterior window type by using *String* node and *Element.GetParameterValueByName* node. The fourth step extracts the value of the annual service unit rate of the selected exterior window type by using *String* node and *Element.GetParameterValueByName* node. The fifth step extracts the value of the heat transfer coefficient of the selected exterior window type by using *String* node and *Element.GetParameterValueByName* node. The sixth step extracts the value of the solar heat gain coefficient parameter of the selected exterior window type by using *String* node and *Element.GetParameterValueByName* node. The seventh step extracts the value of the service life of the selected window type by using *String* node and *Element.GetParameterValueByName* node.

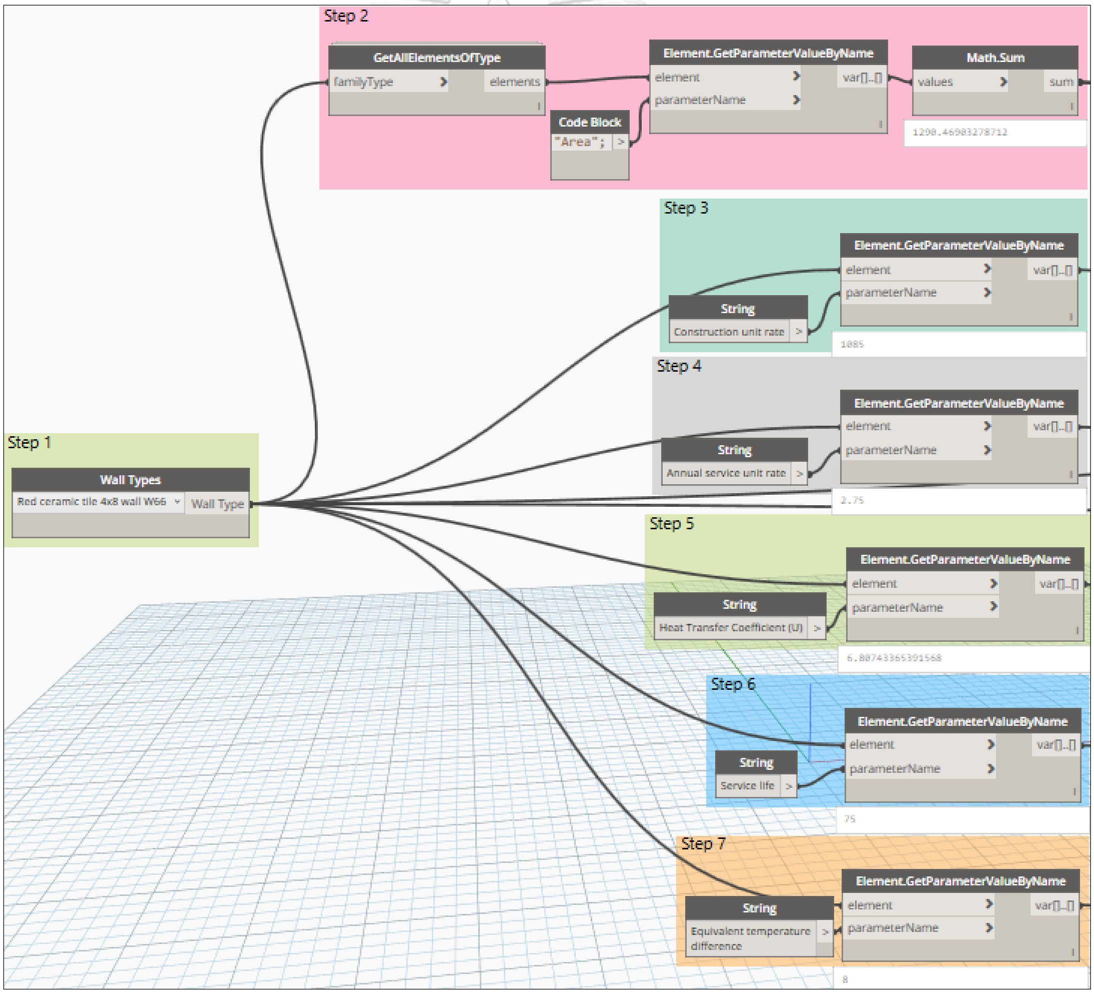


Figure 6.3 Workflow for acquiring the required parameters of an exterior wall type

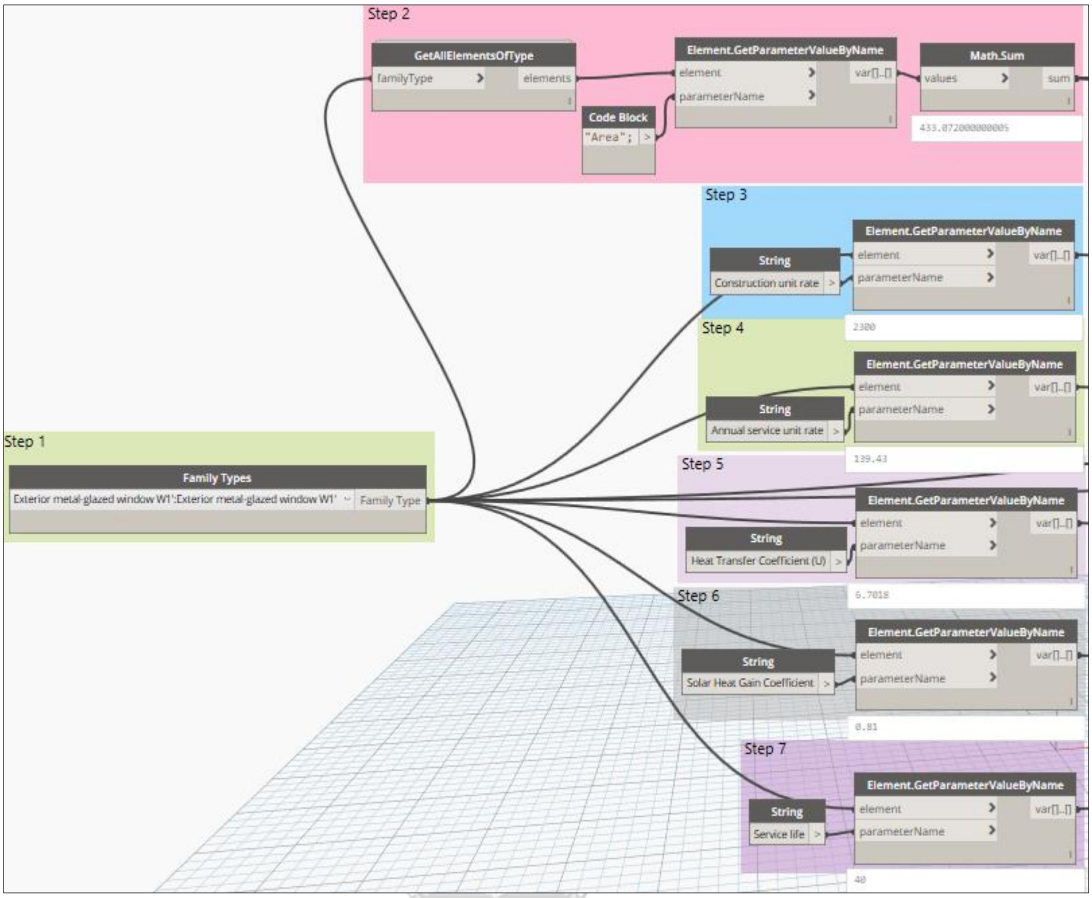


Figure 6.4 Workflow for acquiring required parameters of an exterior window type

The workflow for acquiring the required parameters for a roof type includes seven main steps, as shown in Figure 6.5. The first step selects a roof type by using *Floor Types* node. The second step gets the total surface area of the selected roof type by using a group of Dynamo node consist of *Get.AllElementsOfType* node, *Code Block* node, *Element.GetParameterValueByName* node, and *Math.Sum* node. The current Dynamo programming do not have the node that is written to collect all elements of a roof type in order that *Get.AllElementsOfType* node is developed by Python scripts to perform this function. *Code Block* node is used to call the name of the area parameter. *Element.GetParameterValueByName* node is used to collect the area value of all elements of selected roof type. *Math.Sum* node is used to compute the sum of the surface area of the selected roof type. The third step extracts the value of the construction unit rate of the selected roof type by using *String* node and

Element.GetParameterValueByName node. *String* node is used to call the name of construction unit rate parameter. *Element.GetParameterValueByName* node is used to get the value of that parameter of the selected roof type. The fourth step extracts the value of the annual service unit rate of the selected roof type by using *String* node and *Element.GetParameterValueByName* node. The fifth step extracts the value of the heat transfer coefficient of the selected roof type by using *String* node and *Element.GetParameterValueByName* node. *String* node is used to call the name of the heat transfer coefficient parameter. *Element.GetParameterValueByName* node is used to get the value of that parameter of the selected roof type. The sixth step extracts the value of the service life of the selected roof type by using *String* and *Element.GetParameterValueByName* node. String node is used to call the name of service life parameter. Element.GetParameterValueByName node is used to get the value of that parameter for the selected roof type. The seventh step extracts the value of the average equivalent temperature difference of the roof type by using *String* node and *Element.GetParameterValueByName* node. String node is used to call the name of the average equivalent temperature difference parameter for the selected roof type. Element.GetParameterValueByName node is used to get the value of that parameter for the selected roof type.

6.4.3 The building LCCA using visual programming

The calculation of a building LCC is usually take a long time for preparing the cost coefficients. The conventional approach carries out only single LCC calculation that cannot apply for the 3D BIM model that contains a lot of element models. This research proposed an automatic method for calculating the building LCC through integrating the BIM authoring software (Revit Architecture) with visual programming interface (Dynamo). This section represents the calculating process for the cost categories of a LCC by using visual programming. The formulation for these calculation is developed from the section 6.2. The parameters for calculating process is collected from the section 6.4.2 and 6.4.3.

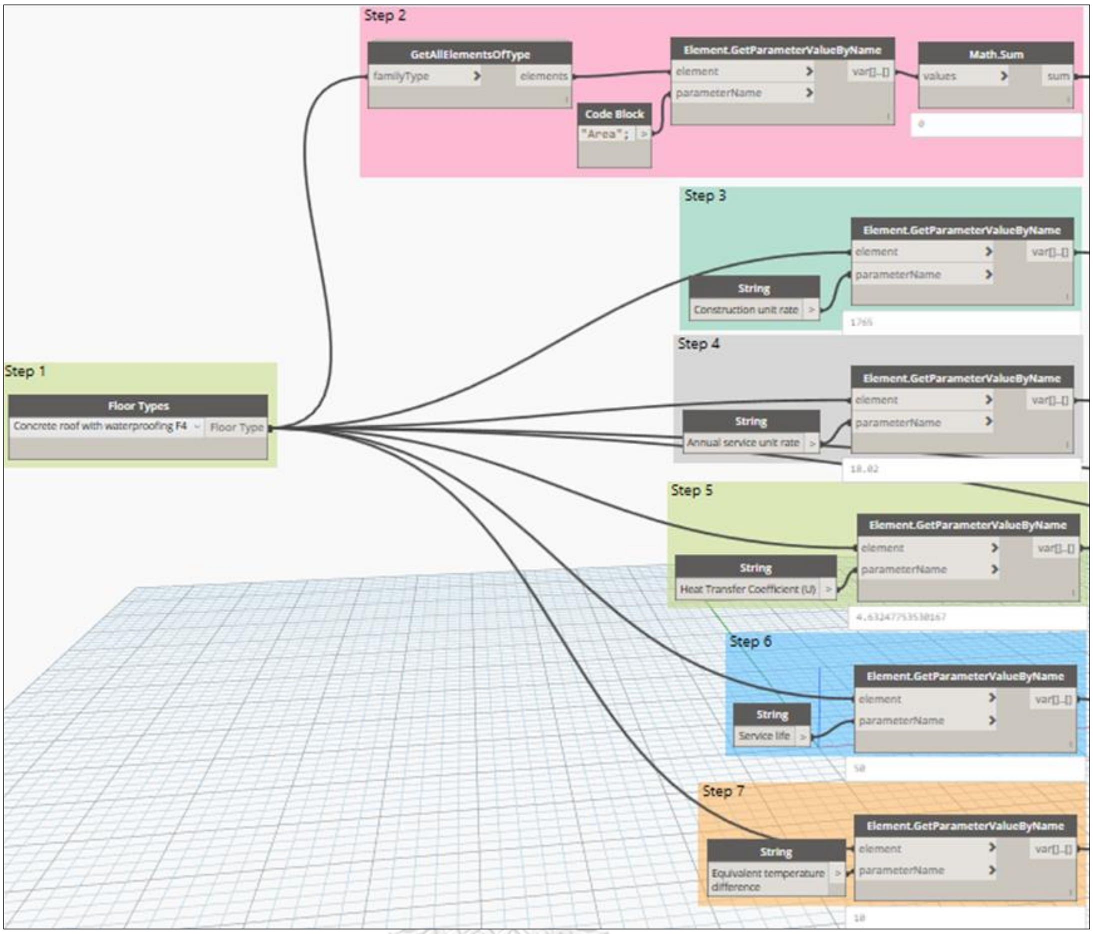


Figure 6.5 Workflow for acquiring the required parameters of a roof type

The workflow for calculating the LCC of an exterior wall type or a roof types consists of five main steps, as shown in Figure 6.6. The first step computes the construction cost by using three Dynamo nodes including *Math.Sum* node, *Element.GetParameterValueByName* node, and a multiplication node. *Math.Sum* node provides the value of the total surface area of the selected exterior wall type or roof type, *Element.GetParameterValueByName* node provides the value of the construction unit rate of the selected exterior wall type or roof type. Multiplication node is used to multiply two acquired value. The second step computes the maintenance cost by using five Dynamo nodes including one *Math.Sum* node, one *Element.GetParameterValueByName* node, one *String.ToNumber* node, and two multiplication nodes. *Math.Sum* node provides the value of total surface area of the selected exterior wall type or roof type that is described in the section 6.4.2.

Element.GetParameterValueByName node provides the value of the annual service unit rate of the selected exterior wall type or roof type. Two multiplication nodes are used to multiply three acquired value. The third step computes the energy cost by using eleven Dynamo nodes including one *Math.Sum* node, three *String.ToNumber* nodes, two *Element.GetParameterValueByName* nodes, and five multiplication nodes. *Math.Sum* node provides the value of the total surface area of the selected exterior wall type or roof type. Two *Element.GetParameterValueByName* nodes provided the value of the heat transfer coefficient and the average equivalent temperature difference of the selected exterior wall type or roof type. Three *String.ToNumber* nodes provide the value of the hourly usage per year, the electrical unit price, and the energy present worth factor, respectively. Five multiplication nodes are used to multiply six acquired value. The fourth step computes the salvage value by using eight Dynamo nodes including two *String.ToNumber* nodes, one *Element.GetParameterValueByName* node, three multiplication nodes, one division node, and one subtraction node. *Element.GetParameterValueByName* node provides the value of the service life of the selected exterior wall type or roof type. One multiplication node provides the value of the construction cost of the selected exterior wall type or roof type. One division node is used to divide the value of analyzed period by the value of service life. Then the calculated result is multiplied with the construction cost by using one multiplication node. The calculated result is subtracted by the construction cost by using one subtraction node. Finally, the calculated result is multiply with the salvage present worth factor by using one multiplication node. The fifth step computes the LCC by using seven Dynamo nodes including four multiplication nodes, two addition nodes, and one subtraction node. Four multiplication nodes provide the value of the construction cost, the maintenance cost, the energy cost, and the salvage value of the selected exterior wall type or roof type, respectively. Two addition nodes is used to compute the sum of the construction cost, the maintenance cost, and the energy cost. Then the value of the LCC of the selected exterior wall type or roof type is equal the calculated result of step 4 subtract the salvage value by using one subtraction node.

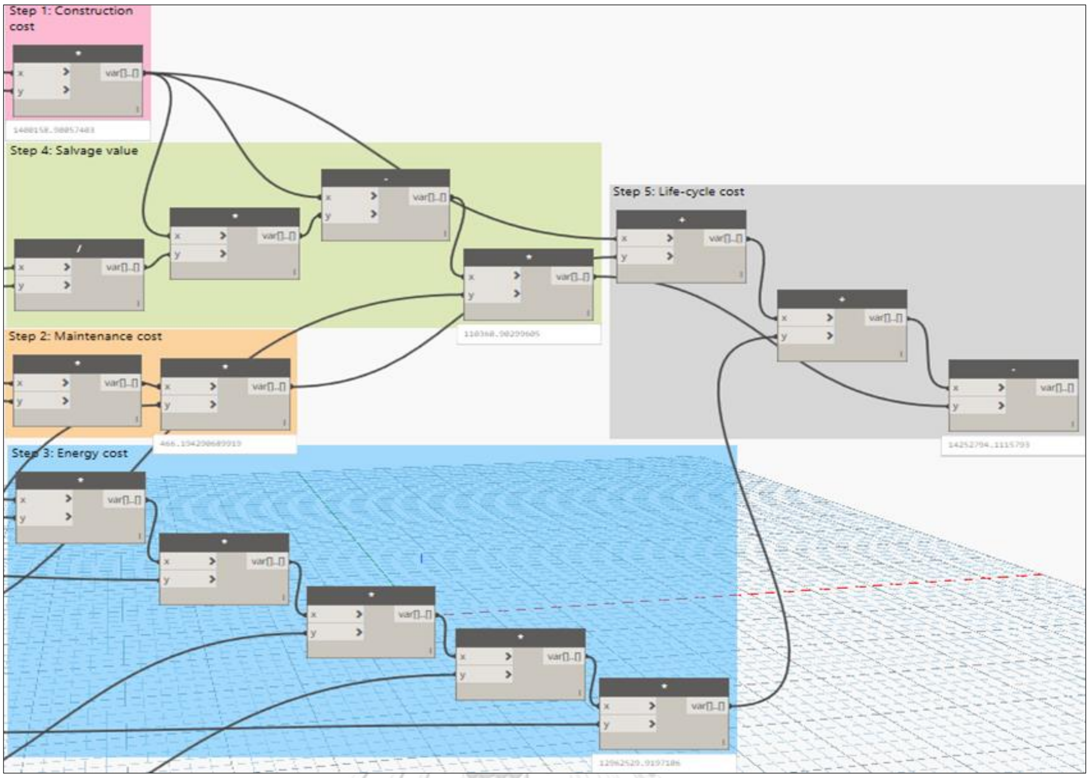


Figure 6.6 Workflow for calculating the LCC of an exterior wall type or a roof type

The workflow for calculating the LCCA of an exterior window type consists of five main steps, as shown in Figure 6.7. The first step computes the construction cost by three Dynamo nodes, including *Math.Sum, Element.GetParameterValueByName*, and a multiplication node. *Math.Sum* node provides the total surface area value of a selected exterior window type and *Element.GetParameterValueByName* node provides the value of the construction unit rate of a selected exterior window type. The multiplication node is used to multiply two acquired values. The second step computes the maintenance cost by using five Dynamo nodes, which consist of one *Math.Sum*, one *Element.GetParameterValueByName* , one *String.ToNumber*, and two multiplication nodes. *Math.Sum* node provides the value of the total surface area of a selected exterior window type and *Element.GetParameterValueByName* node provides the value of the annual service unit rate of a selected exterior window type. *String.ToNumber* node provides the value of the present maintenance worth factor. Two multiplication nodes are used to multiply the three acquired values. The third step computes the energy cost by using eighteen Dynamo nodes, which consist of one *Math.Sum*, seven *String.ToNumber*, two *Element.GetParameterValueByName*, eight multiplication, and one addition node. *Math.Sum* node provides the value of the total surface area of an exterior window type. Two *Element.GetParameterValueByName* nodes provide the value of the heat transfer coefficient and the solar heat gain coefficient a selected exterior window type, respectively. Seven *String.ToNumber* nodes provide the value of the temperature difference between glazing surface and air, the hourly usage per year, the electricity unit price, the present energy worth factor, the average solar shading factor for wall, and the solar heat gain for reference glass respectively. One multiplication nodes is used to multiply the solar heat gain coefficient and the solar heat gain of reference glass. Two multiplication nodes are used to multiply the value of the total surface area by the heat transfer coefficient and the temperature difference between glazing surface and air. Two other multiplication nodes are used to multiply the total surface area by the average solar shading factor for wall and the shading coefficient. Two calculated results are added by one addition node. Three multiplication nodes are used to multiply the calculated result by the hourly usage per year, the electricity unit price, and the present energy worth factor. The fourth step computes the salvage value by using eight Dynamo nodes consist of two *String.ToNumber*, one *Element.GetParameterValueByName*, three multiplication, one division, and one subtraction node. Two *String.ToNumber* nodes provide the value of the analyzed period and the present salvage worth factor. *Element.GetParameterValueByName* node provides the value of the service life of a selected exterior window type. One multiplication node provides the value of the construction cost of a selected exterior window type. One division node is used to divide the value of the analyzed period by the value of the service life. Then, one multiplication node multiplies the calculated result by the construction cost. Then, one subtraction node subtracts the calculated result from the construction cost. Finally, one multiplication node multiplies the calculated result by the present salvage worth factor. The fifth step computes the LCC by using seven Dynamo nodes, which consist of four multiplication nodes, two addition nodes, and one subtraction node. Four multiplication nodes provide the value of the construction cost, the maintenance cost, the energy cost, and the salvage value of a selected exterior window type, respectively. Two addition nodes are used to compute the sum of the construction cost, the maintenance cost, and the energy cost. Then, the subtraction node computes the value of the LCC of a selected exterior window type, which is equal to the calculated result of Step 4 subtracted from the salvage value.

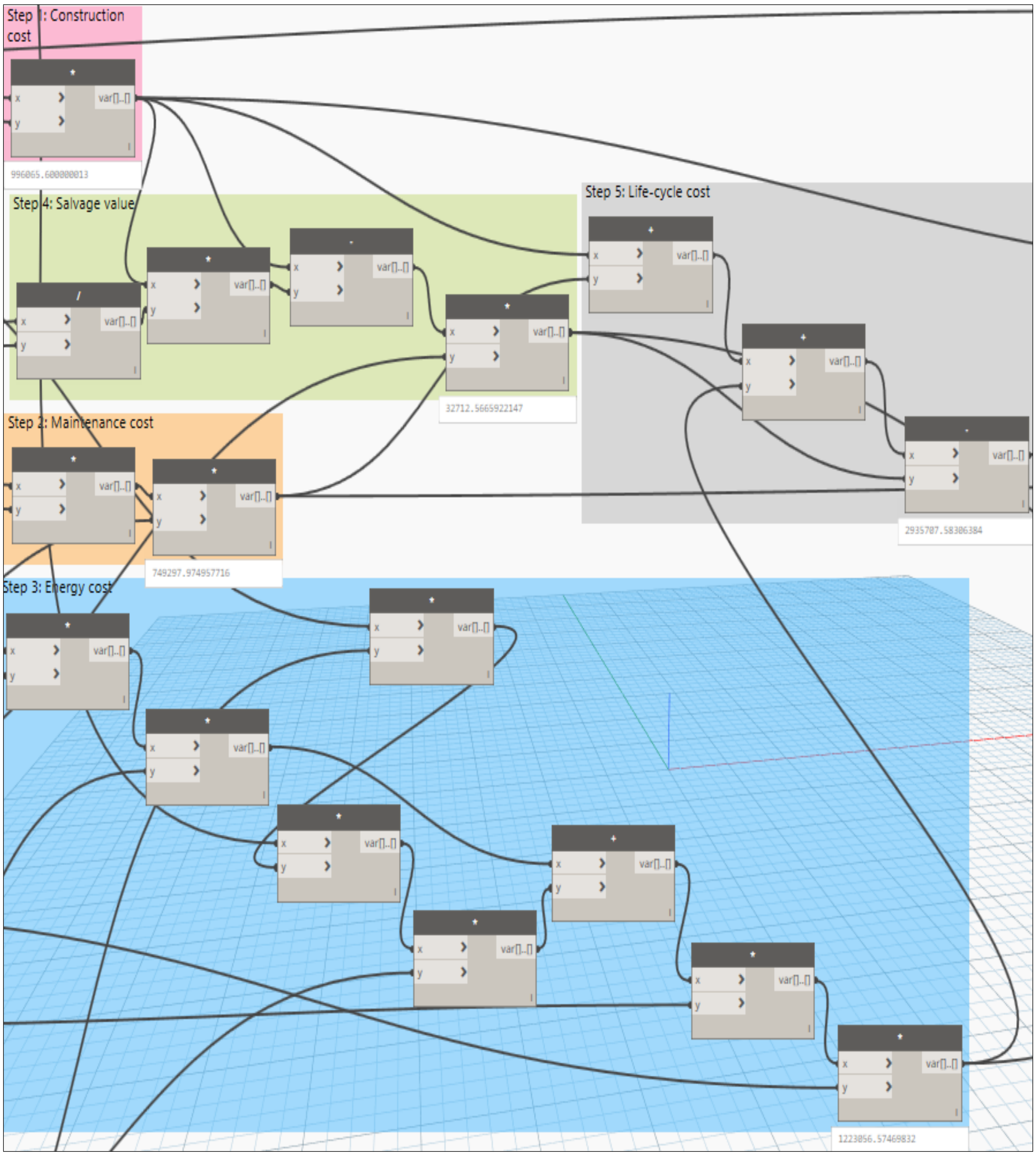


Figure 6.7 Workflow for calculating the LCC of an exterior window type

The workflow for calculating the LCCA of an interior wall type consists of three main steps, as shown in Figure 6.8. The first step computes the construction cost by using three Dynamo nodes including *Math.Sum*, *Element.GetParameterValueByName*, and a multiplication node. *Math.Sum* node provides the value of the total surface area of the selected interior wall type that is acquiring from the section 6.4.2, *Element.GetParameterValueByName* node provides the value of the construction unit rate of the selected interior wall type. Multiplication node is used to multiply two acquired value. The second step computes the maintenance cost by using five Dynamo nodes including one *Math.Sum*, one *Element.GetParameterValueByName*, one *String.ToNumber*, and two multiplication nodes. *Math.Sum* node provides the value of total surface area of the selected interior wall type that is described in the section 6.4.2. *Element.GetParameterValueByName* node provides the value of the annual service unit rate of the selected interior wall type. *String.ToNumber* node provides the value of the maintenance present worth factor that is described in the section 6.4.1. Two multiplication nodes are used to multiply three acquired value. The third step computes the LCC by using five Dynamo nodes including three multiplication nodes, two addition nodes, and one subtraction node. Three multiplication nodes provide the value of the construction cost, the maintenance cost, and the salvage value of the selected interior wall type, respectively. One addition node is used to compute the sum of the construction cost and the maintenance cost. Then the value of the LCC of the selected interior wall type is equal the calculated result of step 4 subtract the salvage value by using one subtraction node.

The workflow for calculating the LCCA of a ceiling type, a floor type, a door type, or an interior window consist of three main steps as the same with an interior wall type, which consist of four main steps. The first step computes the construction cost by using three Dynamo nodes. The second step computes the maintenance cost by using five Dynamo nodes. The third step computes the LCC by using five Dynamo nodes including three multiplication nodes, two addition nodes, and one subtraction node.

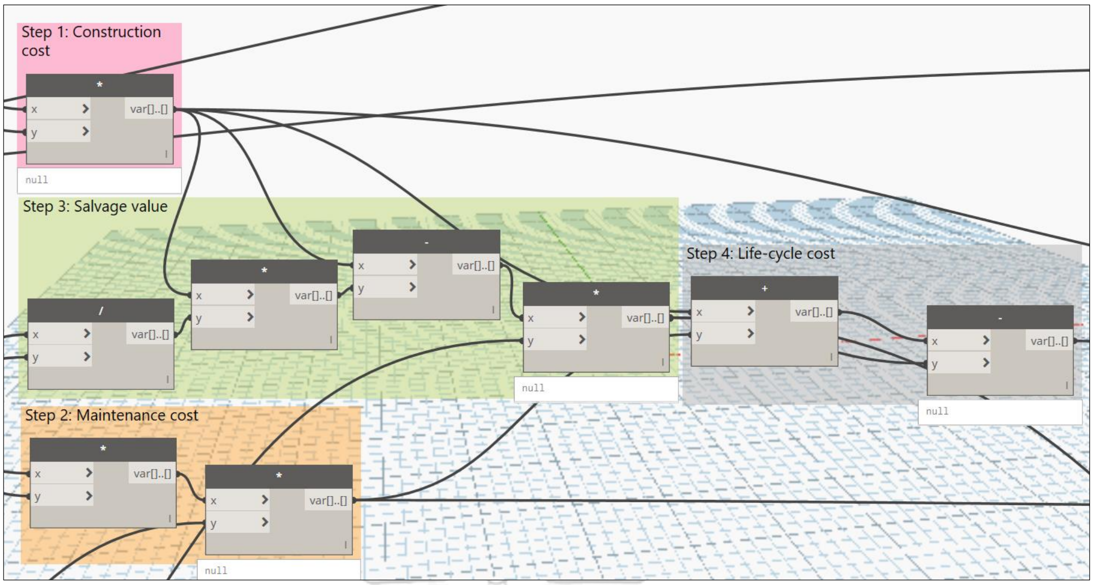


Figure 6.8 Workflow for calculating the LCC of an interior wall type

6.5 Summary

This chapter proposed a methodology for developing the multi-parametric estimation module of the BIM-database-integrated system for evaluating building LCC using a multi-parametric model by integrating the BIM authoring programming, visual programming interface, and the spreadsheet system. This chapter consist of three main parts. First, the formulations for calculating the cost categories of the LCCA are established for the exterior wall, the exterior window, the floor, the roof, the interior wall, and the interior window. Second, the assumptions for the calculation of the building LCCA is identified. This proposed system allows the users change the assumptions based on the characteristic of their building project. Third, the automatic model for evaluating the building LCCA is developed. Autodesk Revit Architecture is adopted as a potential BIM authoring programming to develop the 3D model. Microsoft Excel is adopted as a potential spreadsheet system to develop the spreadsheet template for the assumptions. Dynamo is adopted as a potential visual programming interface to connect the different platforms and to carry out the building LCCA of a huge building elements automatically. This chapter is developed based on the outcomes from the relational database management module and the visualized BIM-integrated module. The results of this module can be used as the criteria for improving the contractor selection following the sustainable growth. With the support of BIM technology, this chapter presented the easily approach to assess the building LCC by using visual programming. The quantity surveys (QSs) who are non-programmer can apply this proposed system for any building projects. The results of the multi-parametric estimation module are not depend on any assumed parameters because the users is allowed to change these data based on the typical requirements that help to improve the accuracy and reliability of the results. This research had select Dynamo as a BIM platform to develop the dynamic model through two section of the proposed system consist of the data acquisition section and the calculation section to fulfill the requirement of the BIM-database-integrated system for evaluating building LCC using a multi-parametric model.

CHAPTER 7
BIM-INTEGRATED REPORT MODULE

This chapter presents the development of the BIM-integrated report module of the BIM-BLCC. The functions of this module are (1) to contain assumed parameters and (2) to present the results of the building LCCA from the multi-parametric model into a spreadsheet format that help the clients easily to visualize and to understand. In addition, this module also helps the quantity surveyors (QSs) reduce the waiting time for accessing and reading the results in visual programming interface. There are two main steps to develop the BIM-integrated report module of the BIM-BLCC. The first step presents the development of the spreadsheet report. The second step presents the process to export the results from the multi-parametric estimation module to the spreadsheet report using visual programming.

7.1 Introduction

The 3D BIM models contain a great of elements that need to perform the economic evaluation throughout their life-cycle. To visualize the results of the building LCCA from the multi-parametric model, the cost estimators need to take a long time to access and run the mathematical model in visual programming interface. In addition, it is an inconvenient approach for the cost estimators present the results to the building stakeholders. Therefore, this research proposed the BIM-integrated report module to solve the time-consuming for inputting the assumed parameter and exporting the building LCCs results. The developing process of the BIM-integrated report module passed to two main steps. The first step designs the spreadsheet report for containing the assumed parameters and the results from the multi-parametric model. The second step exports the results to the spreadsheet report using visual programming interface. Microsoft Excel is adopted as a potential platform for develop the spreadsheet report. Dynamo is adopted as a potential visual programming interface to develop the integrated model.

7.2 Development of the spreadsheet report

The development of the spreadsheet report goes through nine steps, as shown in Figure 7.1. The first step opens Microsoft Excel 2013. The second step types the row number begin at "0" at the cell A1 because the visual programming read the row 1 of the Excel sheet is "0". The third step sets up the project name box at the cell B1. The fourth step creates the element type code column at the column B. This column is used to store the code of element type that would be exported from the Dynamo. The fifth step creates the description column at the column C. This column is used to store the name of element type that would be exported by Dynamo scripts. The sixth step creates the construction cost column at the column D. This column is used to store the value of construction cost of element type that would be export by Dynamo scripts. The seventh step creates the percentage column at the column E. This column is used to store the percent of the construction cost of an element type compare with the total construction cost of the building. The eighth step creates the maintenance cost column at the column F. This column is used to store the value of maintenance cost of element type that would be export by Dynamo scripts. The ninth step creates the percentage column at the column G. This column is used to store the percent of the maintenance cost of an element type compare with the total maintenance cost of the building. The tenth step creates the energy cost column at the column H. This column is used to store the value of energy cost of an element type that would be export by Dynamo scripts. The eleventh step creates the percentage column at the column I. This column is used to store the percent of the energy cost of an element type compare with the total maintenance cost of the building. The twelfth step creates the salvage value column at the column J. This column is used to store the cost of the end of life of an element type that would be export by Dynamo scripts. The thirteenth step creates the percentage column at the column K. This column is used to store the percent of the salvage value of an element type compare with the total salvage value of the building. The fourteenth step creates the life-cycle cost column at the column L. This column is used to store the value of the life-cycle cost of an element type that would be export by Dynamo scripts. The fifteenth step creates the percentage column at the column M. This column is used to store the percent of the

LCC of an element type compare with the total building LCC. The sixteenth step types the column number begin at "1" from the cell B3 to the cell M3. The row number and the column number help to identify exactly the address for exporting the results. A number of rows depend on a number of element types of the BIM models. The seventeenth step clicks File symbol. This prompts the list of activities show up. Then the eighteenth step clicks "Save". Then identified the target folder to save the created spreadsheet report. The nineteenth step types the name of the created spreadsheet report. The twentieth step clicks "Save".

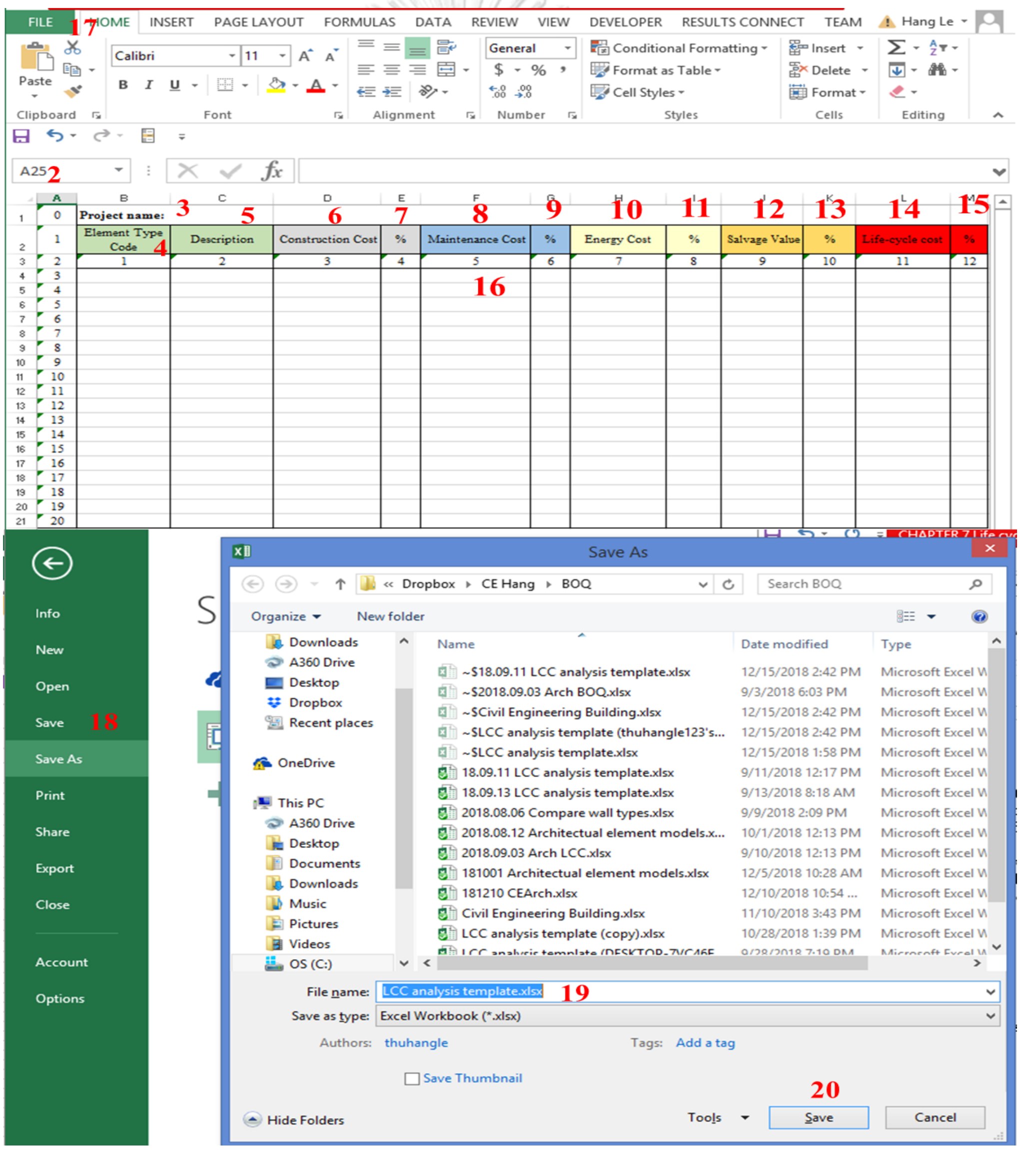


Figure 7.1 Workflow for developing the spreadsheet report

7.3 Exporting results of the BIM-BLCC to the spreadsheet report

Figure 7.2 proposes the workflow for exporting the results of the building LCCA from the multi-parametric model to spreadsheet report using visual scripting consists of five steps. The first step selects the results of building LCCA from the multi-parametric model including type name, element type code, construction cost, maintenance cost, salvage value, energy cost, and life-cycle cost of selected element type. Type name and element type code are extracted from the element properties by using two *String* and *Element.GetParameterValueByName* nodes. Construction cost is extracted from the calculated result of the chapter 6 by using a multiplication node. Maintenance cost is extracted from the calculated result of the chapter 6 by using a multiplication node. Salvage value is extracted from the calculated result of the chapter 6 by using a multiplication node. Life-cycle cost is extracted from the calculated result of the chapter 6 by using a multiplication node. The second step selects the path to the building LCCA spreadsheet workbook that would contain the reported results by using *File Path* node. The third step controls the program flow by using a *Boolean* node. *Boolean* node only store two values "True" or "False" that allows the programmer to evaluate an action or set of actions based on the test. The fourth step selects the address to save the exported results by using seven *Code Block* nodes. These nodes are written by Python programming language to locate Microsoft Excel sheet, row, and column would obtain the exported results. The fifth step writes the results to Microsoft Excel file by using seven *Excel.WriteToFile* nodes. When the BIM users click on Run button, the system would run to extract the results to the spreadsheet report.

7.4 Summary

This chapter presents two steps to develop of the BIM-integrated report module of the BIM-BLCC. The first step is to develop the spreadsheet report. And the second step is to develop the automatic model for exporting the results of the building LCCA from the multi-parametric model to the spreadsheet report. The main function of this module is to represent the results of the multi-parametric estimation module into the spreadsheet report. This module is built based on the integration between the spreadsheet system with visual programming interface. Microsoft Excel is adopted to develop the spreadsheet report for this module. Dynamo is adopt to develop an automatic approach from exporting the results of the building LCCA to the spreadsheet report.

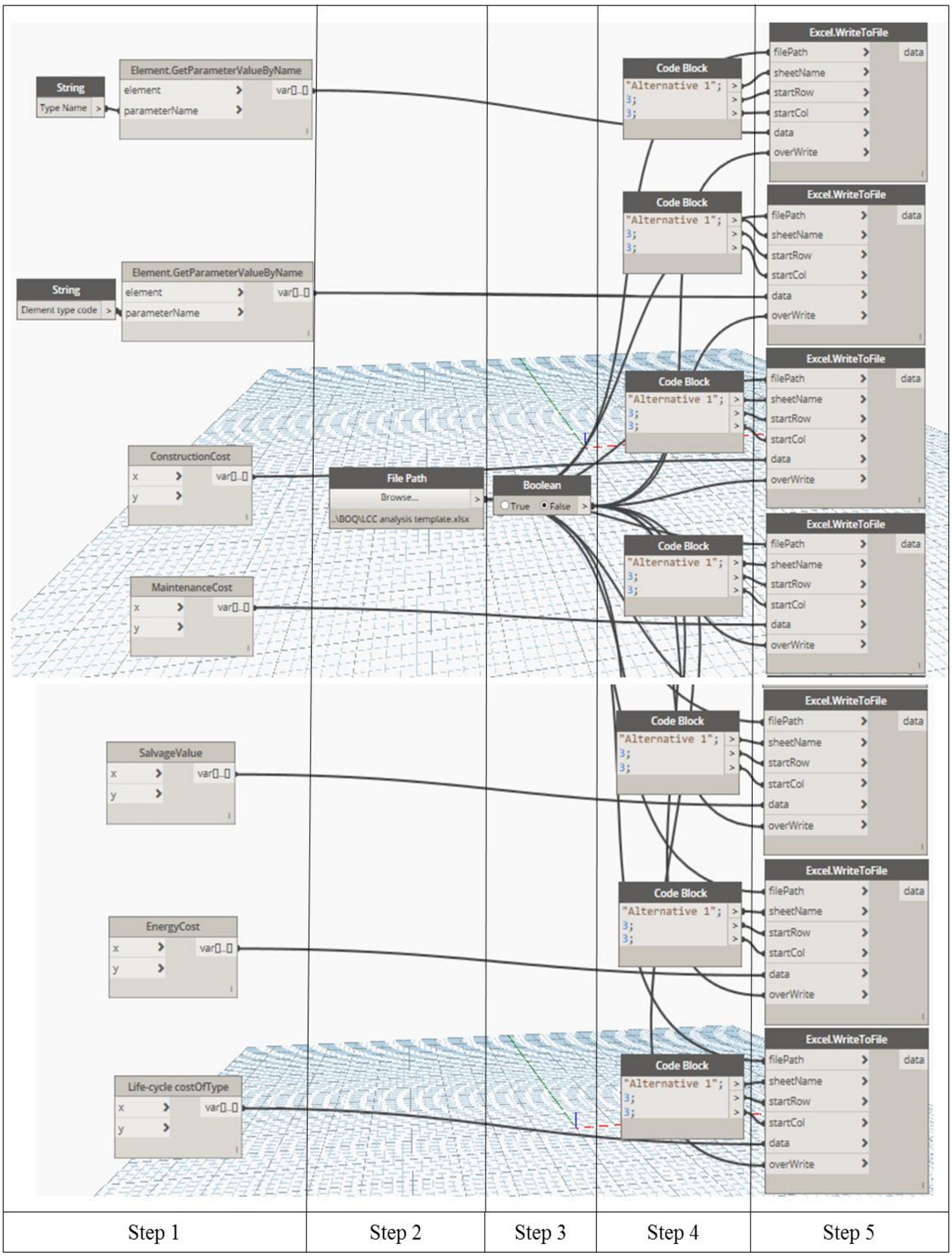


Figure 7.2 Workflow for extracting the results to the spreadsheet report

CHAPTER 8
SYSTEM VERIFICATION AND VALIDATION

This chapter introduces the verification of the BIM-BLCC to an actual case study building. The system verification demonstrates the practical application of the BIM-BLCC while the system validation make sure the reliability of the results of the BIM-BLCC. This chapter represents five parts. First, it defines the objectives of system verification and validation of the research. Second, it defines the characteristics of the case study building that is adopted to apply the BIM-BLCC. Third, it performs the building LCCA for selected case study project. Four, the results are discusses. Five, it describes the evaluation of the BIM-BLCC implementation by the expert interview. The objective of this chapter is to determine whether the BIM-BLCC is appropriate with the practice for estimating LCC criterion of a building project for the tender submission. Furthermore, it also ensures that the calculating results of the BIM-BLCC are near with manual calculating method.

8.1 The objectives of system verification and validation

System verification is defined as the process of evaluating the workability of a system in practice (Grady, 2010). In this research, the purposed of system verification is to make sure that the structure, process, and various modules inside the system is according to requirements. However, a developed system has passed the verification process. It does not mean that this world be complete without errors when applied it in the practice building projects because it is possible that the verification process would not cover enough in order to meet with error hidden in the BIM-BLCC.

System validation is defined as a process of measuring the reliability of a product. According to Fellows (2015), there are three common ways to evaluate the reliability of a research finding: (1) test-re-test reliability, (2) inter-item reliability, and (3) inter-rater reliability. The test-re-test method determines the reliability by measuring participants on two time tests. Then the two sets of scores are correlated to see how closely related the second set of scores is to the first. The inter-rater test determines the reliability by measuring the consistency among two or more researchers who observe and record the participant responses. The inter-item test determines the reliability by measuring the degree of consistency of a product on an ordered reference standard. In this study, to measure the reliability of the results using the BIM-BLCC. The authors used the inter-item test to compare the results from the BIM-BLCC and the results from the manual calculation to evaluate the accuracy of the prototype system. In addition, both results are also compare with the results from related research that is considered as a reference standard to measure the reliability of the BIM-BLCC. Furthermore, the expert interviews is conducted to evaluate the appropriate of the prototype system. This process also helps to confirm whether the BIM-BLCC can help to improve the implementation of the building LCCA in practice. There are two experts who will participant in system validation process. The profile of the respondents are described in Table 8.1.

8.2 System verification of the research

According to Chung (2014), university buildings are classified among the buildings present the highest energy consumption. They are also demonstrated the potential for energy conservation from 6 to 29 percent. In addition, the Menezes research pointed out that the measured electricity demands is approximately from 60 to 70 percent higher than predicted in the university building. Therefore, the university building is adopted as a representative sample for this research. The verification process for the BIM-BLCC had been completed through the applying the system for an office building project in Thailand. This is a typical building that is constructed based on some standard steps in the construction industry. In addition, this case study building is selected for system application because it is very convenient for the authors to collect the availability of required data, to survey the hourly usage of the building to estimate the really electrical consumption, to provide data about maintenance policies, and to validate the results of the building LCCA easily. The case study building is located at the Department of Civil Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok, Thailand. It is a six-story building with a total gross area of 3,576 m^2. It is an unconditional building in the hot and humid climate.

Table 8.1 Characteristics of repondents for validating the BIM-BLCC

Respondent No.	Field of expertise	Experience	Education
1	BIM manager in consulting company	10 - 20 years	Ph.D.
2	Sustainable building consultant	20 - 30 years	Ph.D.

The building procurement consists of several parts consist of structural, architectural, mechanical, plumbing, and electrical system. However, due to the limitation of this research, only the architectural system is considered in this case study building project.

8.3 Process of system application

This chapter describes the capabilities of applying the BIM-BLCC with respect to its four modules: 1) relational database management module, 2) visualized BIM-integrated module, 3) multi-parametric estimation module, 4) BIM-integrated report module. Figure 8.1 illustrates the workflow for applying the BIM-BLCC in form of a matrix that describes the various platforms.

- Step 1: The conceptual BIM model is created by Autodesk Revit Architecture
- Step 2: The necessary data of all the building element types is queried from the relational database management using Structure Query Language (SQL)
- Step 3: The queried table is exported to Microsoft Excel by using the direct link between Microsoft Access and Microsoft Excel. The output is a project spreadsheet database.
- Step 4: The conceptual BIM model is connected with the project spreadsheet database using Dynamo scripts. The output is a completed BIM model for the target building project that contains the added information into the type properties to carry out the building LCCA.
- Step 5: The value of assumptions is input to the spreadsheet template

- Step 6: The completed BIM model is connected with the spreadsheet template to extract the value of assumptions
- Step 7: The building LCCA is carried out using Dynamo scripts
- Step 8: The results are exported to the spreadsheet workbook.

8.4 Results and discussions

8.4.1 The BIM model of the case study building

The 3D model of the case study building is created by using Autodesk Revit, as shown in Figure 8.2. The 3D model contains the total 44 element types. There are fourteen exterior window types consist of exterior metal-glazed window W1’, exterior metal-glazed window W1”, exterior metal-glazed window W1’”, exterior metal-glazed window W1””, exterior metal-glazed window W4’, exterior metal-glazed window W4”, exterior metal-glazed window W4’”, exterior metal-glazed window W5’, exterior metal-glazed window W5”, exterior frosted glazed window W2, exterior glazed window W2’, exterior glazed window W3, exterior glazed window W3’, and exterior metal window W10. There are three interior window types consist of interior glazed window W7, interior glazed window W7’, and interior glazed window W8. There are eight door types consist of exterior metal-glazed double door D1, exterior metal single door D4, exterior plywood double door D9, interior metal-glazed double door D2, interior metal-glazed single door D3, interior metal-glazed double door D10, interior wood single door D5, and interior wood single door D7. There are four exterior wall types consist of red ceramic tile 4x8 wall W66, cladding tile 12x12 and red ceramic tile 4x8 wall W36, brick and red ceramic tile 4x8 wall W16, and balcony wall W8-1. There are four interior wall types consist of brick wall W11, gypsum wall W55, cladding tile 12x12 wall W3, and brick and cladding tile 12x12 wall W13. There are eight floor types consist of gray stone floor F1, gray tile floor F2, ceramic tile floor F3, white-gray terrazzo floor F5, concrete floor F6, gray tile floor F2’, gray stone floor F1’, and concrete floor F6’. There are three roof types consist of concrete roof with waterproofing F4, gray tile roof F2’, and concrete roof F6’.

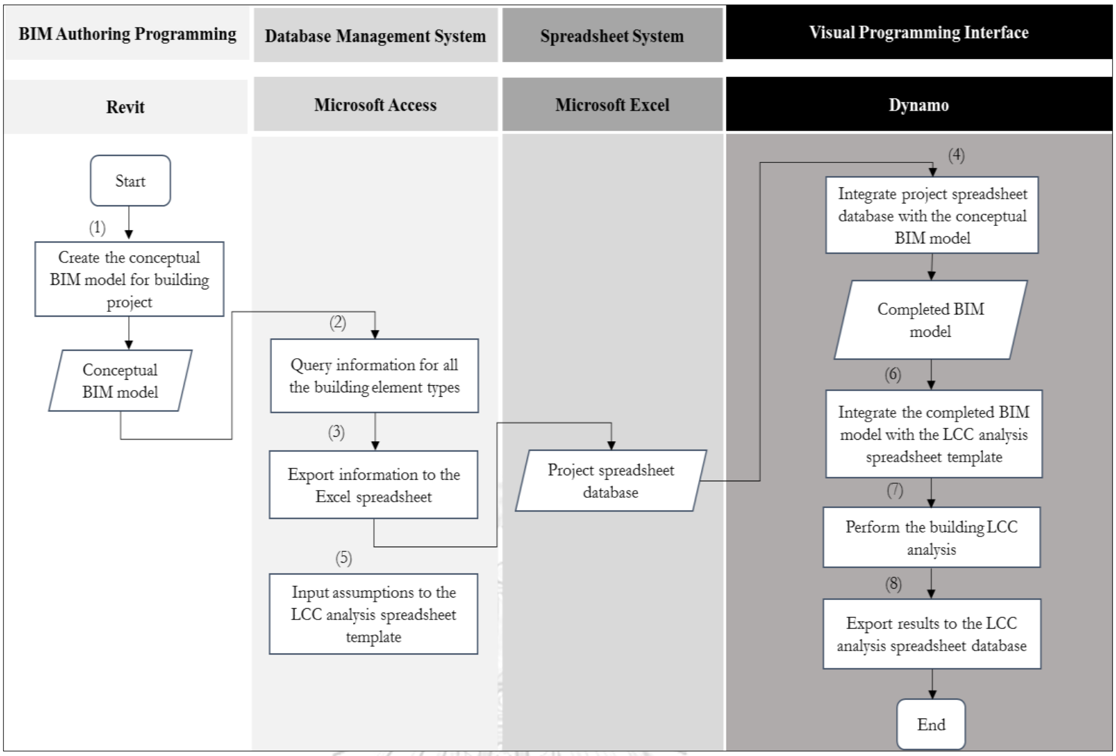


Figure 8.1 Workflow for applying the BIM-BLCC

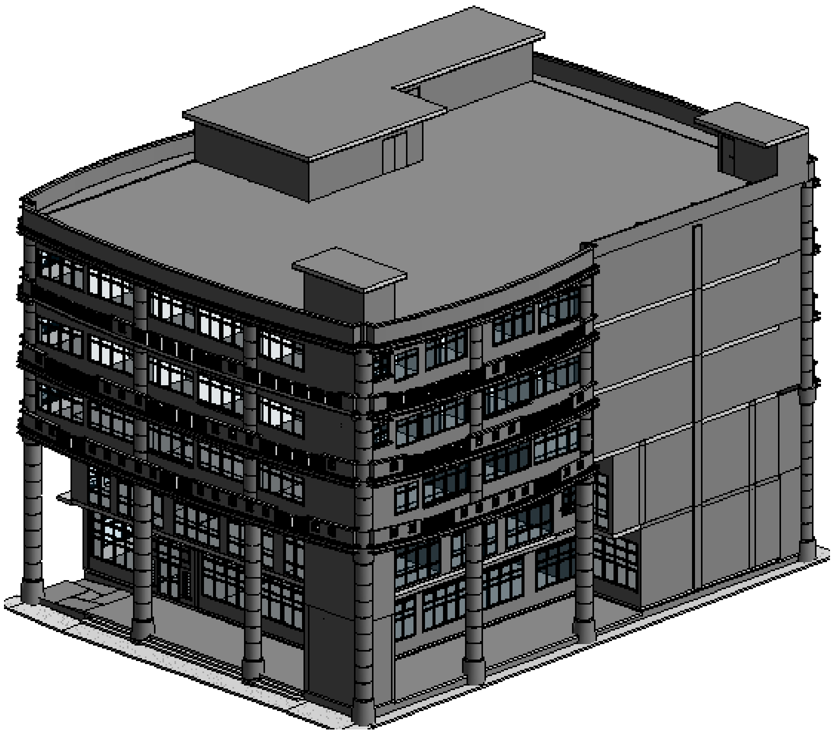
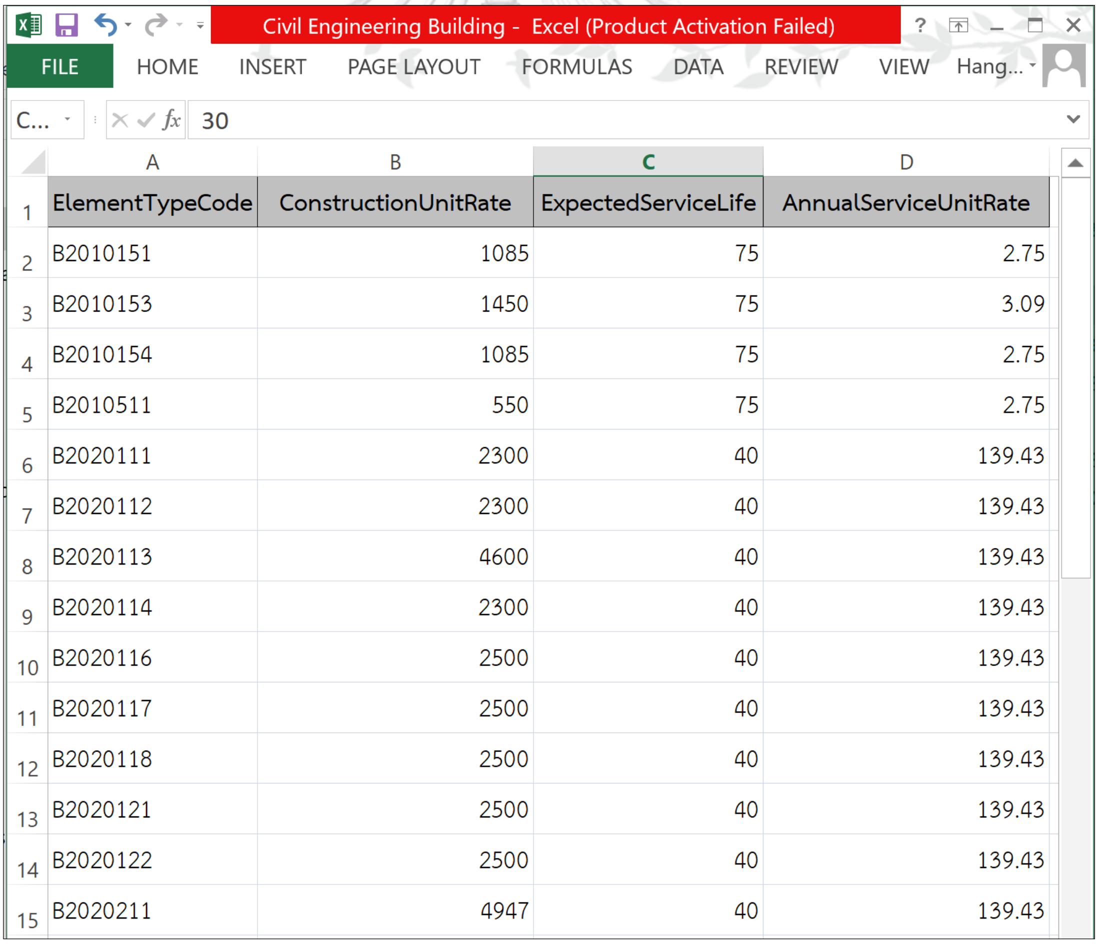


Figure 8.2 3D BIM model of the case study building project

8.4.2 The project spreadsheet database

A query expression is used to provide a successful information retrieval. There are six SQL statements are wrote to query added information into six tables of the relational LCC database for the case study building. The “UNION” statement is used to connect six SQL statements. In this paper, the query returns result is a list of 44 element types of the case study building with their appropriate information for the 3D BIM model consist of construction unit rate, expected service life, and annual service unit rate. These value are queried based on their element type code. Then, the queried table is exported to Microsoft Excel and save into the Excel spreadsheet database. Figure 8.3 showed an Excel spreadsheet workbook for the case study building project.



ElementTypeCode	ConstructionUnitRate	ExpectedServiceLife	AnnualServiceUnitRate
B2010151	1085	75	2.75
B2010153	1450	75	3.09
B2010154	1085	75	2.75
B2010511	550	75	2.75
B2020111	2300	40	139.43
B2020112	2300	40	139.43
B2020113	4600	40	139.43
B2020114	2300	40	139.43
B2020116	2500	40	139.43
B2020117	2500	40	139.43
B2020118	2500	40	139.43
B2020121	2500	40	139.43
B2020122	2500	40	139.43
B2020211	4947	40	139.43

Figure 8.3 An Excel spreadsheet workbook for the case study building project

8.4.3 Added parameters into the BIM model of the case study building

To carry out the building LCCA, all elements of BIM model need to be added required parameters to their properties. There are four parameters need to be extract for each element model into the 3D model to carry out the LCCA. However, the BIM model of building projected usually contain a great of elements so that it is difficult to add all required parameters to each element model by the manual method. This research developed an automatic model to add required parameters for all element models of the BIM model using Dynamo scripts.

The results of Figure 8.4 illustrates an example four required parameters that are added for all elements of four exterior wall types of the BIM model of the case study building. For example, the element type code of a red ceramic tile wall W66 element is B2010511, the values of construction unit rate, expected service life, and annual service unit rate of this element are 1085 Bath per square meter, 75 years, and 2.75 Bath per square meter, respectively. All elements of other three exterior wall types of the BIM model of the case study building are also extracted the values for four added parameters as same as red ceramic tile 4x8 wall W66 using Dynamo scripts.

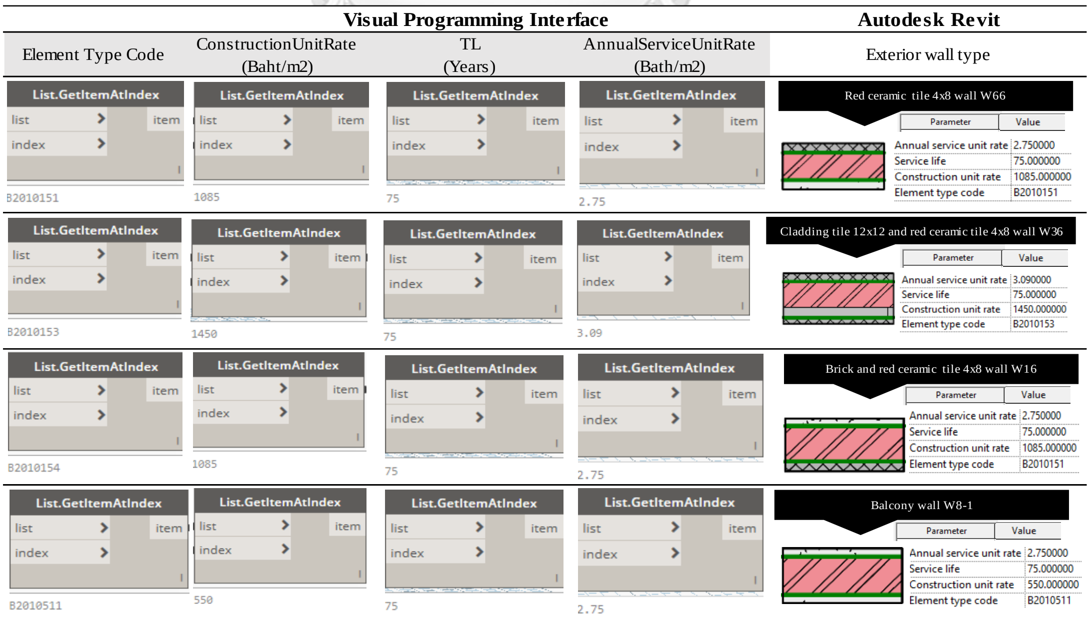


Figure 8.4 Required data for the exterior wall types of the case study

The same with four exterior wall types, all element models of fourteen exterior window types, three interior window types, eight door types, eight floor types, and four roof types of the BIM model of the case study building are also acquired four required parameters for estimate the LCCs using Dynamo scripts.

8.4.4 Assumed parameters for the building LCCA

There are ten assumed parameters that need to be input to the multi-parametric model to carry out the building LCCA including the analyzed period, the discount rate for present-worth calculations, the electrical unit price, the hourly usage per year of project, the average hourly outside air temperature, the design temperature difference of exterior surfaces, and the design temperature difference of interior surfaces.

The values of assumed parameters for the case study building are extracted from the spreadsheet report. For the analyzed period, the 30 years is adopted for carrying out the LCCA of the case study building. For the discount rate, the National Energy Conservation Policy Act mentioned about the discount rate for all the building LCCA studies that related to energy is seven percent (S. Kirk, J., and Dell'Isola, A., J., 1995). Therefore, this paper adopted a seven percent discount rate for this case study building. The maintenance present worth factor, the energy present worth factor, and the salvage present worth factor are computed from seven percent discount rate. The electrical unit price is adopted based on the average value of last years is 0.131 Baht per Wh. The temperature difference between glazing surface and air is computed from the average hourly outside air temperature and the inside surface temperature. In this research, the average hourly outside air temperature, the inside surface temperature are collected form the Royal Thai Meteorological Department (RTMD) in 2017 are 30^{o}C and 25^{o}C, repetitively. Ten assumed parameters are automatically acquired from the spreadsheet report using Dynamo scripts as shown in Appendix D. Figure 8.5 shows the assumed parameters of the BIM model of the case study building project. The users can change the value of assumed parameters to appropriate with their practical project.

Assumption parameters				
Analyzed period (Years)	Maintenance/Energy present worth factor	Salvage present worth factor	Electrical unit price (Baht/Wh)	Hourly usage per year
String.ToNumber str number 30	String.ToNumber str number 12.4090411835059	String.ToNumber str number 0.13136711715459	String.ToNumber str number 0.0034407	String.ToNumber str number 4320
Temperature difference between glazing surface and air	Design temperature difference, uncontitioned area to room	Average solar shading factor for wall	Average solar shading factor for roof	Solar heat gain of reference glass
String.ToNumber str number 5	String.ToNumber str number 2.8	String.ToNumber str number 168	String.ToNumber str number 357	String.ToNumber str number 1.15

Figure 8.5 Assumed parameters of the case study building

8.4.5 Extraction of required parameters from the BIM model

The 3D BIM model contains details of the geometric and non-geometric information of building elements. The physical properties of each element is defined through the support of material library in Autodesk Revit. An automated approach for acquiring required parameter of the 3D BIM model was developed by using visual programing.

For the exterior window, the case study building project has fourteen exterior window types with contain many element models into each type. They are three parameters that need to extract for the LCCA consist of the total surface area, the heat transfer coefficient, and the solar heat gain coefficient. The total surface area of each exterior widow type is automatic quantity take-off by using Python script node to identify and sum the area value of all the element of each exterior window type. The heat transfer coefficient and the solar gain coefficient are automatic calculation through the structural design of each exterior window type. The BIM-BLCC can save the time-consuming for estimating coefficient of energy cost by using BIM technology. After the designer establishes the structural design of an exterior window type including the height, width, and glass type of an exterior window type. Revit would support the heat transfer coefficient and the solar heat gain coefficient of that exterior window type. Table 8.2 shows the value of three parameters that are extracted from the BIM model of the case study building. The results showed the value of the total surface area of exterior metal-glazed window W1’, exterior metal-glazed window W1”, exterior metal-glazed window W1’”, exterior metal-glazed window W1””, exterior metal-glazed window W4’, exterior metal-glazed window W4”, exterior metal-glazed window W4’”, exterior metal-glazed window W5’, exterior metal-glazed window W5”, exterior frosted glazed window W2, exterior glazed window W2’, exterior glazed window W3, exterior glazed window W3’, and exterior metal window W10 are near 422.5m^2, 42.9m^2, 27.3m^2, 30.6m^2, 231.6m^2, 8.4m^2, 15.0m^2, 234.9m^2, 45.9m^2, 164.3m^2, 25.3m^2, 36.7m^2, 22.5m^2, 1.4m^2 respectively. Exterior metal-glazed window W1’ has the largest surface area. There parameters are automatically computed from the surface area of 41 elements of red ceramic tile 4x8 wall W66 by using a group of Dynamo nodes that is develop by using Python scripts. And exterior metal window W10 had the smallest total surface area. All the exterior window types have the same value of heat transfer coefficient and solar heat gain coefficient are 6.7018 W/(m^2/K) and 0.81, respectively.

Table 8.2 Extraction required parameters from exterior window types

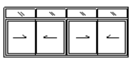
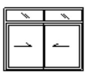
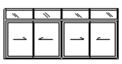
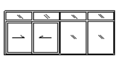
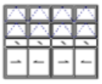
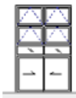
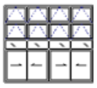
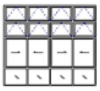
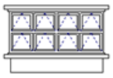
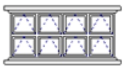
Autodesk Revit	Dyanmo		
Exterior window	Total surface area (m2)	Heat transfer coefficient W/(m2/K)	Solar heat gain coefficient
 Dimensions: Height 1.9500, Width 3.8000; Exterior metal-glazed window W1'	Math.Sum (values → sum): 422.514580000006	Element.GetParameterValueByName (element, parameterName → var[]..[]): 6.7018	Element.GetParameterValueByName (element, parameterName → var[]..[]): 0.81
 Dimensions: Height 1.9500, Width 1.9000; Exterior metal-glazed window W1"	Math.Sum (values → sum): 42.9839999999993	Element.GetParameterValueByName (element, parameterName → var[]..[]): 6.7018	Element.GetParameterValueByName (element, parameterName → var[]..[]): 0.81
 Dimensions: Height 1.9500, Width 3.4000; Exterior metal-glazed window W1'"	Math.Sum (values → sum): 27.3389999999996	Element.GetParameterValueByName (element, parameterName → var[]..[]): 6.7018	Element.GetParameterValueByName (element, parameterName → var[]..[]): 0.81
 Dimensions: Height 1.9500, Width 3.8000; Exterior metal-glazed window W1""	Math.Sum (values → sum): 30.6284999999995	Element.GetParameterValueByName (element, parameterName → var[]..[]): 6.7018	Element.GetParameterValueByName (element, parameterName → var[]..[]): 0.81

Table 8.2 Extraction required parameters from exterior window types (continued)

Autodesk Revit	Dyanmo		
Exterior window	Total surface area (m2)	Heat transfer coefficient W/(m2/K)	Solar heat gain coefficient
 Dimensions: Height 2.9500, Width 3.8000 Exterior metal-glazed window W4'	Math.Sum (values > sum) 231.587999999994	Element.GetParameterValueByName (element, parameterName > var[]..[]) 6.7018	Element.GetParameterValueByName (element, parameterName > var[]..[]) 0.81
 Dimensions: Height 2.9500, Width 1.9000 Exterior metal-glazed window W4"	Math.Sum (values > sum) 8.39949999999978	Element.GetParameterValueByName (element, parameterName > var[]..[]) 6.7018	Element.GetParameterValueByName (element, parameterName > var[]..[]) 0.81
 Dimensions: Height 2.9500, Width 3.4000 Exterior metal-glazed window W4'''	Math.Sum (values > sum) 15.0179999999997	Element.GetParameterValueByName (element, parameterName > var[]..[]) 6.7018	Element.GetParameterValueByName (element, parameterName > var[]..[]) 0.81
 Dimensions: Height 3.3000, Width 3.8000 Exterior metal-glazed window W5'	Math.Sum (values > sum) 234.883999999994	Element.GetParameterValueByName (element, parameterName > var[]..[]) 6.7018	Element.GetParameterValueByName (element, parameterName > var[]..[]) 0.81
 Dimensions: Height 3.3000, Width 1.9000 Exterior metal-glazed window W5"	Math.Sum (values > sum) 45.8999999999989	Element.GetParameterValueByName (element, parameterName > var[]..[]) 6.7018	Element.GetParameterValueByName (element, parameterName > var[]..[]) 0.81
 Dimensions: Height 1.8500, Width 2.9500 Exterior frosted glazed window W2	Math.Sum (values > sum) 164.269625000096	Element.GetParameterValueByName (element, parameterName > var[]..[]) 6.7018	Element.GetParameterValueByName (element, parameterName > var[]..[]) 0.81
 Dimensions: Height 1.4500, Width 2.9500 Exterior glazed window W2'	Math.Sum (values > sum) 25.3364999999995	Element.GetParameterValueByName (element, parameterName > var[]..[]) 6.7018	Element.GetParameterValueByName (element, parameterName > var[]..[]) 0.81
 Dimensions: Height 1.8600, Width 1.6500 Exterior glazed window W3	Math.Sum (values > sum) 36.7079999999991	Element.GetParameterValueByName (element, parameterName > var[]..[]) 6.7018	Element.GetParameterValueByName (element, parameterName > var[]..[]) 0.81
 Dimensions: Height 1.4500, Width 1.6500 Exterior glazed window W3'	Math.Sum (values > sum) 22.4824999999996	Element.GetParameterValueByName (element, parameterName > var[]..[]) 6.7018	Element.GetParameterValueByName (element, parameterName > var[]..[]) 0.81
 Dimensions: Height 1.0000, Width 1.0000 Exterior metal window W10	Math.Sum (values > sum) 1.40699999999995	Element.GetParameterValueByName (element, parameterName > var[]..[]) 6.7018	Element.GetParameterValueByName (element, parameterName > var[]..[]) 0.81

For the exterior wall, the BIM model of the case study building project contains four exterior wall types. They are three parameters that need to extract the value from all elements of these types for estimate the LCCs: (1) the total surface area, (2) the heat transfer coefficient, and (3) the equivalent temperature difference. The total surface area of each exterior wall type is automatic quantity take-off by using Python script nodes. The heat transfer coefficient is supported through the structural design of each exterior wall type. The equivalent temperature difference are input to the BIM model. Table 8.3 shows the value of total surface area, heat transfer coefficient, and equivalent temperature difference of four exterior wall types the BIM model of the case study building. The results showed that the red ceramic tile 4x8 wall W66, cladding tile 12x12 and red ceramic tile 4x8 wall W36, brick and red ceramic tile 4x8 wall W16, and balcony wall W8-1 have the total surface area: 1290.5m^2, 98.3m^2, 148.1m^2, and 240.4m^2 respectively. Red ceramic tile 4x8 wall W66 has the largest total surface area. This value is automatically summed from the surface area of 32 elements of red ceramic tile 4x8 wall W66 by using Python scripts. The heat transfer coefficient of red ceramic tile 4x8 wall W66, cladding tile 12x12 and red ceramic tile 4x8 wall W36, brick and red ceramic tile 4x8 wall W16, and balcony wall W8-1 are 6.8 W/(m^2/K), 6.9 W/(m^2/K), 6.2 W/(m^2/K), and 6.3 W/(m^2/K) respectively. Cladding tile 12x12 and red ceramic tile 4x8 wall W36 has the largest value of heat transfer coefficient and brick and red ceramic tile 4x8 wall W16 has the smallest value of heat transfer coefficient. The research used the average equivalent temperature difference for all exterior wall types is 8^{o}C.

Table 8.3 Extraction required parameters from exterior wall types

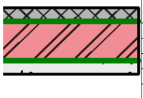
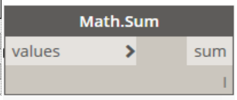
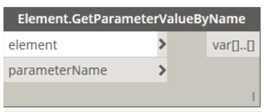
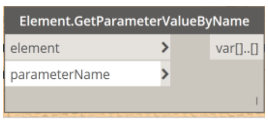
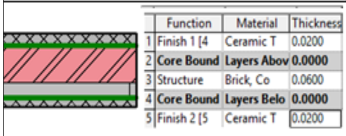
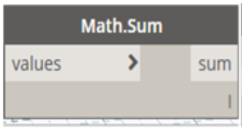
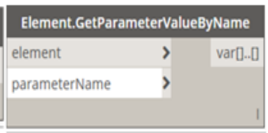
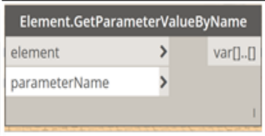
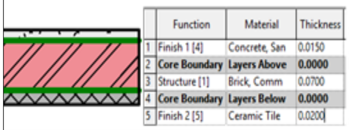
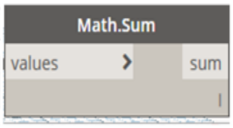
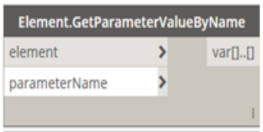
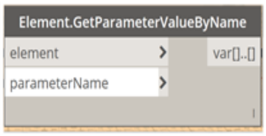
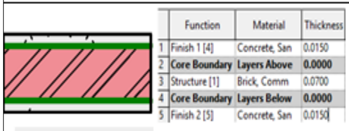
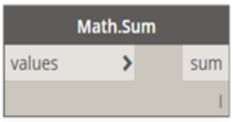
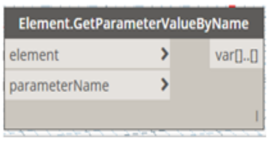
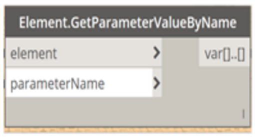
Autodesk Revit	Dynamo		
Exterior wall	Total surface area (m2)	Heat transfer coefficient W/(m2/K)	Equivalent temperature difference
 Function / Material / Thickness 1 Finish 1 [4] / Ceramic Tile / 0.0200 2 Core Boundary / Layers Above / 0.0000 3 Structure [1] / Brick, Comm / 0.0600 4 Core Boundary / Layers Below / 0.0000 5 Finish 2 [5] / Concrete, San / 0.0200 Red ceramic tile 4x8 wall W66	 1290.46903278712	 6.80743365391568	 8

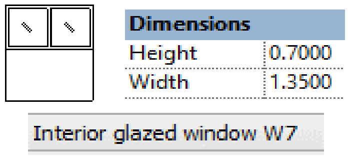
Table 8.3 Extraction required parameters from exterior wall types (continued)

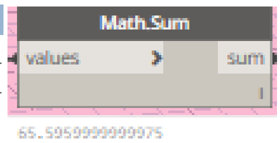
Autodesk Revit	Dynamo		
Exterior wall	Total surface area (m2)	Heat transfer coefficient W/(m2/K)	Equivalent temperature difference
 Cladding tile 12x12 and red ceramic tile 4x8 wall W36	 98.2849999999981	 6.92307692307692	 8
 Brick and red ceramic tile 4x8 wall W16	 148.103000000072	 6.22522979258051	 8
 Balcony wall W8-1	 240.381295810763	 6.31670767166182	 8

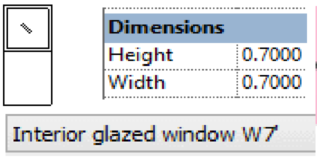
For the interior window, the BIM model of the case study building project contains three interior window types. There is only one parameter that is the total surface area of each type need to be extract to carry out the LCCs. The total surface area of each interior widow type is automatic quantity take-off by using Python script nodes to identify and sum the area value of all the element of each interior window type. After the designer establishes the structural design of an interior window type including the height, width, and glass type of an interior window type. Table 8.4 shows the value of total surface area of three interior window types of the case study building. The results showed the value of the total surface are of interior glazed window W7, interior glazed window W7', interior glazed window W8 are near 65.6m^2, 3.1m^2, 57.9m^2 respectively. Interior glazed window W7 has the largest surface area. This value is automatically compute from the surface area of 46 elements of interior glazed window W7 by using a group of Dynamo nodes that is develop by using Python scripts. And, interior glazed window W7' had the smallest total surface area.

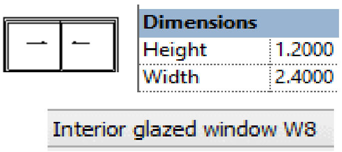
Table 8.4 Extraction required parameters from interior window types

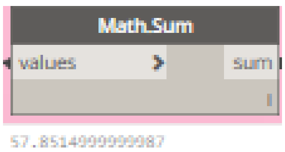
Autodesk Revit	Dynamo
Interior window	Total surface area (m2)





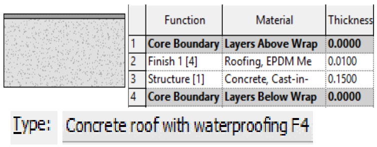
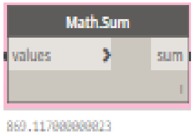
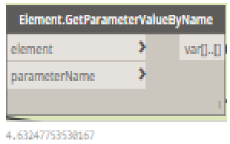
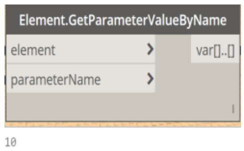
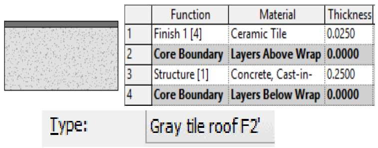
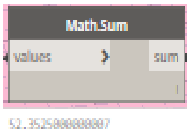
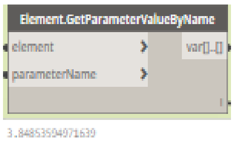
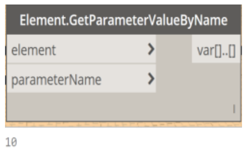
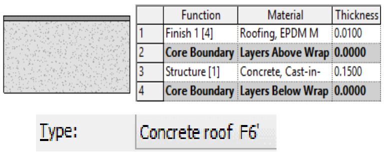
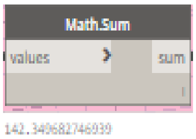
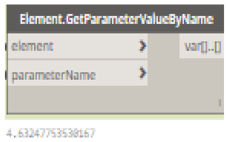
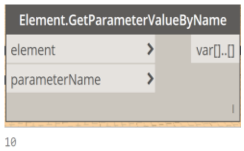






For the roof, the BIM model of the case study building project contains three roof types. There are three parameters that need to extract for calculating the LCCs of each roof type consist of the total surface area, the heat transfer coefficient, and the equivalent temperature difference. Similar with the exterior wall type, the total surface area of each roof type is automatic quantity take-off by using Python scripts. The heat transfer coefficient is supported through the structural design of each roof type. The equivalent temperature difference is input to the BIM model. Table 8.5 shows the value of total surface area of concrete roof with waterproofing F4, gray tile roof F2', and concrete roof F6' are 869.1m^2, 52.4m^2, and 142.3m^2 respectively. Concrete roof with waterproofing F4 has the largest surface area while gray tile roof F2' has the smallest total surface area. The values of heat transfer coefficient of concrete roof with waterproofing f4 and concrete roof F6' are the same is over 4.6 W/(m^2/K). The heat transfer coefficient of gray tile roof F2' is 3.8 W/(m^2/K). The average equivalent temperature difference of three roof types of the case study building is 10^{o}C.

Table 8.5 Extraction required parameters from roof types

Autodesk Revit	Dynamo		
Roof	Total surface area (m2)	Heat transfer coefficient W/(m2/K)	Equivalent temperature difference
			
			
			

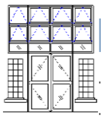
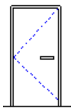
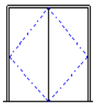
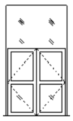
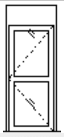
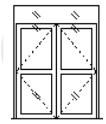
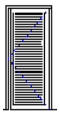
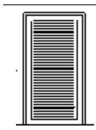
For the floor, the BIM model of the case study building project contains eight floor types. They are one parameter that need to extract the value for the LCCA that is the total surface area. Table 8.6 shows the value of total surface area of gray stone floor F1, gray tile floor F2, ceramic tile floor F3, white-gray terrazzo floor F5, concrete floor F6, gray tile floor F2’, gray stone floor F1’, and concrete floor F6’ are 232.8m^2, 637.2m^2, 188.7m^2, 148.1m^2, and 11.0m^2, 171.0m^2, 2523.5m^2, 888.0m^2, 441.1m^2 respectively. Gray tile floor F2’ has the largest surface area and white-gray terrazzo floor F5 has the smallest total surface area.

For the door, the BIM model of the case study building project has eight door types with contain many element models of each type. There is a parameter that need to extract the value for the LCCA that is the total surface area. The total surface area of each door type is automatic quantity take-off by using Python script nodes to identify and sum the area value of all the elements of each door type. Table 8.7 shows the value of total surface area and heat transfer coefficient of eight door types of the case study building. The results showed the value of the total surface area of exterior metal-glazed double door D1, exterior metal single door D4, exterior plywood double door D9, interior metal-glazed double door D2, interior metal-glazed single door D3, interior metal-glazed double door D10, interior wood single door D5, and interior wood single door D7 are 31.3m^2, 38.2m^2, 15.6m^2, 244.7m^2, 321.8m^2, 259.5m^2, 38.1m^2, 3.4m^2 respectively. Interior metal-glazed single door D3 has the largest surface area. This value is automatically compute from the surface area of 59 elements of interior metal-glazed double door D3 by using a group of Dynamo nodes that is develop by using Python scripts. Interior wood single door D7 has the smallest total surface area.

Table 8.6 Extraction required parameters from floor types

Autodesk Revit Floor	Dynamo Total surface area (m2)
Function / Material / Thickness 1 Finish 1 [/ Ceramic Til / 0.0250 2 Core Bound / Layers Above / 0.0000 3 Structure / Concrete, C / 0.1250 4 Core Bound / Layers Below / 0.0000 Type: Gray stone floor F1	Math.Sum values sum 232.846558338005
Function / Material / Thickness 1 Finish 1 [/ Ceramic Til / 0.0250 2 Core Bound / Layers Abov / 0.0000 3 Structure / Concrete, / 0.1250 4 Core Bound / Layers Below / 0.0000 Type: Gray tile floor F2	Math.Sum values sum 637.28395
Function / Material / Thickness 1 Finish 1 [4] / Ceramic Til / 0.0250 2 Core Boundary / Layers Above / 0.0000 3 Structure [1] / Concrete, C / 0.1250 4 Core Boundary / Layers Below / 0.0000 Type: Ceramic tile floor F3	Math.Sum values sum 188.658949999945
Function / Material / Thickness 1 Finish 1 [4] / Ceramic Til / 0.0250 2 Core Boundar / Layers Above / 0.0000 3 Structure [1] / Concrete, C / 0.2500 4 Core Boundar / Layers Below / 0.0000 Type: White-gray terrazzo floor F5	Math.Sum values sum 18.9744999999993
Function / Material / Thickness 1 Core Boundary / Layers Above / 0.0000 2 Structure [1] / Concrete, Ca / 0.1250 3 Core Boundary / Layers Below / 0.0000 Type: Concrete floor F6	Math.Sum values sum 171.001424485355
Function / Material / Thickness 1 Finish 1 [4] / Ceramic Tile / 0.0250 2 Core Boundary / Layers Above / 0.0000 3 Structure [1] / Concrete, C / 0.2500 4 Core Boundary / Layers Below / 0.0000 Type: Gray tile floor F2'	Math.Sum values sum 2523.54254388573
Function / Material / Thickness 1 Finish 1 [4] / Ceramic Tile / 0.0250 2 Core Boundary / Layers Above / 0.0000 3 Structure [1] / Concrete, Cas / 0.2500 4 Core Boundary / Layers Below / 0.0000 Type: Gray stone floor F1'	Math.Sum values sum 888.003718885727
Function / Material / Thickness 1 Core Boundary / Layers Above Wra / 0.0000 2 Structure [1] / Concrete, Cast-i / 0.2000 3 Core Boundary / Layers Below Wra / 0.0000 Type: Concrete floor F6'	Math.Sum values sum 441.074323241297

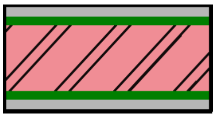
Table 8.7 Extraction required parameters from door types

Autodesk Revit			Dynamo
Door			Total surface area (m2)
 Exterior metal-glazed double door D1	Dimensions Height Width	 3.8000 3.5000	Math.Sum (values > sum) 31.3272999999999
 Exterior metal single door D4	Dimensions Height Width	 2.1500 1.0000	Math.Sum (values > sum) 38.2442999999999
 Exterior plywood double door D9	Dimensions Height Width	 2.0500 1.9000	Math.Sum (values > sum) 15.588
 Interior metal-glazed double door D2	Dimensions Height Width	 3.4500 1.9000	Math.Sum (values > sum) 244.7864999999999
 Interior metal-glazed single door D3	Dimensions Height Width	 2.5000 1.0000	Math.Sum (values > sum) 321.7682999999999
 Interior metal-glazed double door D10	Dimensions Height Width	 2.5000 1.9000	Math.Sum (values > sum) 259.5412499999999
 Interior wood signle door D5	Dimensions Height Width	 2.1500 0.9000	Math.Sum (values > sum) 38.8727749999989
 Interior wood single door D7	Dimensions Height Width	 2.1500 1.1000	Math.Sum (values > sum) 3.4813749999991

For the interior wall, the BIM model of the case study building contains four interior wall types. The total surface area of each interior wall type is automatic quantity take-off by using Python script nodes. Table 8.8 shows the value of total surface area of brick wall W11, gypsum wall W55, cladding tile 12x12 wall W3, and brick and cladding tile 12x12 wall W13 are 3632.9m^2, 890.8m^2, 3.4m^2, and 473.6m^2 respectively. Brick wall W11 has the largest surface area. This value is automatically compute from the surface area of 280 elements of brick wall W11 by using a group of Dynamo scripts. And cladding tile 12x12 wall W3 has the smallest total surface area.

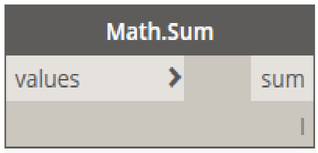
Table 8.8 Extraction required parameters from interior wall types

Autodesk Revit	Dynamo
Interior wall	Total surface area (m2)



	Function	Material	Thickness
1	Finish 1 [4]	Concrete, San	0.0150
2	**Core Boundary**	**Layers Above**	**0.0000**
3	Structure [1]	Brick, Comm	0.0700
4	**Core Boundary**	**Layers Below**	**0.0000**
5	Finish 2 [5]	Concrete, San	0.0150

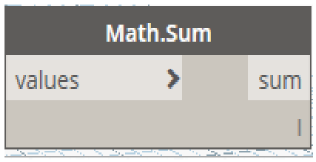
Type: Brick wall W11



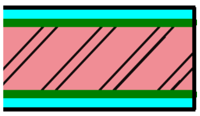
3632.89089289876

	Function	Material	Thickness
1	**Core Boundary**	**Layers Above**	**0.0000**
2	Structure [1]	Gypsum Wall	0.1000
3	**Core Boundary**	**Layers Below**	**0.0000**

Type: Gypsum wall W55

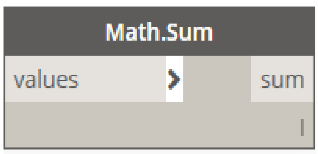


890.834999991308

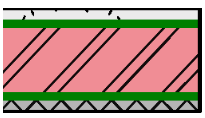


	Function	Material	Thickness
1	Finish 1 [4]	Ceramic Tile	0.0150
2	**Core Boundary**	**Layers Above**	**0.0000**
3	Structure [1]	Brick, Comm	0.0700
4	**Core Boundary**	**Layers Below**	**0.0000**
5	Finish 2 [5]	Ceramic Tile	0.0150

Type: Cladding tile 12X12 wall W3

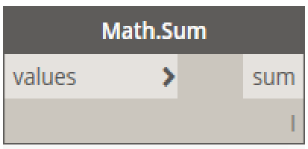


3.39999999999996



	Function	Material	Thickness
1	Finish 1 [4]	Concrete, San	0.0150
2	**Core Boundary**	**Layers Above**	**0.0000**
3	Structure [1]	Brick, Comm	0.0700
4	**Core Boundary**	**Layers Below**	**0.0000**
5	Finish 2 [5]	Ceramic Tile	0.0150

Type: Brick and cladding tile 12X12 wall W13



473.646528077081

8.4.6 Results of the building LCCA for the case study building

The results of the building LCCA of the case study project is exported to the spreadsheet report automatically as shown in Table 8.9. There are twelve results to be selected represent into the spreadsheet report consist of (1) Element type code, (2) Description, (3) Construction cost, (4) Percentage of construction cost over the total building construction cost, (5) Maintenance cost, (6) Percentage of maintenance cost over the total building maintenance cost, (7) Energy cost, (8) Percentage of energy cost over the total building maintenance cost, (9) Salvage value, (10) Percentage of salvage value over the total building salvage value, (11) Life-cycle cost, (12) Percentage of life-cycle cost over the total building life-cycle cost. For example, the total construction cost of exterior metal-glazed window W1', exterior metal-glazed window W1", exterior metal-glazed window W1'", exterior metal-glazed window W1"", exterior metal-glazed window W4', exterior metal-glazed window W4", exterior metal-glazed window W4'", exterior metal-glazed window W5', exterior metal-glazed window W5", exterior frosted glazed window W2, exterior glazed window W2', exterior glazed window W3, exterior glazed window W3', and exterior metal window W10 are 971,290.00 Baht; 86,344.30 Baht; 125,759.40 Baht; 70,445.55 Baht; 620,325.00 Baht; 20,998.75 Baht; 37,545.00 Baht; 587,210.00 Baht; 114,750.00 Baht; 707,594.76 Baht; 125,365.00 Baht; 161,478.49 Baht; 98,900.52 Baht; and 3,517.50 Baht, respectively. The exterior metal-glazed window W1' spend the highest construction cost among all exterior window types accounting for 3.35 percentage of the total construction cost of the case study building. Exterior metal window W10 spend the smallest construction cost among all exterior window types of the case study building. The total maintenance cost of fourteen exterior window are 730,660.34 Bath; 64,953.16 Baht; 47,301.74 Baht; 52,993.20 Baht; 429,312.69 Baht; 14,532.75 Baht; 25,984.03 Baht; 406,394.56 Baht; 79,415.84 Baht; 247,478.32 Baht; 43,837.03 Baht; 63,511.91 Baht; 38,899.06 Baht; 2,434.38 Baht respectively. The exterior metal-glazed window W1' spend the highest maintenance cost among all exterior window types accounting for 8.10 percentage of the total maintenance cost of the case study building. Exterior metal-glazed window W4" spend the smallest maintenance cost among all exterior window types of the case study building. The total energy cost of fourteen exterior window types are 1,192,634.92 Baht; 106,021.09

Baht; 77,209.20 Baht; 86,499.22 Baht; 700,754.21 Baht; 23,721.38 Baht; 42,412.96 Baht; 663,345.63 Baht; 129,628.09 Baht; 403,951.42 Baht; 71,553.86 Baht; 103,668.58 Baht; 63,493.76 Baht; 3,973.57 Baht, respectively. The exterior metal-glazed window W1' spend the highest energy cost among all exterior window types accounting for 3.69 percentage of the total energy cost of the case study building. Exterior metal window W10 spend the smallest energy cost among all exterior window types of the case study building. The salvage value of fourteen exterior window types are 31,898.89 Baht; 2,835.70 Baht; 4,130.16 Baht; 2,313.56 Baht; 20,372.58 Baht; 689.64 Baht; 1,233.04 Baht; 19,285.02 Baht; 3,768.59 Baht; 23,238.67 Baht; 4,117.21 Baht; 5,303.24 Baht; 3,248.07 Baht; 115.52 Baht, respectively. That mean exterior metal-glazed window W1' saves the highest salvage value among all exterior window types accounting for 2.33 percentage of the total energy cost of the case study building. Exterior metal window W10 saves the smallest salvage value among all exterior window types of the case study building. The total life-cycle cost of fourteen window types are 2,862,686.37 Baht; 254,482.85 Baht; 246,140.18 Baht; 207,624.41 Baht; 1,730,019.33 Baht; 58,563.24 Baht; 104,708.94 Baht; 1,637,665.17 Baht; 320,025.34 Baht; 1,335,785.83 Baht; 236,638.68 Baht; 323,355.74 Baht; 198,045.26 Baht; 9,809.93 Baht respectively. The exterior metal-glazed window W1' spend the highest life-cycle cost among all exterior window types accounting for 4.21 percentage of the total life-cycle cost of the case study building. Exterior metal window W10 spend the smallest life-cycle cost among all exterior window types of the case study building.

Table 8.9 Exported the LCC results of the case study building

Element Type Code	Element Name	Construction Cost	Percent	Maintenance Cost	Percent	Energy Cost	Percent	Salvage Value	Percent	Life-cycle cost	Percent
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
B2020111	Exterior metal-glazed window W1'	971,290.00	3.35	730,660.34	7.85	1,192,634.92	3.69	31,898.89	2.33	2,862,686.37	4.13
B2020112	Exterior metal-glazed window W1''	86,344.30	0.30	64,953.16	0.70	106,021.09	0.33	2,835.70	0.21	254,482.85	0.37
B2020113	Exterior metal-glazed window W1'''	125,759.40	0.43	47,301.74	0.51	77,209.20	0.24	4,130.16	0.30	246,140.18	0.36
B2020114	Exterior metal-glazed window W1''''	70,445.55	0.24	52,993.20	0.57	86,499.22	0.27	2,313.56	0.17	207,624.41	0.30
B2010151	Exterior metal-glazed window W4'	620,325.00	2.14	429,312.69	4.61	700,754.21	2.17	20,372.58	1.49	1,730,019.33	2.50
B2010153	Exterior metal-glazed window W4''	20,998.75	0.07	14,532.75	0.16	23,721.38	0.07	689.64	0.05	58,563.24	0.08
B2020118	Exterior metal-glazed window W4'''	37,545.00	0.13	25,984.03	0.28	42,412.96	0.13	1,233.04	0.09	104,708.94	0.15
B2020121	Exterior metal-glazed window W5'	587,210.00	2.02	406,394.56	4.36	663,345.63	2.05	19,285.03	1.41	1,637,665.17	2.36
B2020121	Exterior metal-glazed window W5''	114,750.00	0.40	79,415.84	0.85	129,628.09	0.40	3,768.59	0.28	320,025.34	0.46
B2020211	Exterior frosted glazed window W2	707,594.76	2.44	247,478.32	2.66	403,951.42	1.25	23,238.67	1.70	1,335,785.83	1.93
B2020311	Exterior glazed window W2'	125,365.00	0.43	43,837.03	0.47	71,553.86	0.22	4,117.21	0.30	236,638.68	0.34
B2020312	Exterior glazed window W3	161,478.49	0.56	63,511.91	0.68	103,668.58	0.32	5,303.24	0.39	323,355.74	0.47
B2020313	Exterior glazed window W3'	98,900.52	0.34	38,899.06	0.42	63,493.76	0.20	3,248.07	0.24	198,045.26	0.29
B2020511	Exterior metal window W10	3,517.50	0.01	2,434.38	0.03	3,973.57	0.01	115.52	0.01	9,809.93	0.01
C1010711	Interior glazed window W7	163,990.00	0.56	113,493.71	1.22	-	-	-	-	277,483.71	0.40
C1010712	Interior glazed window W7'	7,680.00	0.03	5,315.15	0.06	-	-	-	-	12,995.15	0.02
C1010713	Interior glazed window W8	144,628.75	0.50	100,094.24	1.07	-	-	-	-	244,722.99	0.35
B2030121	Exterior metal-glazed double door D1	117,759.32	0.41	3,568.65	0.04	-	-	3,867.43	0.28	117,460.54	0.17
B2030122	Exterior metal single door D4	444,704.71	1.53	4,356.60	0.05	-	-	14,604.89	1.07	434,456.43	0.63
B2030131	Exterior plywood double door D9	200,103.16	0.69	2,696.44	0.03	-	-	6,571.74	0.48	196,227.86	0.28
C1020111	Interior metal-glazed double door D2	1,045,386.17	3.60	22,713.57	0.24	-	-	-	-	1,068,099.73	1.54
C1020112	Interior metal-glazed single door D3	1,544,487.84	5.32	29,866.41	0.32	-	-	-	-	1,574,354.25	2.27
C1020113	Interior metal-glazed double door D10	1,529,995.67	5.27	24,090.52	0.26	-	-	-	-	1,554,086.19	2.24
C1020121	Interior wood signle door D5	236,127.35	0.81	4,835.02	0.05	-	-	-	-	240,960.48	0.35
C1020122	Interior wood single door D7	17,258.58	0.06	431.79	0.00	-	-	-	-	17,690.36	0.03
B2010151	Red ceramic tile 4x8 wall W66	1,400,158.90	4.82	44,037.08	0.47	12,962,529.92	40.12	110,360.90	8.06	14,296,365.00	20.63
B2010153	Cladding tile 12x12 and red ceramic tile 4x8 wall W36	142,513.25	0.49	3,768.63	0.04	1,004,026.48	3.11	11,232.93	0.82	1,139,075.43	1.64
B2010154	Brick and red ceramic tile 4x8 wall W16	138,720.51	0.48	4,362.97	0.05	1,174,424.43	3.63	10,933.99	0.80	1,306,573.92	1.89
B2010511	Balcony wall W8-1	132,195.79	0.46	8,202.12	0.09	2,240,291.32	6.93	10,419.71	0.76	2,370,269.52	3.42
C1010131	Brick wall W11	4,541,113.62	15.64	4,325,492.47	46.45	-	-	357,931.80	26.13	8,508,674.28	12.28
C1010151	Gypsum wall W55	596,859.45	2.06	83,018.61	0.89	-	-	11,201.10	0.82	668,676.95	0.97
C1010131	Cladding tile 12X12 wall W3	3,009.00	0.01	2,211.22	0.02	-	-	237.17	0.02	4,983.05	0.01
C1010211	Brick and cladding tile 12X12 wall W13	1,234,741.32	4.25	854,536.12	9.18	-	-	97,322.64	7.11	1,991,954.80	2.88
C3020411	Gray stone floor F1	334,367.66	1.15	52,067.03	0.56	-	-	17,569.97	1.28	368,864.73	0.53
C3020431	Gray tile floor F2	778,663.23	2.68	142,485.76	1.53	-	-	40,916.30	2.99	880,232.69	1.27
C3020441	Ceramic tile floor F3	149,095.00	0.51	27,282.54	0.29	-	-	7,834.47	0.57	168,543.07	0.24
C3020461	White-gray terrazzo floor F5	23,913.44	0.08	2,454.02	0.03	-	-	1,256.58	0.09	25,110.88	0.04
C3020471	Concrete floor F6	132,974.23	0.46	37,261.26	0.40	-	-	6,987.38	0.51	163,248.11	0.24
C3020432	Gray tile floor F2'	5,372,234.60	18.51	564,250.98	6.06	-	-	282,293.99	20.61	5,654,191.59	8.16
C3020412	Gray stone floor F1'	1,801,390.27	6.21	198,526.63	2.13	-	-	94,657.38	6.91	1,905,259.52	2.75
C3020472	Concrete floor F6'	701,297.07	2.42	107,115.90	1.15	-	-	36,850.95	2.69	771,562.02	1.11
C3020452	Concrete roof with waterproofing F4	405,979.56	1.40	51,434.26	0.55	1,965,357.52	6.08	21,332.95	1.56	2,401,438.40	3.47
C3020431	Gray tile roof F2'	111,458.47	0.38	11,706.59	0.13	371,622.29	1.15	5,856.79	0.43	488,930.56	0.71
C3020417	Concrete roof F6'	1,843,831.41	6.35	233,598.21	2.51	8,926,035.34	27.62	96,887.53	7.07	10,906,577.44	15.74
		29,028,162.59	100.00	9,312,981.63	100.00	32,313,155.20	100.00	1,369,678.48	100.00	69,284,620.94	100.00

8.5 System validation of the research

8.5.1 The manual calculation for an example interior wall type

To evaluate the reliability of the results from the BIM-BLCC, the inter-item test is applied to evaluate the reliability of the BIM-BLCC. This research conducted the manual calculation for the LCCs of an interior wall type of the case study building, namely a brick wall W11. This building element type consist of 280 elements that are located: (1) one element 2 elements at the at the ground level, (2) 34 elements at the first floor, (3) 43 elements at the second floor, (4) 59 elements at the third floor, (5) 62 elements at the fourth floor, (6) 62 elements at the fifth floor, and (7) 19 elements at the sixth floor. The manual calculation applied the formulations in Section 6.2 that are used to develop the BIM-BLCC for evaluating the building LCCs. Furthermore, all assumed parameters of the case study building also applied in the manual calculation for calculating the LCCs of the brick wall W11. After conducting the comparison between the results from the manual calculation and the results from the BIM-BLCC, the authors found the similar results from both approaches, it indicates that the reliability of the BIM-BLCC is acceptable.

The total LCCs of the case study building is 69,284,620.94 baht. The total construction cost of the case study building is 29,028,162.59 baht, accounting for nearly 41.90 percent of the total building LCCs. The total maintenance cost of the case study building is 9,312,981.63 baht, accounting for nearly 13.44 percent of the total building life-cycle cost. The total cost of the energy consumption of the case study building is 32,313,155.20 baht, accounting for near 46.64 percent of the total building LCCs. The total salvage value of the case study building after the period of 30 years is 1,369,678.48 baht, accounting for nearly 1.98 percent of the total building LCCs. According to S. Kirk, J., and Dell'Isola, A., J. (1995), the operation cost accounts for from 40 to 50 percentage of the architectural life-cycle cost for a 30 years period. This value is used as a reference standard to measure the reliability of the BIM-BLCC. Based on the resuls of the building LCCA for the case study building, we can conclude that the reliability of the BIM-BLCC is acceptable.

8.5.2 Evaluation of the BIM-BLCC by expert interview

It is the process to evaluate whether the BIM-BLCC meet real world situation in term of the method proposed and the results obtained. There are two executors who have experience in the BIM and sustainability are interviewed. The validation process was conducted by presenting the works and discussing the outcomes.

Both respondents gave the positive response towards the BIM-BLCC. The interesting issues and suggestions from the respondents who joined the validation process as below. These suggestions will be discussed on the Chapter 9 of this research.

- From the BIM implementation in construction management
  - The BIM-BLCC can help the cost estimators solve the time consuming caused by the repetitive works in the building LCCA.
  - The BIM-BLCC can solve a main difficulty of the building LCCA that is data problem by providing a logical and systematic approach for the data organization and a data warehouse for the BIM models to estimate the whole life costing of building projects.
  - The BIM-BLCC can help to reduce cost for investing and maintaining compare with the conventional building LCCA tools.
  - The building LCCA is not considered in procurement system in Thailand. Because of the deadline time of tender submission, the tender evaluation usually relies on the lowest construction cost to assign the construction contract awards.
  - The respondent agreed that the integrated BIM platforms contribute to solve the difficulties of the conventional building LCCA methods.
  - The respondent suggested the extension of the BIM-BLCC for the safety training system
  - Most of Thailand construction companies are using the BIM technology for clash detection. The respondent suggested the extension of the BIM implementation to develop the cost estimation system that is very necessary tool for Thailand construction industry.
- From the sustainability

- The BIM-BLCC complies with the practical building LCCA process in the construction industry.
- The assumed parameters of mathematical model should be applied following the building energy code in Thailand.
- The BIM-BLCC should be extended for evaluating the building design alternative
- The BIM-BLCC should be extended to evaluate the building LCCA for the real building projects.
- The respondent suggested the limitation of the BIM-BLCC for the simple energy cost calculation.

8.6 **Summary**

After developed the BIM-database-integrated system for evaluating building LCCs using a multi-parametric model, system application needs to be implemented in order to make sure the workability of the BIM-BLCC that complies with the initial objectives of the developers. In addition, system validation is also implemented to evaluate the reliability of the developed system. This chapter represents five parts of system verification and validation. The first step presented the purposes of system verification and validation of the research. The second step presented characteristics of the case study building project. The third step presented a process of the BIM-BLCC application into a real project. The fourth step presented the results and discussions of system application. The final step presented system validation through the manual calculation and the expert interview. Compare the results from the BIM-BLCC and the results from the manual calculation, the authors found that both building LCCA approaches yielded similar results, it indicates that the BIM-BLCC is acceptable. However, the BIM-BLCC can save time for the calculating process. Furthermore, it also helps to improve the accuracy of the results by excluding human errors in the data exchange process. The result of the BIM-BLCC is similar with a reference standard to measure the building LCCA. Therefore, it can be concluded that the BIM-BLCC has enough capacity to be used in the real building projects.

CHAPTER 9
SUMMARY AND CONCLUSION

This chapter presents the summary of this research by focusing on the structure of the proposed BIM-database-integrated system for evaluating building life-cycle costs using a multi-parametric model (BIM-BLCC), which consists of four modules, namely, the relational database management module, the visualized BIM-integrated module, the multi-parametric estimation module, and the BIM-integrated report module. It will then discuss the conclusions for this research, the contributions, and the limitations of the BIM-BLCC. The final section presents the recommendations for further research.

9.1 Summary and conclusion of the research

This research develops the BIM-database-integrated system for evaluating building life-cycle costs using a multi-parametric model, called the BIM-BLCC. It provides a systematic observational approach to clearly define the building elements for the building LCCA. The BIM-BLCC consists of four main modules: the relational database management module (module 1), the visualized BIM-integrated module (module 2), the multi-parametric estimation module (module 3), and the BIM-integrated report module (module 4).

The relational database management module accommodates the required data for the 3D BIM models. The required data form the integration between the visualized BIM-integrated module and the relational database management module. The relational database is used to store and update the required data for the BIM models. The results of this module are a systematic approach for the data organization and a data warehouse for the BIM models. This module also represents the solution to increase the consistency of the data for evaluating the building LCCA and to reduce waste data.

The visualized BIM-integrated module establishes an appropriate level of development (LOD) of each building element model of the BIM model. Another purpose of this module is to support the thermal coefficients of the building element models for calculating energy costs. In addition, this module integrates the relational database management with the BIM model for extracting the required data for the building LCCA. The results of this module is the prepared BIM model, which can be used for assessing the building LCCA.

The multi-parametric estimation module is an automated system for evaluating the building LCCA. It entails the mathematical formulas for calculating different cost categories of the building LCCA. The multi-parametric model is designed to efficiently compute the building LCC. It is also flexible to modify to the change of the parameters while analyzing. This module can also minimize human errors due to data input.

The BIM-integrated report module summarizes the results of the multi-parametric estimation module and assists in visualizing them. This module offers a simple approach for the project stakeholders to access and comprehend the system results. Another objective of this module is to enhance the calculation efficiency of the multi-parametric estimation module. Its outcome is an automatic report of the system.

The efficacy and practicality of the BIM-BLCC were verified through applying it to an actual building project. Visual programming interface was used as the programming language for the software development. The LCCs of all building elements of the 3D BIM model were assessed using the multi-parametric model. The manual calculation was conducted and its results were compared with those provided by the BIM-BLCC. Since both approaches yield similar results, it indicates that the BIM-BLCC is acceptable. Thus, it can be concluded that the BIM-BLCC can used to evaluate the building LCCA in real building projects.

9.2 Contribution of the research

According to national Code of many countries, the LCCA criterion is a mandatory article for selecting the contracting authorities for the public building procurement system. The practice of the building LCCA is a time-consuming process due to repetitive works, numerous required data, the complexity of the inputs (e.g., the thermal coefficients for calculating the energy cost), and the regulatory requirements in the traditional building LCCA. Moreover, the accuracy of results is a major limitation of the building LCCA because human errors due to manual data input are unavoidable.

The BIM-BLCC is a visualized approach that clearly defines the element models of the building. Users can better appreciate building details through the 3D model. This merit is not offered by the traditional LCCA approach which is based on 2D CAD drawings. The BIM-BLCC also provides the identification of the location, quantity, and material structures of the target objects. This visualized approach can also vividly and efficiently communicate the LACCA results to all project stakeholders.

The BIM-BLCC adopts a systematic method to organize and store data for the building LCCA. Typically, computing the building LCC requires enormous amount of data, most of which are usually recorded in paper documents and segregated sources. Collecting these data is therefore an extremely challenging task for everyone involved. In addition, a standard or guideline for organizing such data also does not exist. As a result, the building LCCA is a costly and time-consuming process. The proposed system provides a solution for these problems through its organized data structure and relational database. Clearly, this is a main contribution of this research.

The BIM-BLCC is as an automated method to accommodate the required data for the BIM model. The only BIM cannot have the capacities to take care the building LCCA. In order to reduce the cost and time of the building LCCA process, the automated method for extracting the required data for the 3D BIM model is developed by integrating the BIM authoring programming, the database management system, the spreadsheet system, and the visual programming interface.

The BIM-BLCC also employs a new method for yielding the thermal coefficients for the energy cost calculation. The energy cost is considered one of the most complex cost categories for the building LCCA. Estimating its inputs is also a challenging tasks for analysts (e.g., the thermal coefficients such as heat transfer coefficient or the solar heat gain coefficient). To avoid this problem, the energy cost category is often ignored while performing the LCCA. The BIM-BLCC can readily address these problems by estimating the thermal coefficients for the element model through its structural design.

The BIM-BLCC is structured in the form of a multi-parametric model. A building project usually consists of a large number of element models, which subsequently complicated the analysis. The BIM-BLCC employs an automated method to takeoff the total surface area of the building element types by using the Python script. It offers an innovative tool for performing the LCCA through by reducing computation time and human errors.

It should be noted that the primary objective of this research is not to revolutionize the LCCA process. The proposed system is engineered to enhance the efficacy of such process. This can be achieved through the efficient and effective interchange of both human abilities and computer capabilities. Typically, once there is a simple change of any building element design, it might take very long time for re-calculating the LCC. To cope with this problem, contractors usually ignore the LCCA and make their decision on the basis of lowest construction costs. They can now handle with a design change more readily by using the BIM-BLCC. The BIM-BLCC can not only offer a tool for facilitating the collaboration among owners, contractors, and designers, but it can also guide a trend toward the building LCCA criterion for the sustainable procurement system.

9.3 Limitations of the research

Even though the BIM-BLCC has been successfully developed and achieved the proposed objectives, this research entails a number of limitations.

This system is primarily designed for building projects. It was applied to an office building, which consists of structural, architectural, mechanical, electrical, and plumping systems. However, in the case study we focused only one the architectural system. This is one of main limitations of this research.

The BIM-BLCC estimates the building energy cost by focusing only on the building envelop elements, including exterior walls, exterior windows, roofs, and skylight glazing. This is one more limitation of this research.

Another limitation concerns the selected platforms. The BIM-BLCC is developed based on four main platforms: Microsoft Access, Autodesk Revit, Dynamo, and Microsoft Excel. It may limit the enrichment for selecting the platforms to develop the BIM-BLCC.

The next limitation concerns to the raw data used to develop the system. The BIM-BLCC should incorporate more required data to expand its applicability to other building types. In addition, the data must be updated regularly to guarantee the reliability of results.

Although the BIM-BLCC might not be perfect and entails some limitations, it provides an innovative valuable methodology to address several major challenges of the current building LCCA practice. It can therefore promote the implementation of the sustainable procurement system.

9.4 Recommendations for further research

Even though the accuracy of the results by the BIM-BLCC in this research is considered acceptable, we would like to propose some recommendations to improve the efficiency of the BIM-BLCC.

The BIM-BLCC should be extended to perform the building LCCA for other building systems such as structural, mechanical, and electrical systems.

To increase the efficiency of the BIM-BLCC, the relational database should be extended it scope for more various BIM models. This requires the cooperation from the project participants. To reduce time for collecting data, an automatic system for extracting the data in the cloud environment might be a potential option.

To increase the benefits of the BIM-BLCC for the sustainability, it should be integrated with a decision support system for selecting the optimal building design. In addition, it can also be integrated with the project cost monitoring system.

APPENDIX A STRUCTURE QUERY LANGUAGE (SQL) CODE FOR QUERYING REQUIRED DATA OF THE BIM MODEL OF THE CASE STUDY BUILDING PROJECT

```
SELECT ExteriorWindows.ElementTypeCode,
ExteriorWindows.ConstructionUnitRate, ExteriorWindows.ExpectedServiceLife,
ExteriorWindows.AnnualServiceUnitRate
FROM ExteriorWindows
WHERE (((ExteriorWindows.ElementTypeCode)="B2020111" Or
(ExteriorWindows.ElementTypeCode)="B2020112" Or
(ExteriorWindows.ElementTypeCode)="B2020113" Or
(ExteriorWindows.ElementTypeCode)="B2020114" Or
(ExteriorWindows.ElementTypeCode)="B2020117" Or
(ExteriorWindows.ElementTypeCode)="B2020118" Or
(ExteriorWindows.ElementTypeCode)="B2020121" Or
(ExteriorWindows.ElementTypeCode)="B2020211" Or
(ExteriorWindows.ElementTypeCode)="B2020311" Or
(ExteriorWindows.ElementTypeCode)="B2020312" Or
(ExteriorWindows.ElementTypeCode)="B2020313"))
UNION
SELECT InteriorWindows.ElementTypeCode,
InteriorWindows.ConstructionUnitRate, InteriorWindows.ExpectedServiceLife,
InteriorWindows.AnnualServiceUnitRate
FROM InteriorWindows
WHERE (((InteriorWindows.ElementTypeCode)="C1010711" Or
(InteriorWindows.ElementTypeCode)="C1010712" Or
(InteriorWindows.ElementTypeCode)="C1010713"))
UNION
SELECT Doors.ElementTypeCode, Doors.ConstructionUnitRate,
Doors.ExpectedServiceLife, Doors.AnnualServiceUnitRate
```

FROM Doors

WHERE (((Doors.ElementTypeCode)="B2030121" Or
(Doors.ElementTypeCode)="B2030122" Or (Doors.ElementTypeCode)="B2030131"
Or (Doors.ElementTypeCode)="C1020111"Or
(Doors.ElementTypeCode)="C1020112"Or
(Doors.ElementTypeCode)="C1020113"Or (Doors.ElementTypeCode)="C1020121"
Or (Doors.ElementTypeCode)="C1020122"))

UNION

SELECT ExteriorWalls.ElementTypeCode, ExteriorWalls.ConstructionUnitRate,
ExteriorWalls.ExpectedServiceLife, ExteriorWalls.AnnualServiceUnitRate

FROM ExteriorWalls

WHERE (((ExteriorWalls.ElementTypeCode)="B2010151" Or
(ExteriorWalls.ElementTypeCode)="B2010153" Or
(ExteriorWalls.ElementTypeCode)="B2010154" Or
(ExteriorWalls.ElementTypeCode)= "B2010511"))

UNION

SELECT InteriorWalls.ElementTypeCode, InteriorWalls.ConstructionUnitRate,
InteriorWalls.ExpectedServiceLife, InteriorWalls.AnnualServiceUnitRate

FROM InteriorWalls

WHERE (((InteriorWalls.ElementTypeCode)="C1010111" Or
(InteriorWalls.ElementTypeCode)="C1010151" Or
(InteriorWalls.ElementTypeCode)="C1010131" Or
(InteriorWalls.ElementTypeCode)="C1010211"))

UNION

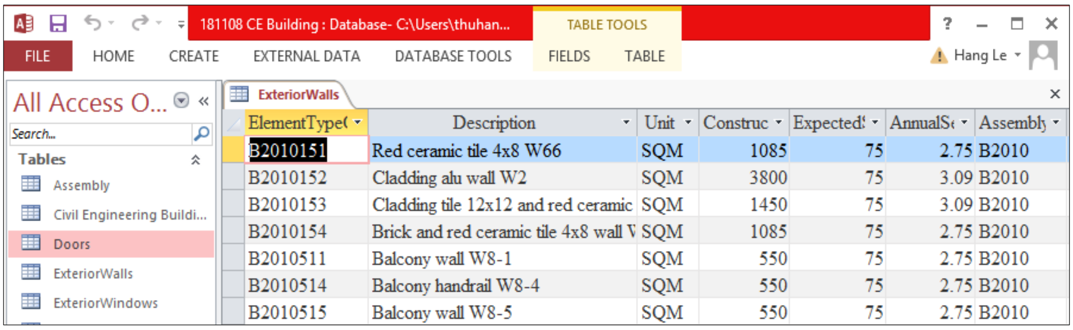
SELECT Floors.ElementTypeCode, Floors.ConstructionUnitRate,
Floors.ExpectedServiceLife, Floors.AnnualServiceUnitRate

FROM Floors

WHERE (((Floors.ElementTypeCode)="C3020411" Or
(Floors.ElementTypeCode)="C3020431" Or
(Floors.ElementTypeCode)="C3020441"Or(Floors.ElementTypeCode)="C3020461"
Or (Floors.ElementTypeCode)="C3020471" Or

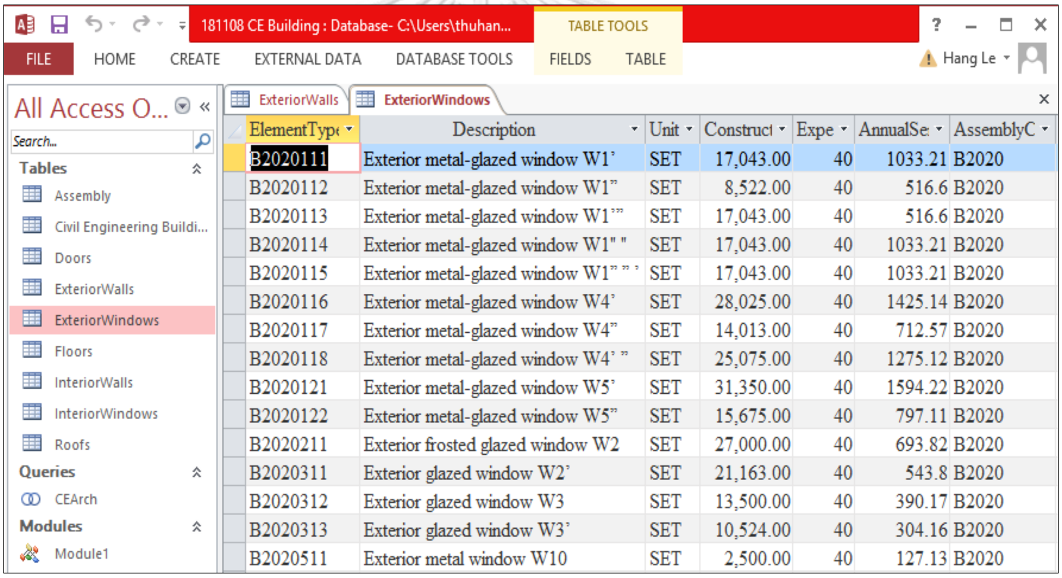
```
(Floors.ElementTypeCode)="C3020432" Or (Floors.ElementTypeCode)="C3020412"
Or (Floors.ElementTypeCode)="C3020472"))
    UNION
    SELECT Roofs.ElementTypeCode, Roofs.ConstructionUnitRate,
Roofs.ExpectedServiceLife, Roofs.AnnualServiceUnitRate
    FROM Roofs
    WHERE (((Roofs.ElementTypeCode)="C3020452" Or
(Roofs.ElementTypeCode)="C3020431" Or (Roofs.ElementTypeCode)="C3020471"));
```

APPENDIX B TABLES OF THE RELATIONAL DATABASE OF THE BIM-BLCC



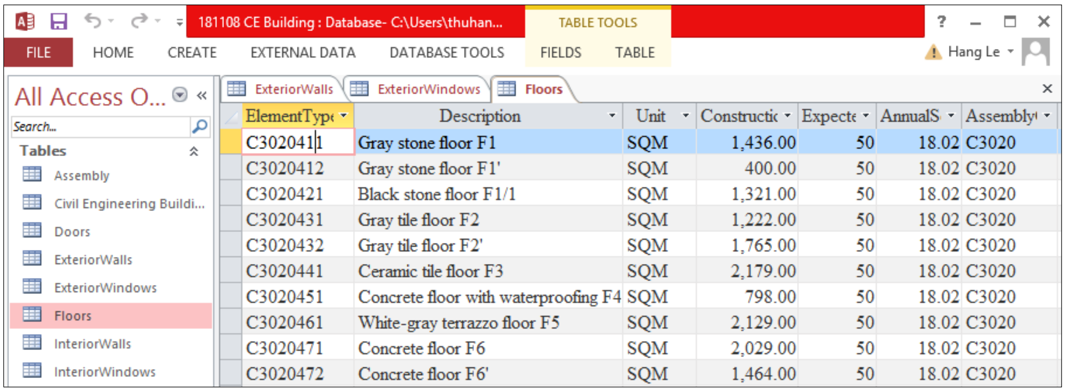
ElementType(	Description	Unit	Construc	Expected!	AnnualS	Assembly
B2010151	Red ceramic tile 4x8 W66	SQM	1085	75	2.75	B2010
B2010152	Cladding alu wall W2	SQM	3800	75	3.09	B2010
B2010153	Cladding tile 12x12 and red ceramic	SQM	1450	75	3.09	B2010
B2010154	Brick and red ceramic tile 4x8 wall V	SQM	1085	75	2.75	B2010
B2010511	Balcony wall W8-1	SQM	550	75	2.75	B2010
B2010514	Balcony handrail W8-4	SQM	550	75	2.75	B2010
B2010515	Balcony wall W8-5	SQM	550	75	2.75	B2010

The ExteriorWalls table of the relational database of the BIM-BLCC



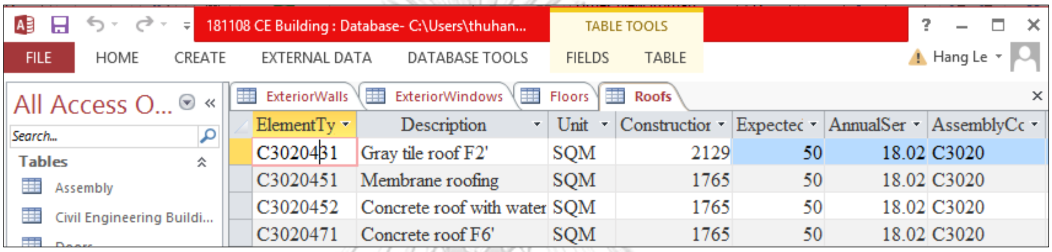
ElementTyp	Description	Unit	Construct	Expe	AnnualSe	AssemblyC
B2020111	Exterior metal-glazed window W1'	SET	17,043.00	40	1033.21	B2020
B2020112	Exterior metal-glazed window W1"	SET	8,522.00	40	516.6	B2020
B2020113	Exterior metal-glazed window W1'"	SET	17,043.00	40	516.6	B2020
B2020114	Exterior metal-glazed window W1" "	SET	17,043.00	40	1033.21	B2020
B2020115	Exterior metal-glazed window W1" " '	SET	17,043.00	40	1033.21	B2020
B2020116	Exterior metal-glazed window W4'	SET	28,025.00	40	1425.14	B2020
B2020117	Exterior metal-glazed window W4"	SET	14,013.00	40	712.57	B2020
B2020118	Exterior metal-glazed window W4' "	SET	25,075.00	40	1275.12	B2020
B2020121	Exterior metal-glazed window W5'	SET	31,350.00	40	1594.22	B2020
B2020122	Exterior metal-glazed window W5"	SET	15,675.00	40	797.11	B2020
B2020211	Exterior frosted glazed window W2	SET	27,000.00	40	693.82	B2020
B2020311	Exterior glazed window W2'	SET	21,163.00	40	543.8	B2020
B2020312	Exterior glazed window W3	SET	13,500.00	40	390.17	B2020
B2020313	Exterior glazed window W3'	SET	10,524.00	40	304.16	B2020
B2020511	Exterior metal window W10	SET	2,500.00	40	127.13	B2020

The ExteriorWindows table of the relational database of the BIM-BLCC



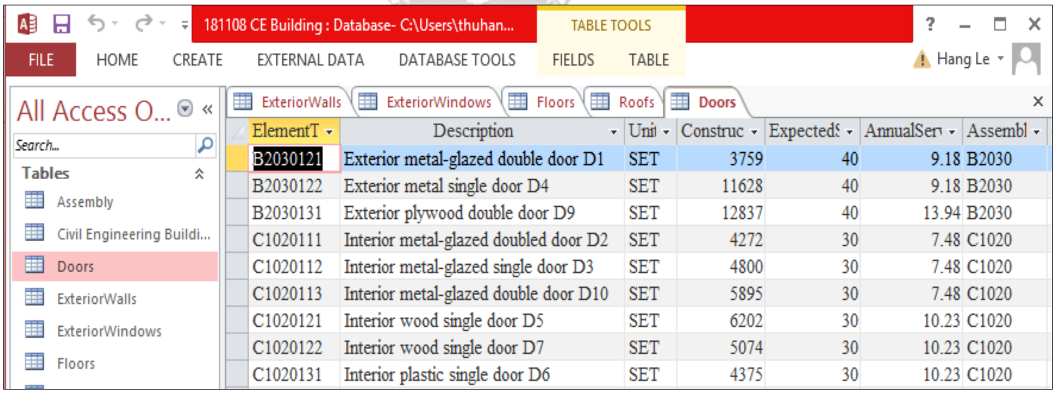
ElementTyp	Description	Unit	Constructic	Expecte	AnnualS	Assembly
C3020411	Gray stone floor F1	SQM	1,436.00	50	18.02	C3020
C3020412	Gray stone floor F1'	SQM	400.00	50	18.02	C3020
C3020421	Black stone floor F1/1	SQM	1,321.00	50	18.02	C3020
C3020431	Gray tile floor F2	SQM	1,222.00	50	18.02	C3020
C3020432	Gray tile floor F2'	SQM	1,765.00	50	18.02	C3020
C3020441	Ceramic tile floor F3	SQM	2,179.00	50	18.02	C3020
C3020451	Concrete floor with waterproofing F4	SQM	798.00	50	18.02	C3020
C3020461	White-gray terrazzo floor F5	SQM	2,129.00	50	18.02	C3020
C3020471	Concrete floor F6	SQM	2,029.00	50	18.02	C3020
C3020472	Concrete floor F6'	SQM	1,464.00	50	18.02	C3020

The Floors table of the relational database of the BIM-BLCC



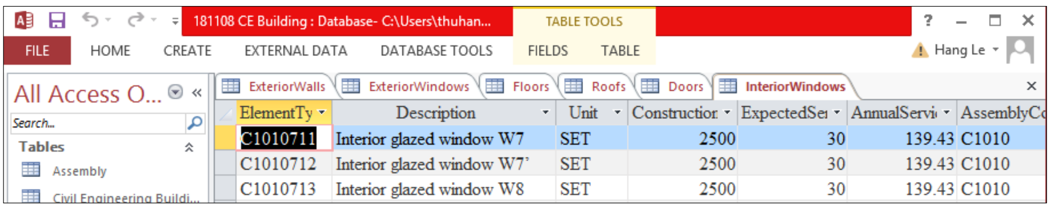
ElementTy	Description	Unit	Constructior	Expectec	AnnualSer	AssemblyCc
C3020431	Gray tile roof F2'	SQM	2129	50	18.02	C3020
C3020451	Membrane roofing	SQM	1765	50	18.02	C3020
C3020452	Concrete roof with water	SQM	1765	50	18.02	C3020
C3020471	Concrete roof F6'	SQM	1765	50	18.02	C3020

The Roofs table of the relational database of the BIM-BLCC



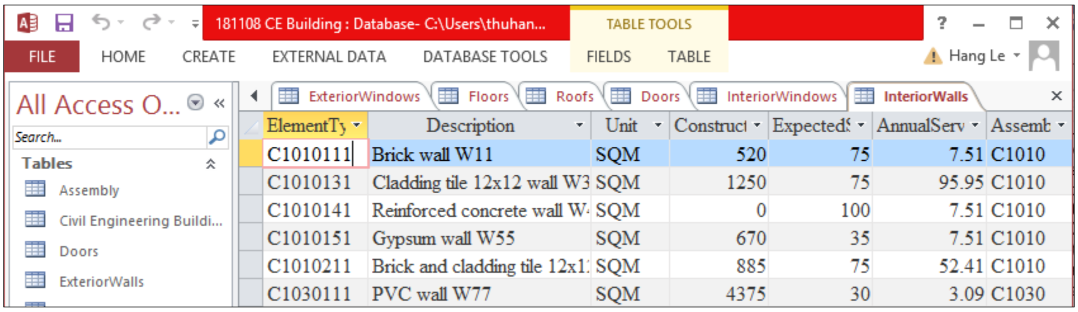
ElementT	Description	Unit	Construc	Expected	AnnualSer	Assembl
B2030121	Exterior metal-glazed double door D1	SET	3759	40	9.18	B2030
B2030122	Exterior metal single door D4	SET	11628	40	9.18	B2030
B2030131	Exterior plywood double door D9	SET	12837	40	13.94	B2030
C1020111	Interior metal-glazed doubled door D2	SET	4272	30	7.48	C1020
C1020112	Interior metal-glazed single door D3	SET	4800	30	7.48	C1020
C1020113	Interior metal-glazed double door D10	SET	5895	30	7.48	C1020
C1020121	Interior wood single door D5	SET	6202	30	10.23	C1020
C1020122	Interior wood single door D7	SET	5074	30	10.23	C1020
C1020131	Interior plastic single door D6	SET	4375	30	10.23	C1020

The Doors table of the relational database of the BIM-BLCC

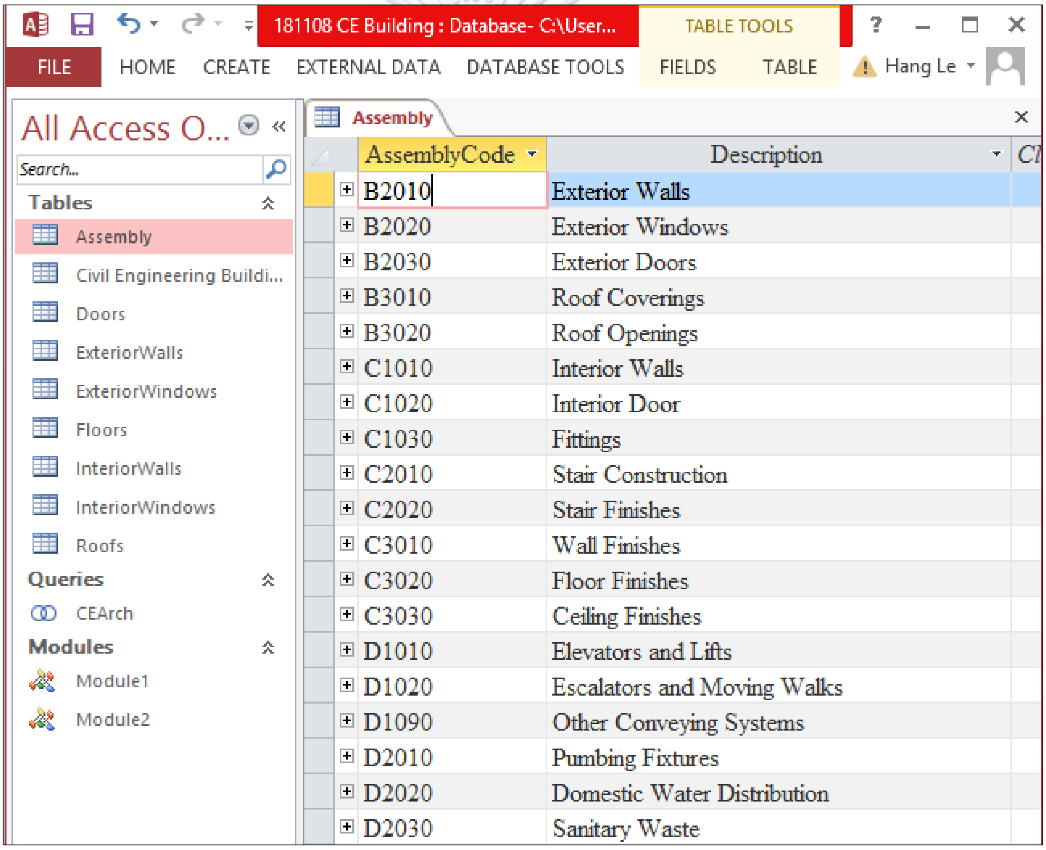


ElementTy	Description	Unit	Construction	ExpectedSe	AnnualServi	AssemblyC
C1010711	Interior glazed window W7	SET	2500	30	139.43	C1010
C1010712	Interior glazed window W7'	SET	2500	30	139.43	C1010
C1010713	Interior glazed window W8	SET	2500	30	139.43	C1010

The InteriorWindows table of the relational database of the BIM-BLCC

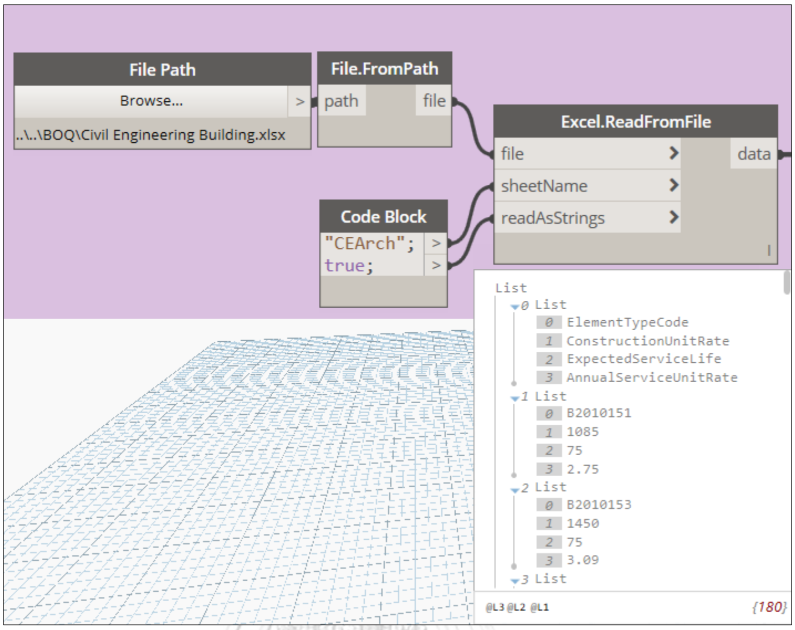


The InteriorWalls table of the relational database of the BIM-BLCC

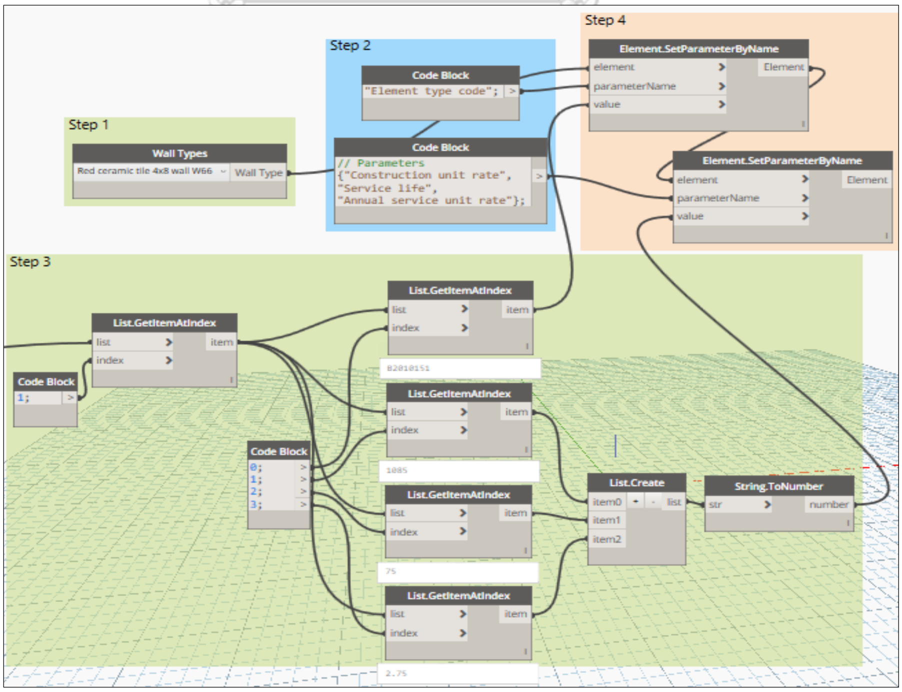


The Assembly table of the relational database of the BIM-BLCC

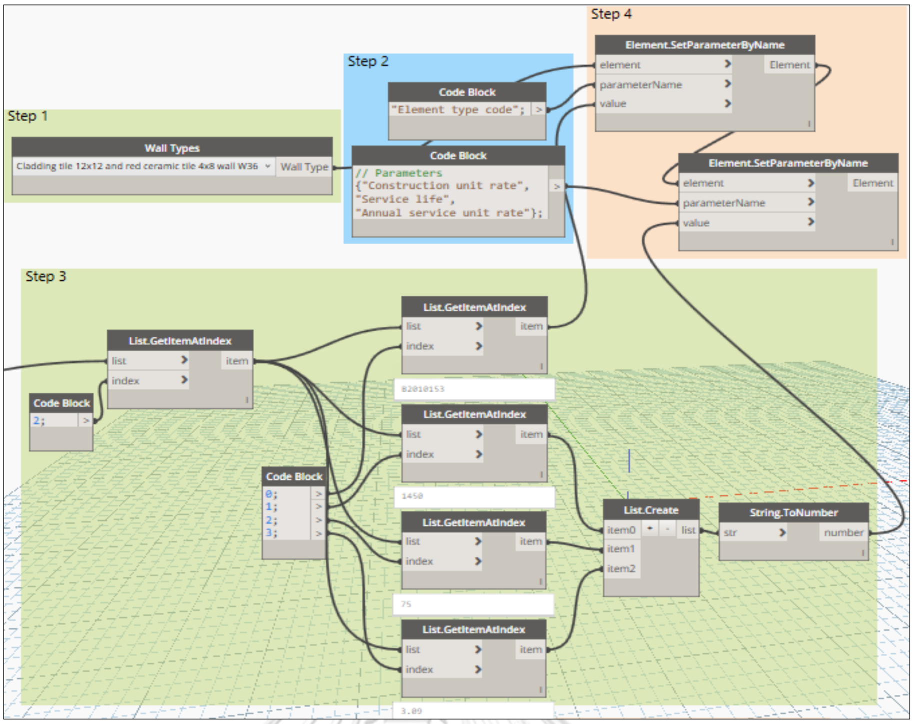
APPENDIX C DYNAMO NODES FOR EXTRACTING REQUIRED DATA FOR THE BIM MODEL



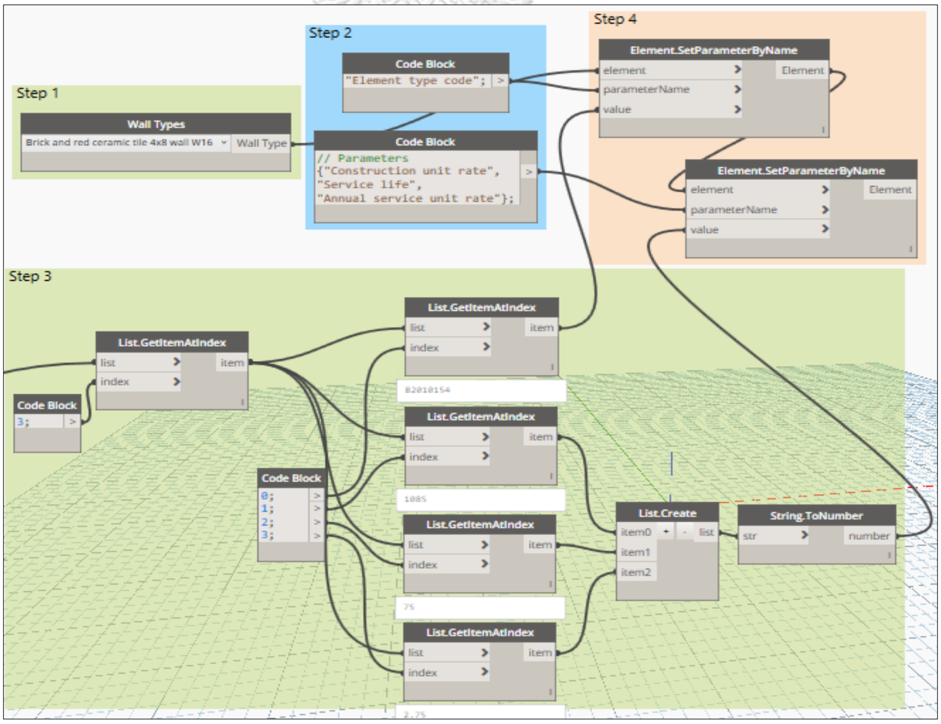
Read data from the Excel spreadsheet database



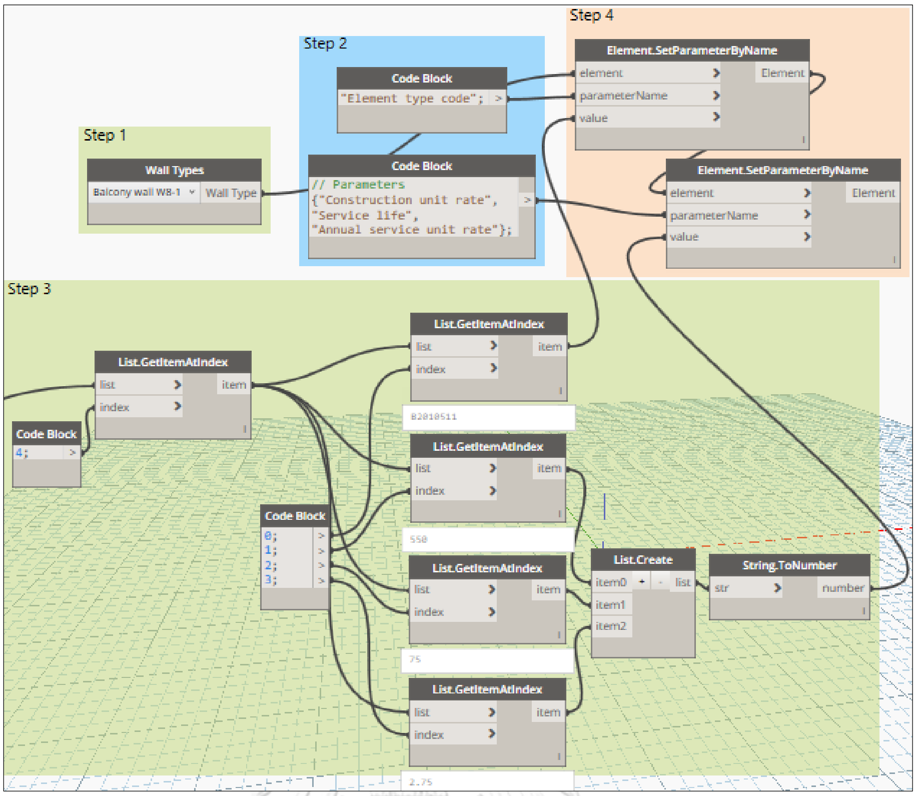
Acquire the value of required parameters for Red ceramic tile 4x8 wall W66



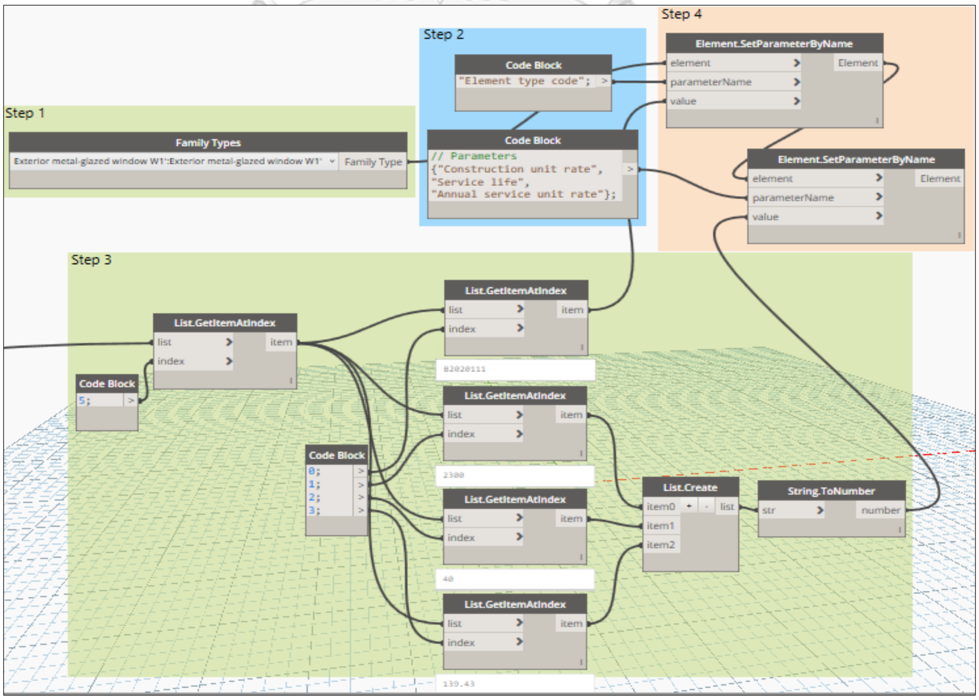
Acquire the value of required parameters for Cladding tile 12x12 and red ceramic tile 4x8 wall W36



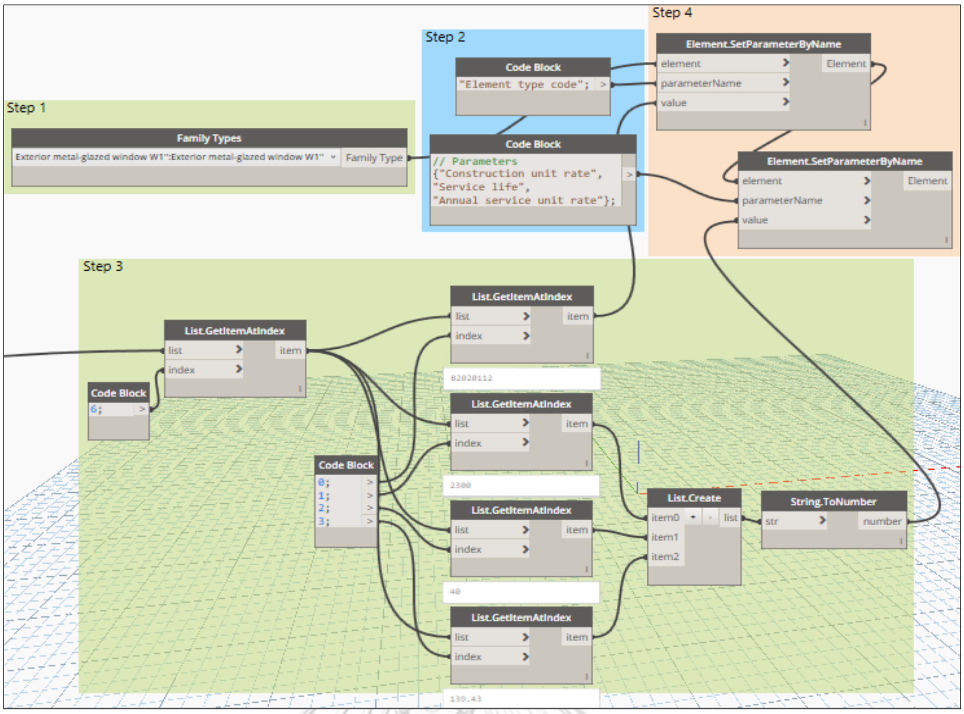
Acquire the value of required parameters for Brick and red ceramic tile 4x8 wall W16



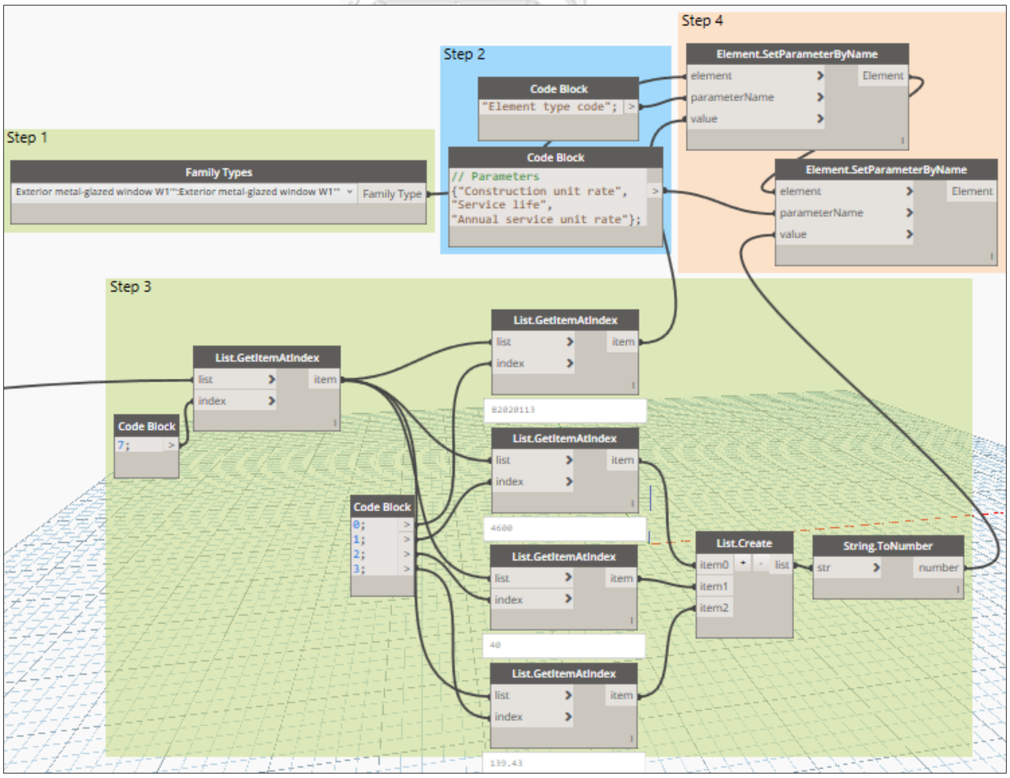
Acquire the value of required parameters for Balcony wall W8-1



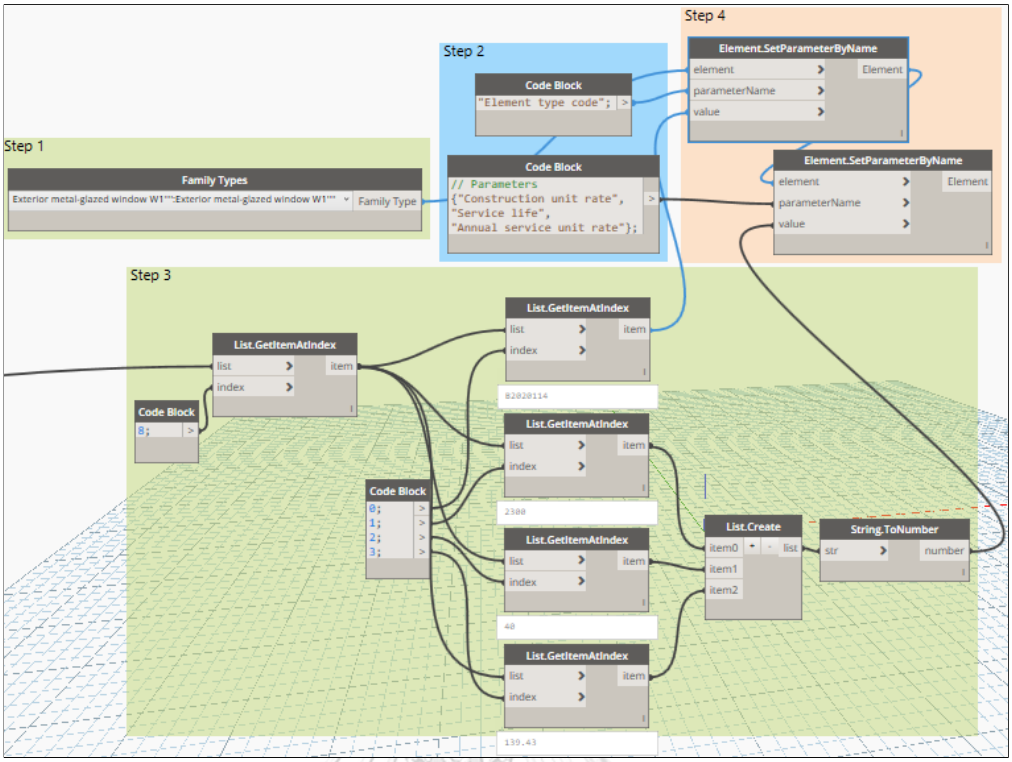
Acquire the value of required parameters for Exterior metal-glazed window W1’



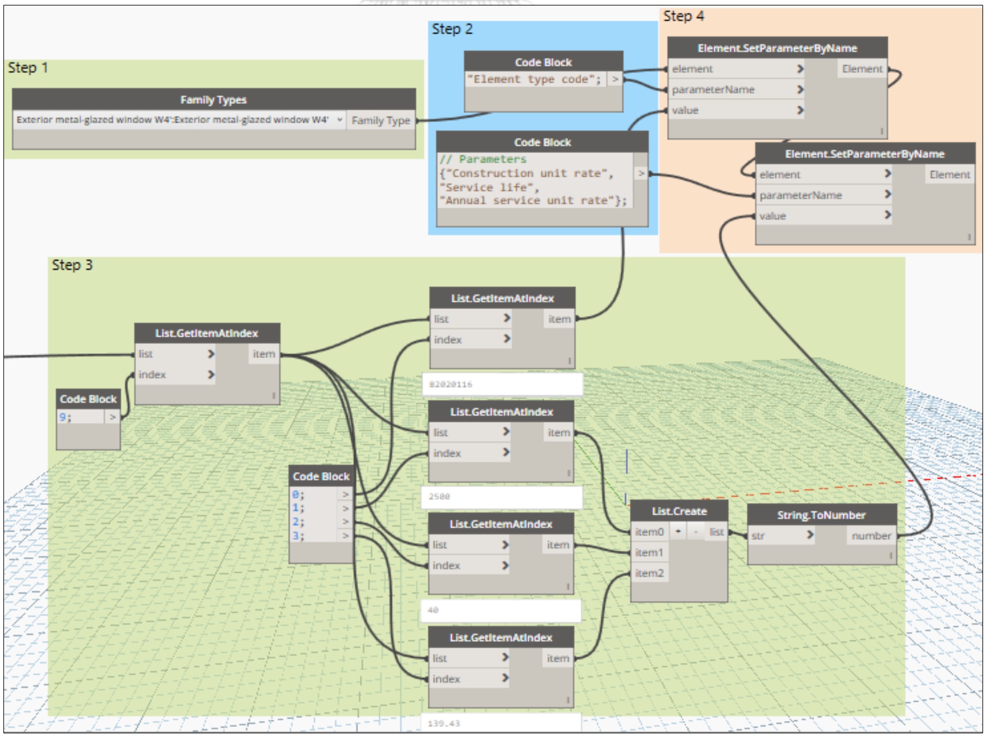
Acquire the value of required parameters for Exterior metal-glazed window W1”



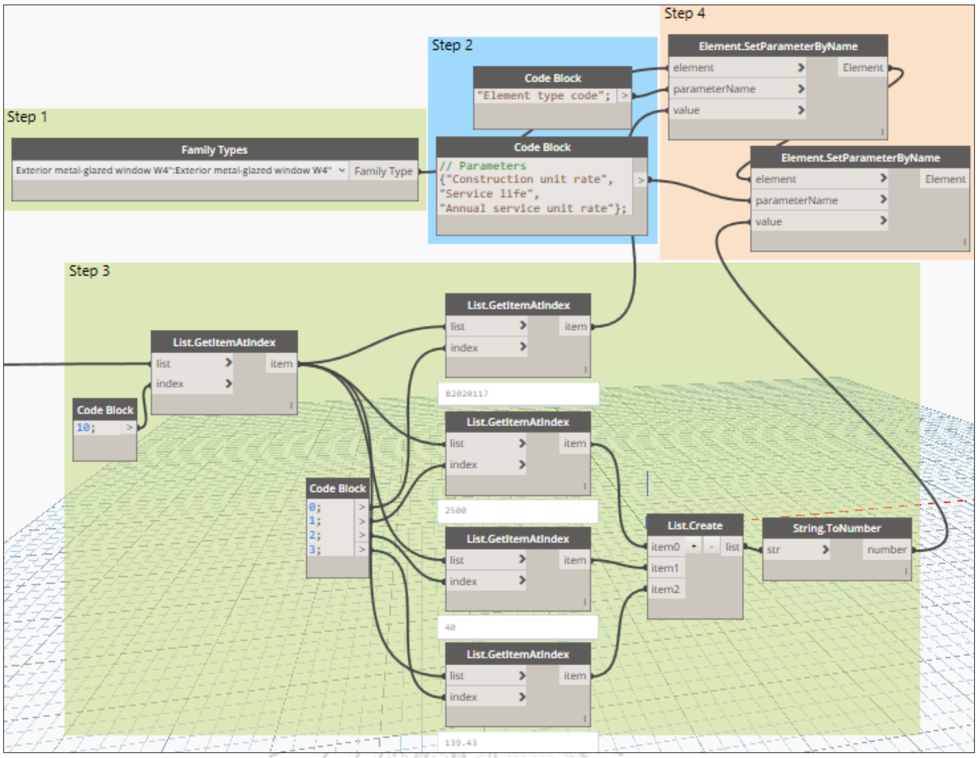
Acquire the value of required parameters for Exterior metal-glazed window W1’ ”



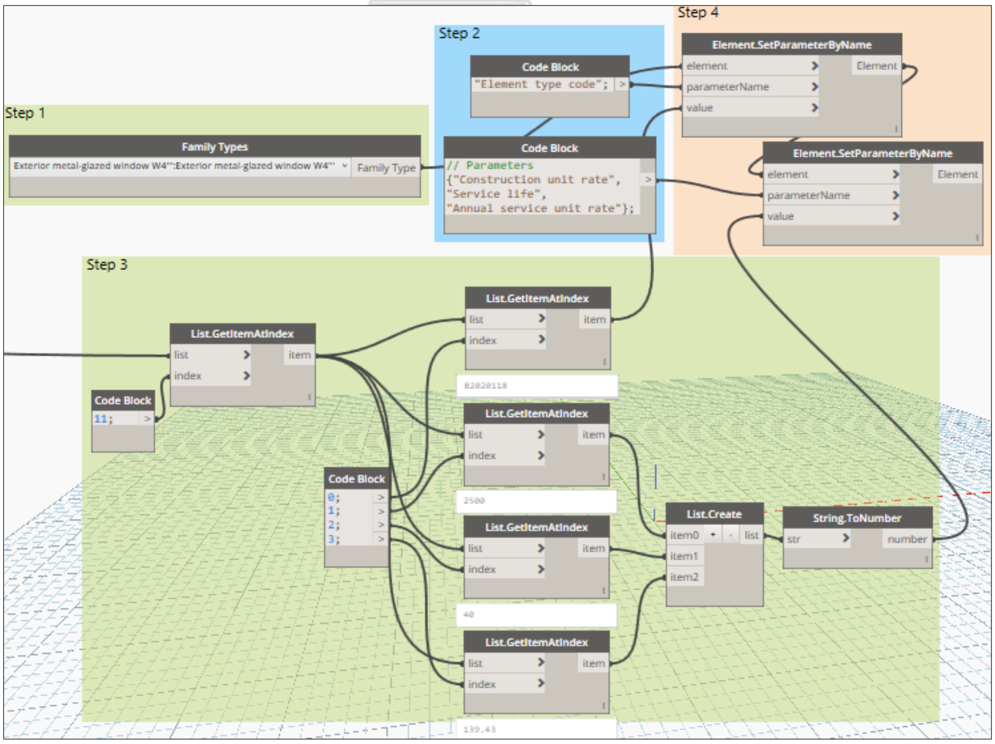
Acquire the value of required parameters for Exterior metal-glazed window W1” ”



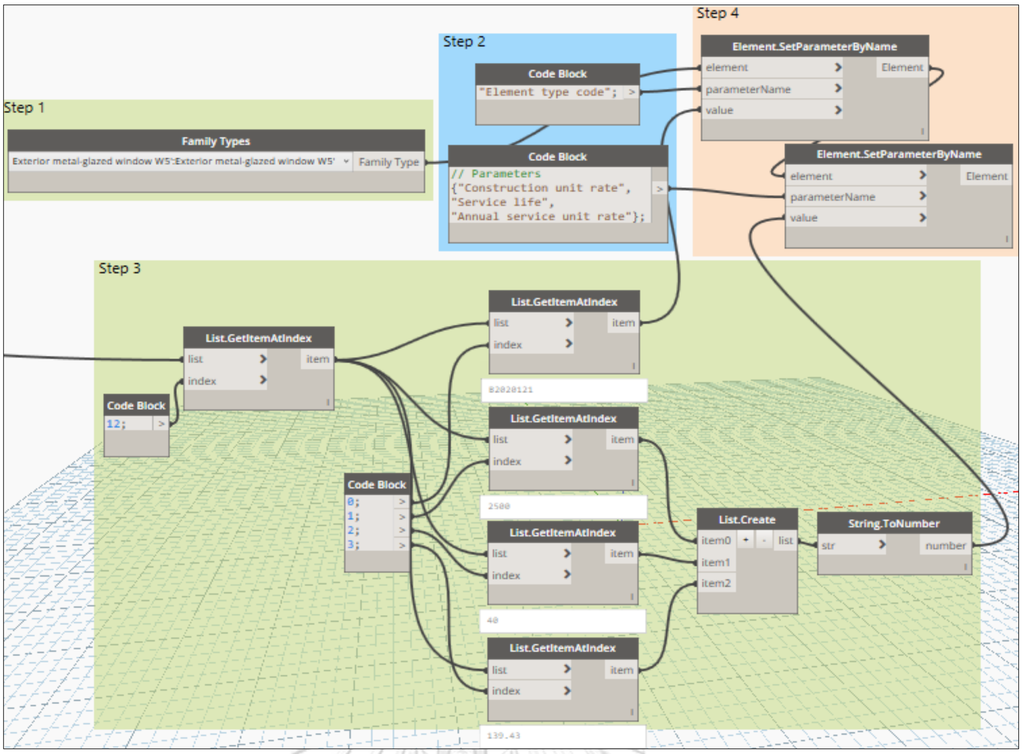
Acquire the value of required parameters for Exterior metal-glazed window W4’



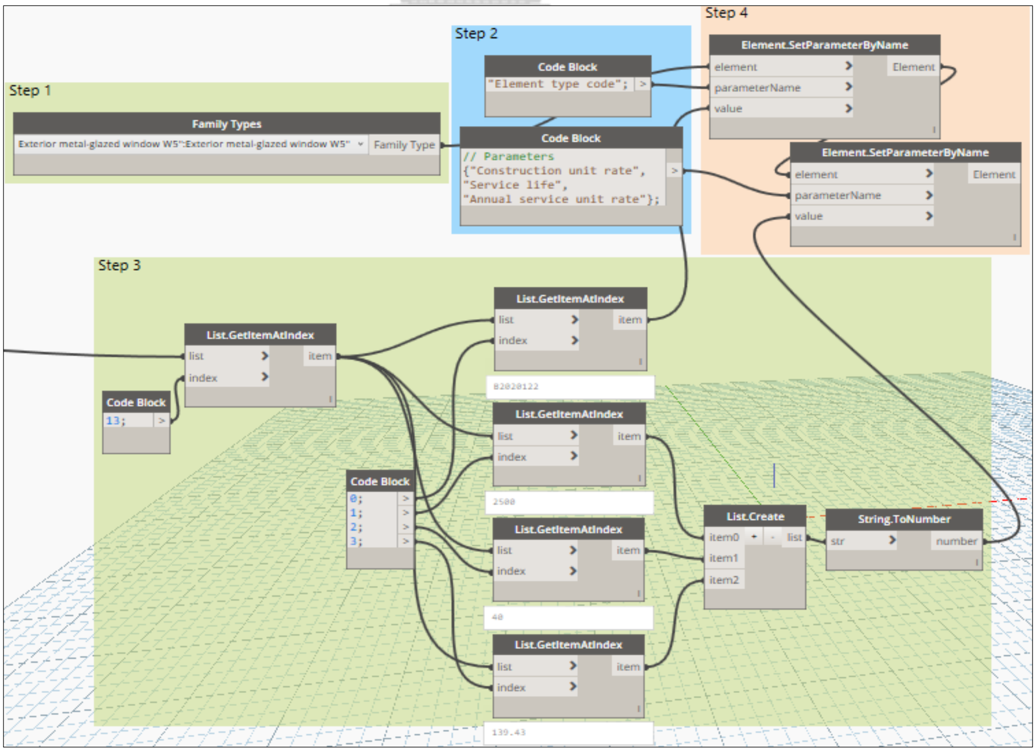
Acquire the value of required parameters for Exterior metal-glazed window W4”



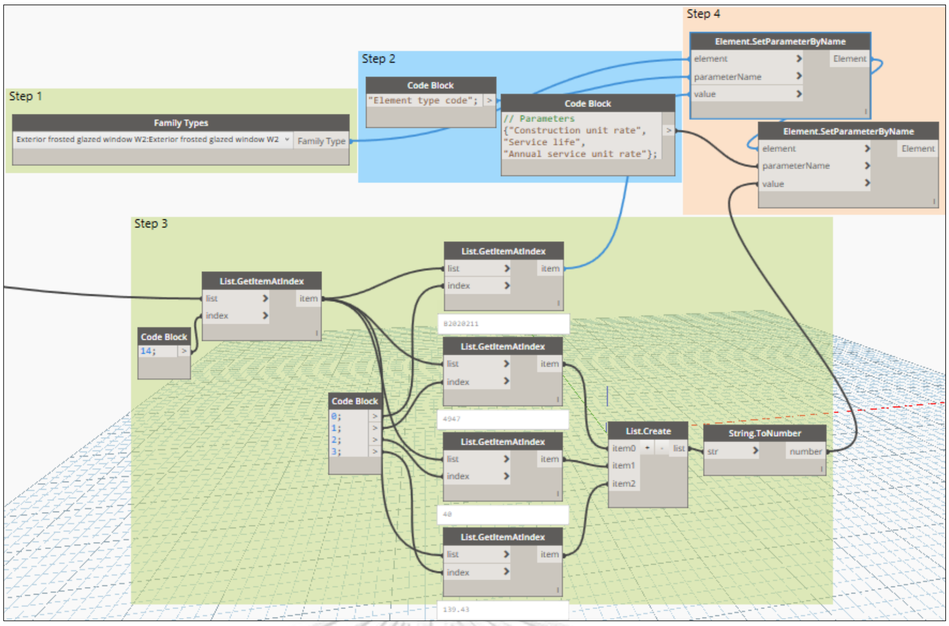
Acquire the value of required parameters for Exterior metal-glazed window W4’ ”



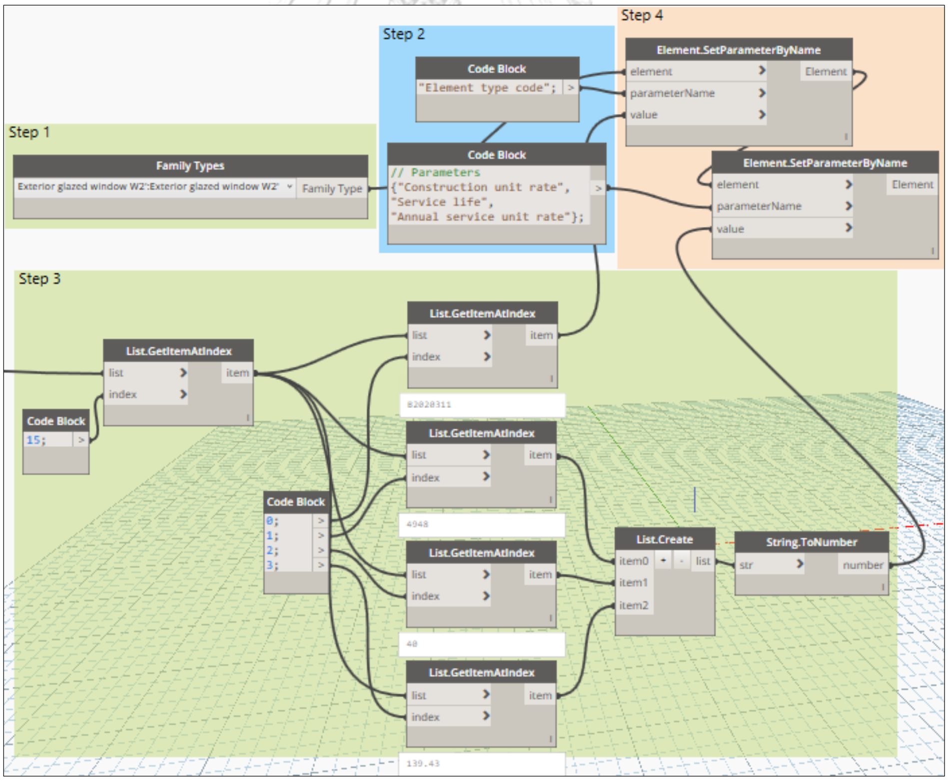
Acquire the value of required parameters for Exterior metal-glazed window W5'



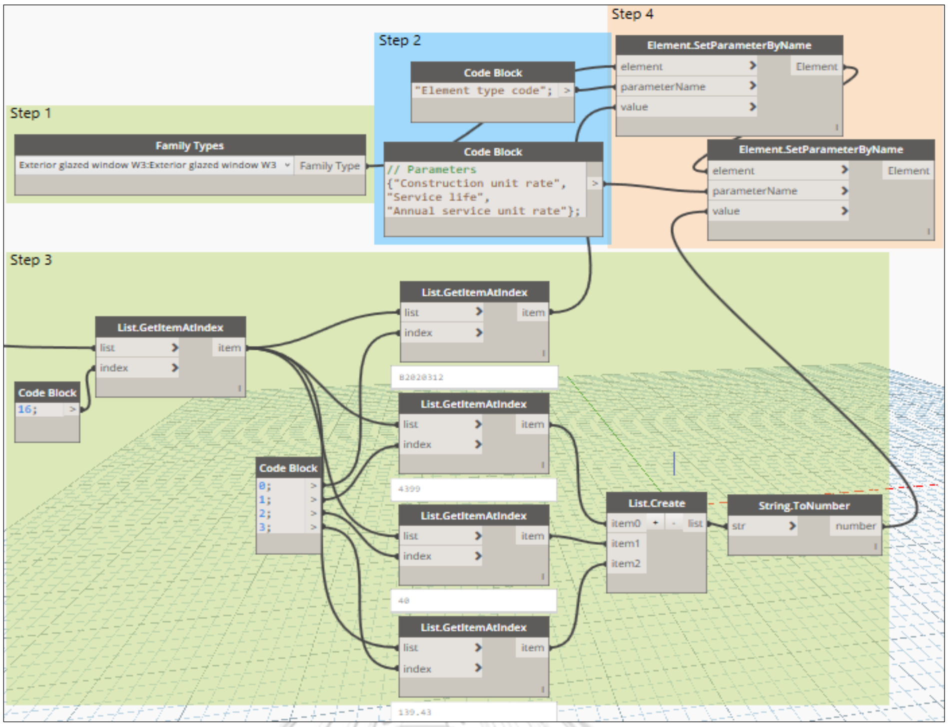
Acquire the value of required parameters for Exterior metal-glazed window W5"



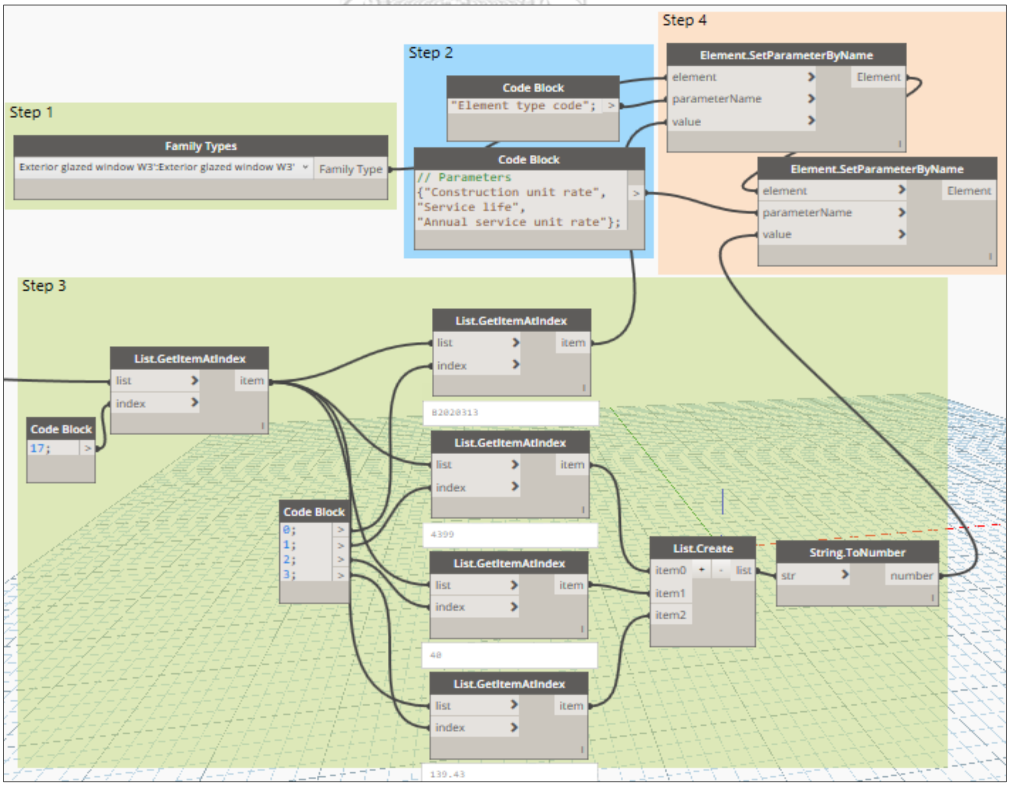
Acquire the value of required parameters for Exterior frosted glazed window W2



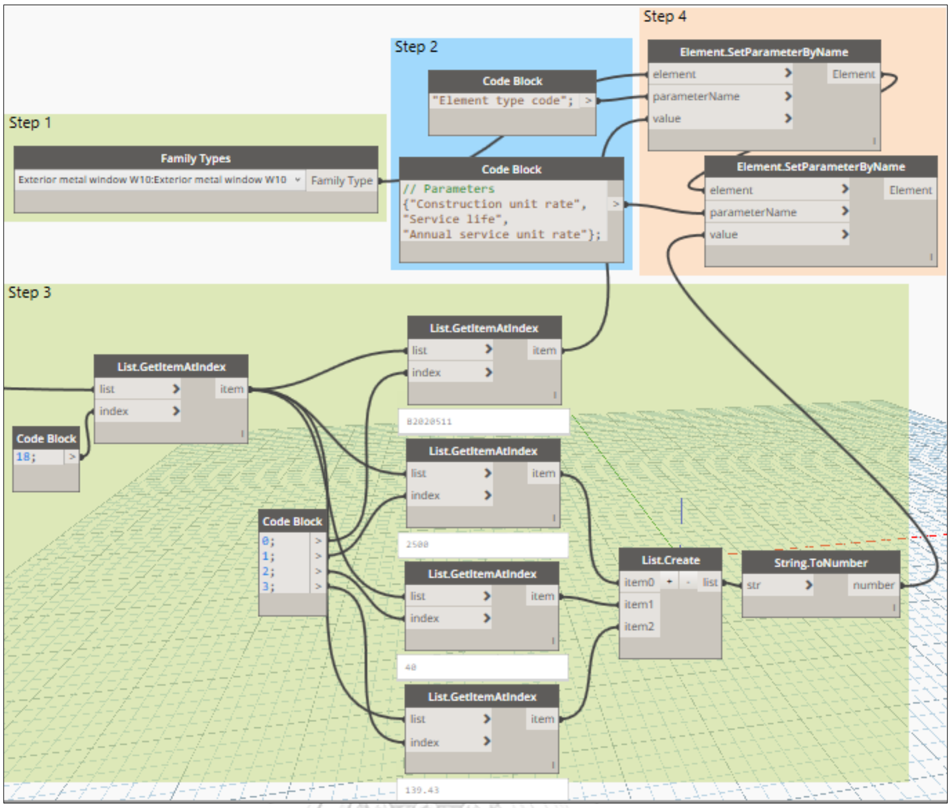
Acquire the value of required parameters for Exterior glazed window W2’



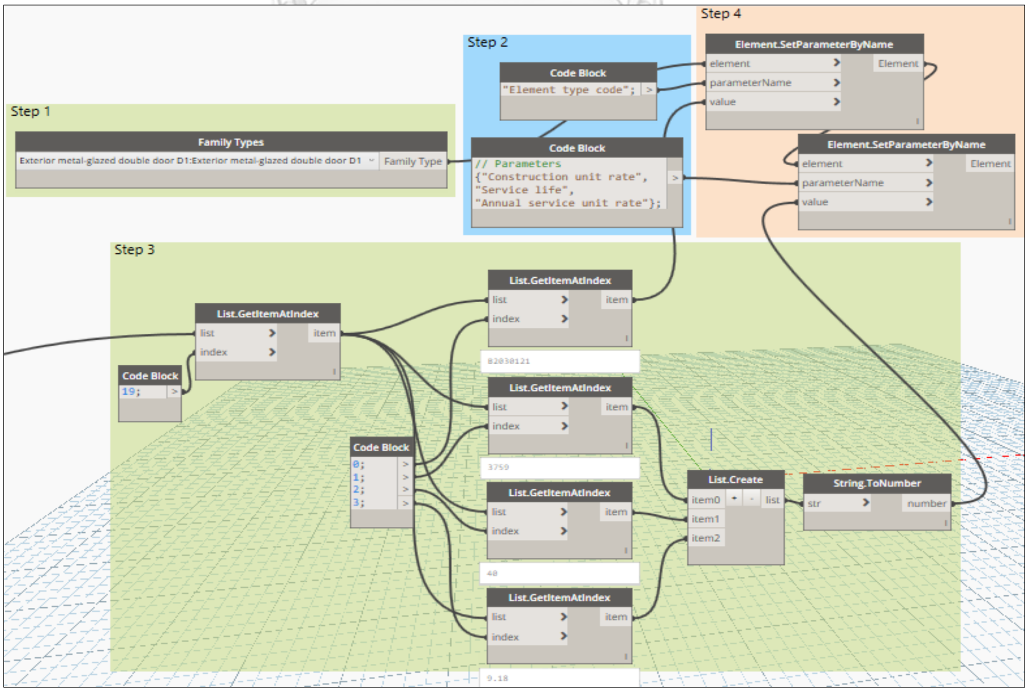
Acquire the value of required parameters for Exterior glazed window W3



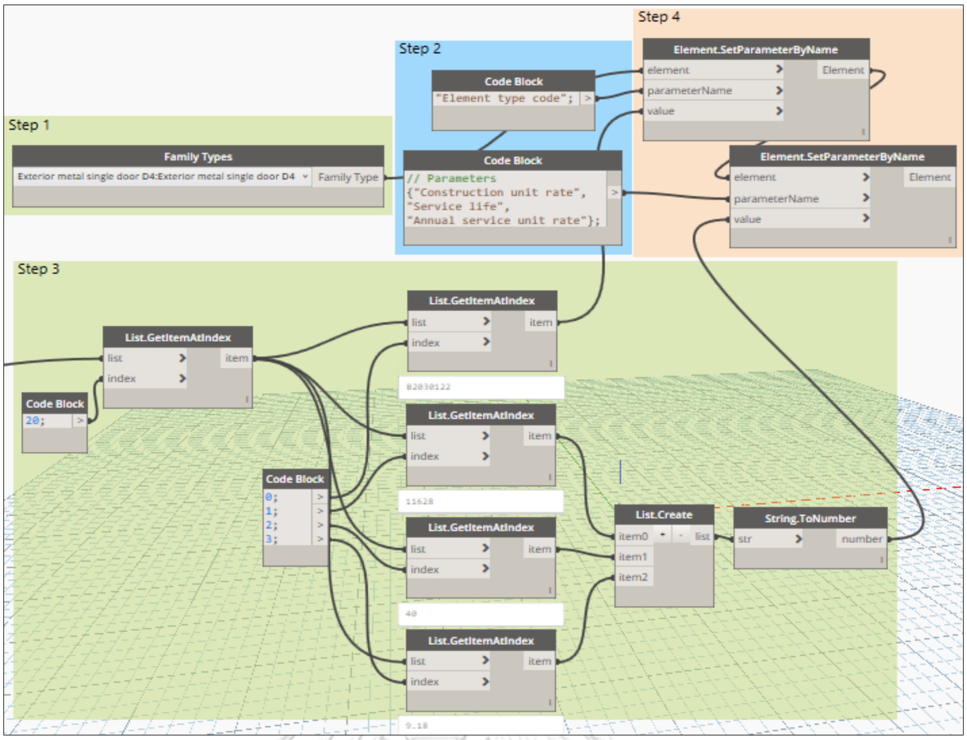
Acquire the value of required parameters for Exterior glazed window W3’



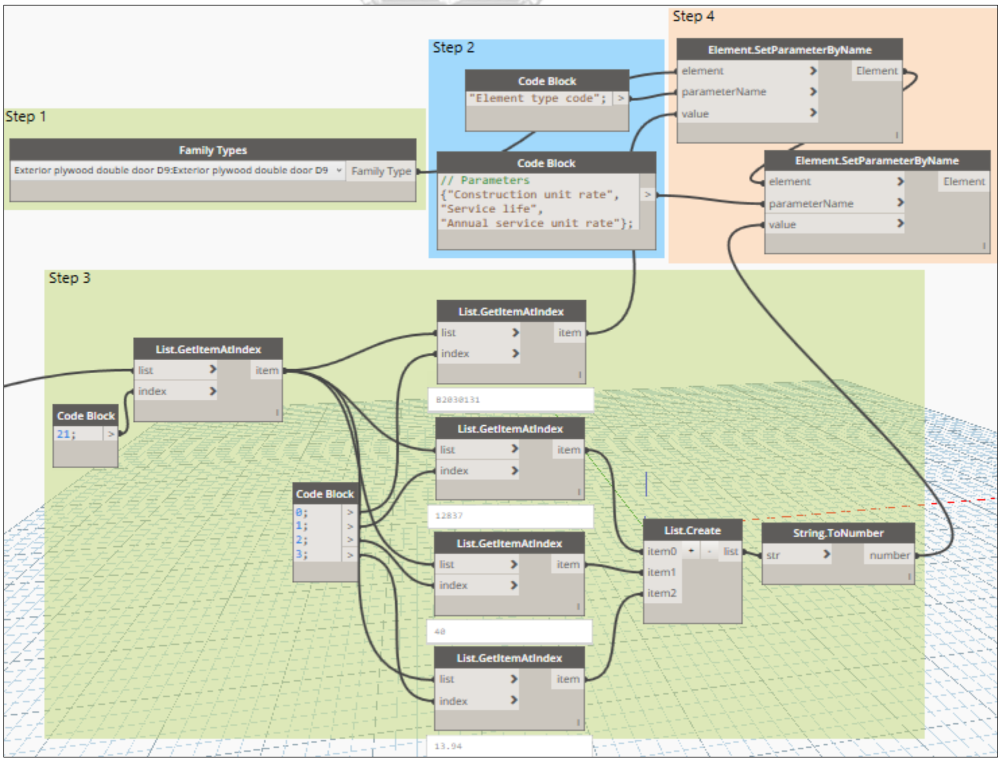
Acquire the value of required parameters for Exterior metal window W10



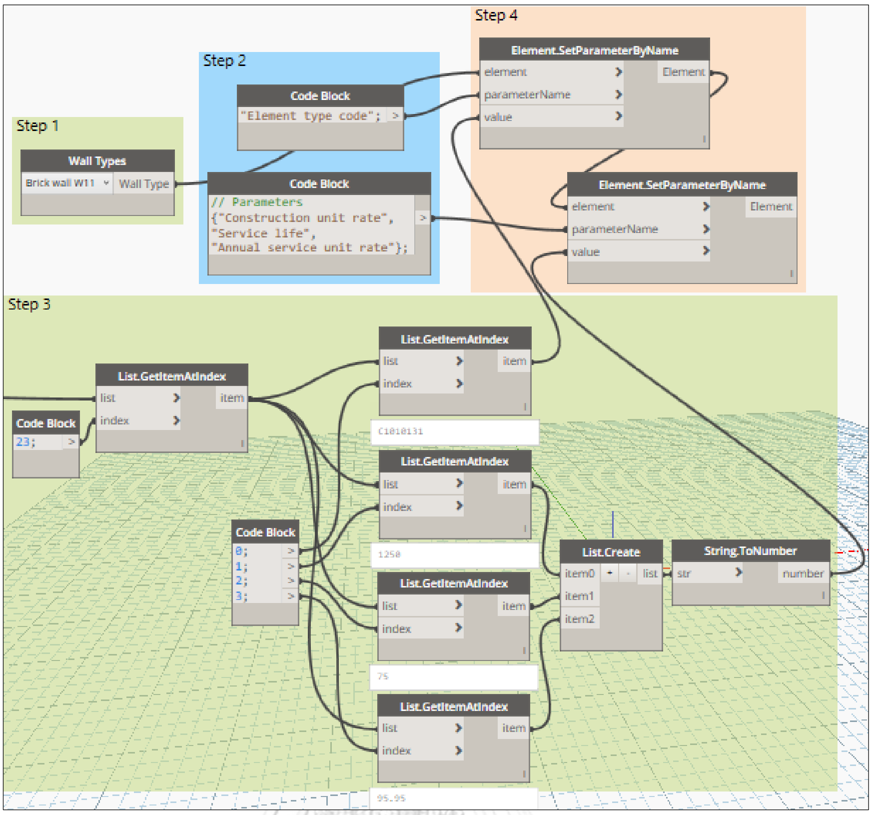
Acquire the value of required parameters for Exterior metal-glazed double door D1



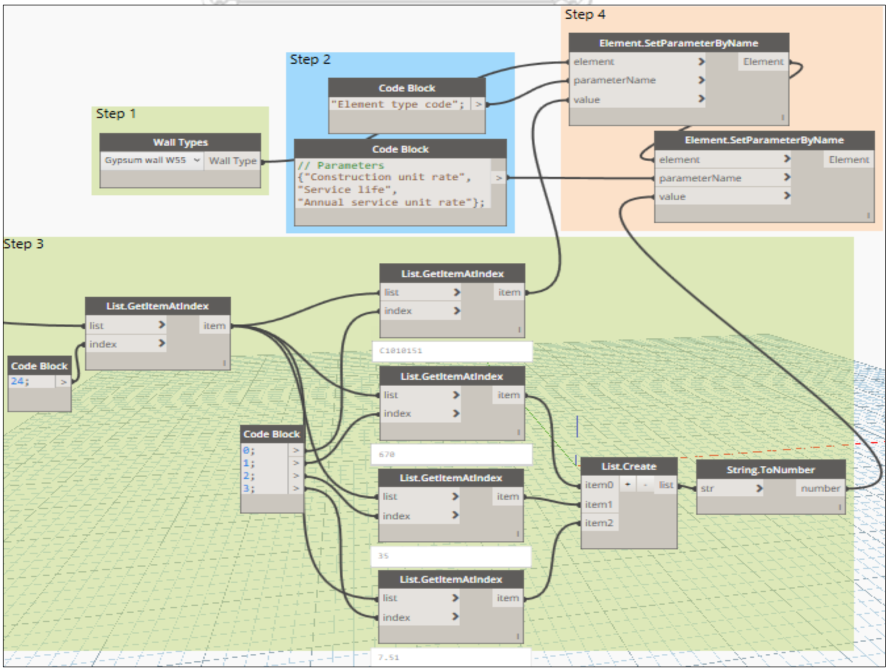
Acquire the value of required parameters for Exterior metal single door D4



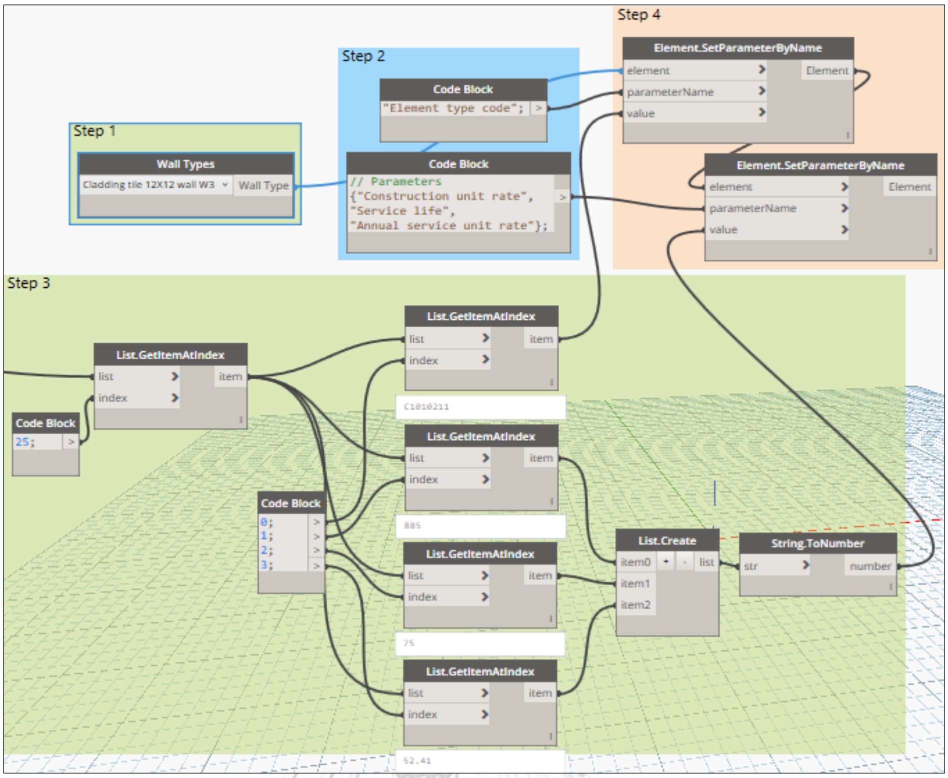
Acquire the value of required parameters for Exterior plywood double door D9



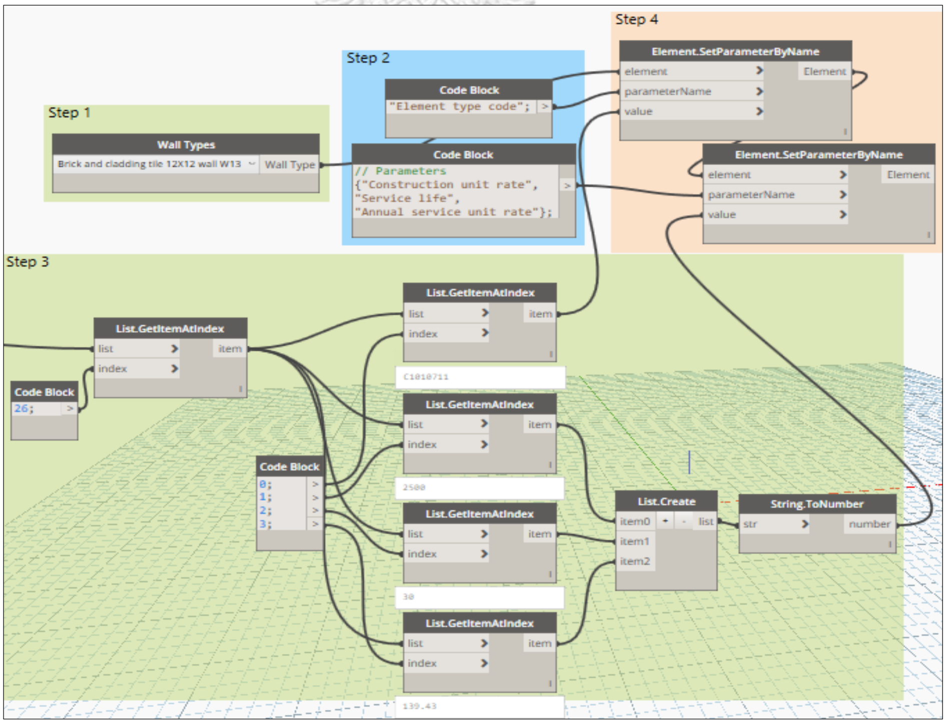
Acquire the value of required parameters for Brick wall W11



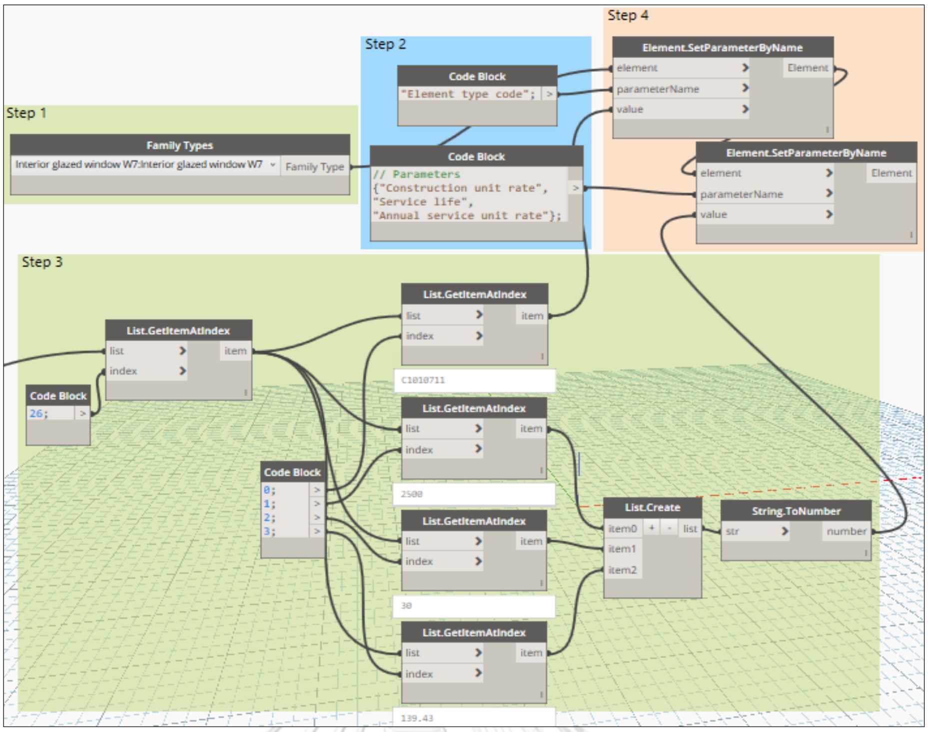
Acquire the value of required parameters for Gypsum wall W55



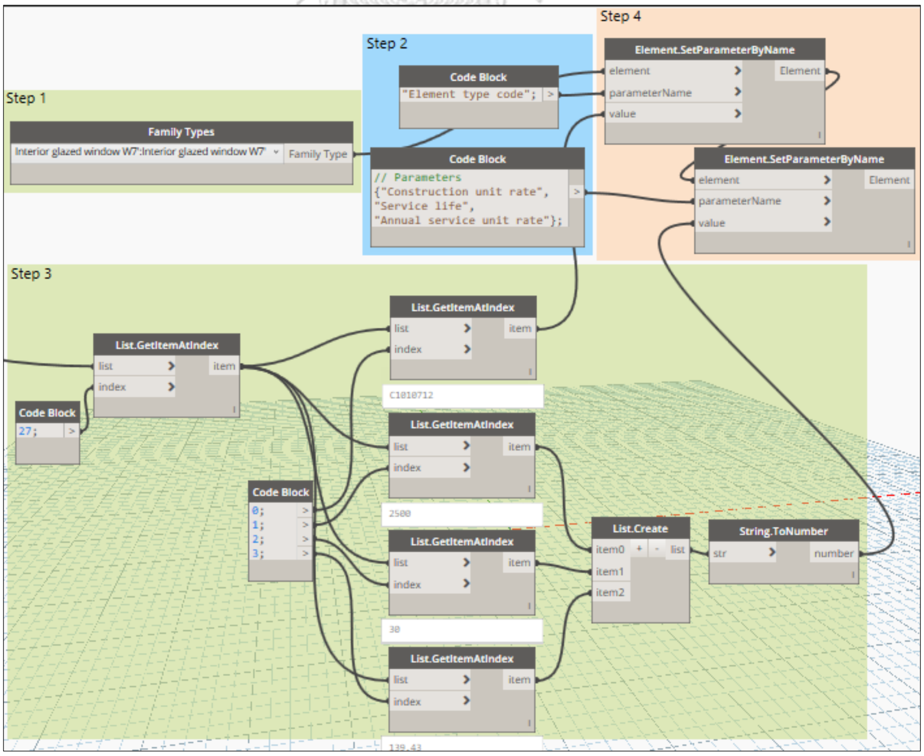
Acquire the value of required parameters for Cladding tile 12x12 wall W3



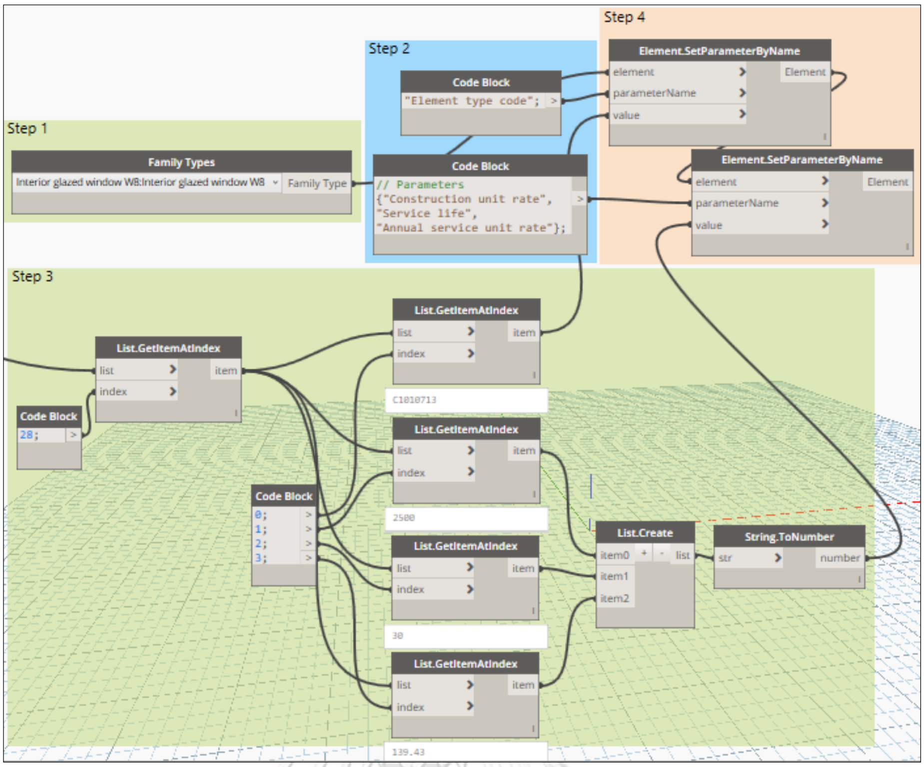
Acquire the value of required parameters for Brick and cladding tile 12x12 wall W13



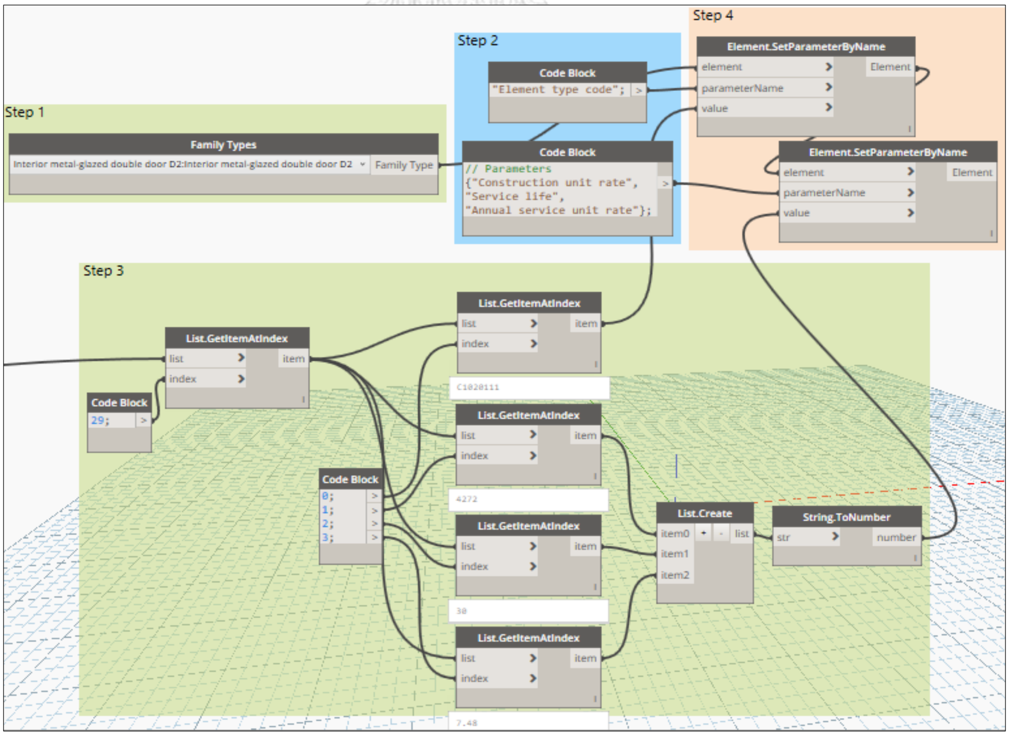
Acquire the value of required parameters for Interior glazed window W7



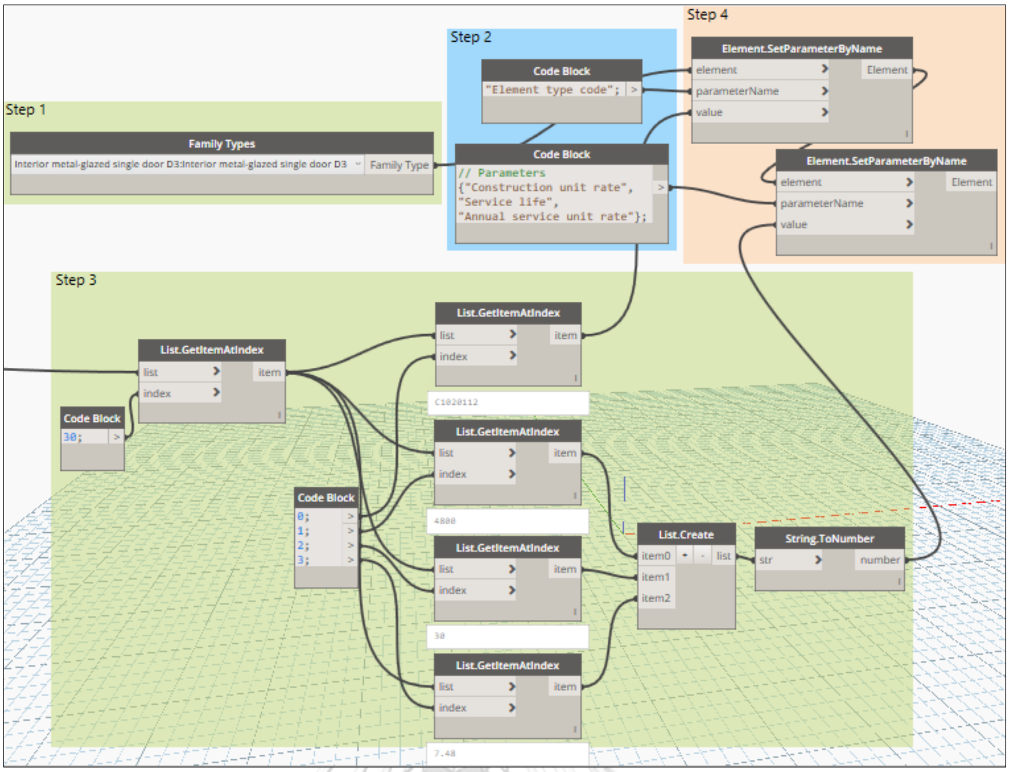
Acquire the value of required parameters for Interior glazed window W7’



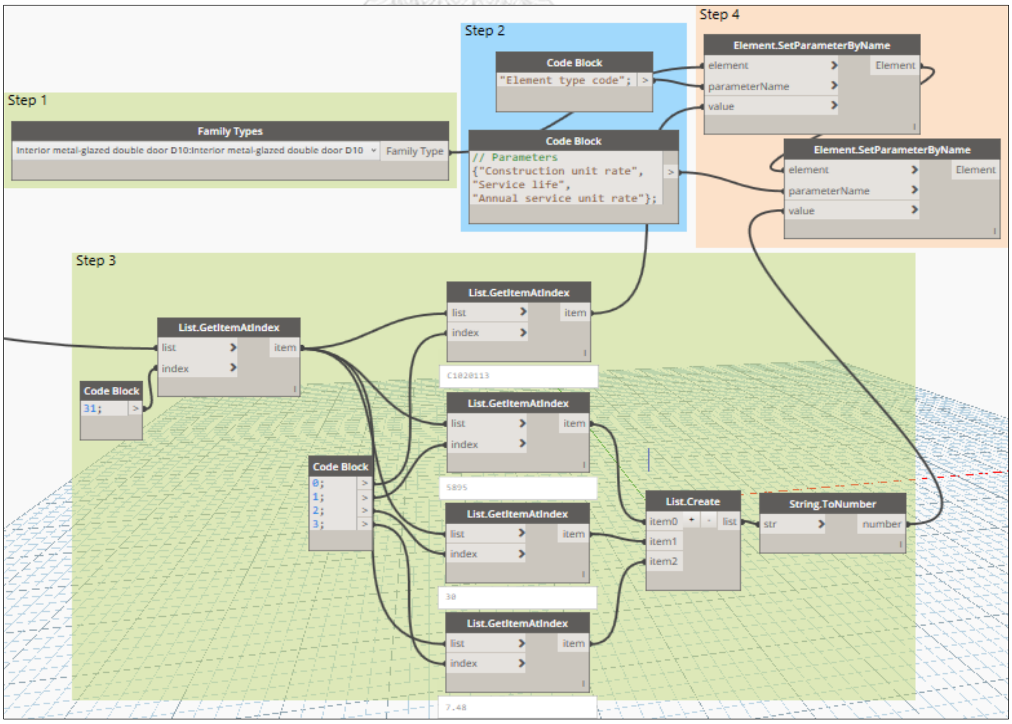
Acquire the value of required parameters for Interior glazed window W8



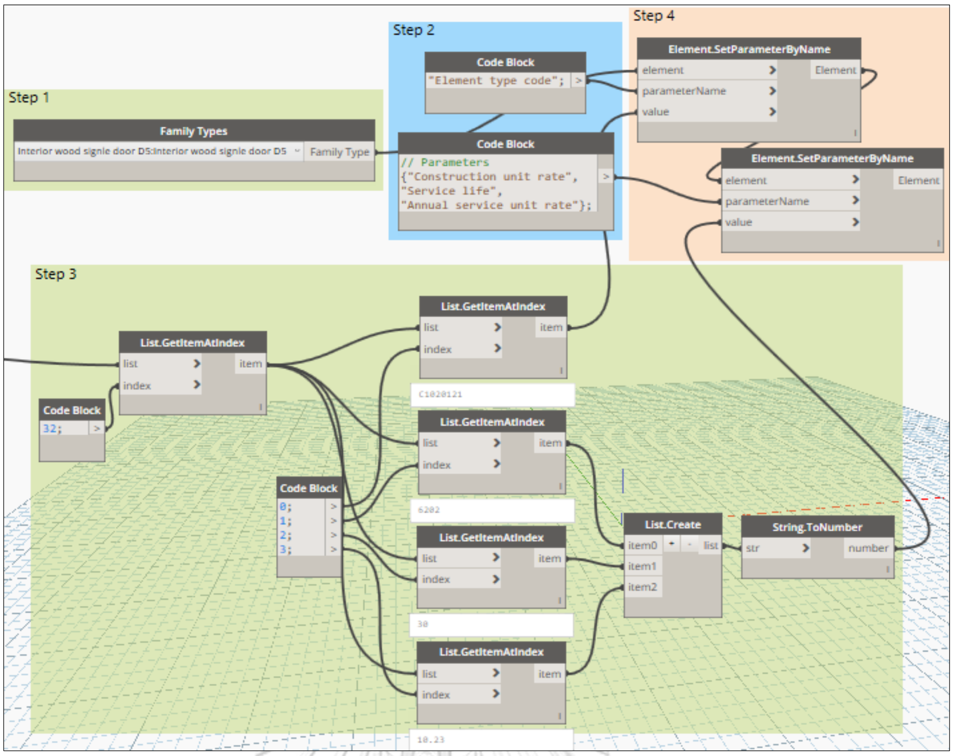
Acquire the value of required parameters for Interior metal-glazed double door D2



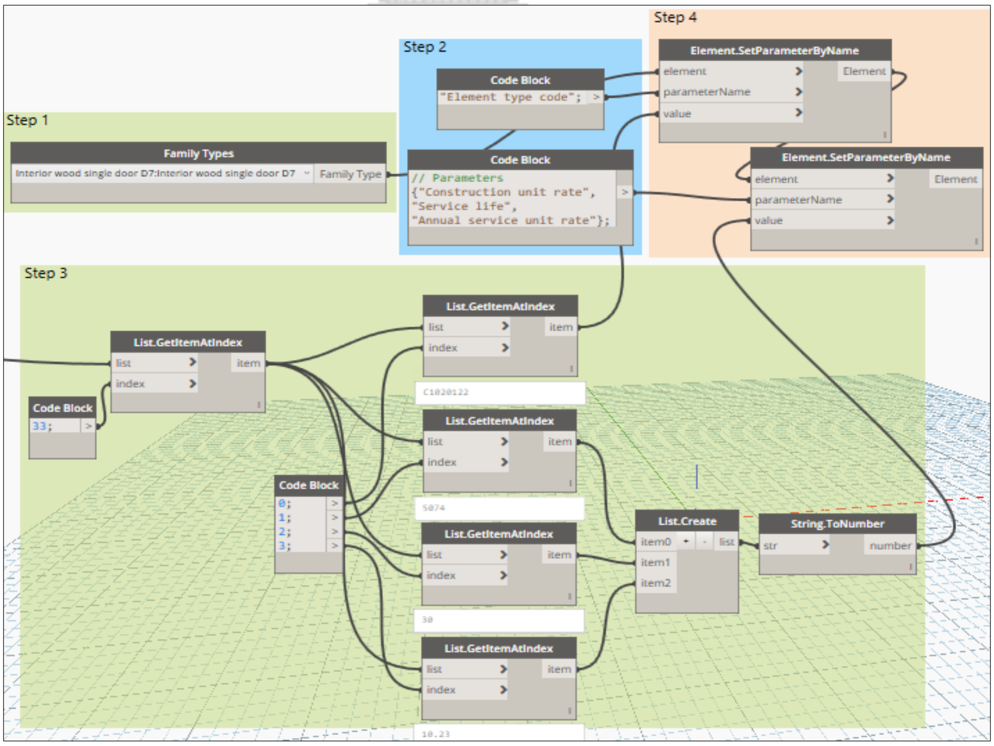
Acquire the value of required parameters for Interior metal-glazed single door D3



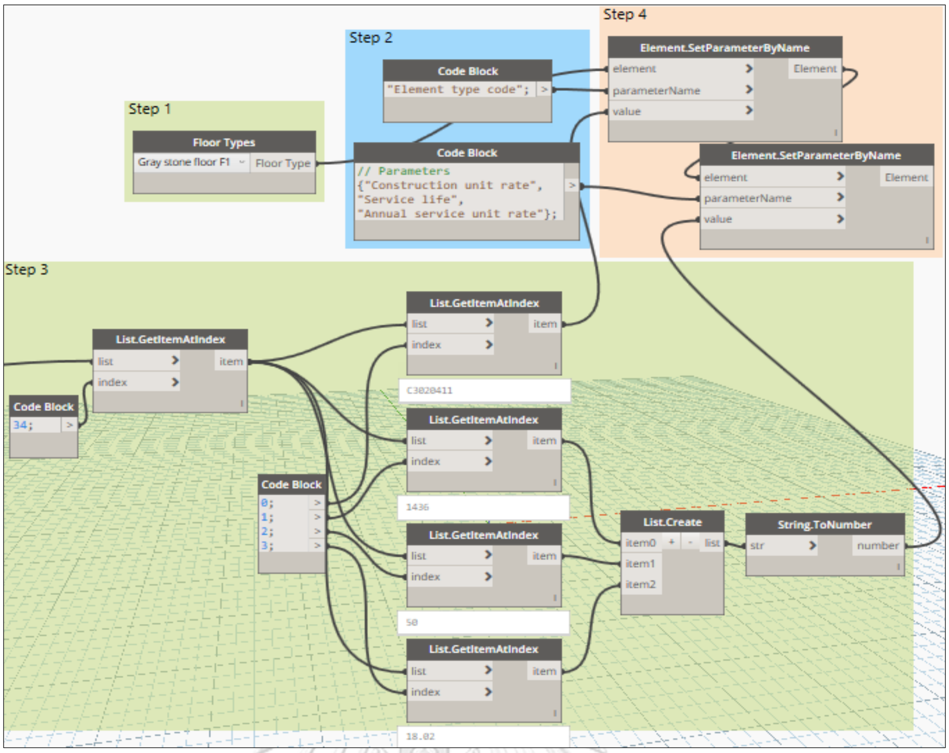
Acquire the value of required parameters for Interior metal-glazed double door D10



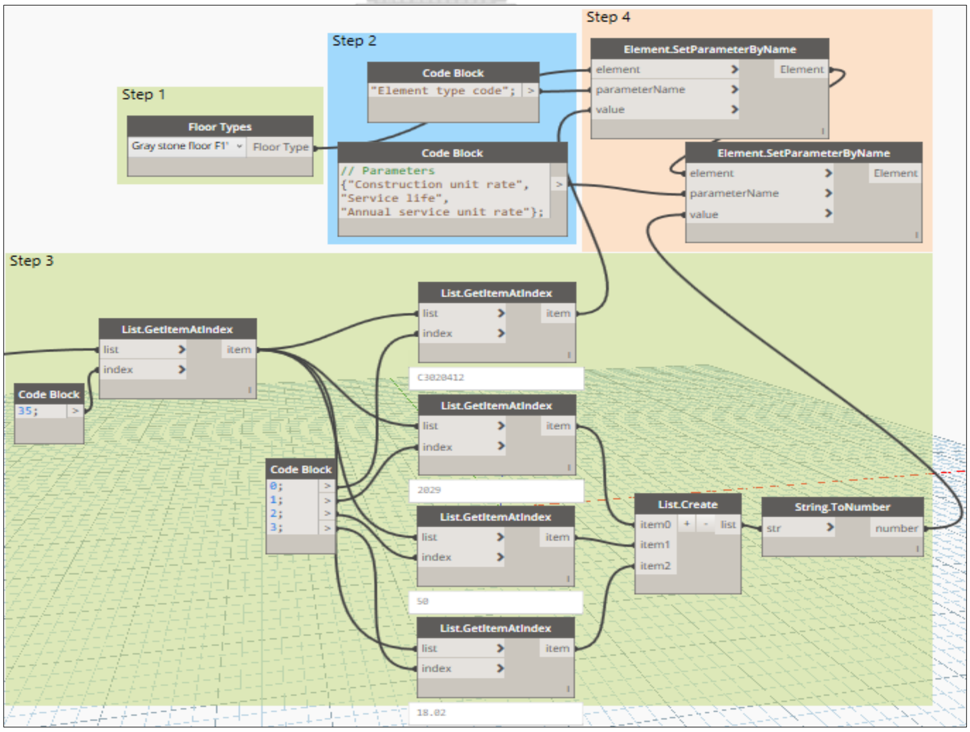
Acquire the value of required parameters for Interior wood single door D5



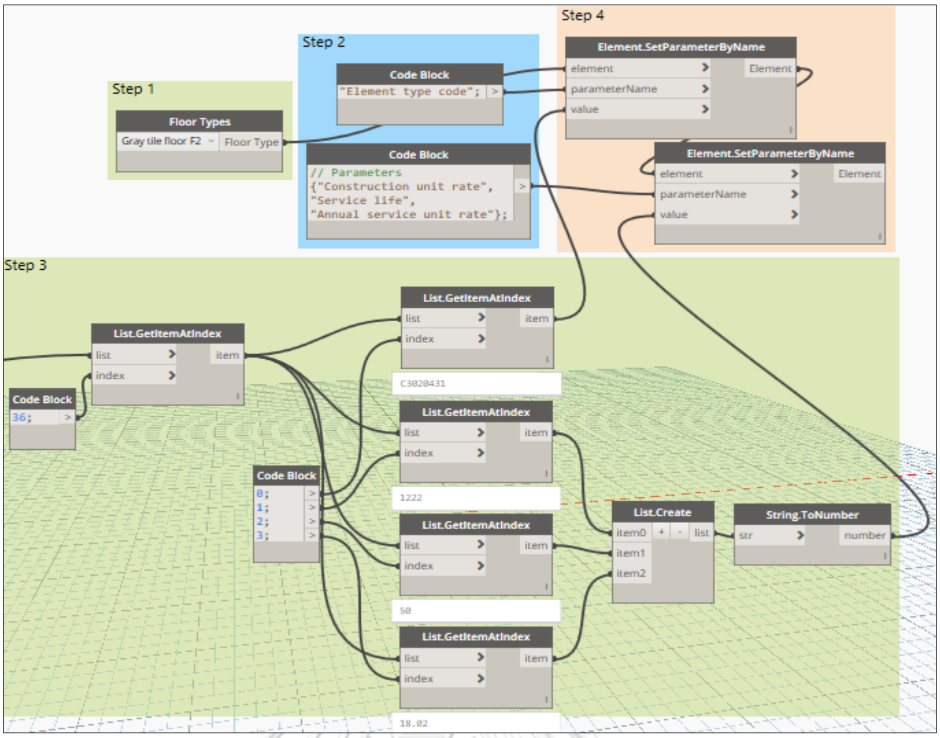
Acquire the value of required parameters for Interior wood single door D7



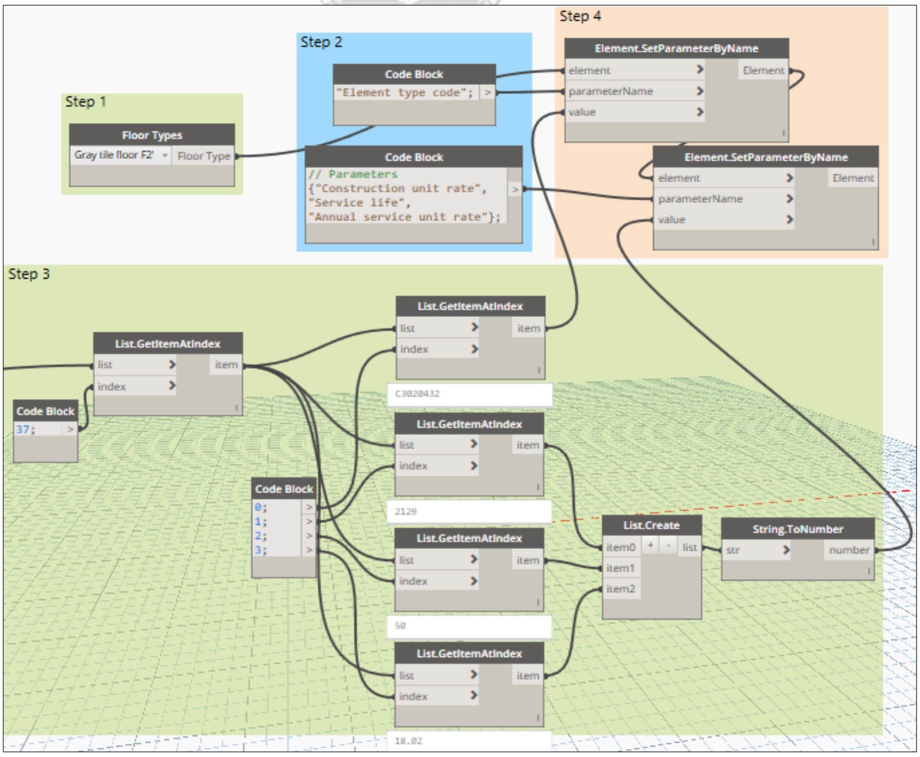
Acquire the value of required parameters for Gray stone floor F1



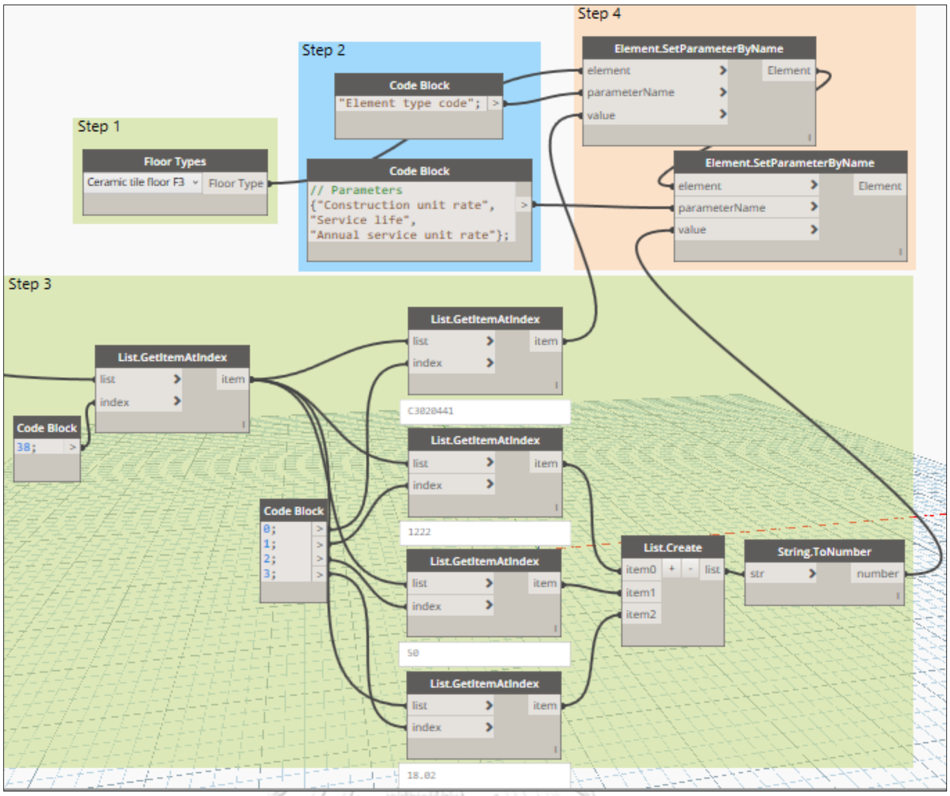
Acquire the value of required parameters for Gray stone floor F1’



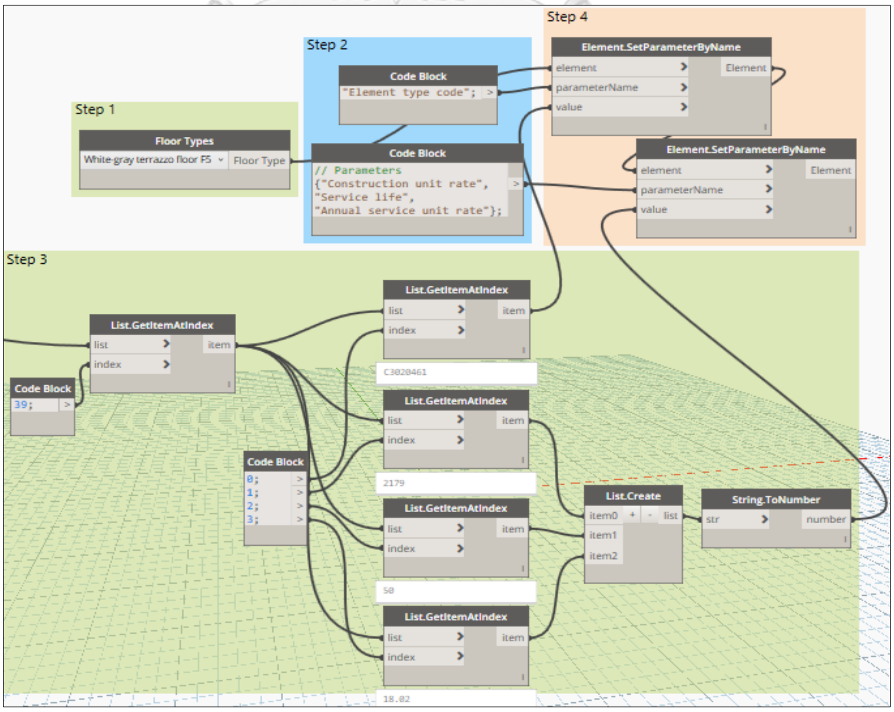
Acquire the value of required parameters for Gray tile floor F2



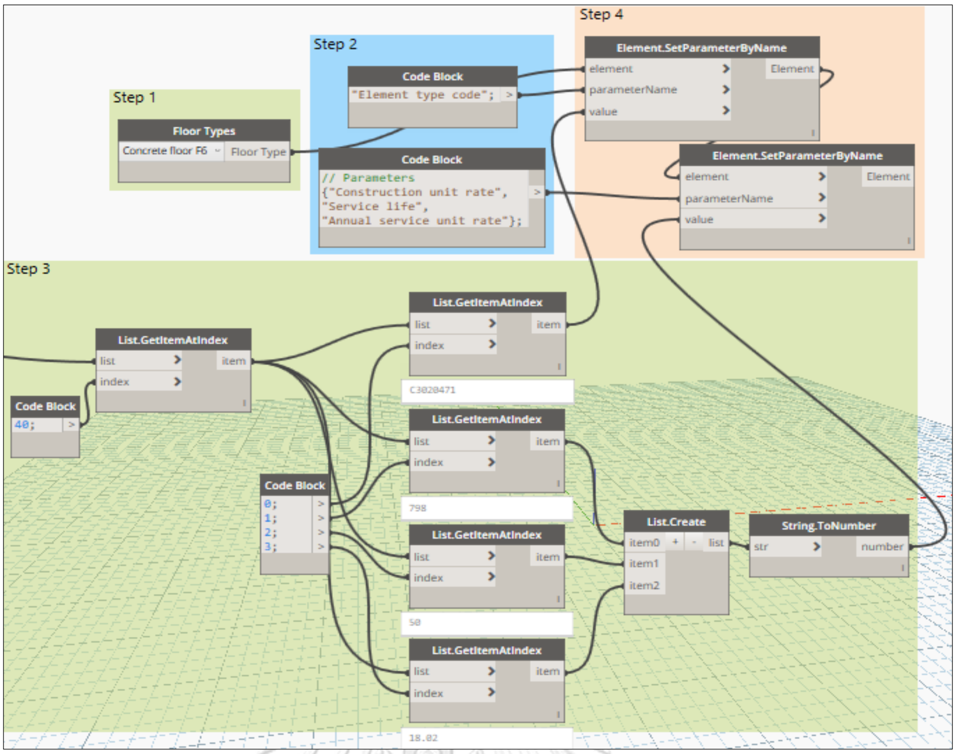
Acquire the value of required parameters for Gray tile floor F2’



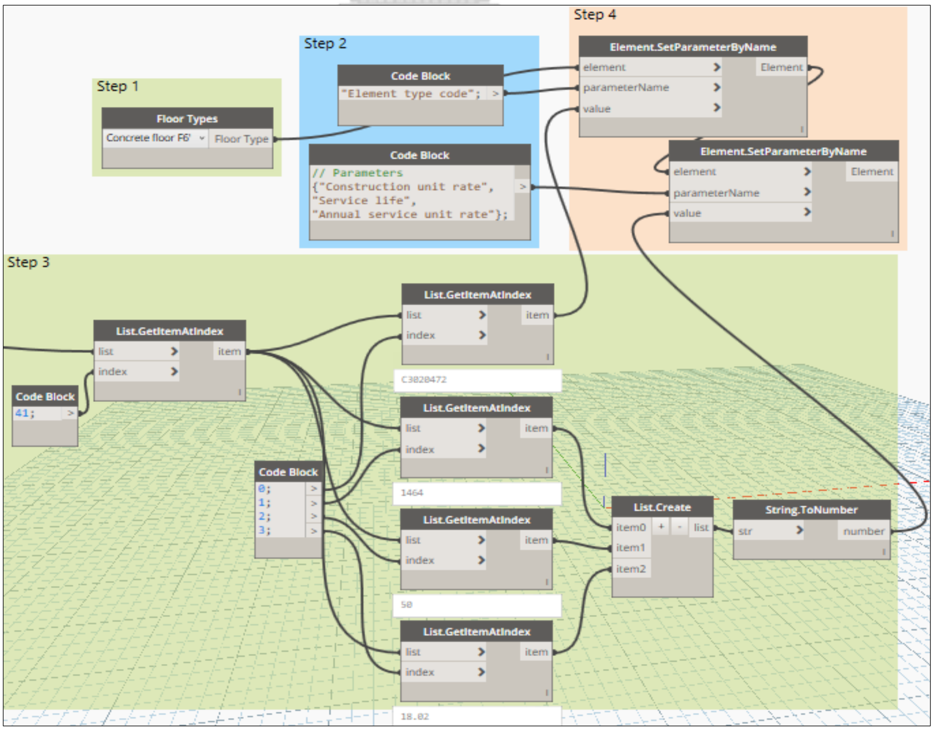
Acquire the value of required parameters for Ceramic tile floor F3



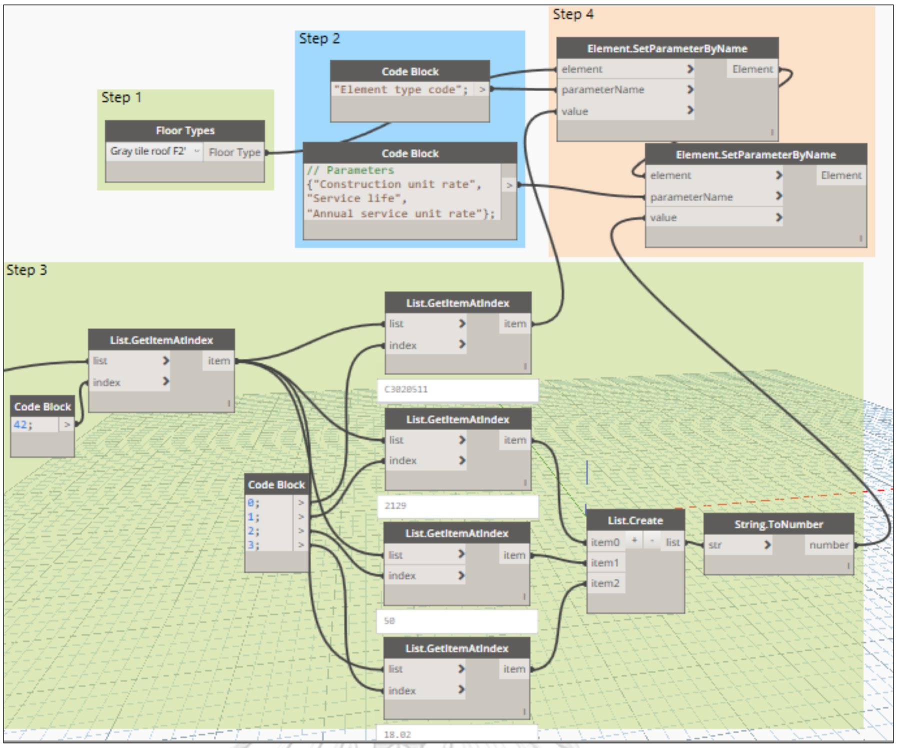
Acquire the value of required parameters for White-gray terrazzo floor F5



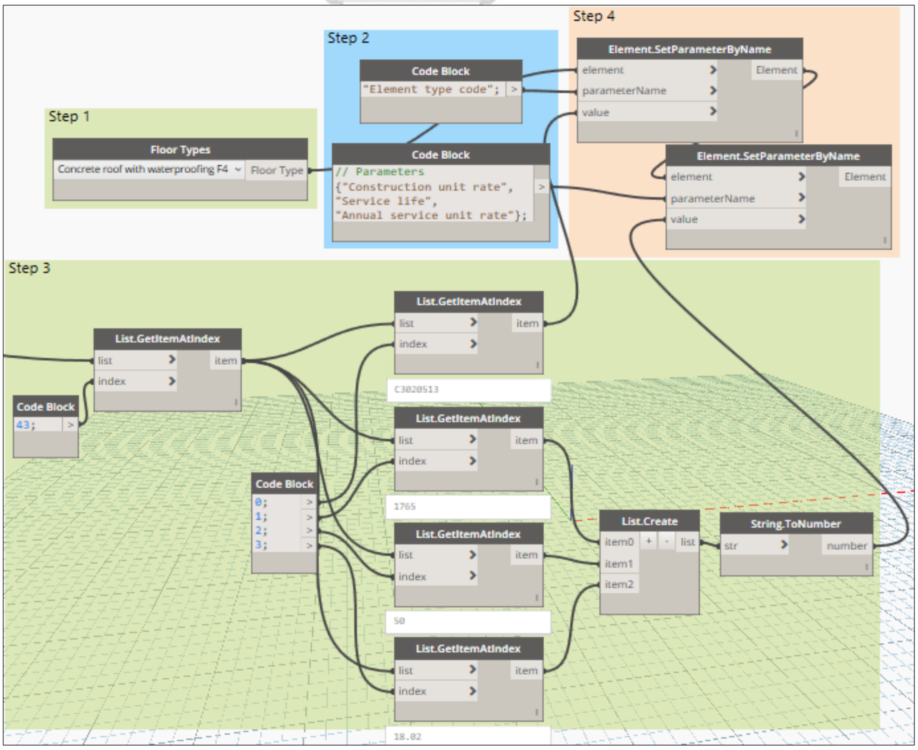
Acquire the value of required parameters for Concrete floor F6



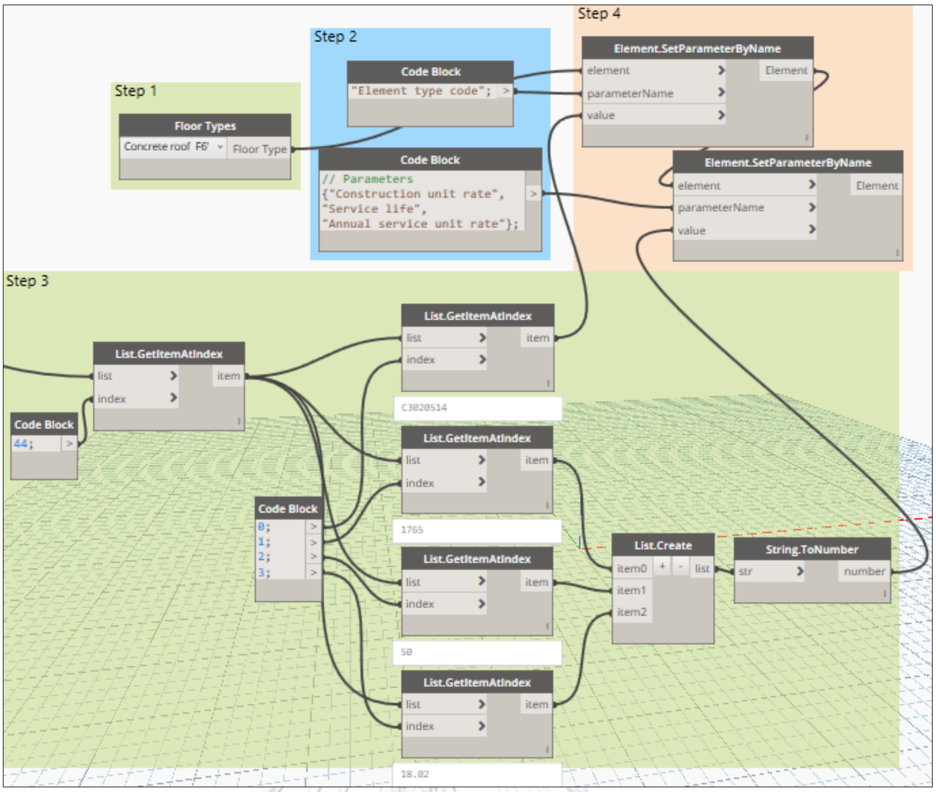
Acquire the value of required parameters for Concrete floor F6’



Acquire the value of required parameters for Gray tile roof F2'

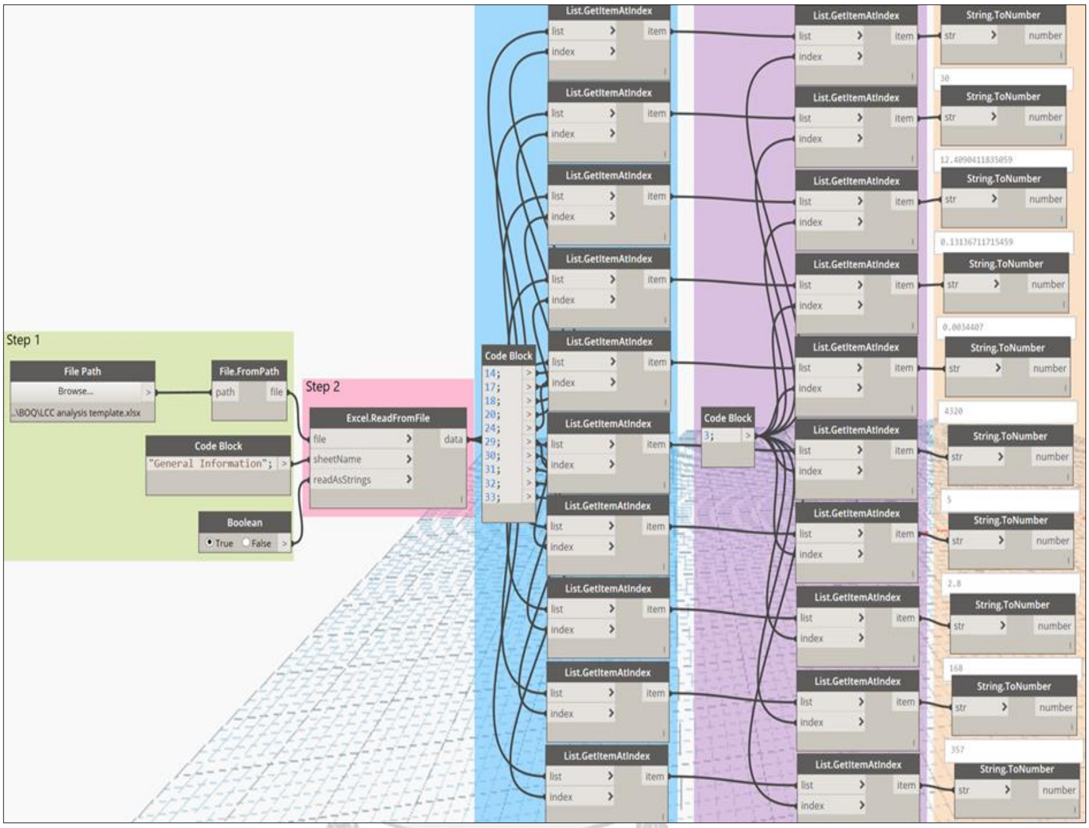


Acquire the value of required parameters for Concrete roof with waterproofing F4

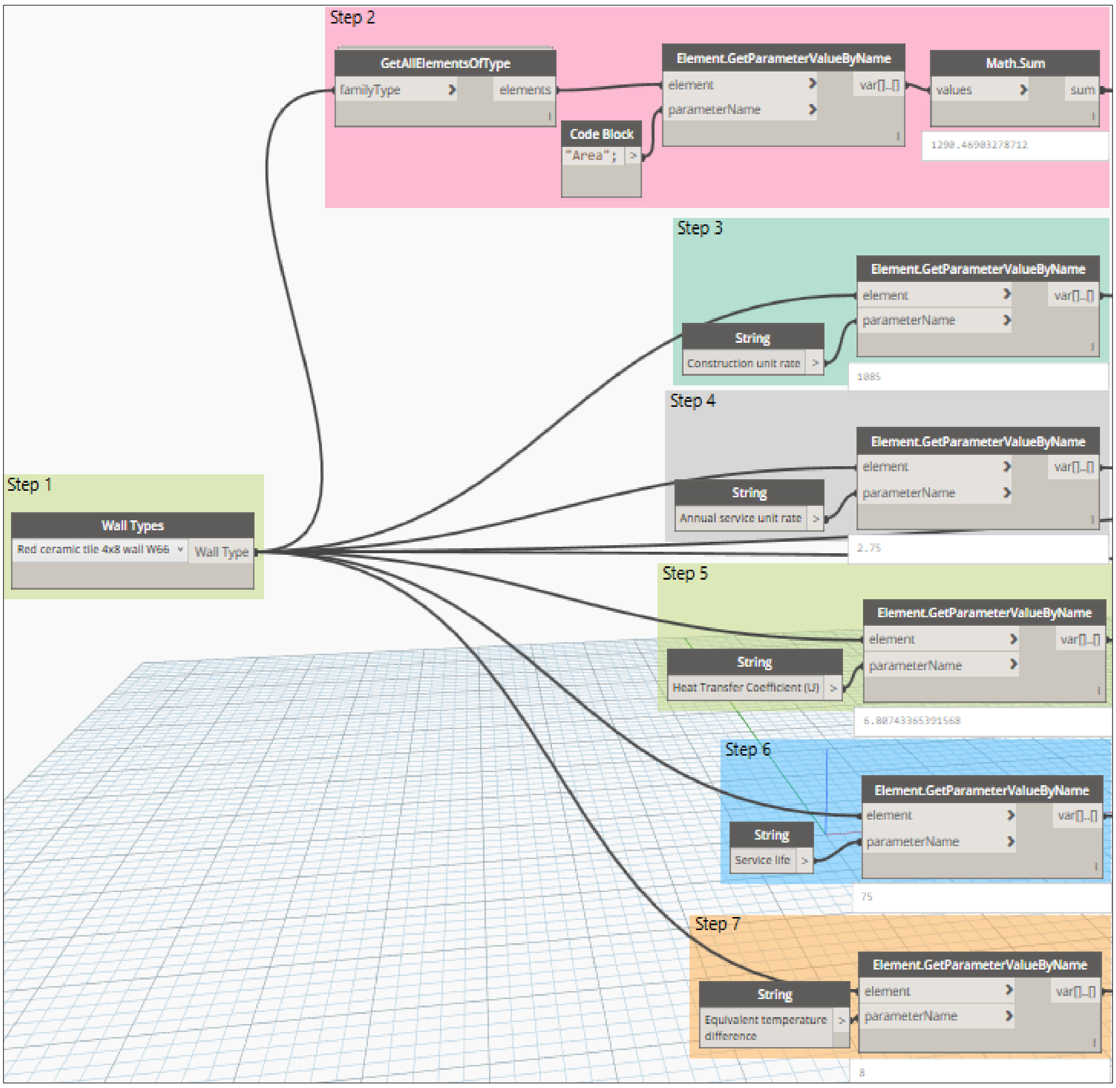


Acquire the value of required parameters for Concrete roof F6’

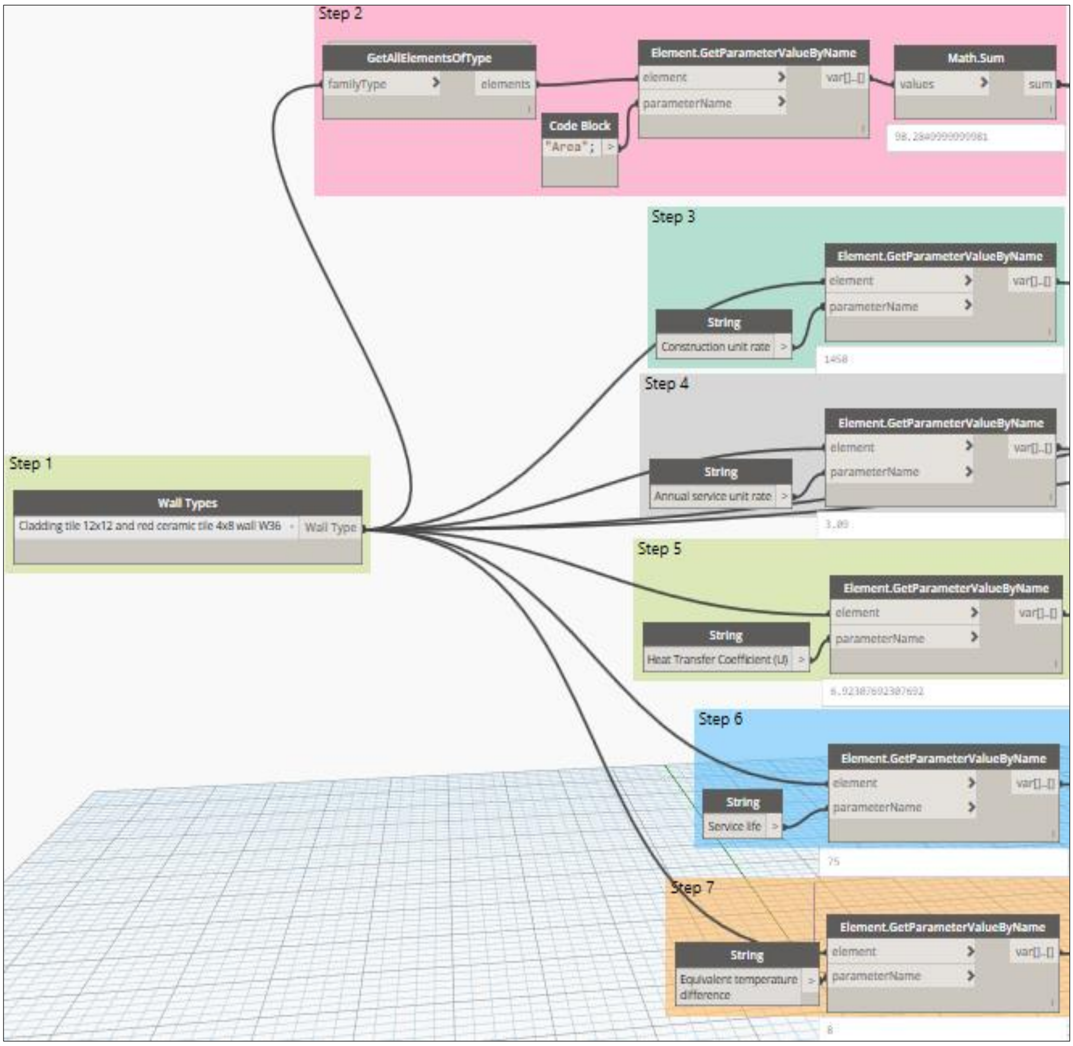
APPENDIX D DYNAMO NODES OF THE ACQUISITION OF ASSUMED PARAMETERS



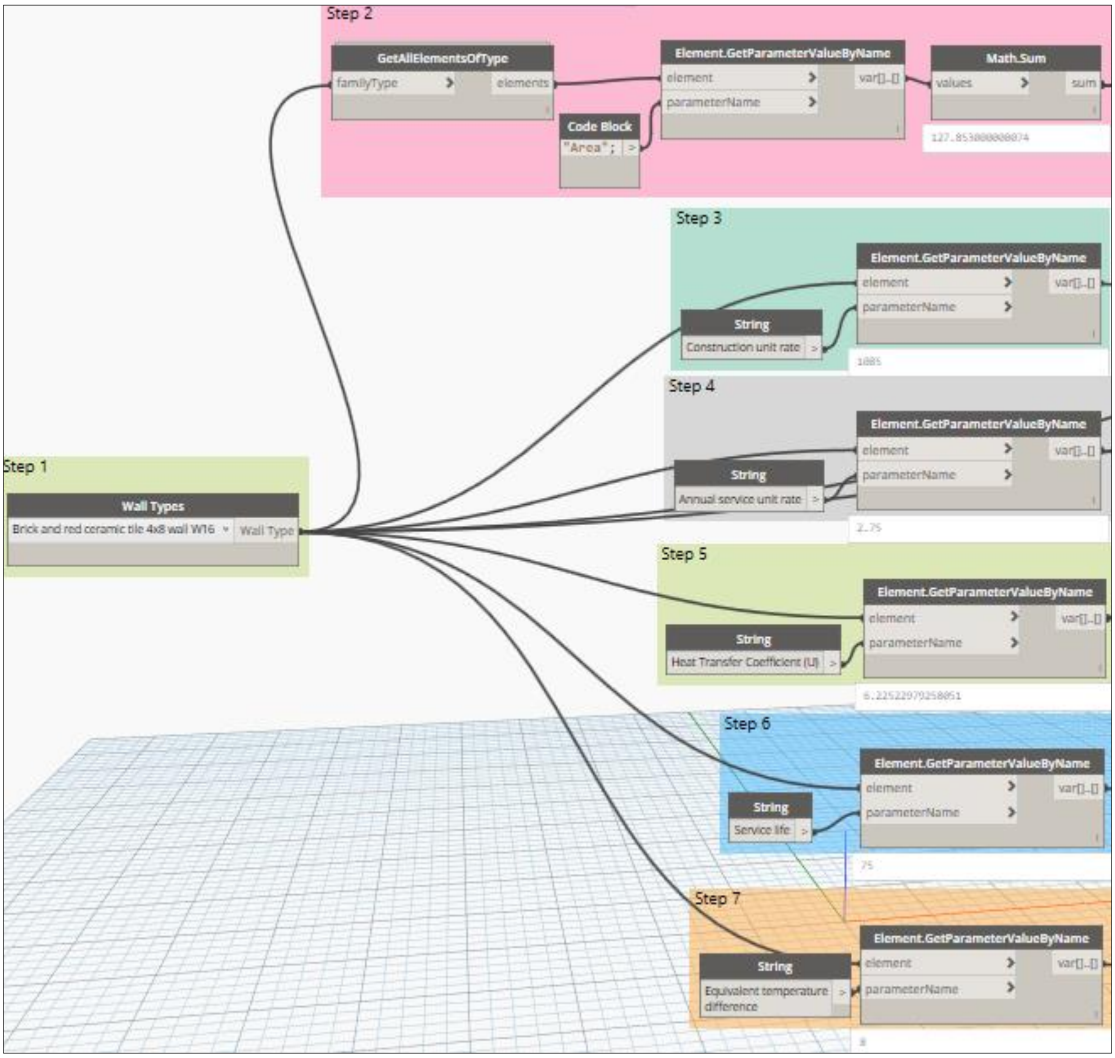
APPENDIX E DYNAMO NODES OF THE ACQUISITION OF TYPE PARAMETERS OF THE BIM MODEL



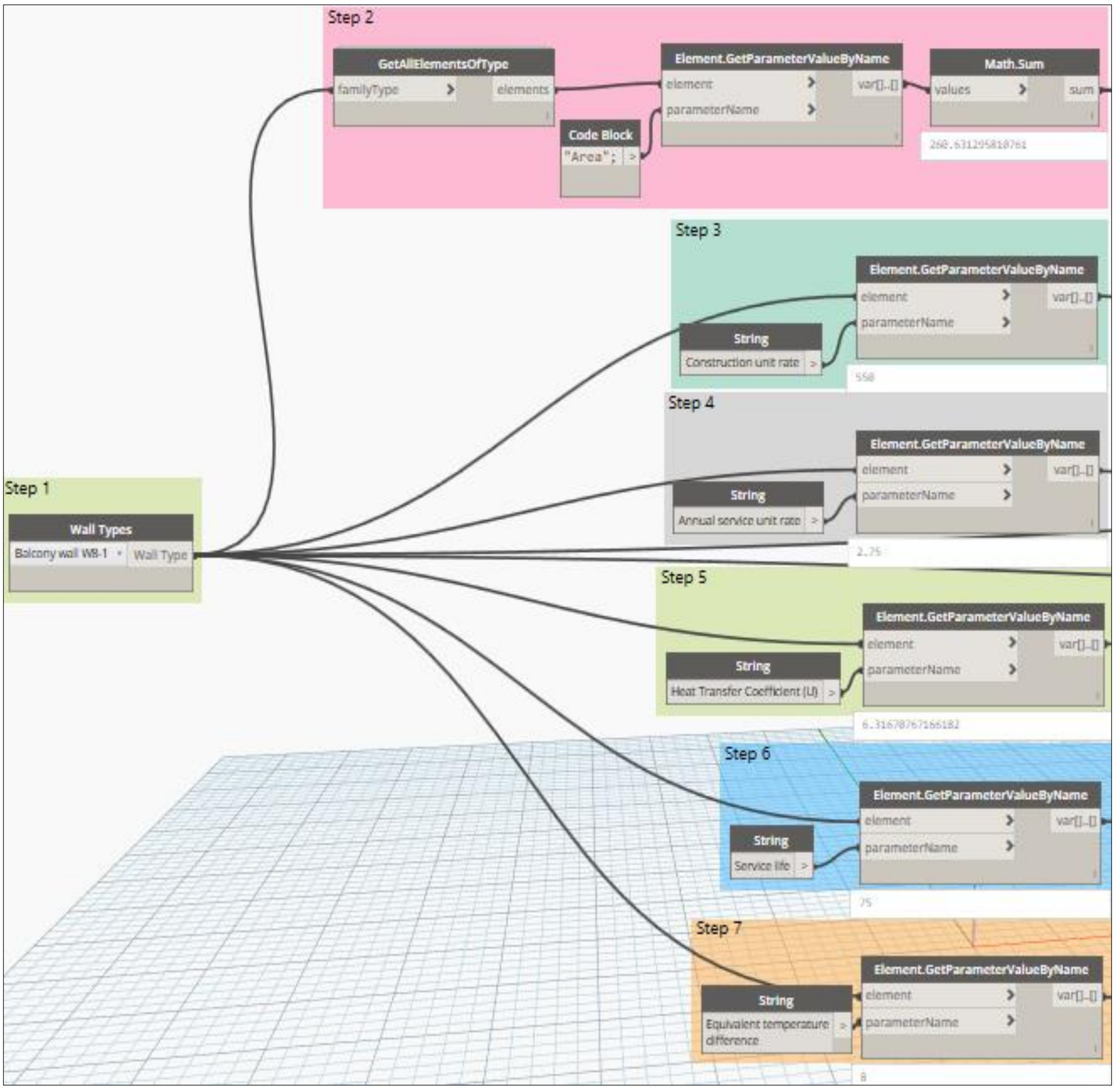
Acquire the required parameters of Red ceramic tile 4x8 wall W66 type



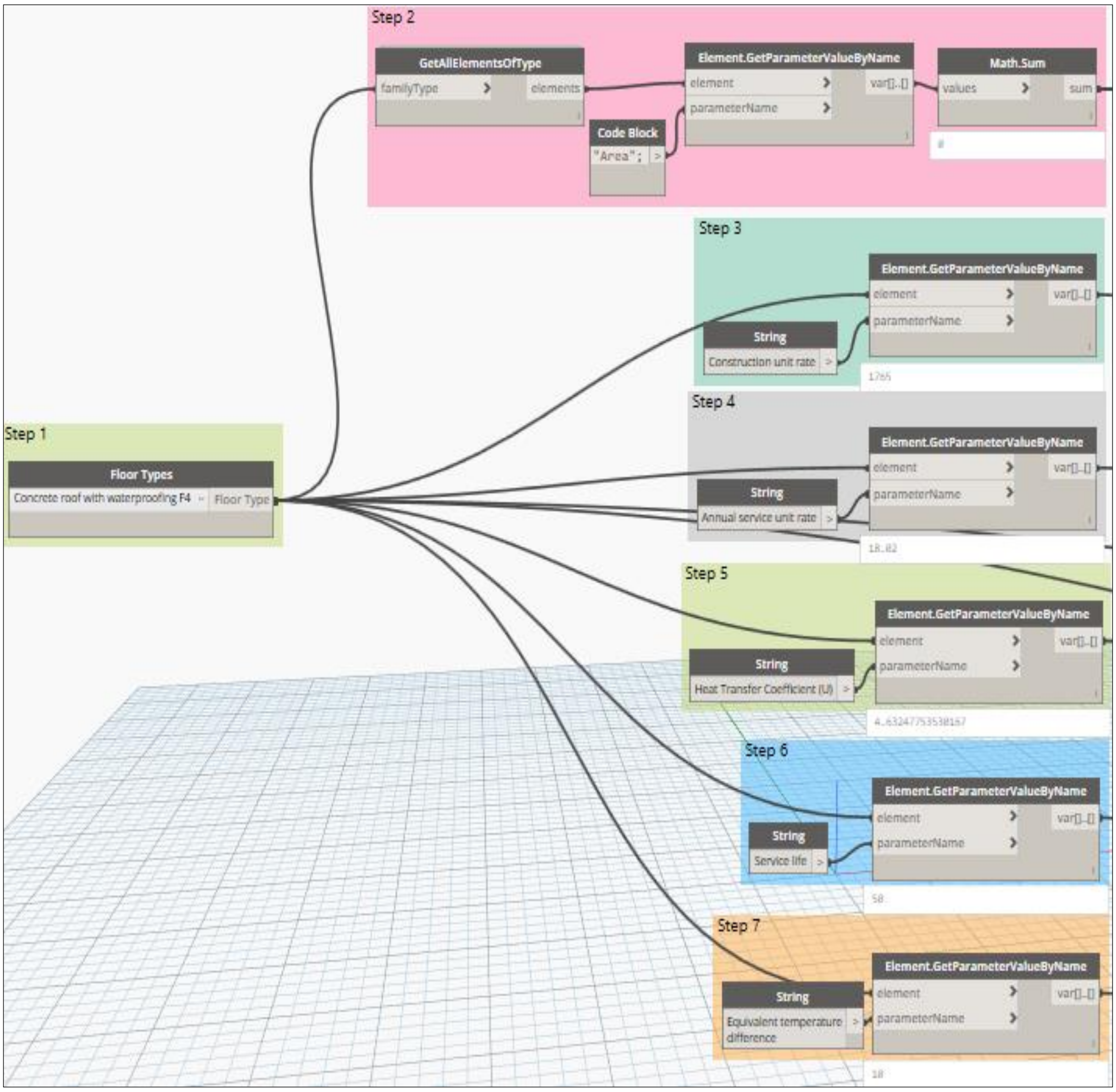
Acquire the required parameters of Cladding tile 12x12 and red ceramic tile 4x8 wall W36 type



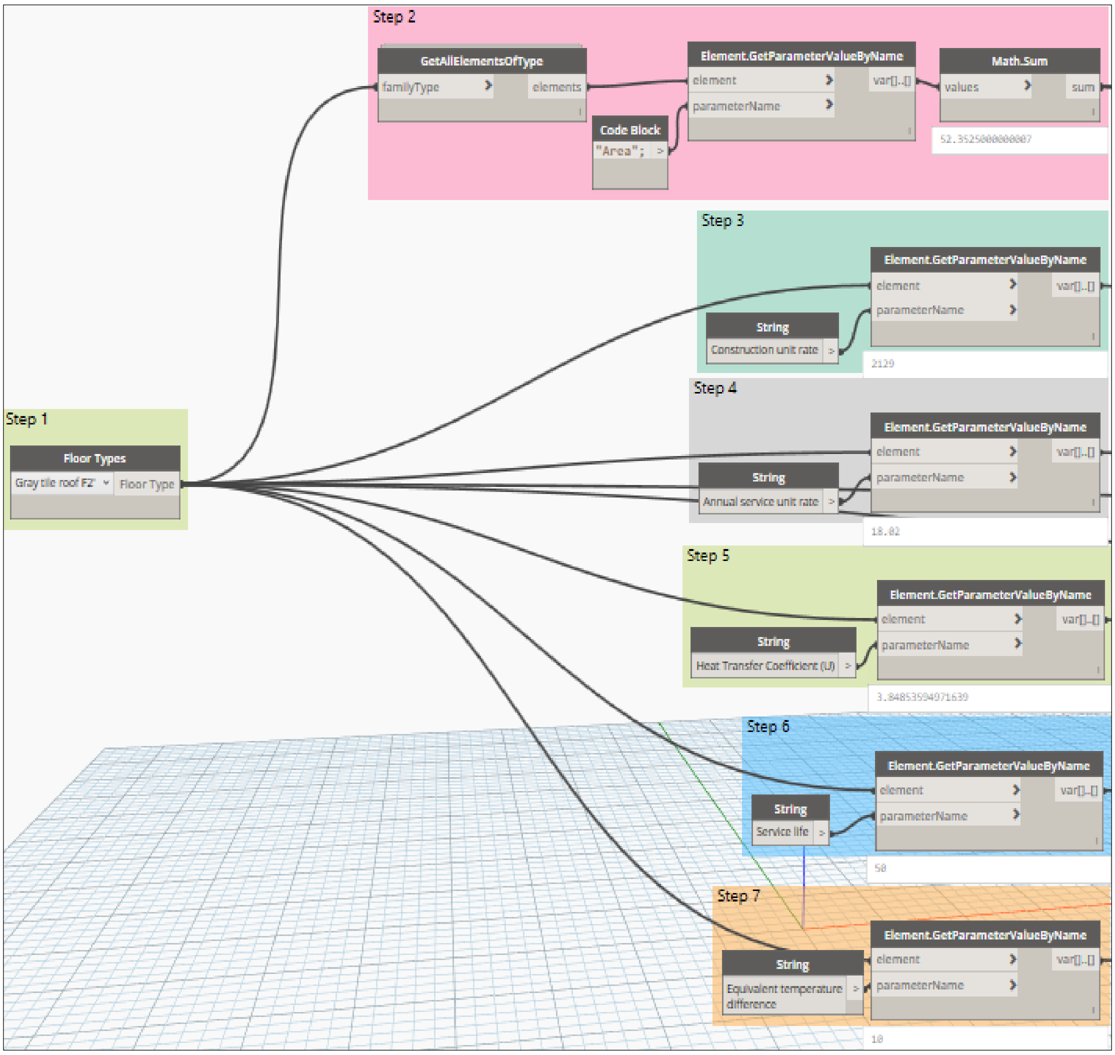
Acquire the required parameters of Brick and red ceramic tile 4x8 wall W16 type



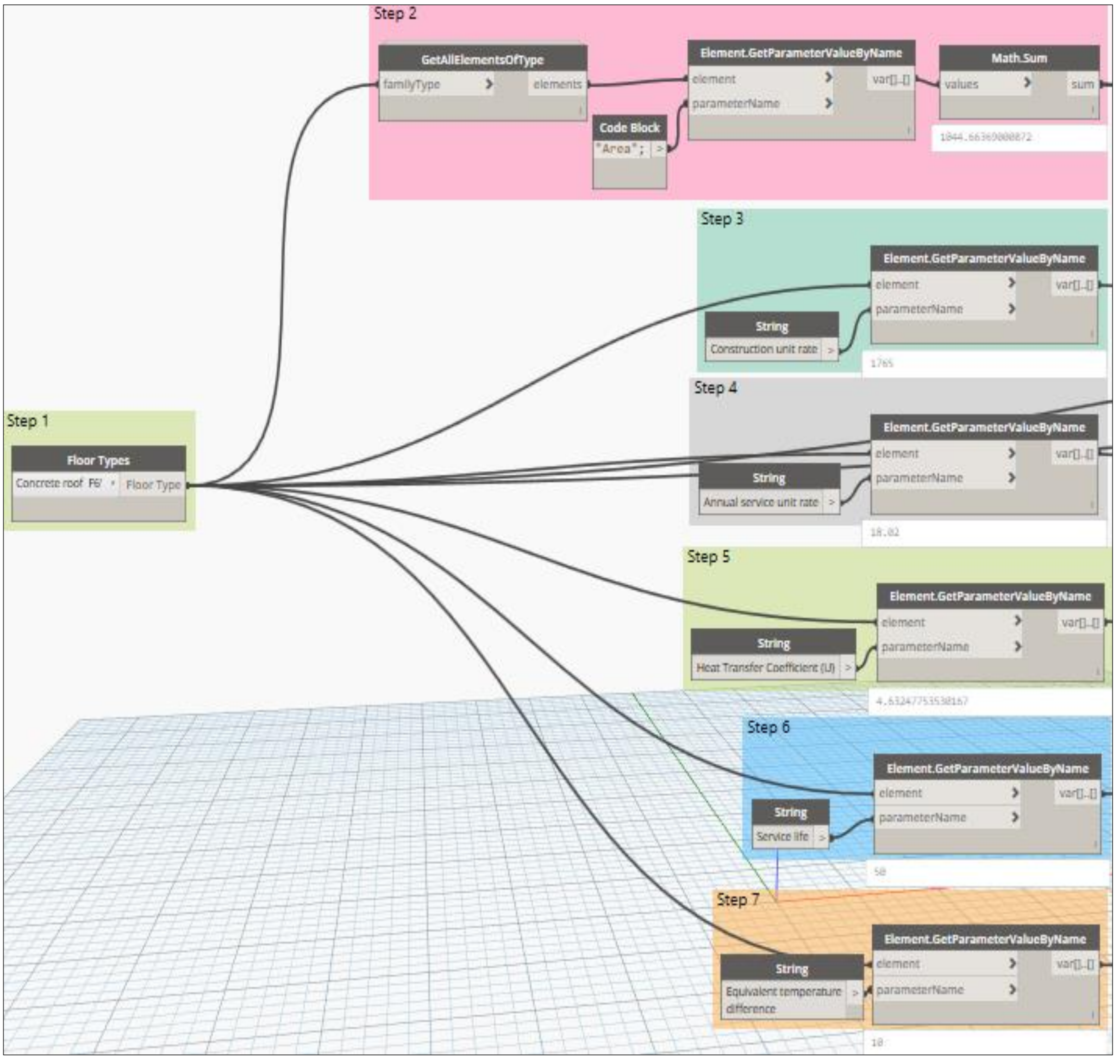
Acquire the required parameters of Balcony wall W8-1 type



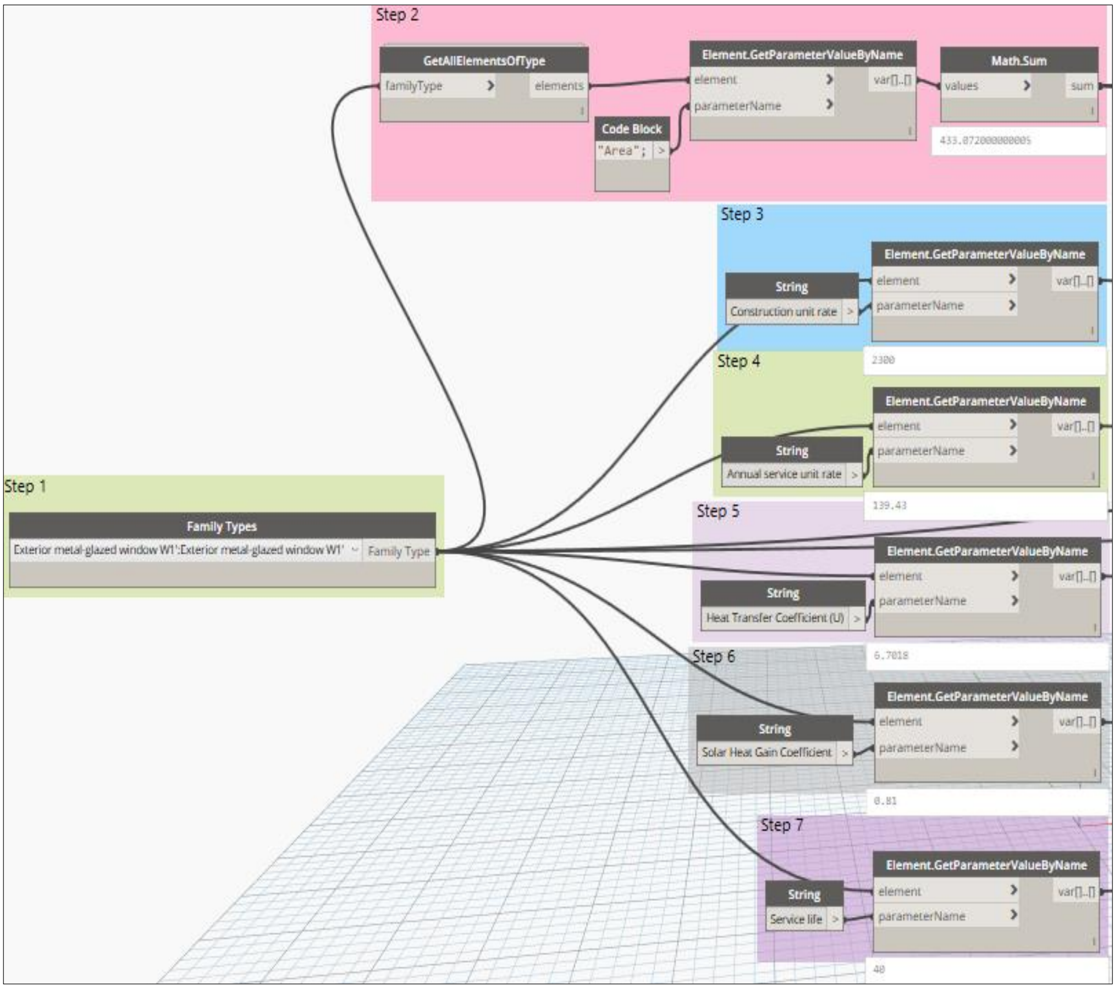
Acquire the required parameters of Concrete roof with waterproofing F4 type



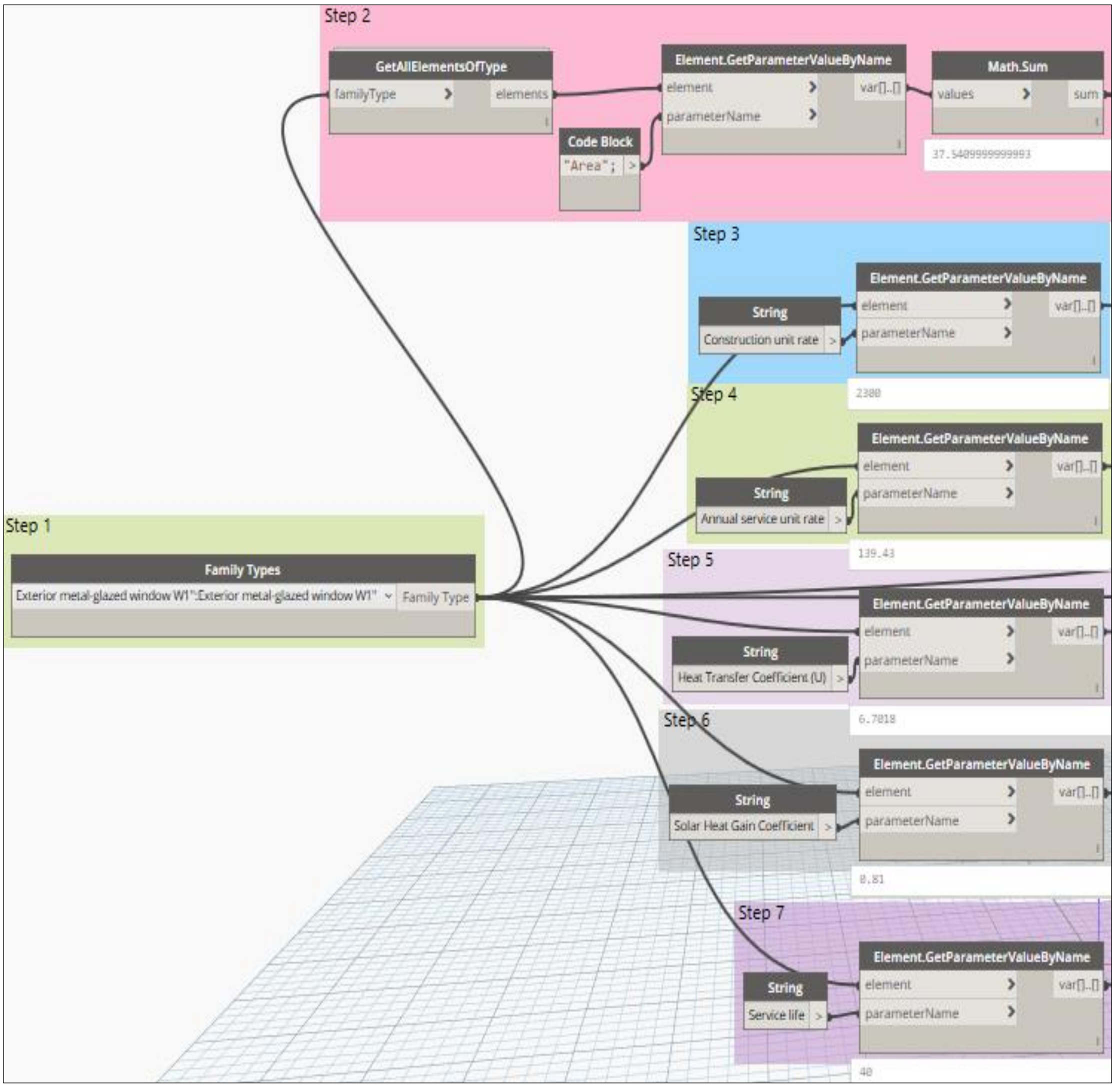
Acquire the required parameters of Gray tile roof F2’ type



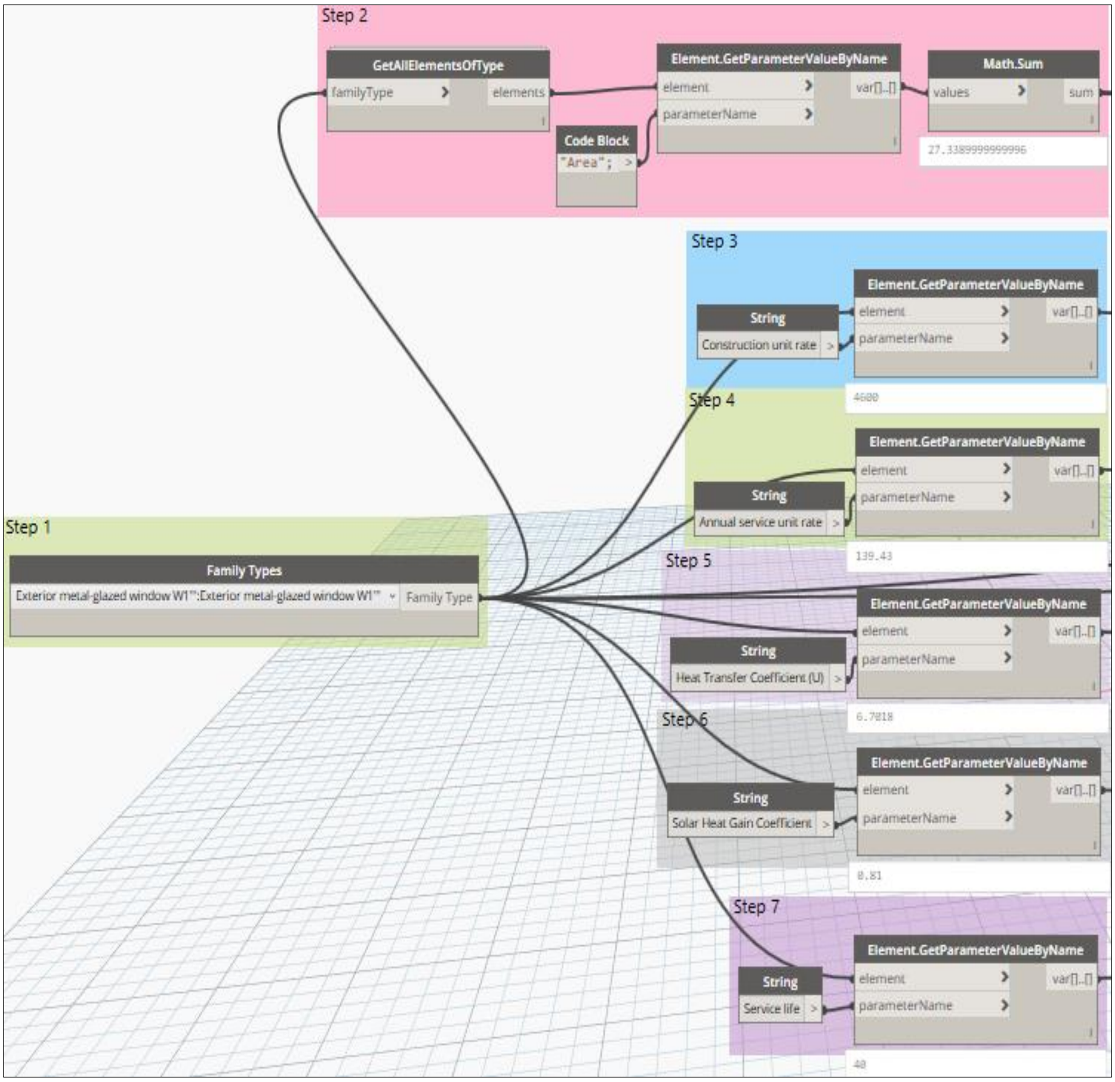
Acquire the required parameters of Concrete roof F6’ type



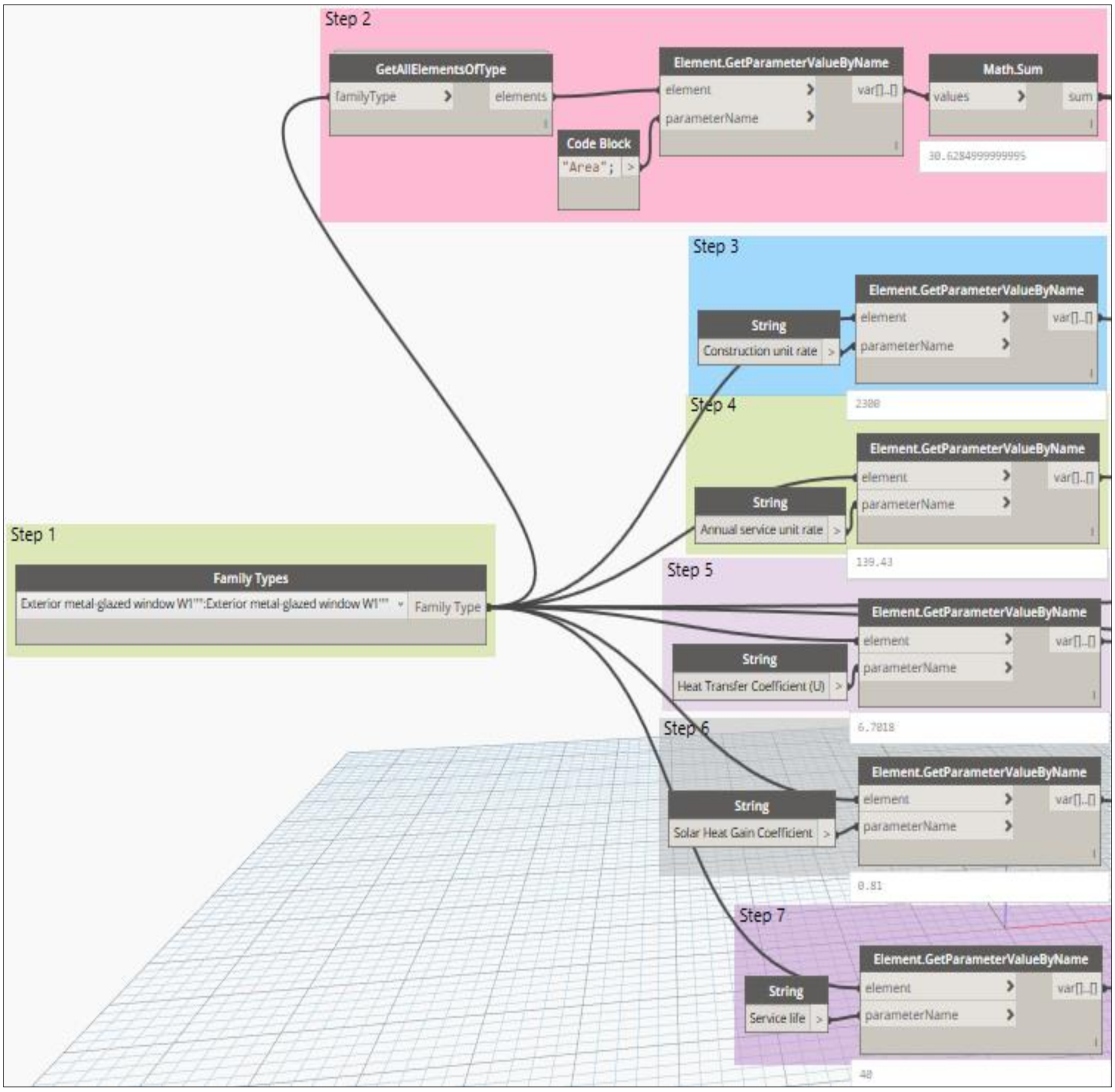
Acquire the required parameters of Exterior metal-glazed window W1' type



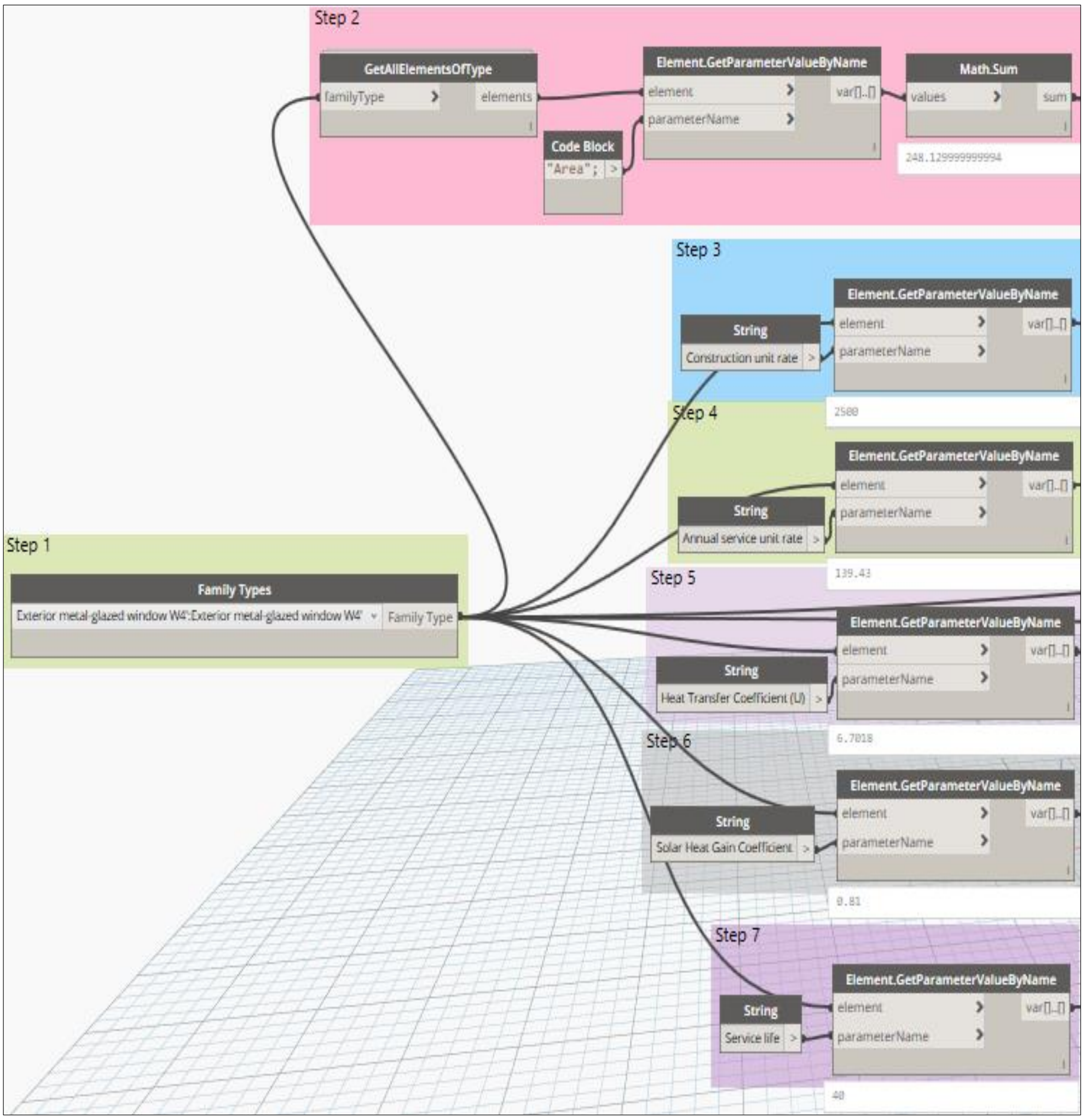
Acquire the required parameters of Exterior metal-glazed window W1” type



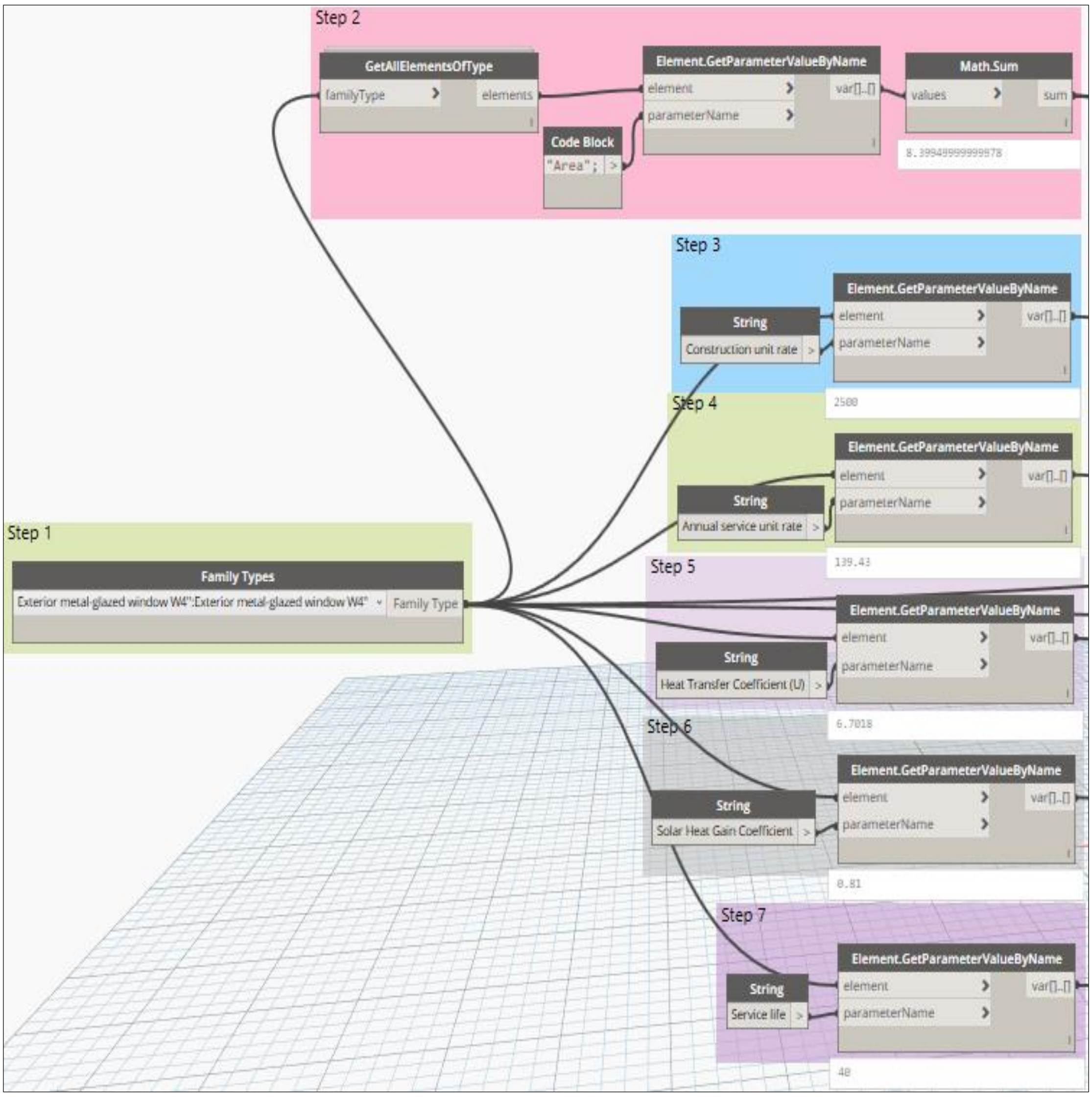
Acquire the required parameters of Exterior metal-glazed window W1’” type



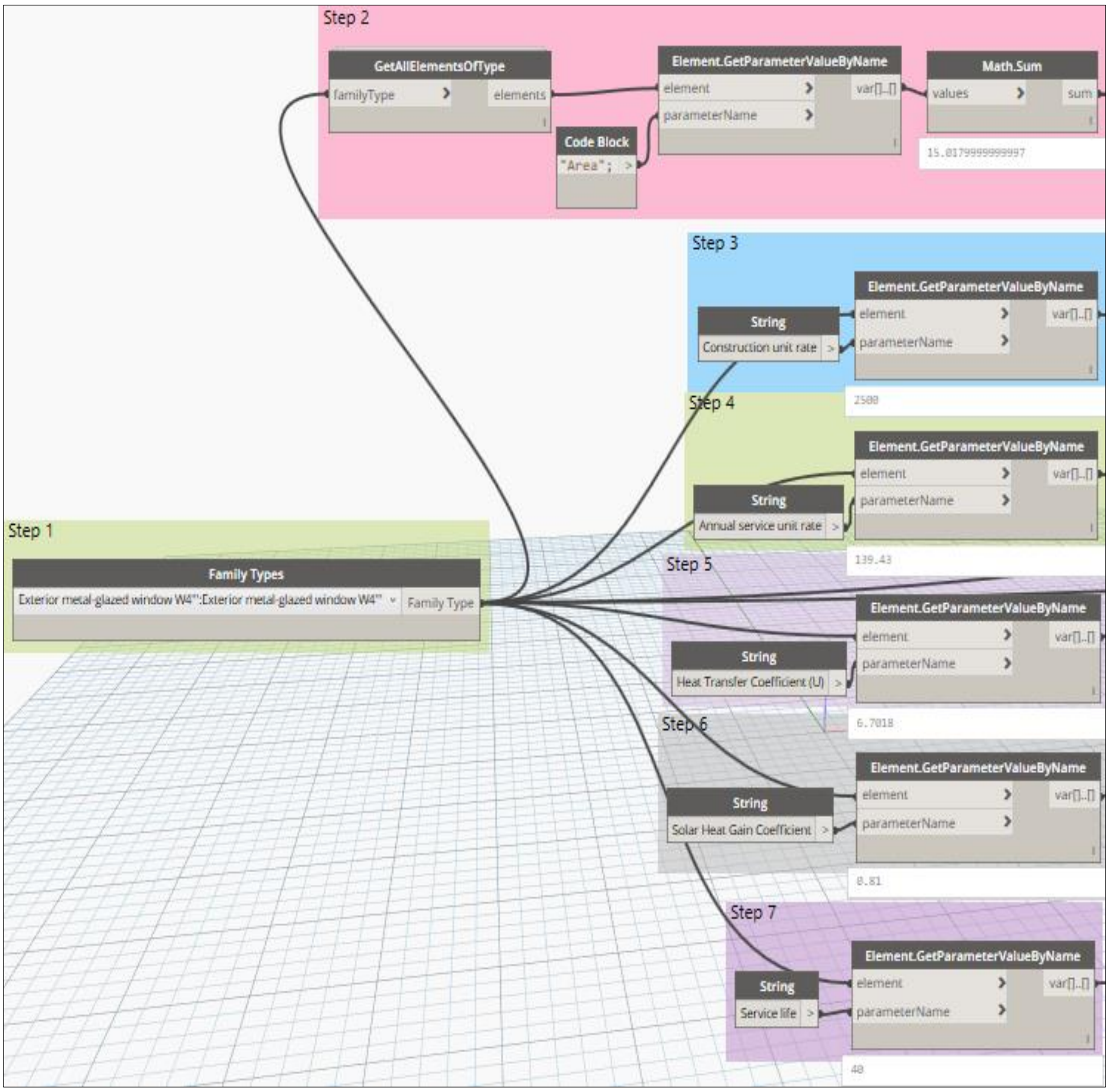
Acquire the required parameters of Exterior metal-glazed window W1”” type



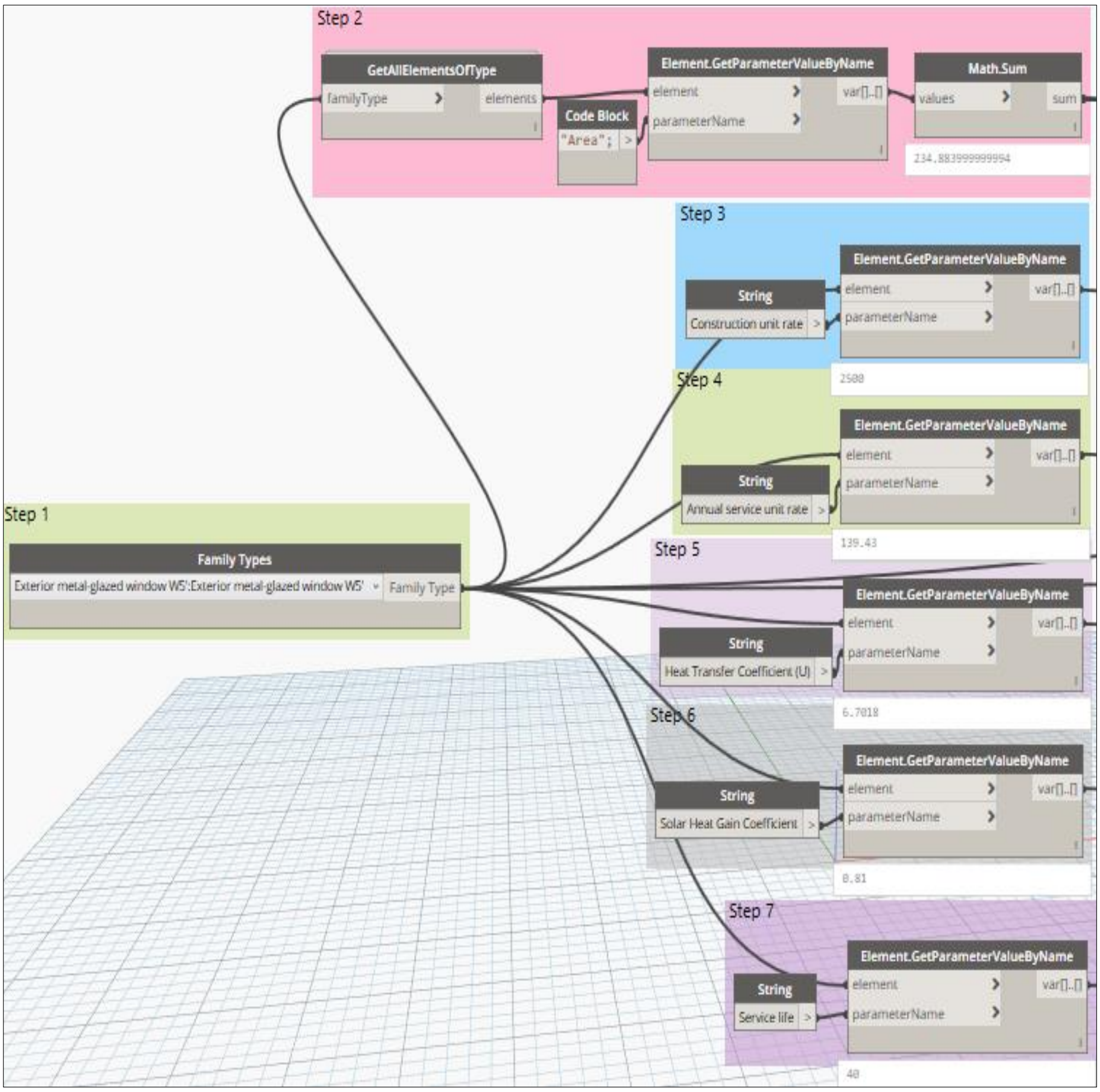
Acquire the required parameters of Exterior metal-glazed window W4’ type



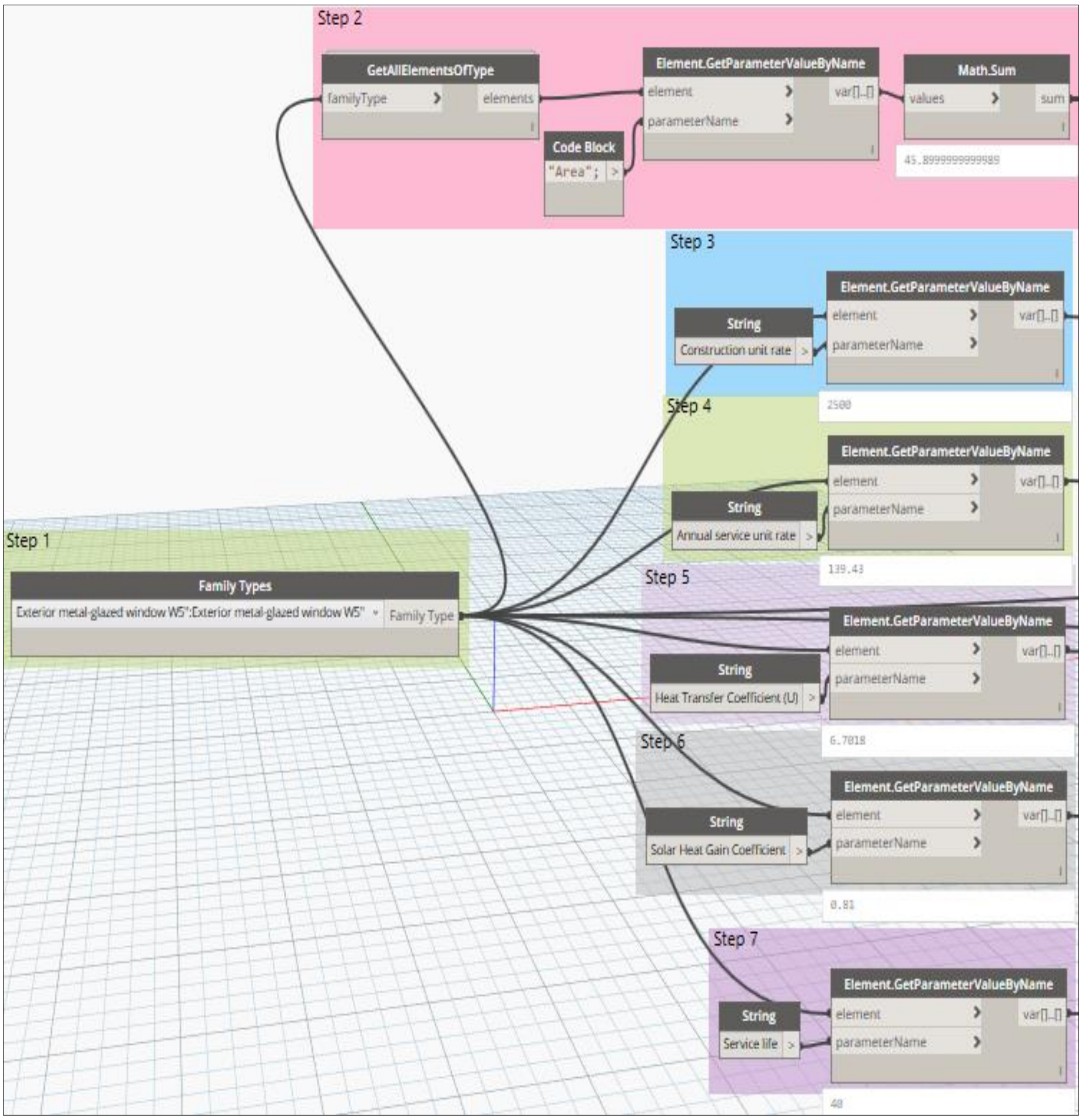
Acquire the required parameters of Exterior metal-glazed window W4” type



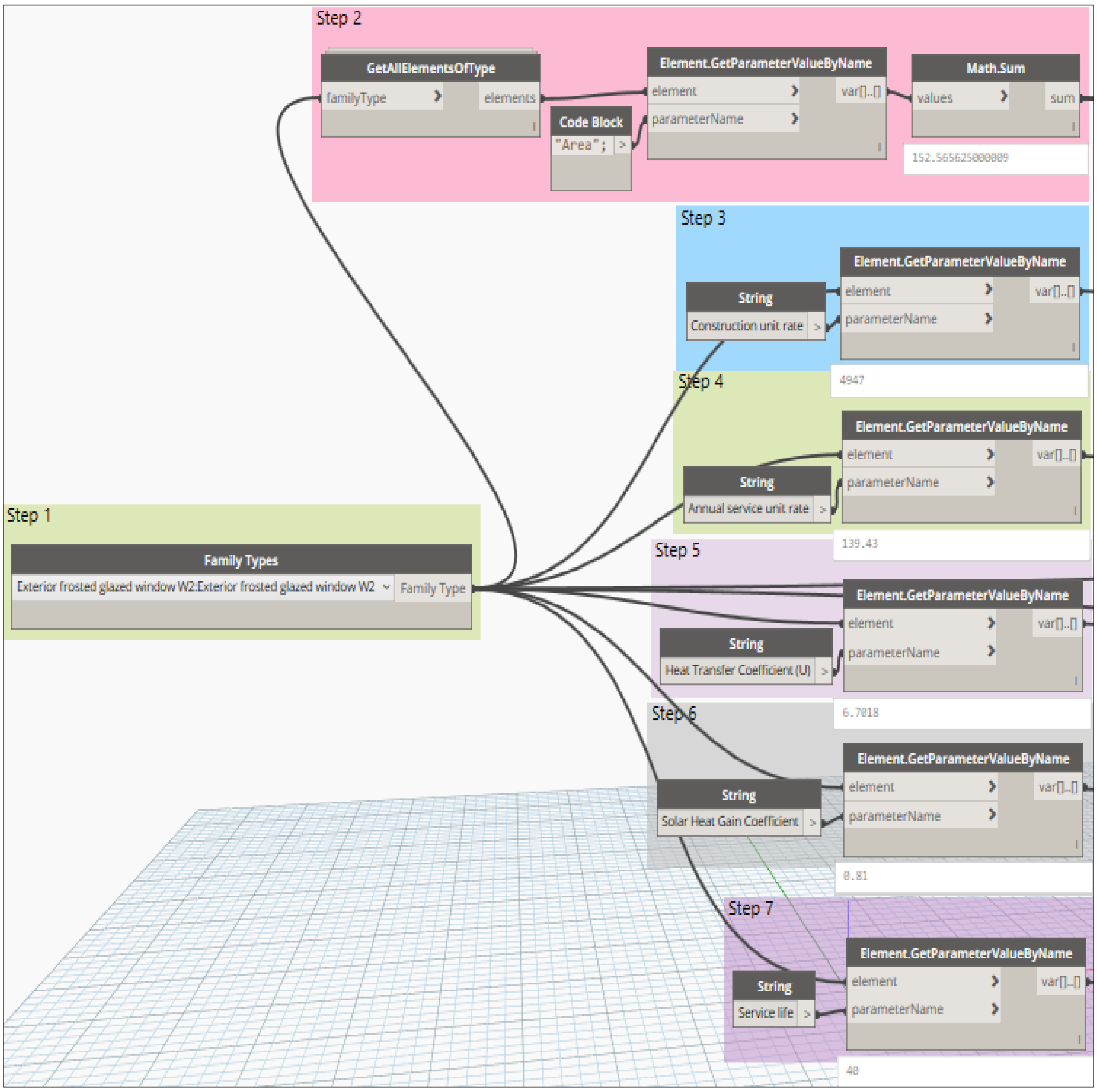
Acquire the required parameters of Exterior metal-glazed window W4'" type



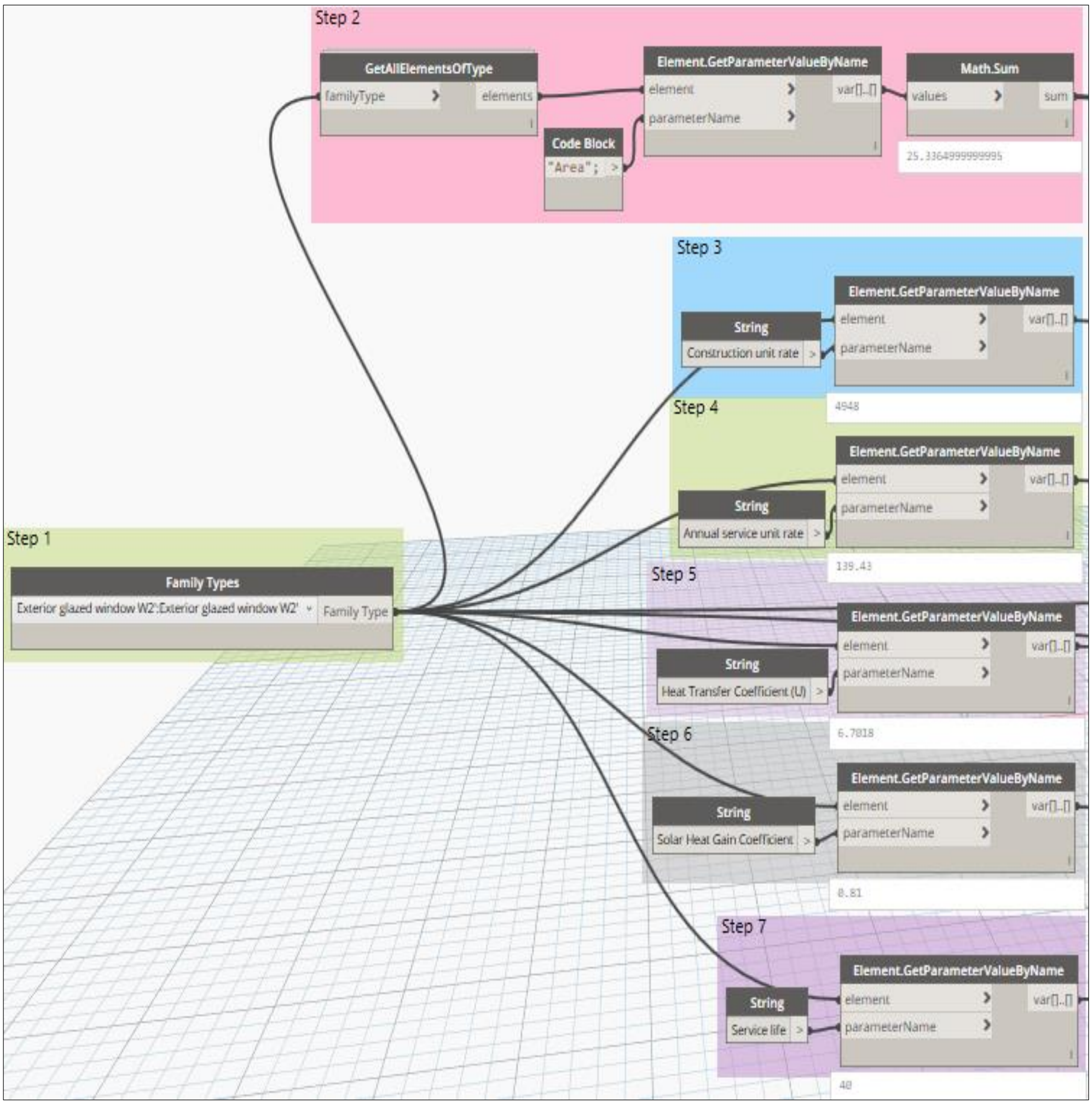
Acquire the required parameters of Exterior metal-glazed window W5' type



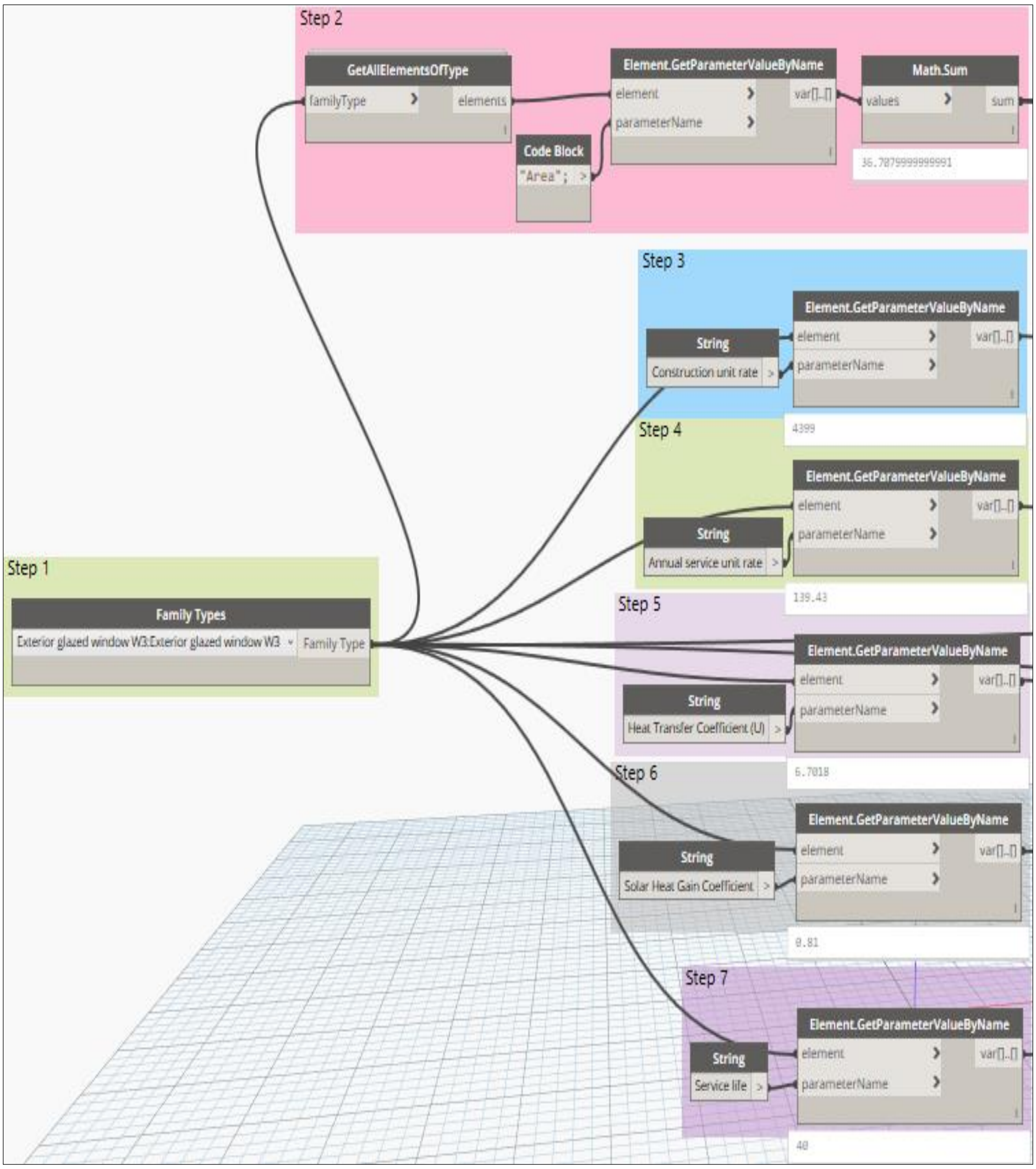
Acquire the required parameters of Exterior metal-glazed window W5” type



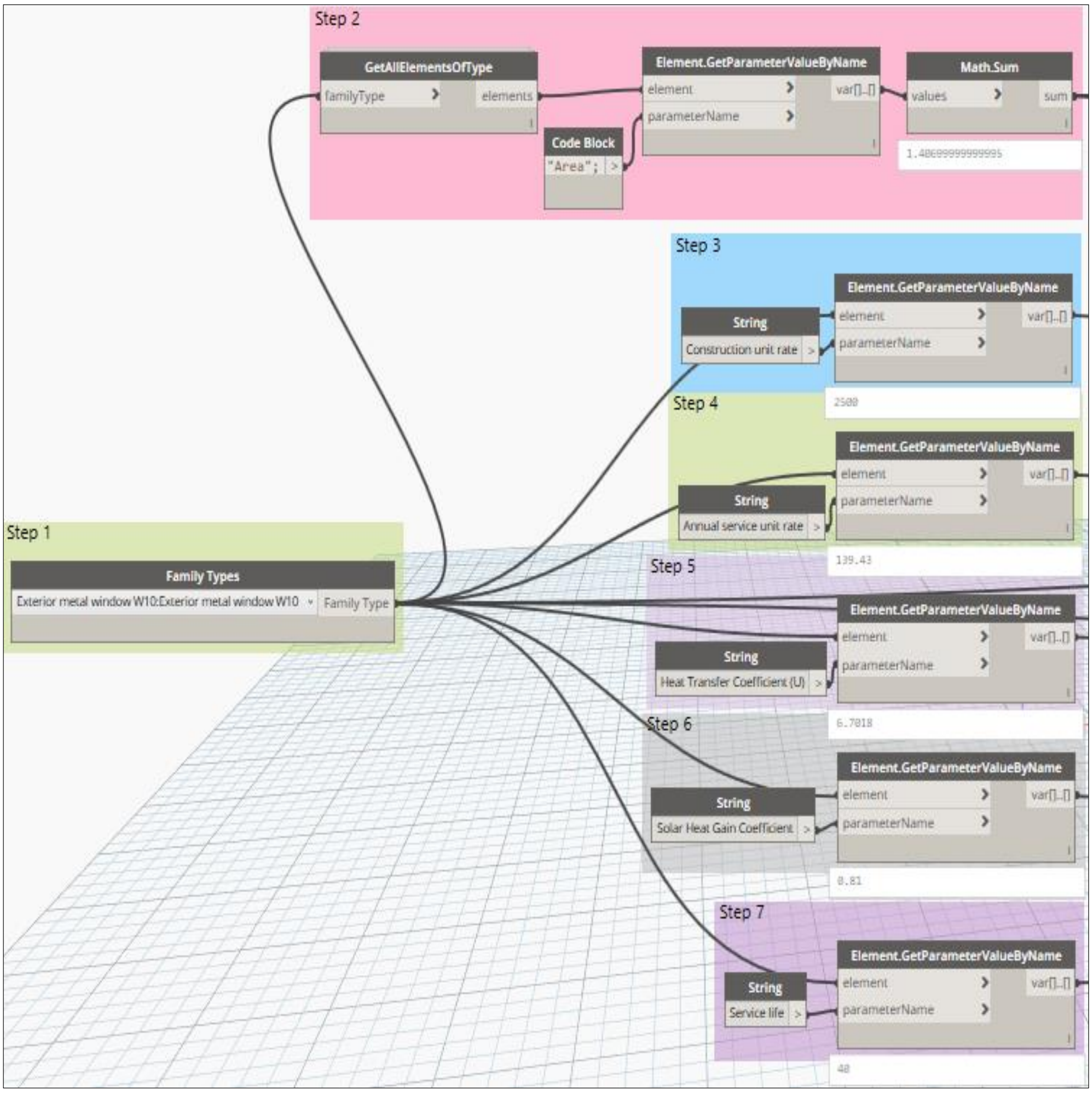
Acquire the required parameters of Exterior frosted glazed window W2 type



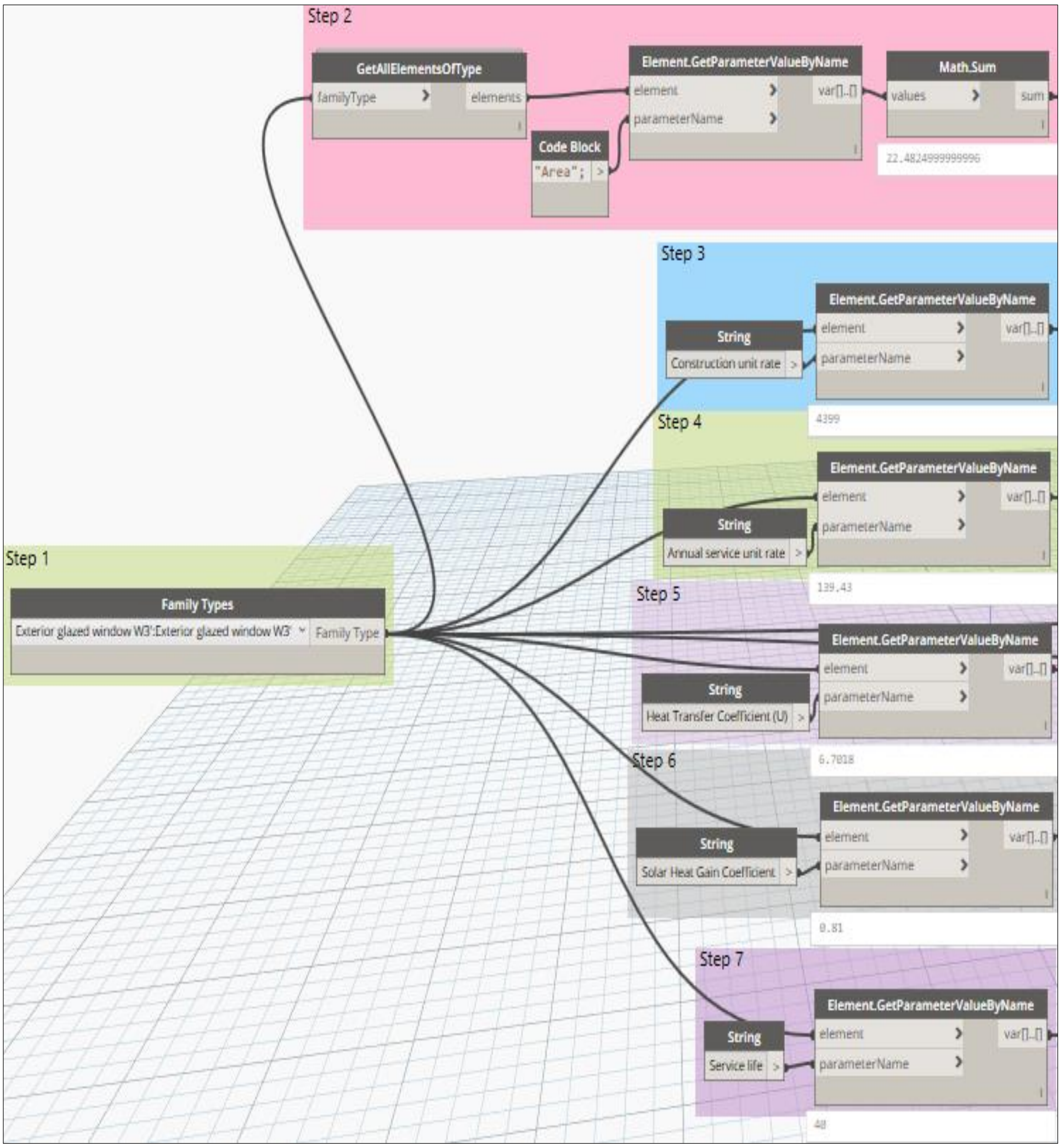
Acquire the required parameters of Exterior glazed window W2’ type



Acquire the required parameters of Exterior glazed window W3 type

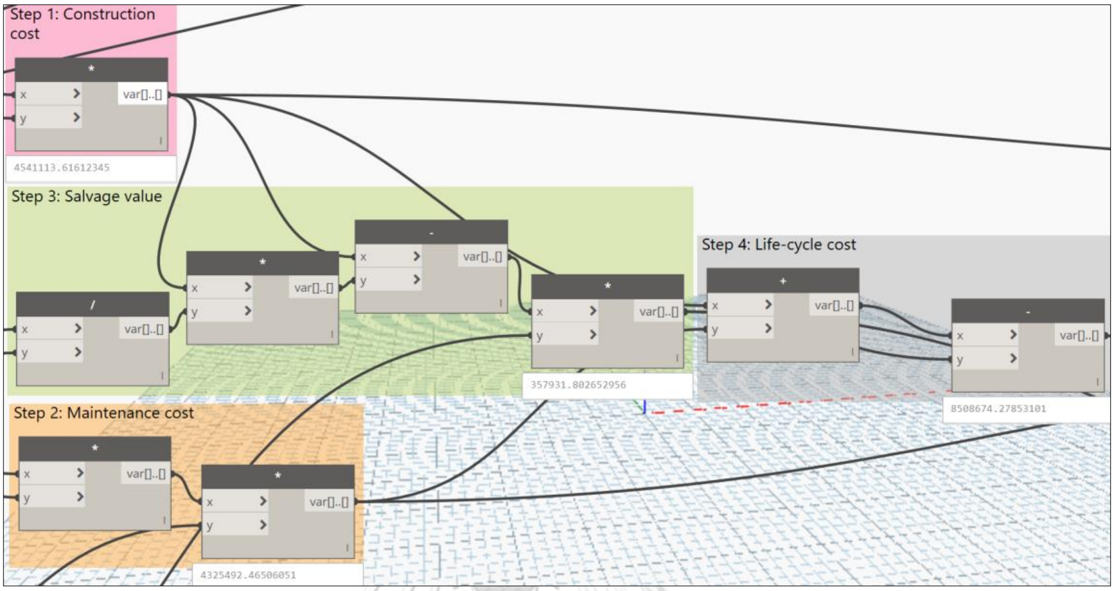


Acquire the required parameters of Exterior metal window W10 type

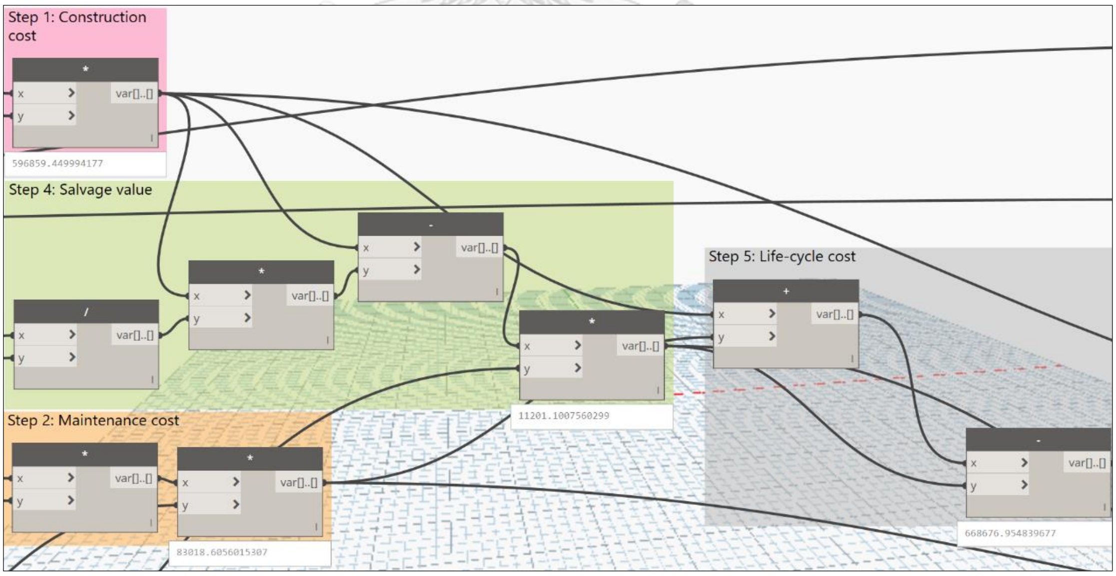


Acquire the required parameters of Exterior glazed window W3’ type

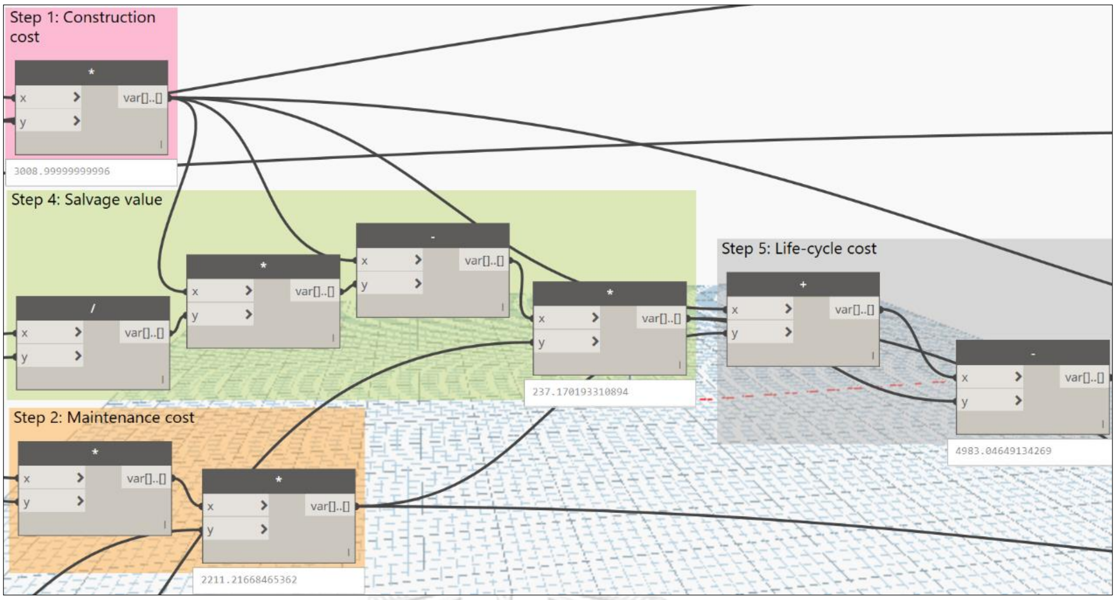
APPENDIX F DYNAMO NODES OF THE MULTI-PARAMETRIC MODEL FOR THE BUILDING LCCA



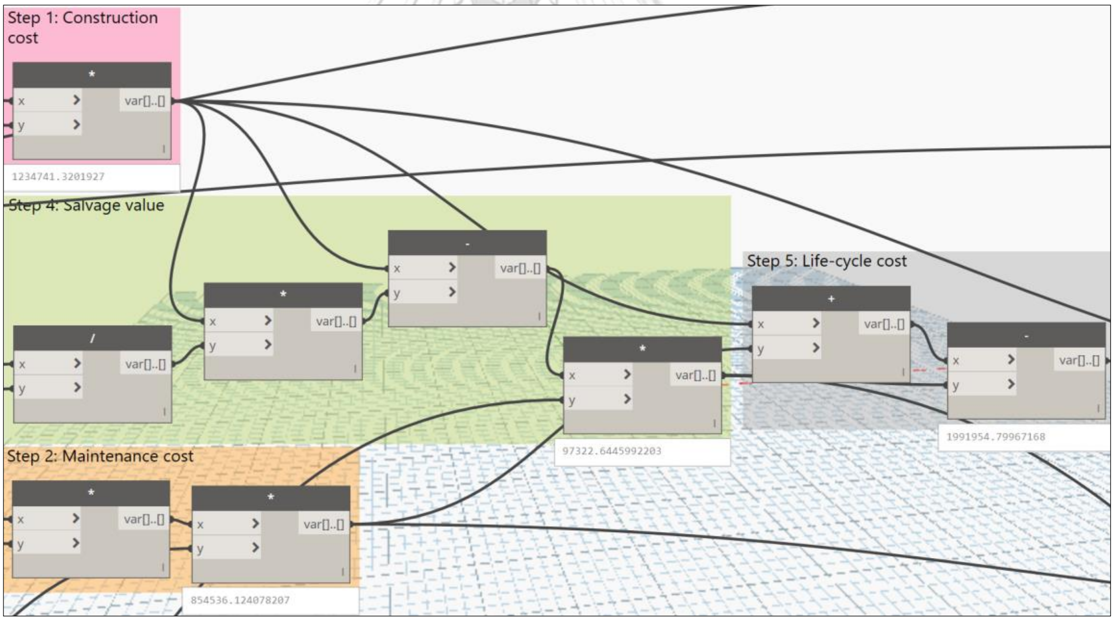
Dynamic auto-upgrade of Brick wall W11 type



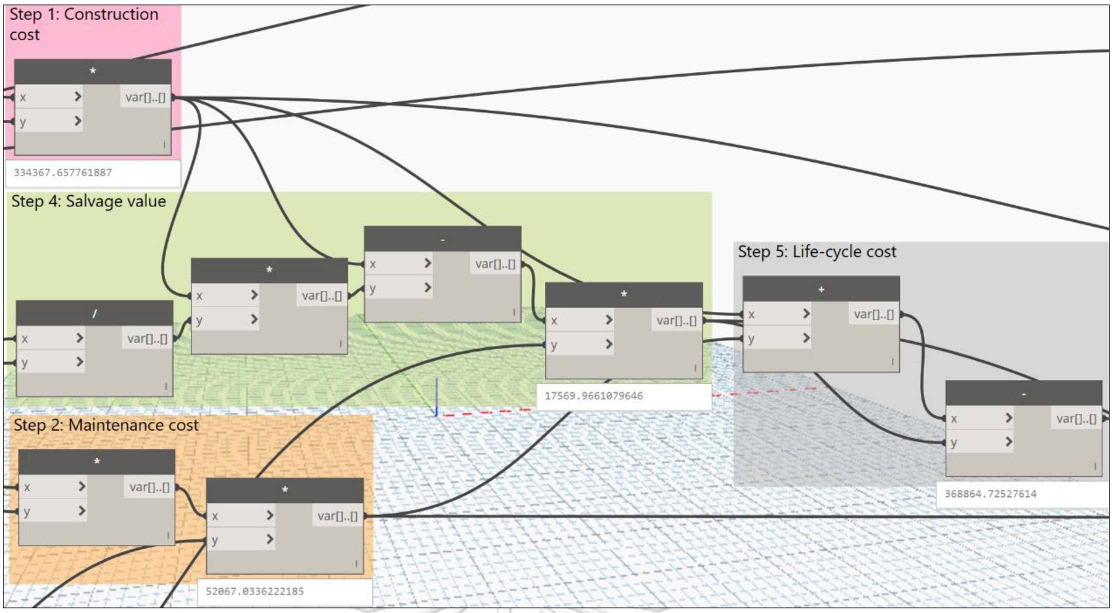
Dynamic auto-upgrade of Gypsum wall W55



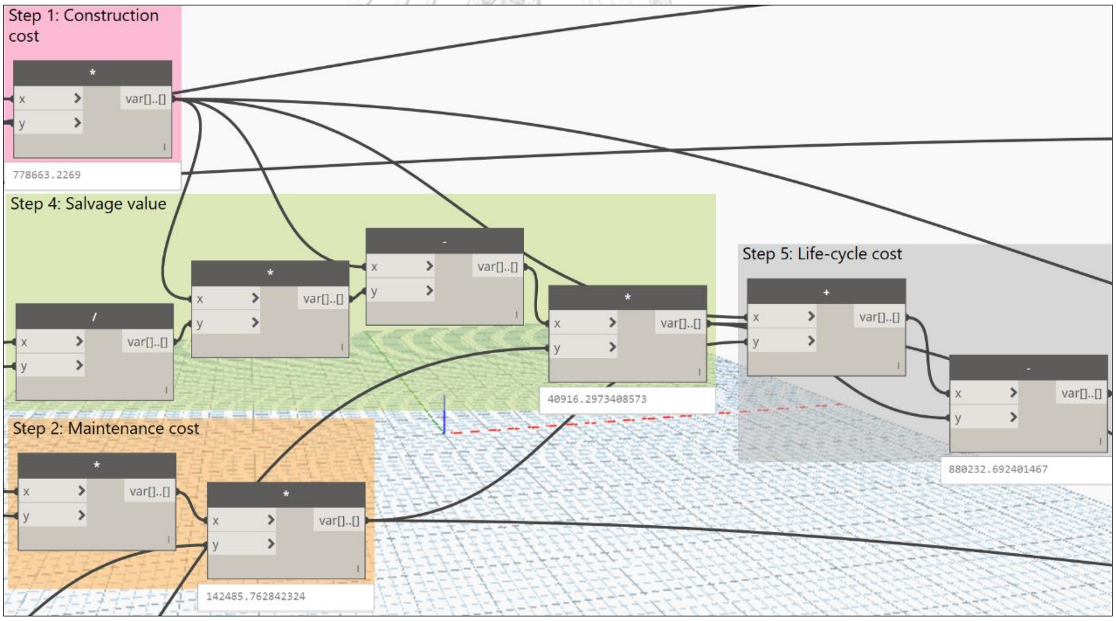
Dynamic auto-upgrade of Cladding tile 12x12 wall W3



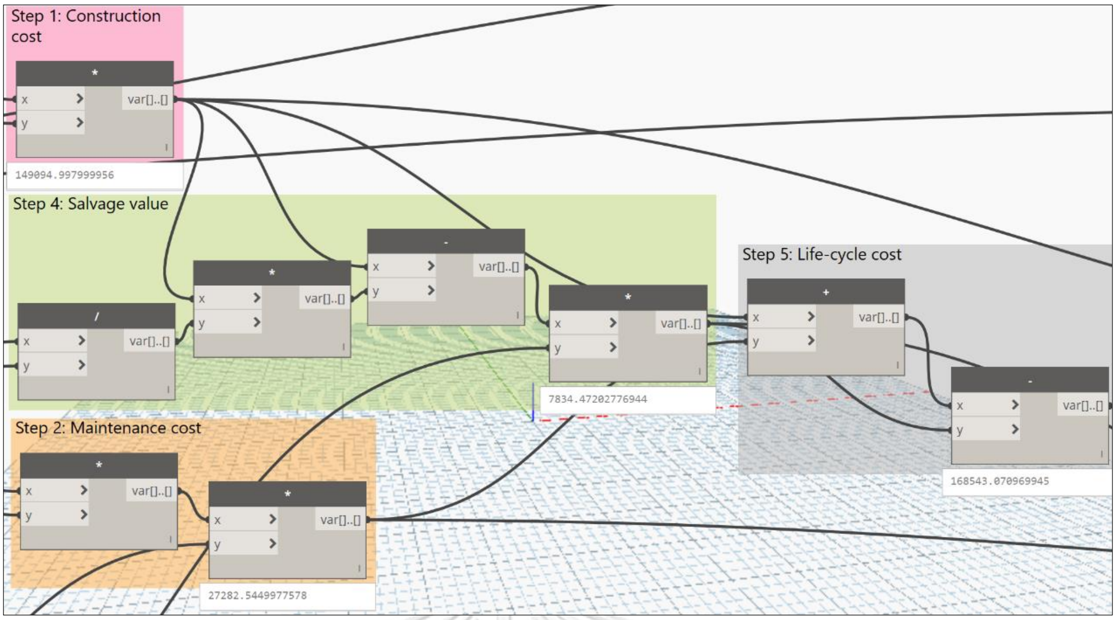
Dynamic auto-upgrade of Brick and cladding tile 12x12 wall W13



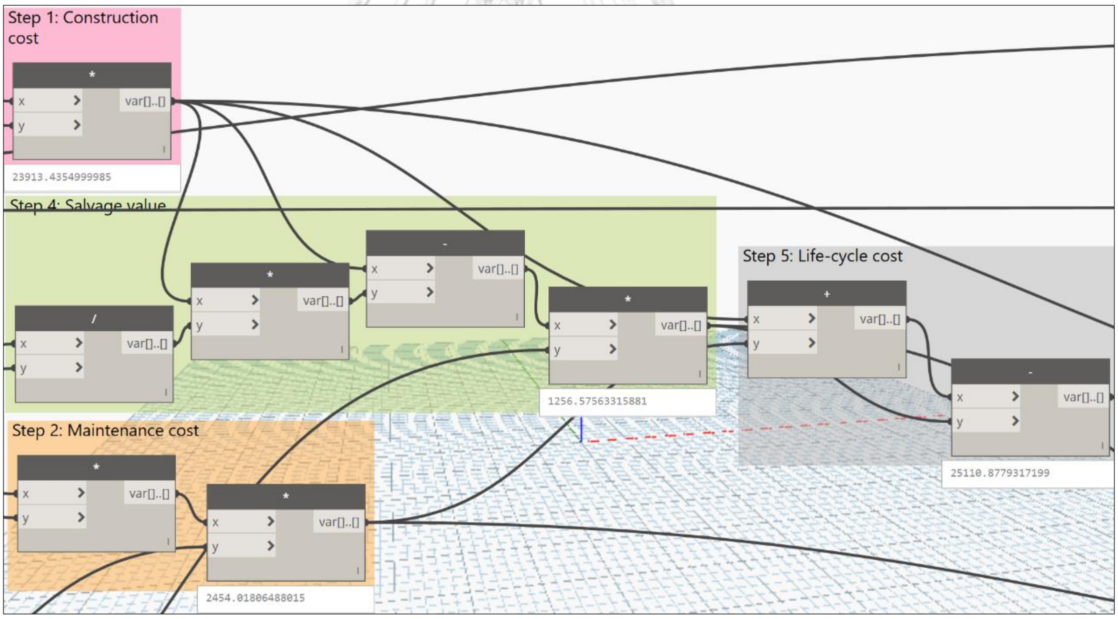
Dynamic auto-upgrade of Gray stone floor F1



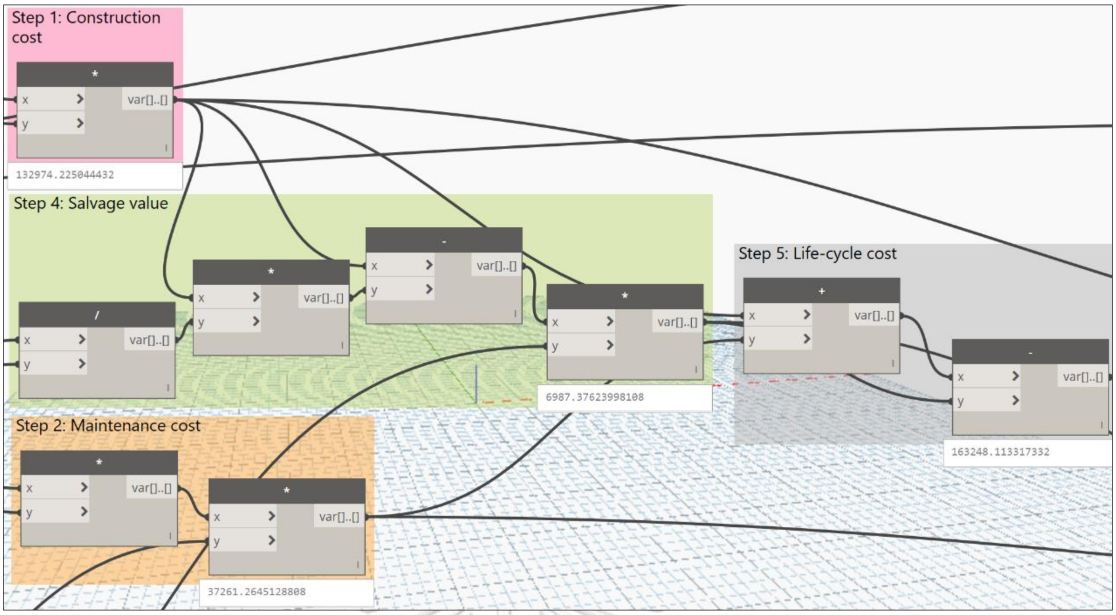
Dynamic auto-upgrade of Gray tile floor F2



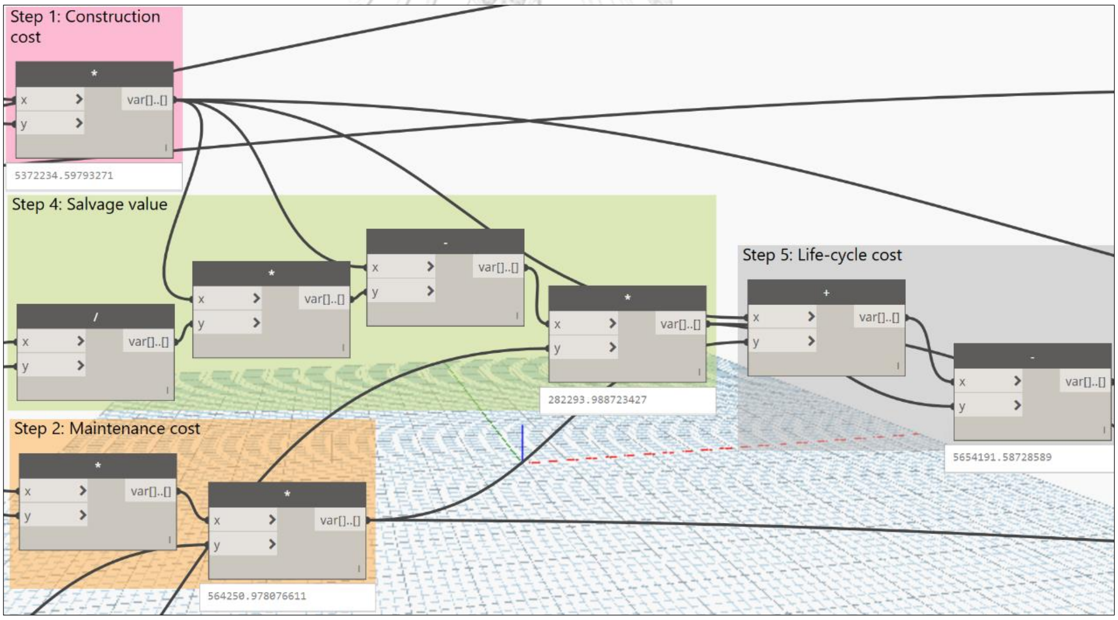
Dynamic auto-upgrade of Ceramic tile floor F3



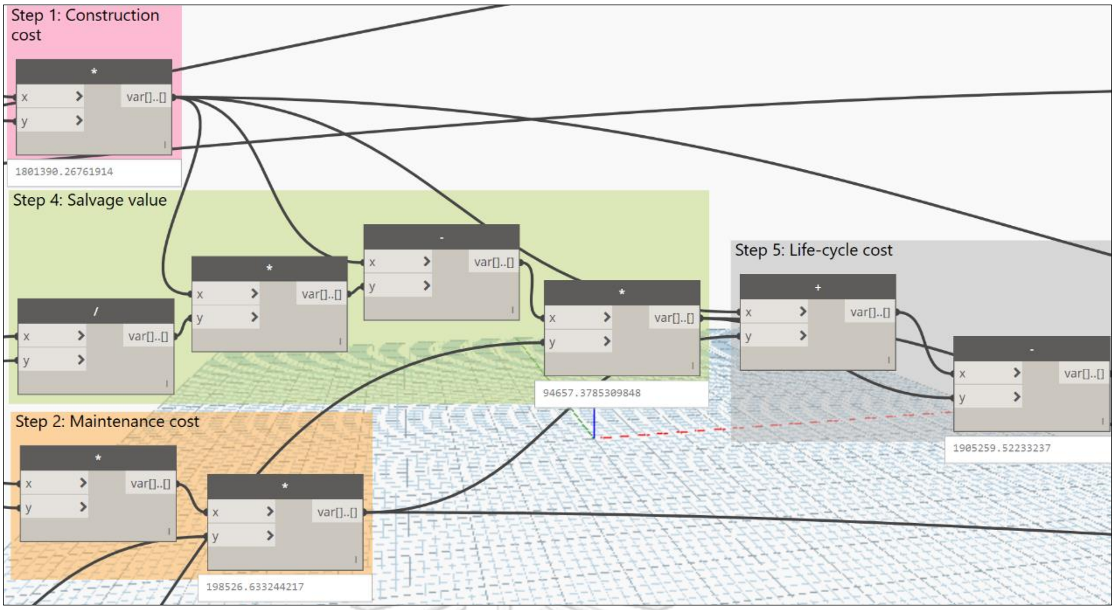
Dynamic auto-upgrade of White-gray terrazzo floor F5



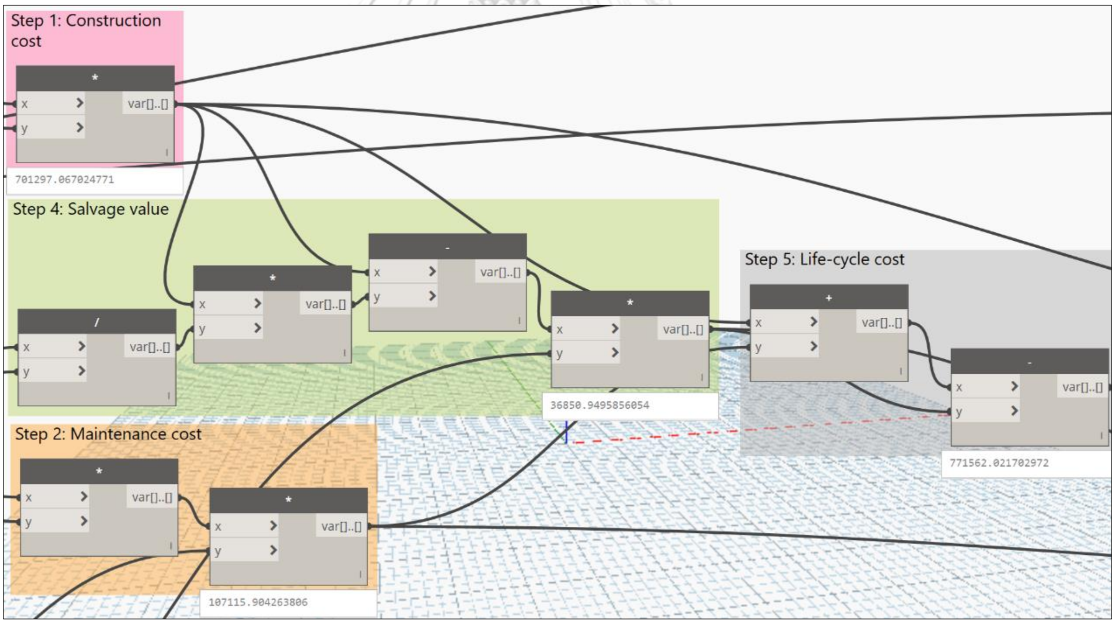
Dynamic auto-upgrade of Concrete floor F6



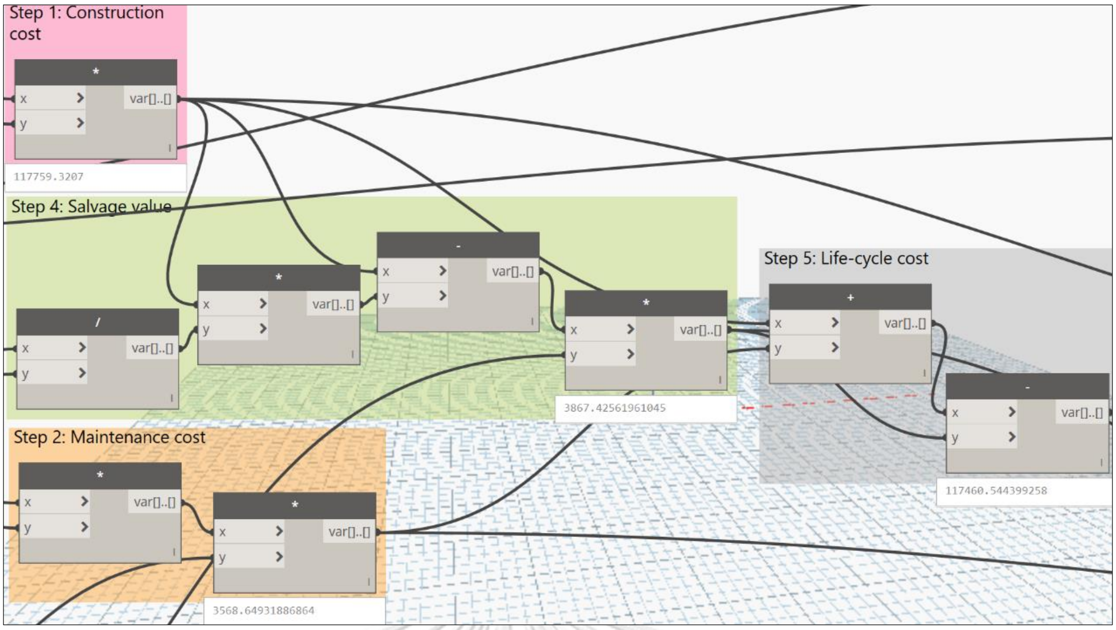
Dynamic auto-upgrade of Gray tile floor F2’



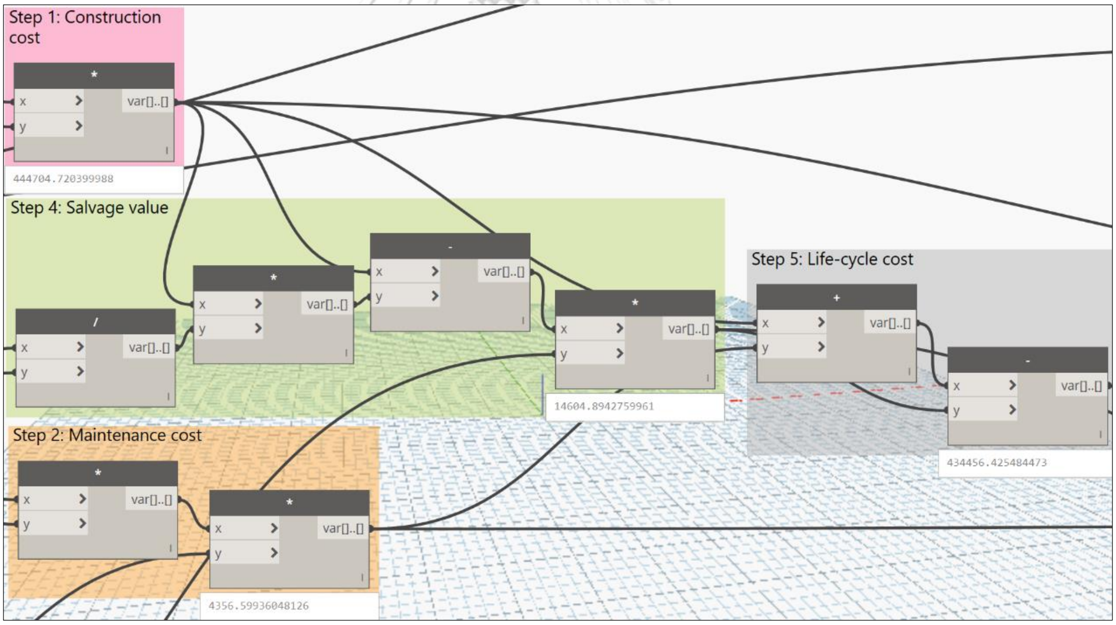
Dynamic auto-upgrade of Gray stone floor F1’



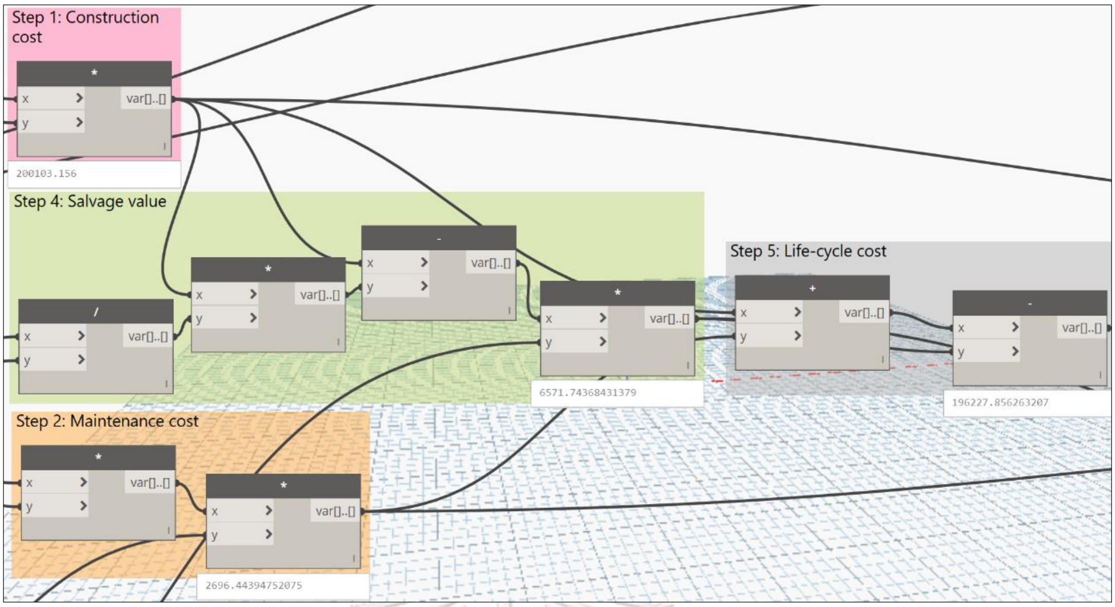
Dynamic auto-upgrade of Concrete floor F6’



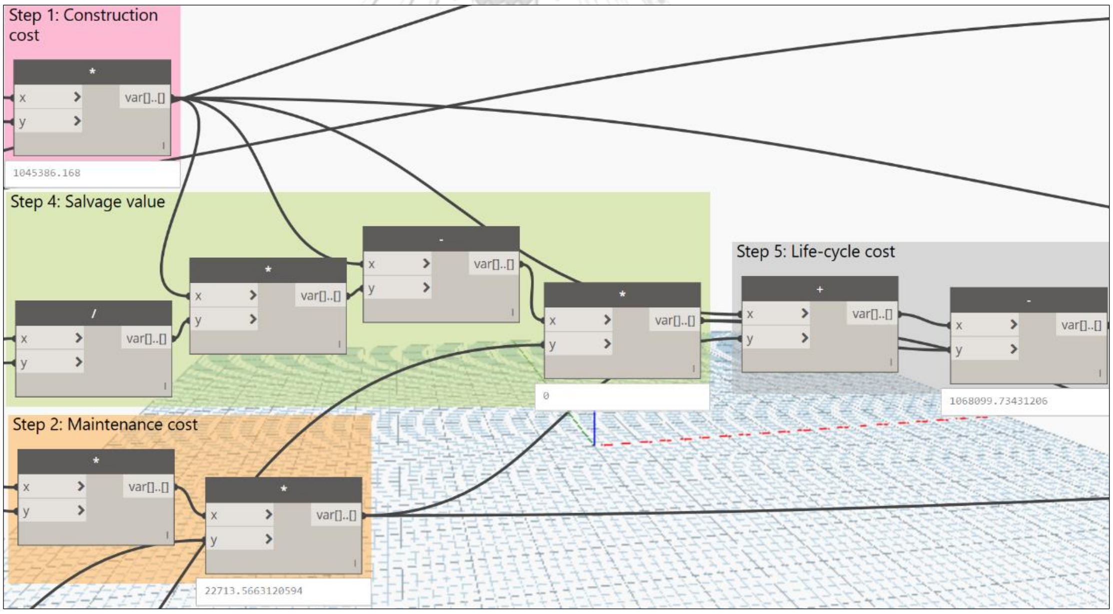
Dynamic auto-upgrade of Exterior metal-glazed double door D1



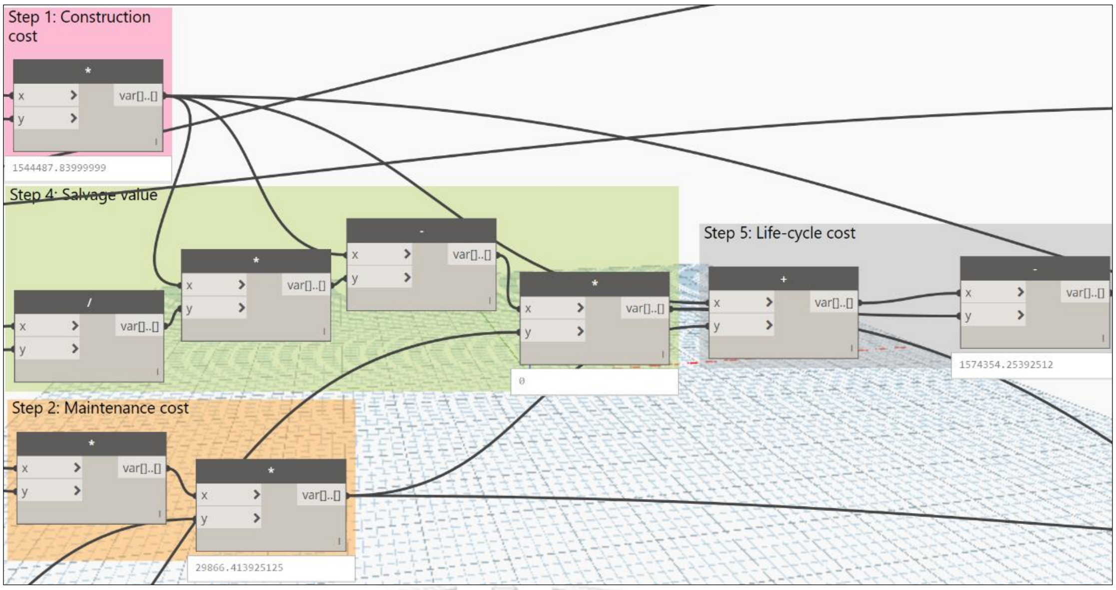
Dynamic auto-upgrade of Exterior metal single door D4



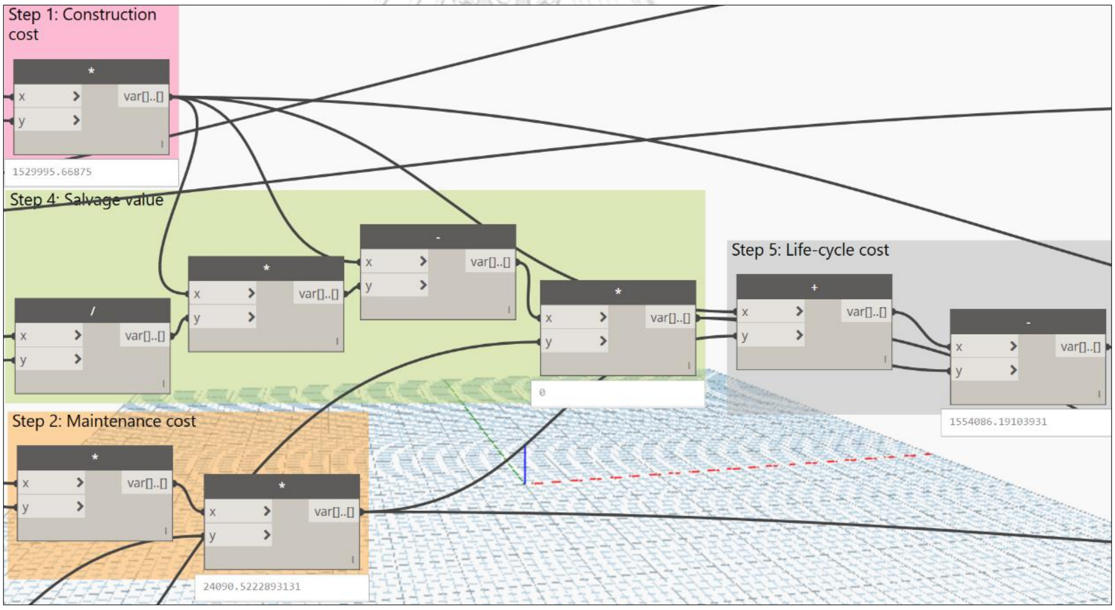
Dynamic auto-upgrade of Exterior plywood double door D9



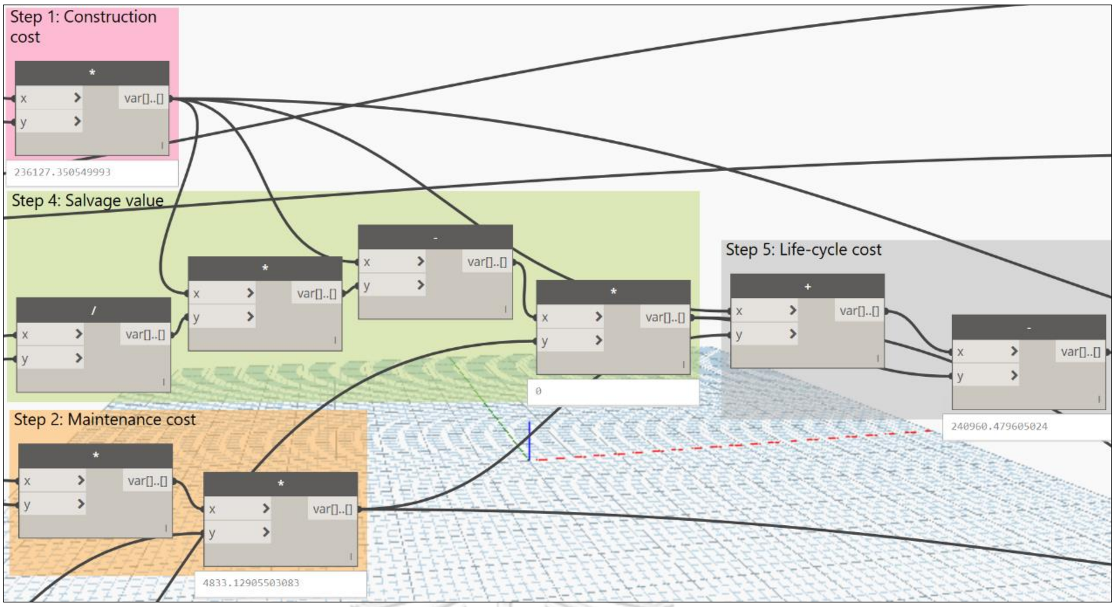
Dynamic auto-upgrade of Interior metal-glazed double door D2



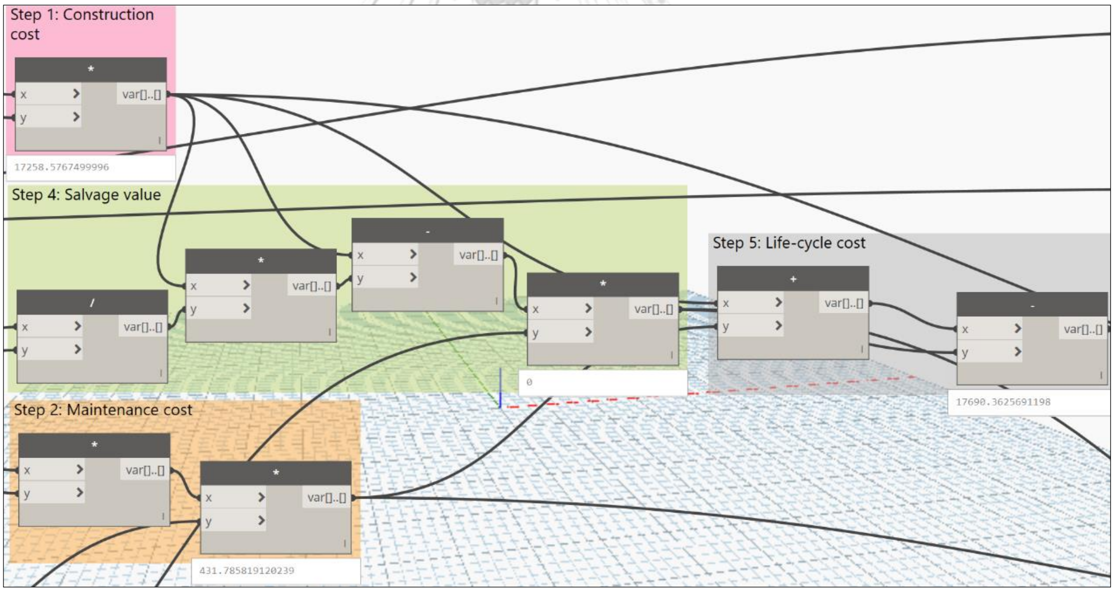
Dynamic auto-upgrade of Interior metal-glazed single door D3



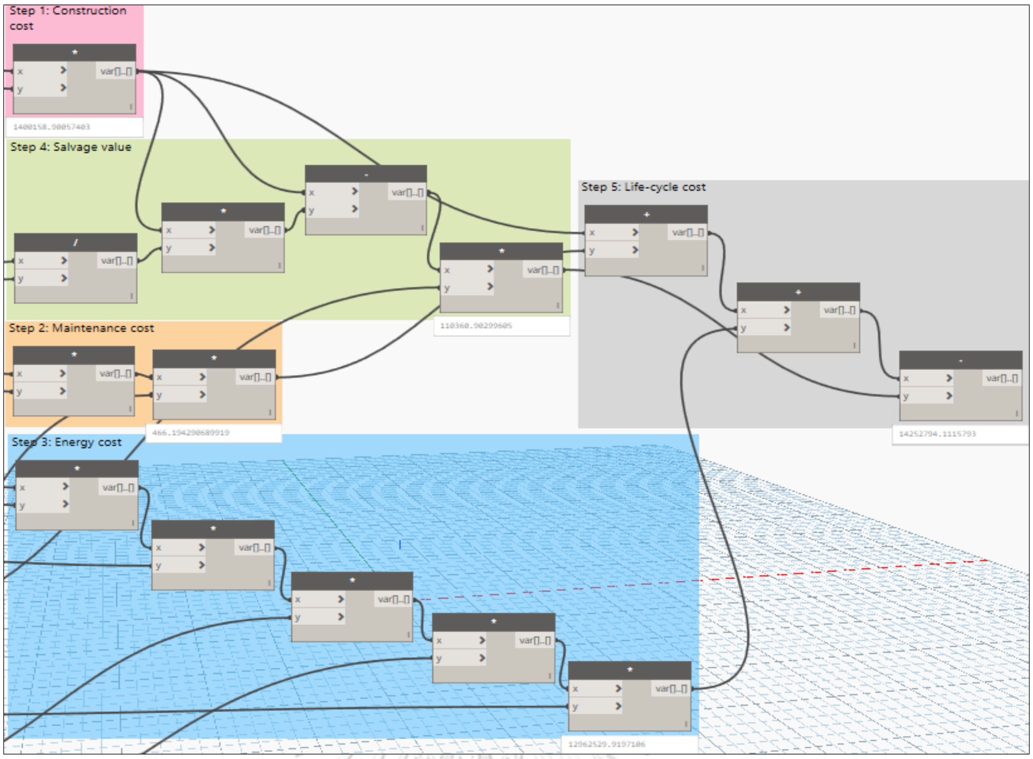
Dynamic auto-upgrade of Interior metal-glazed double door D10



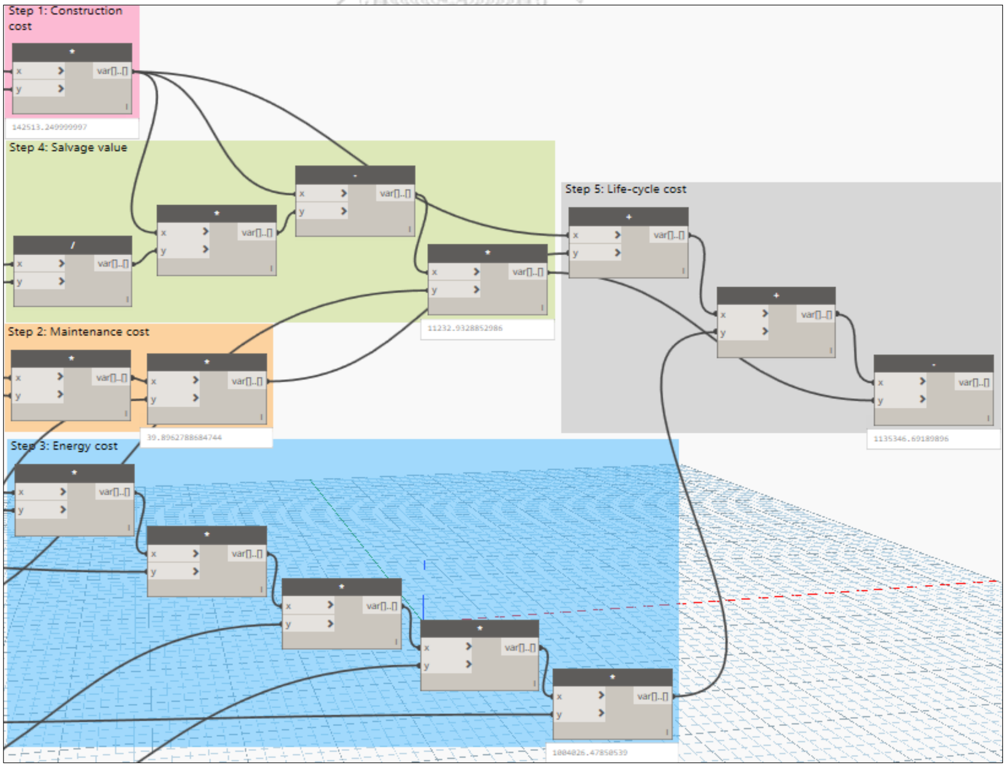
Dynamic auto-upgrade of Interior wood single door D5



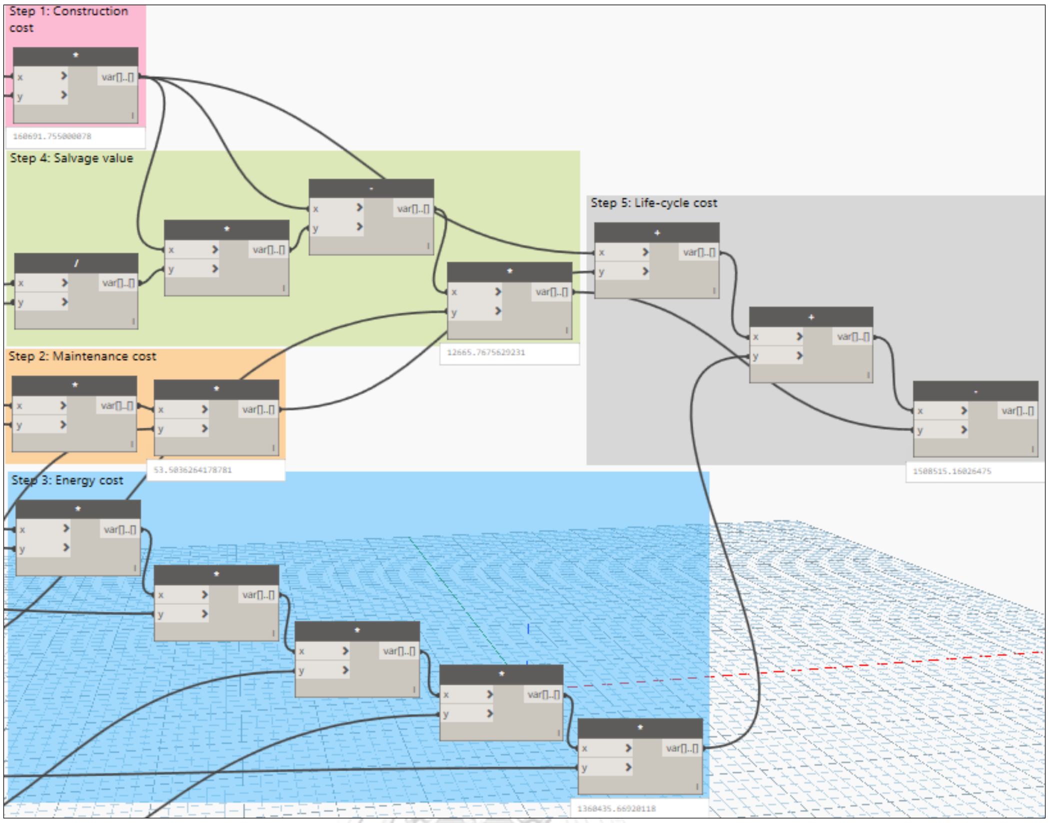
Dynamic auto-upgrade of Interior wood single door D7



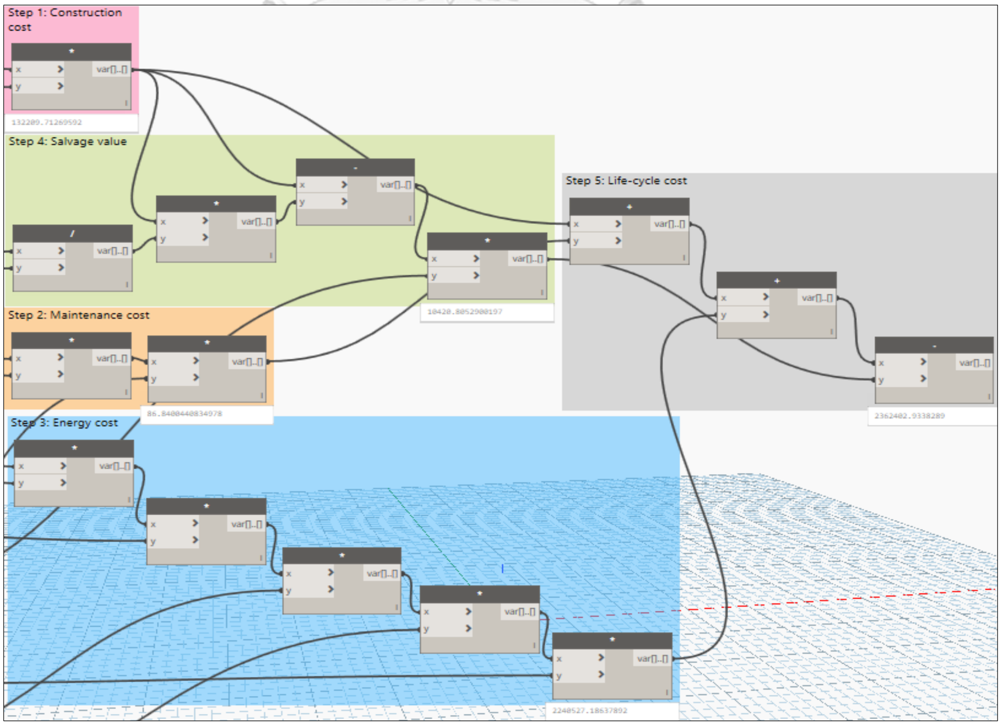
Dynamic auto-upgrade of Red ceramic tile 4x8 wall W66 type



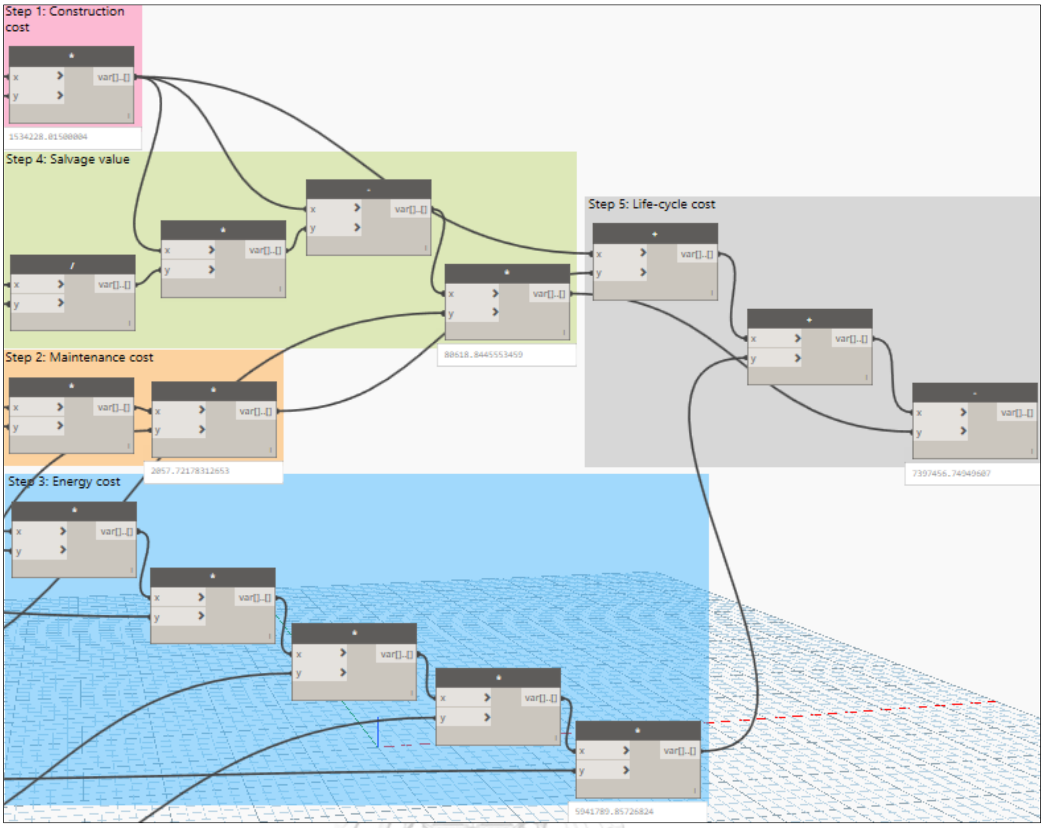
Dynamic auto-upgrade of Cladding tile 12x12 and red ceramic tile 4x8 wall W36 type



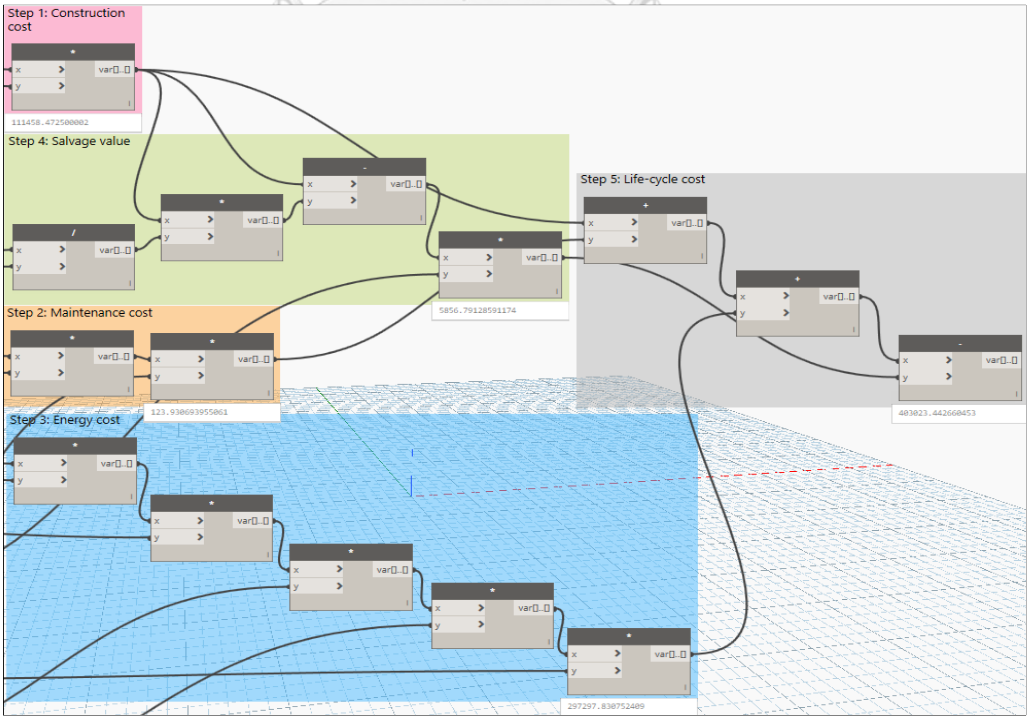
Dynamic auto-upgrade of Brick and red ceramic tile 4x8 wall W16 type



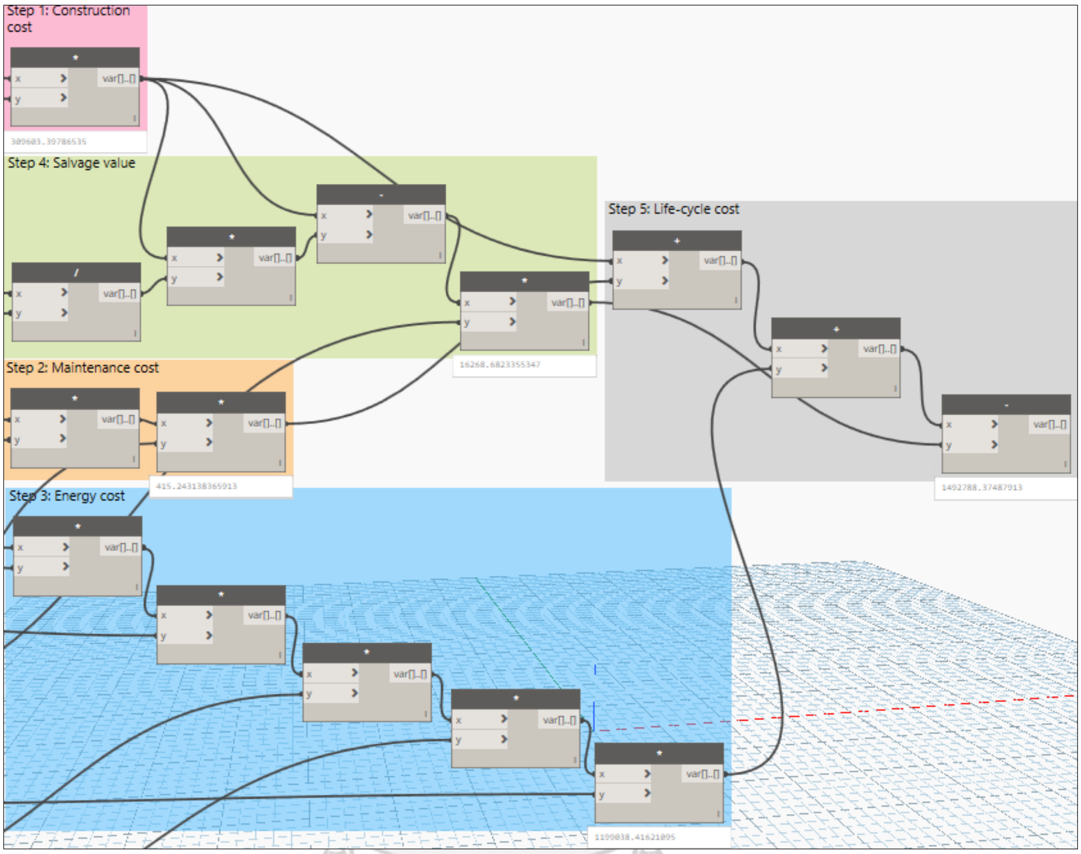
Dynamic auto-upgrade of Balcony wall W8-1 type



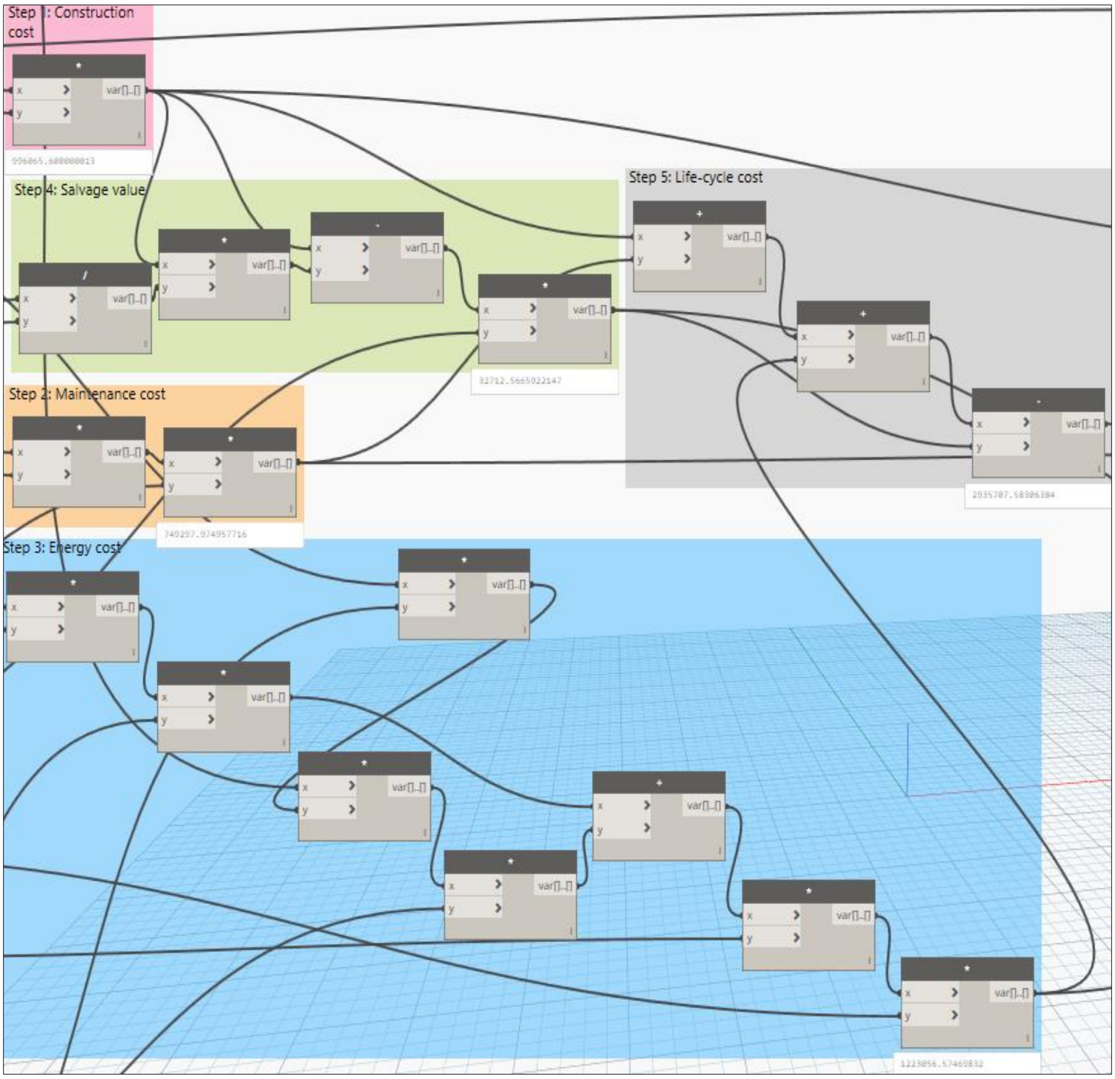
Dynamic auto-upgrade of Concrete roof with waterproofing F4 type



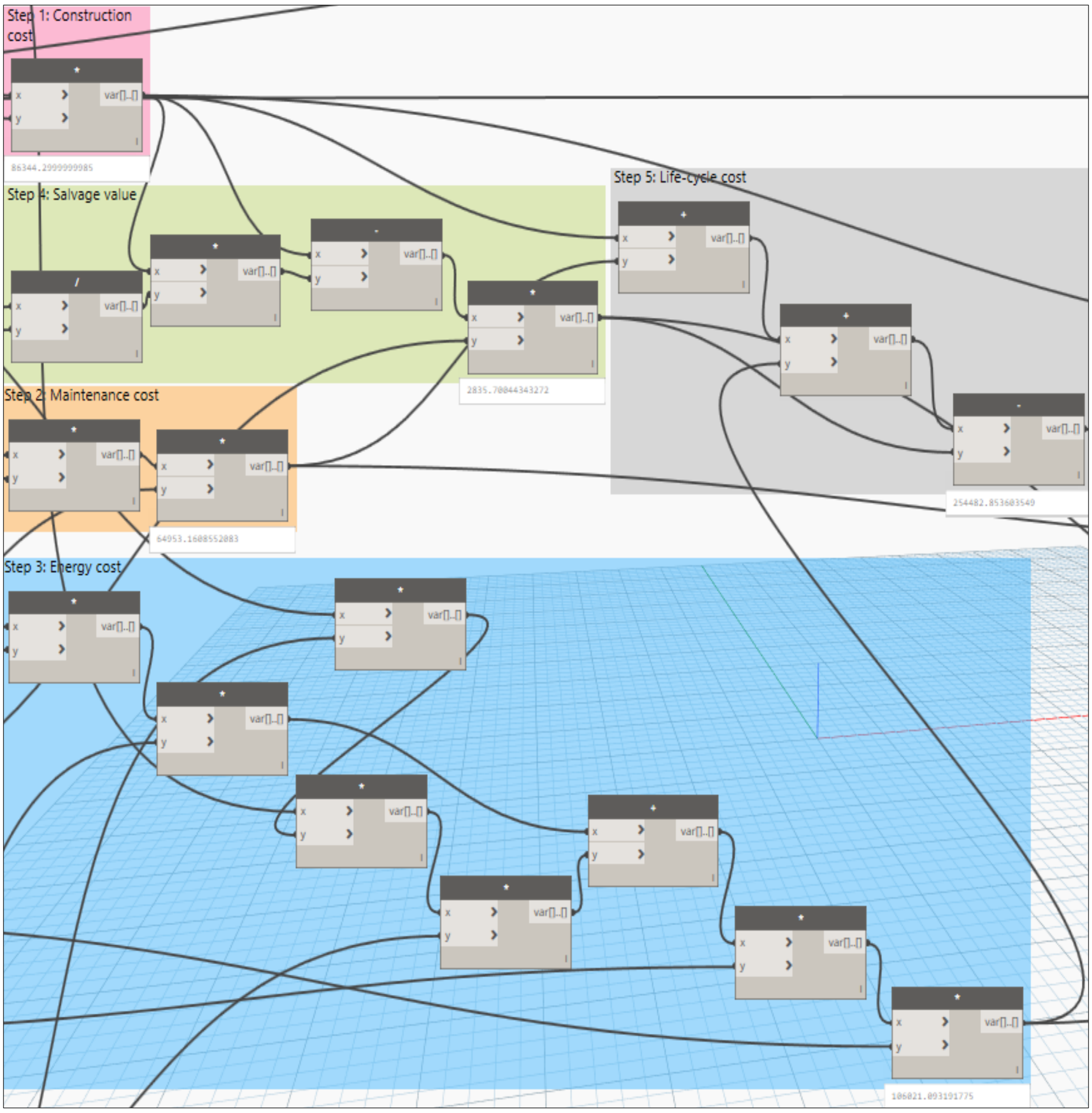
Dynamic auto-upgrade of Gray tile roof F2’ type



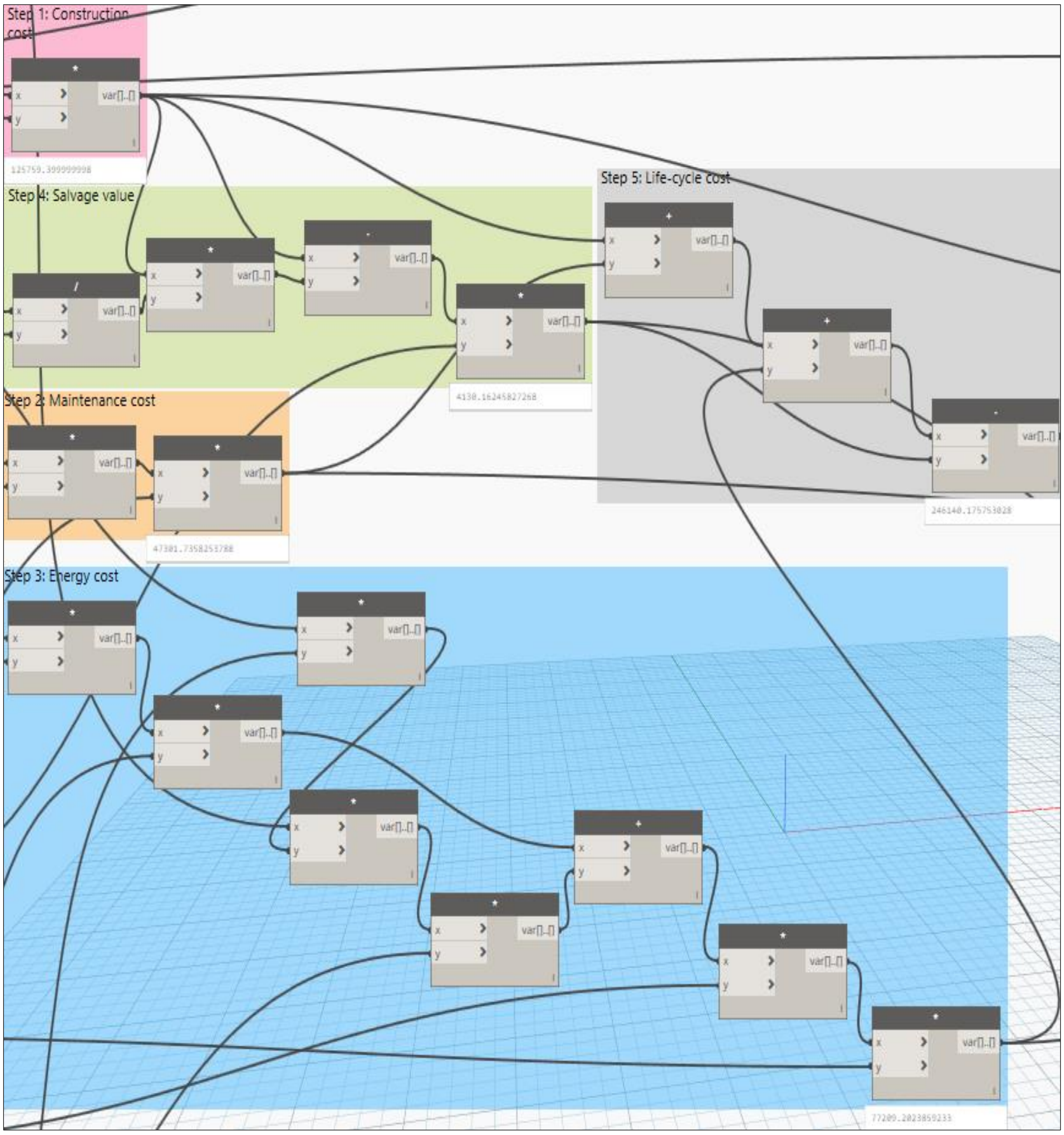
Dynamic auto-upgrade of Concrete roof F6’ type



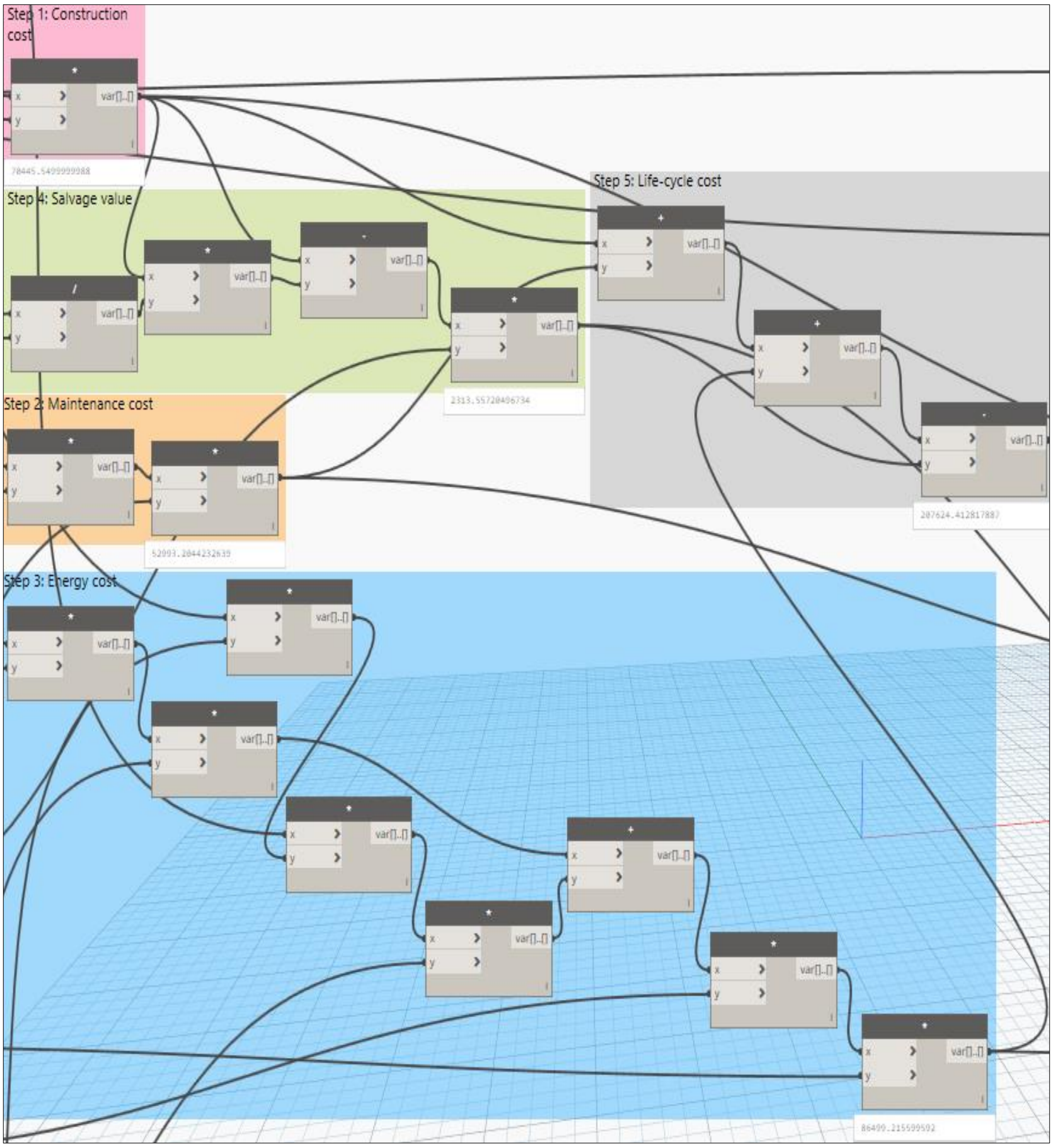
Dynamic auto-upgrade of Exterior metal-glazed window W1’ type



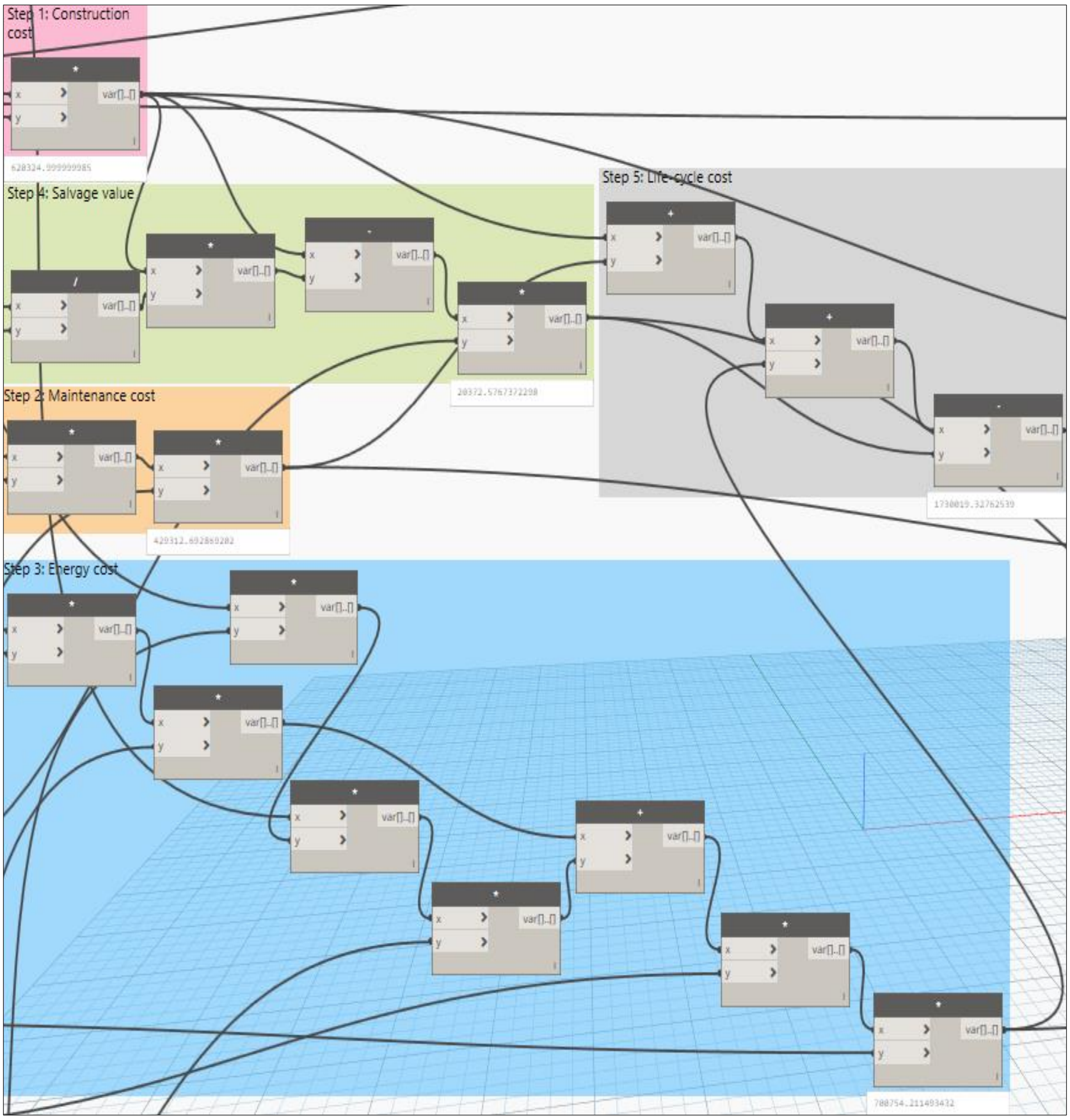
Dynamic auto-upgrade of Exterior metal-glazed window W1” type



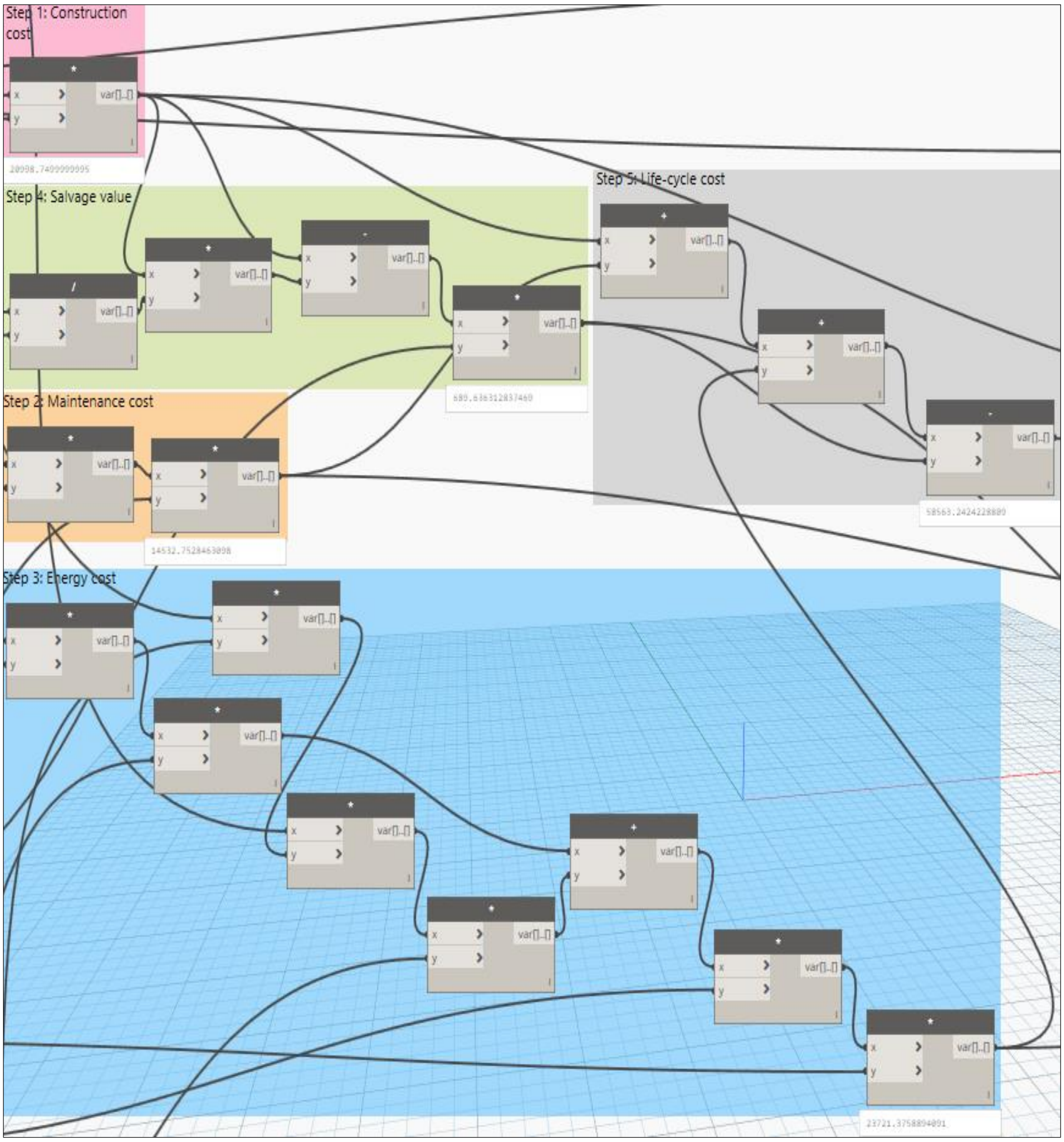
Dynamic auto-upgrade of Exterior metal-glazed window W1'" type



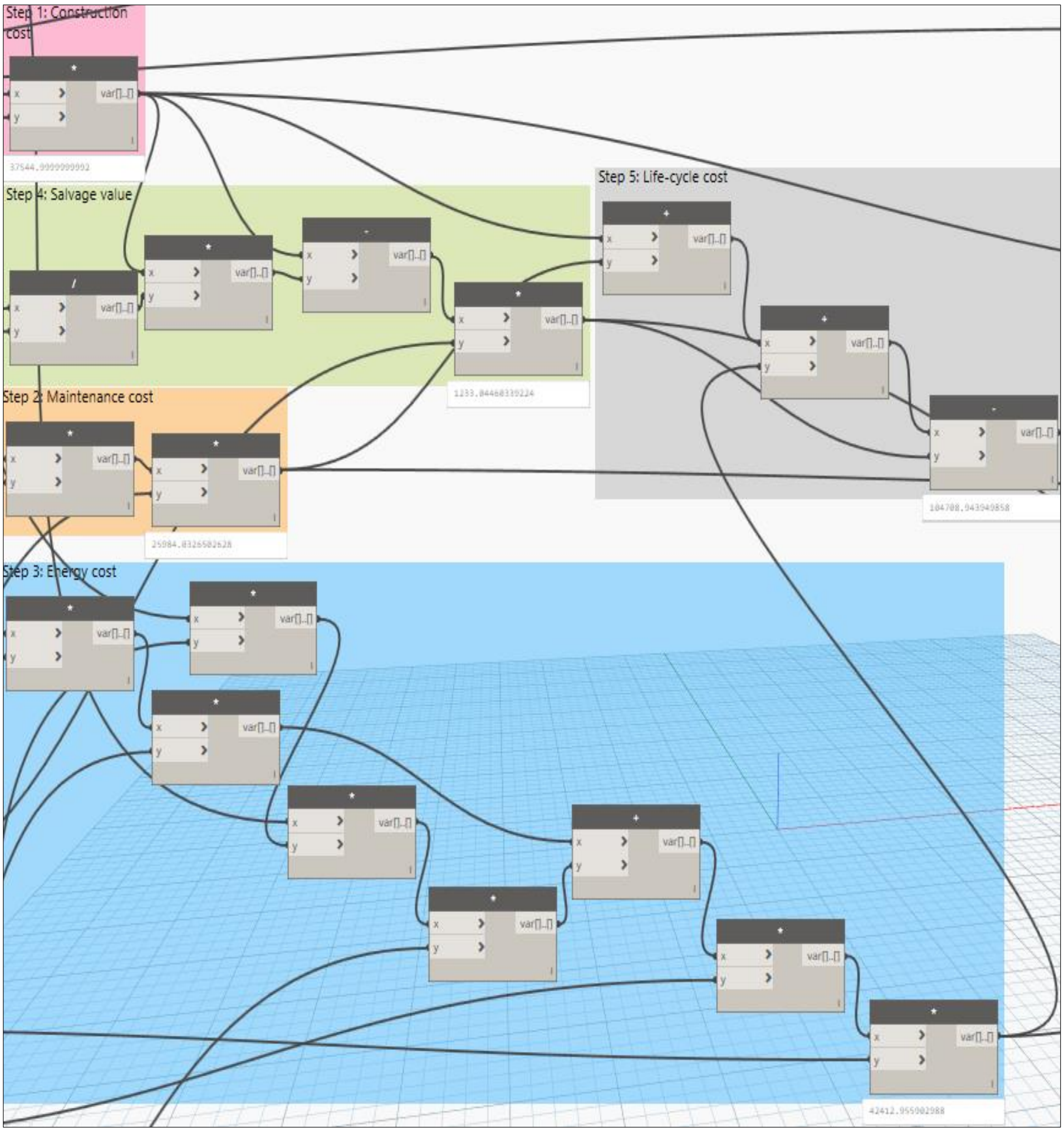
Dynamic auto-upgrade of Exterior metal-glazed window W1”” type



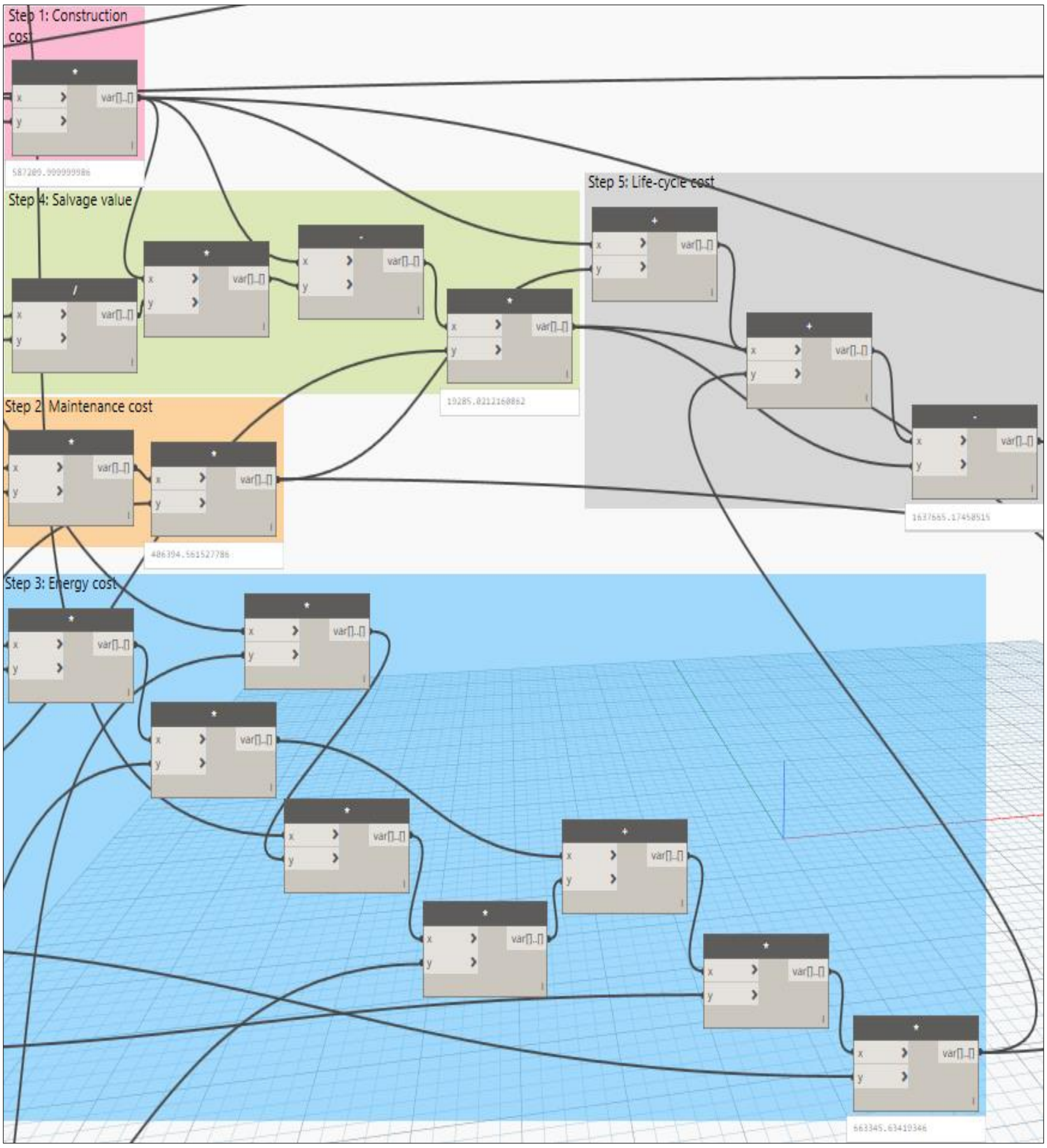
Dynamic auto-upgrade of Exterior metal-glazed window W4' type



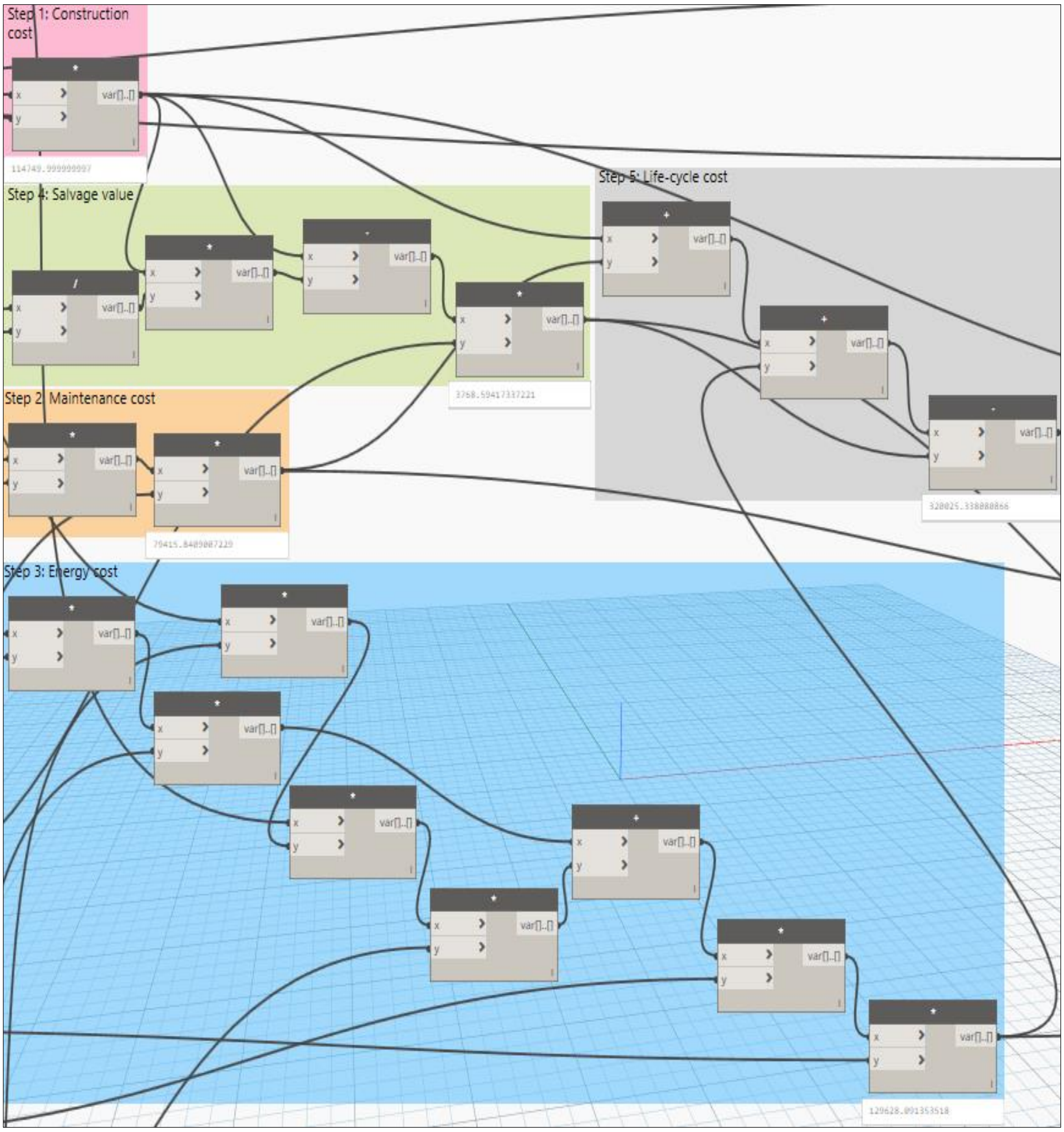
Dynamic auto-upgrade of Exterior metal-glazed window W4” type



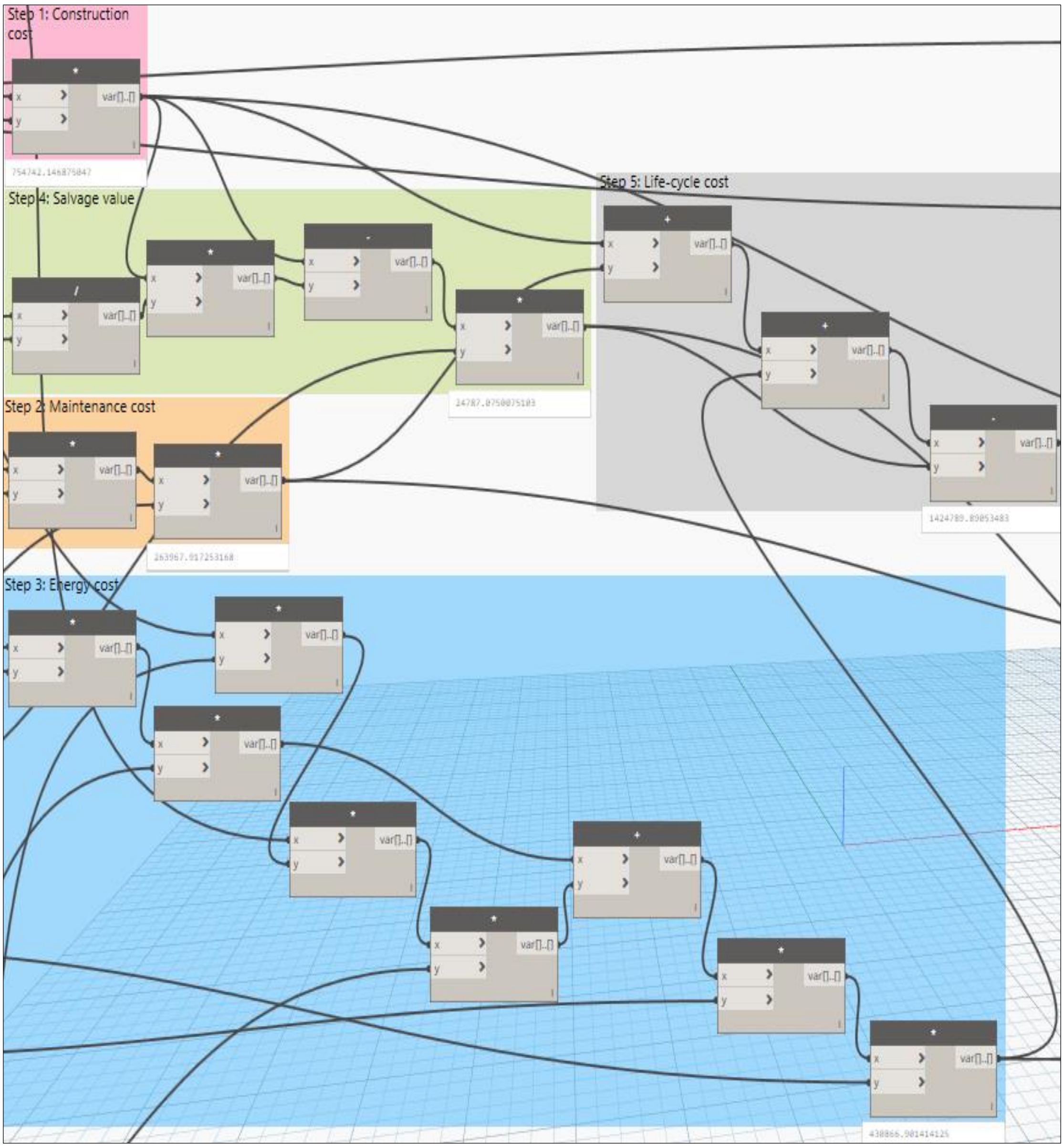
Dynamic auto-upgrade of Exterior metal-glazed window W4'" type



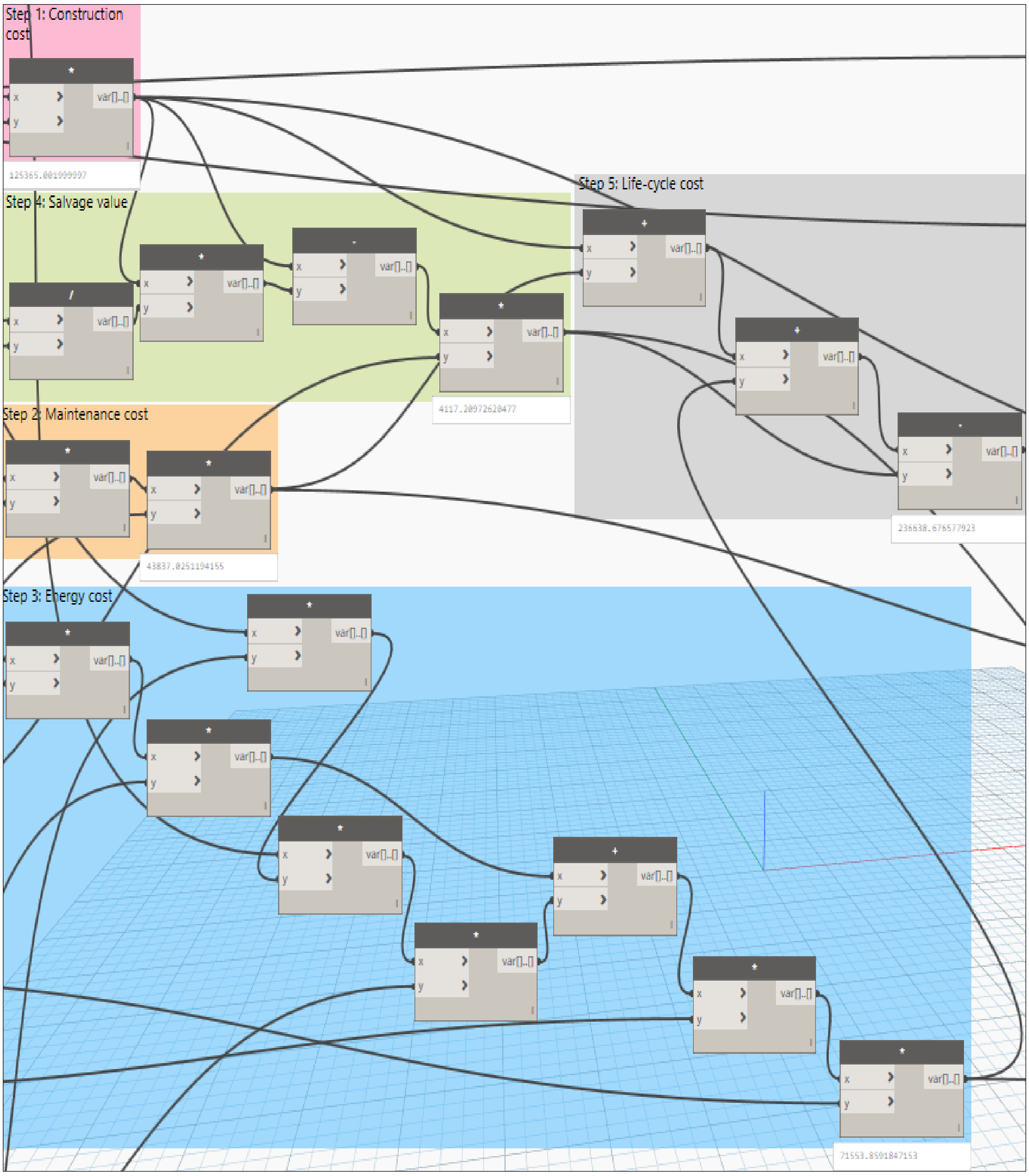
Dynamic auto-upgrade of Exterior metal-glazed window W5’ type



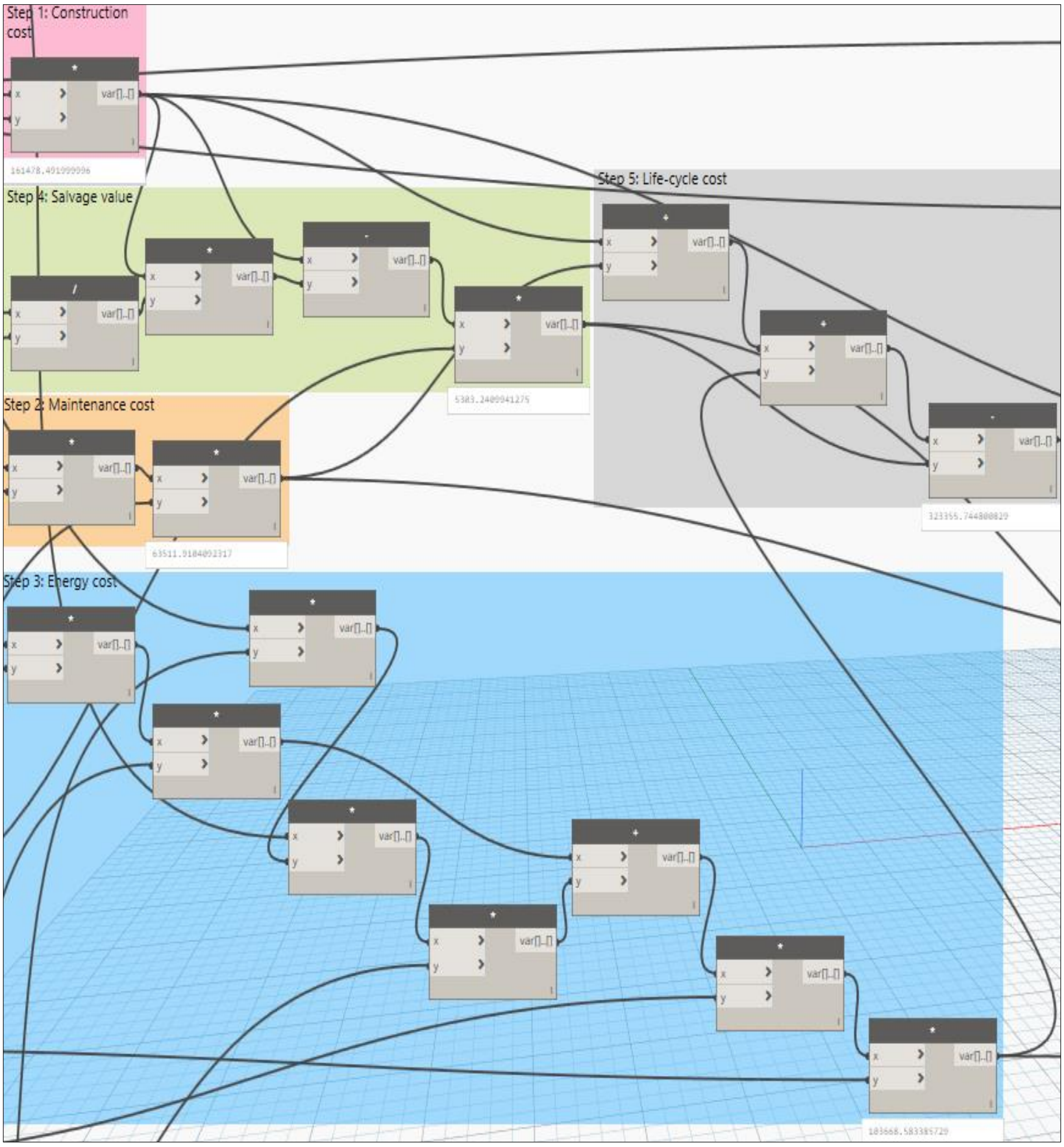
Dynamic auto-upgrade of Exterior metal-glazed window W5” type



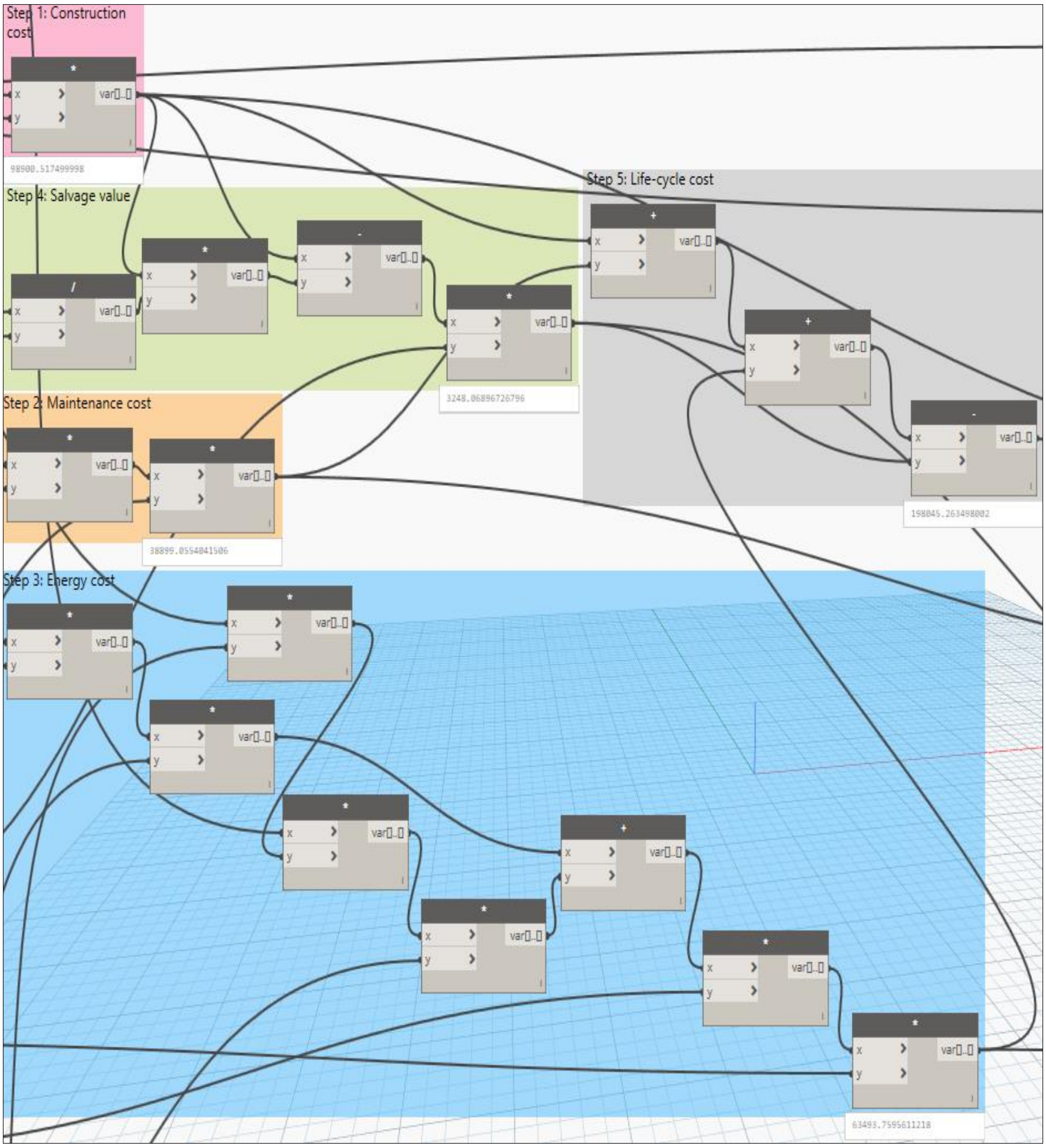
Dynamic auto-upgrade of Exterior frosted glazed window W2 type



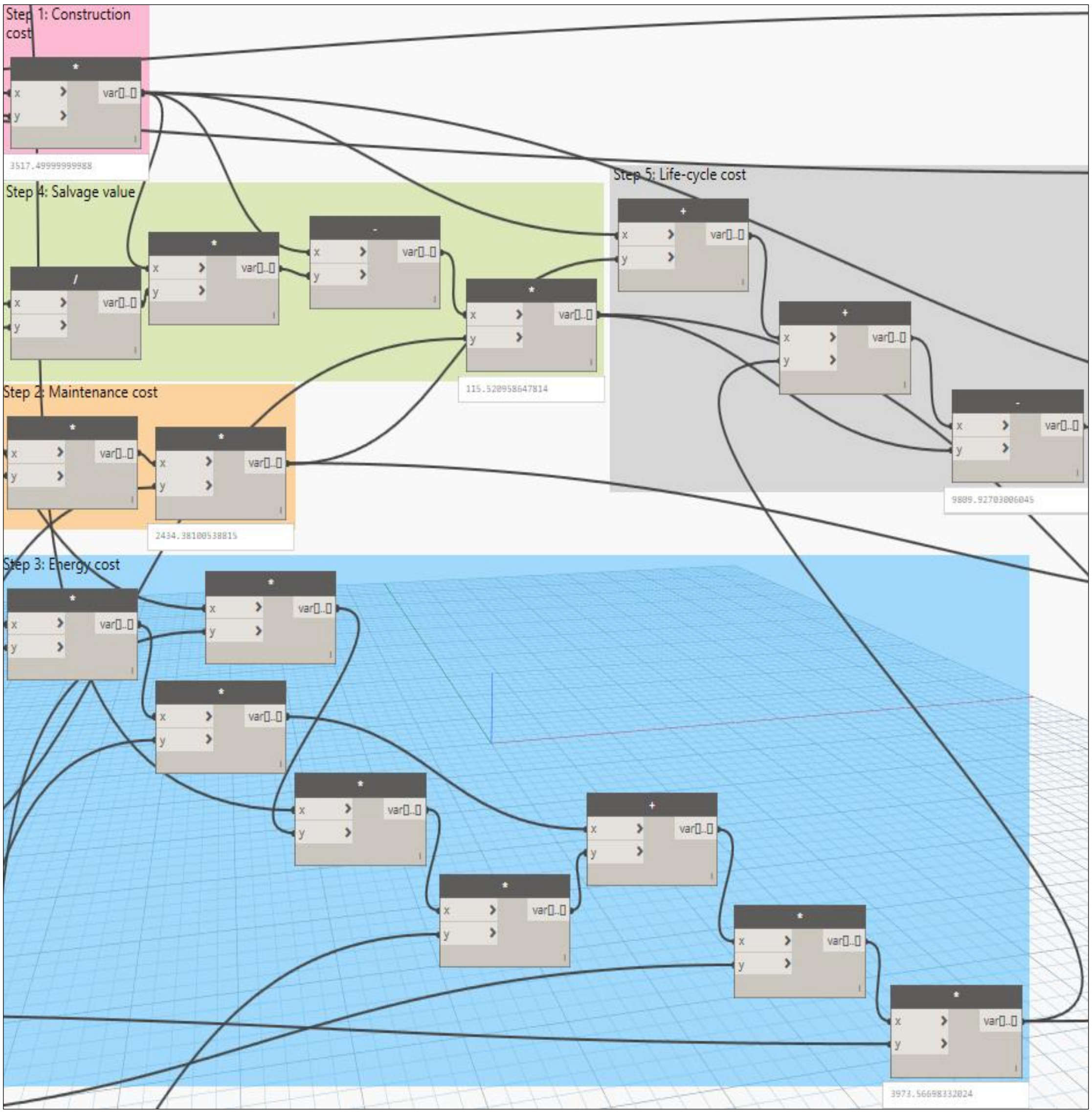
Dynamic auto-upgrade of Exterior glazed window W2’ type



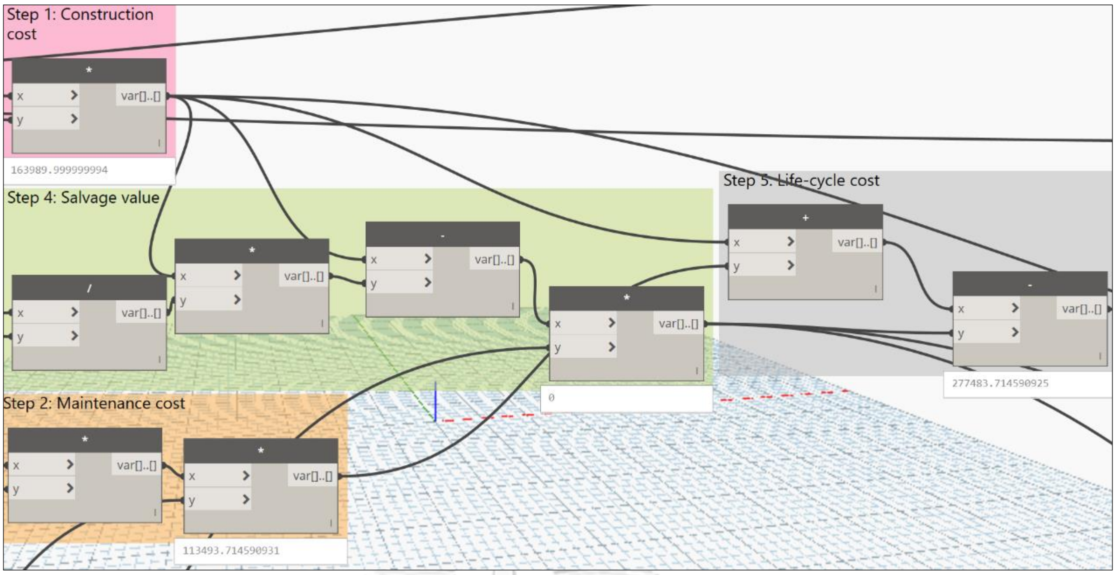
Dynamic auto-upgrade of Exterior glazed window W3 type



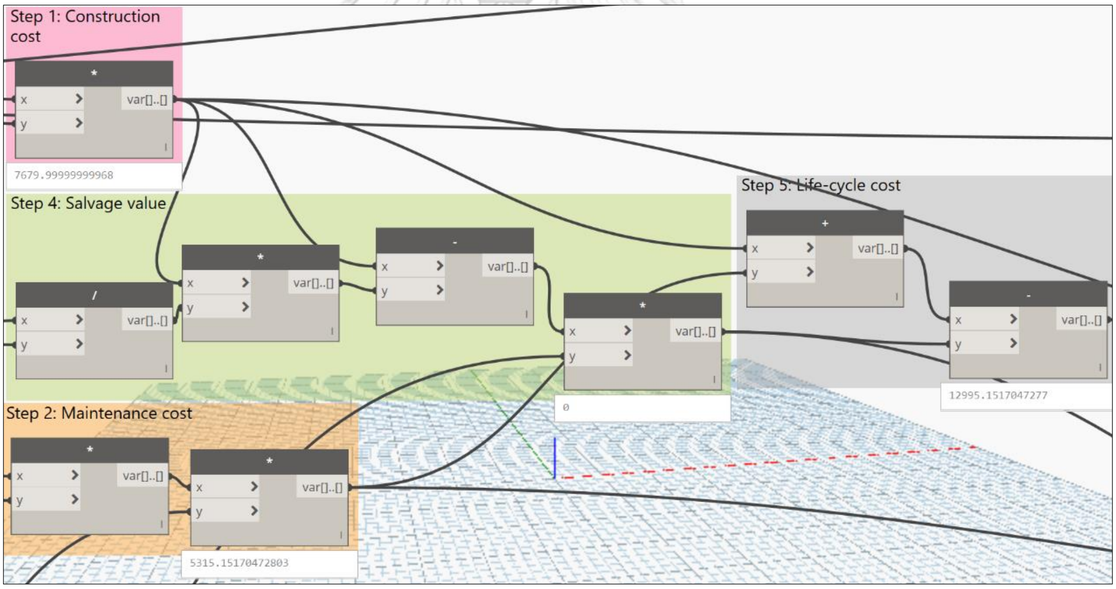
Acquire the required parameters of Exterior glazed window W3' type



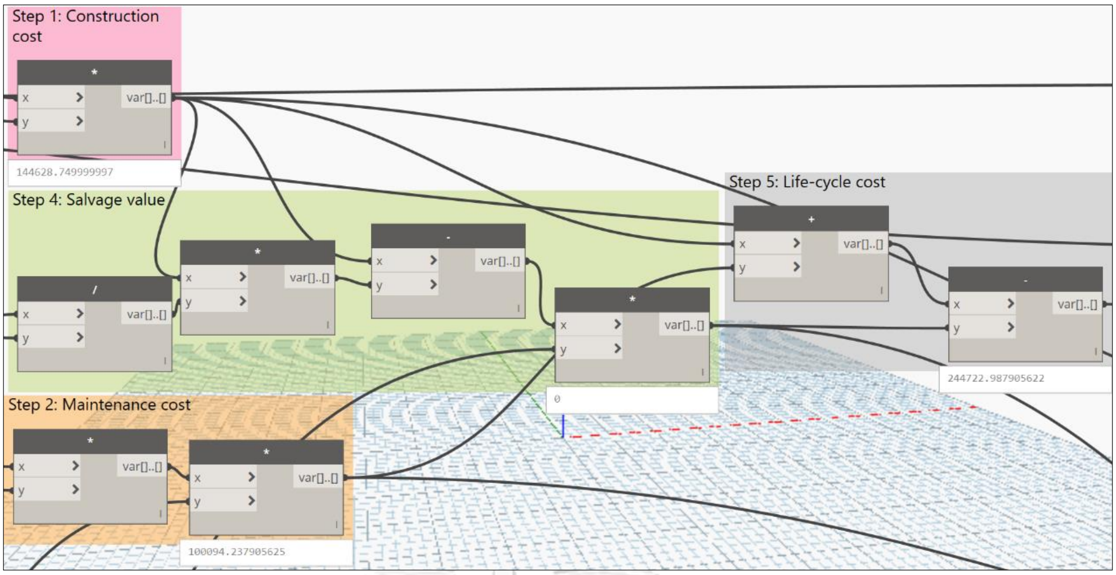
Acquire the required parameters of Exterior metal window W10 type



Acquire the required parameters of Interior metal window W7 type

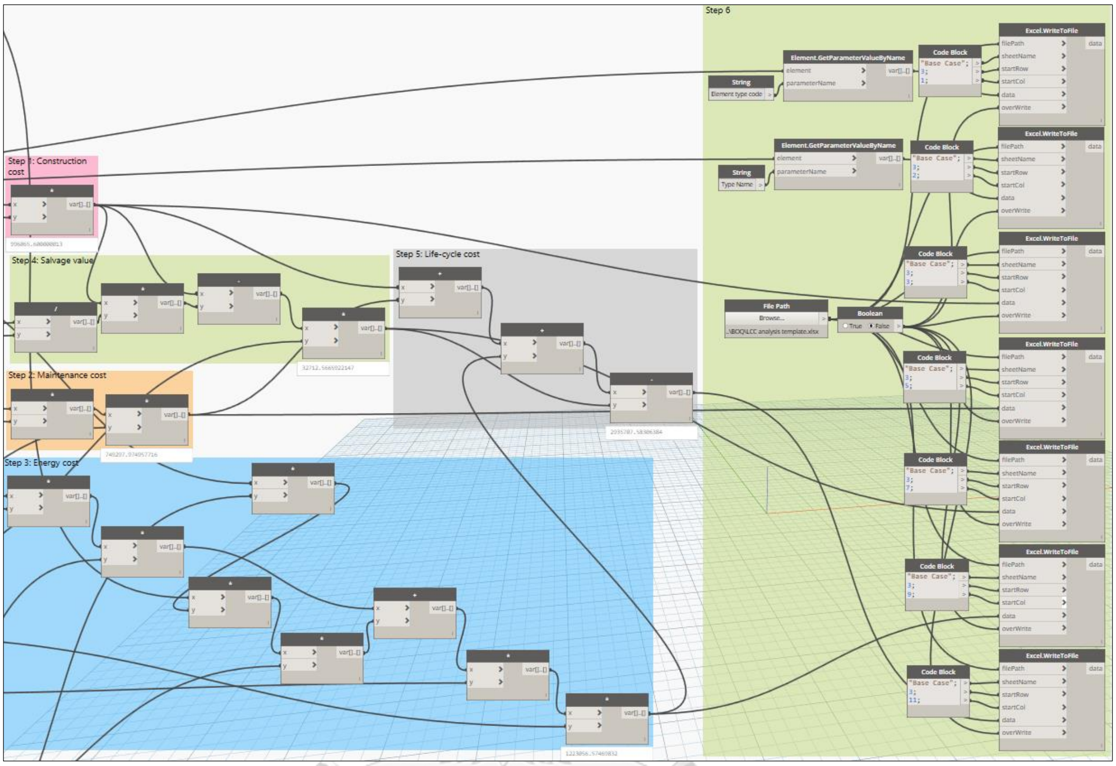


Acquire the required parameters of Interior metal window W7' type

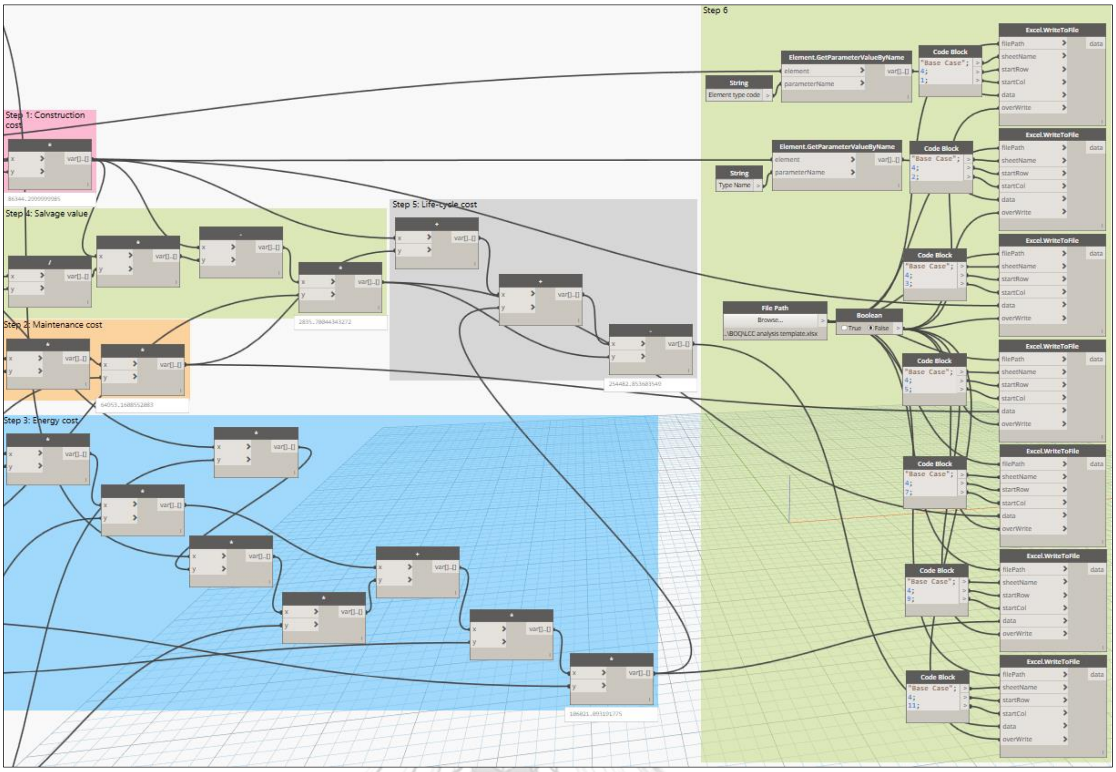


Acquire the required parameters of Interior metal window W8 type

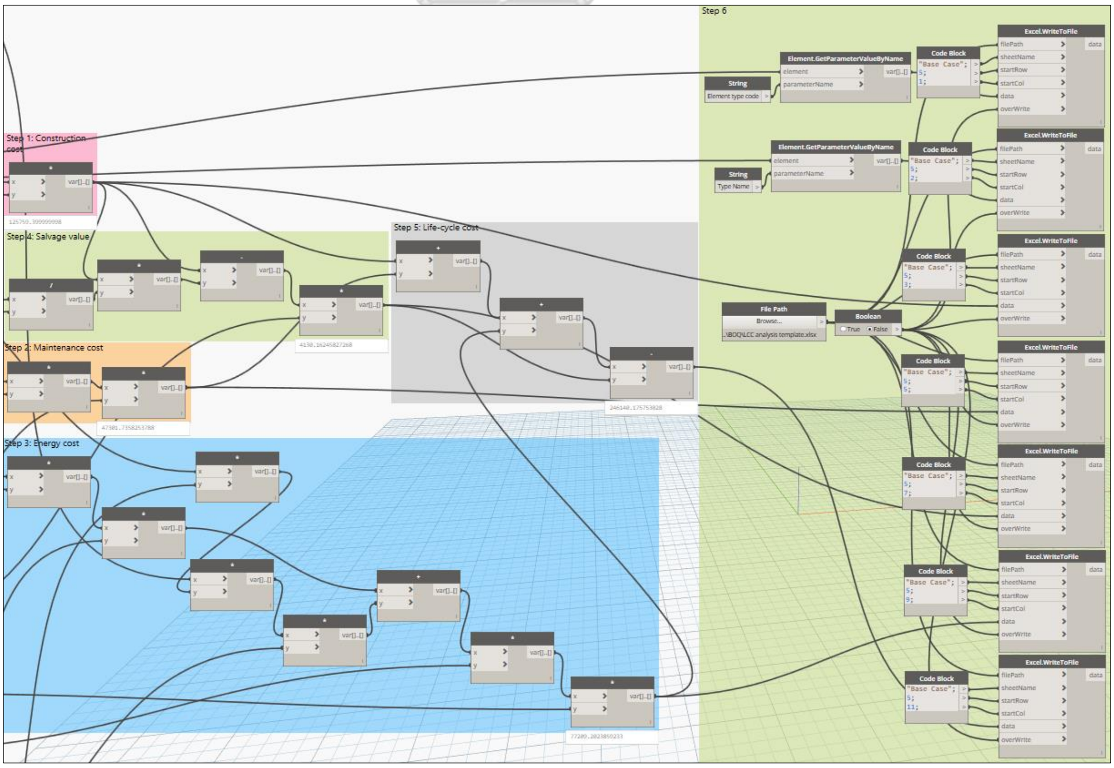
APPENDIX G DYNAMO NODES FOR EXPORTING RESULTS TO THE SPREADSHEET REPORT



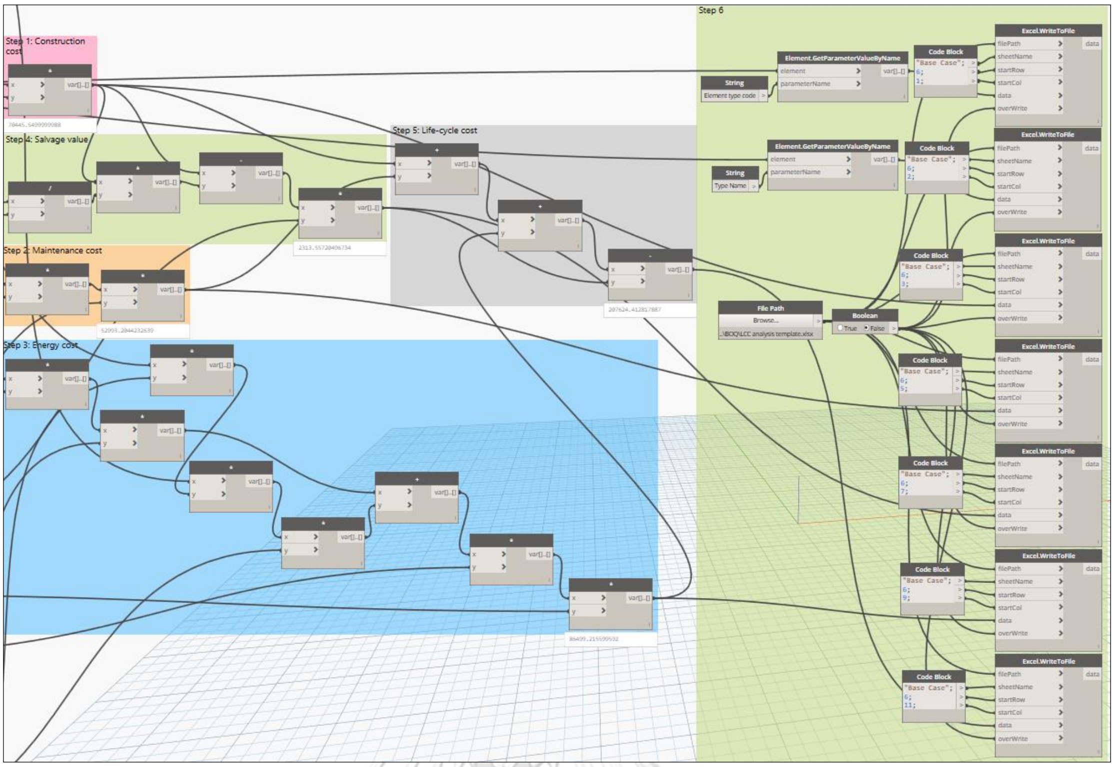
Export LCC results of Exterior metal-glazed window W1' type



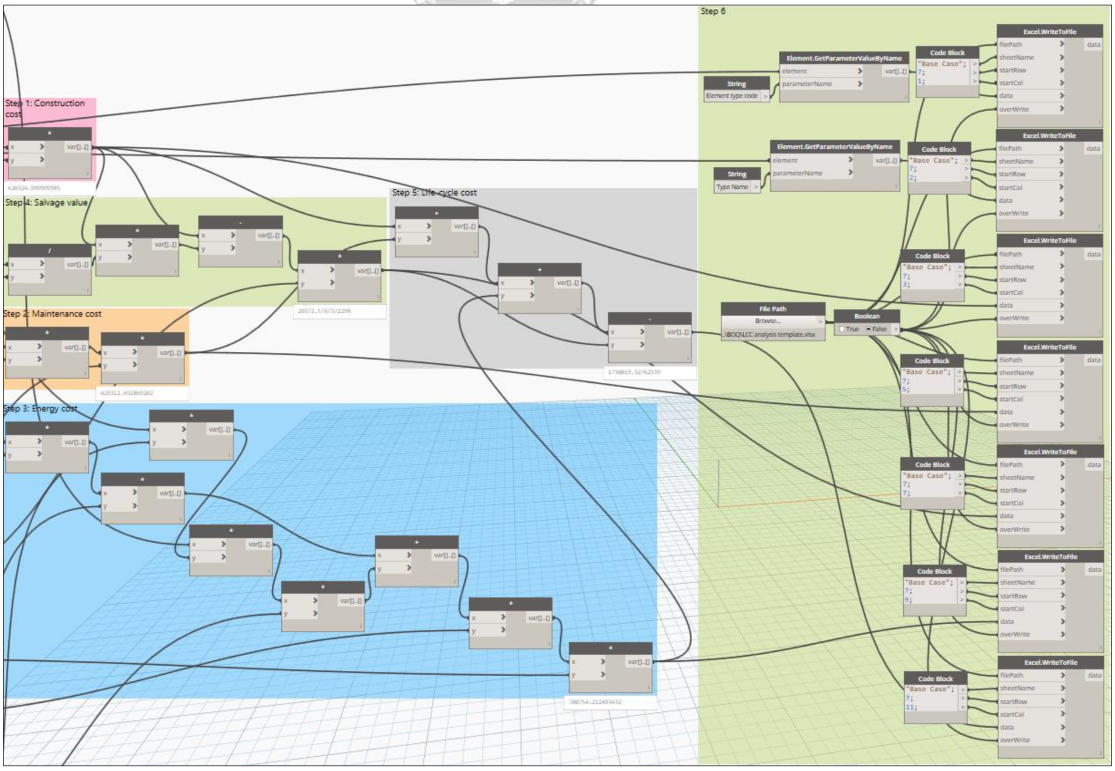
Export LCC results of Exterior metal-glazed window W1” type



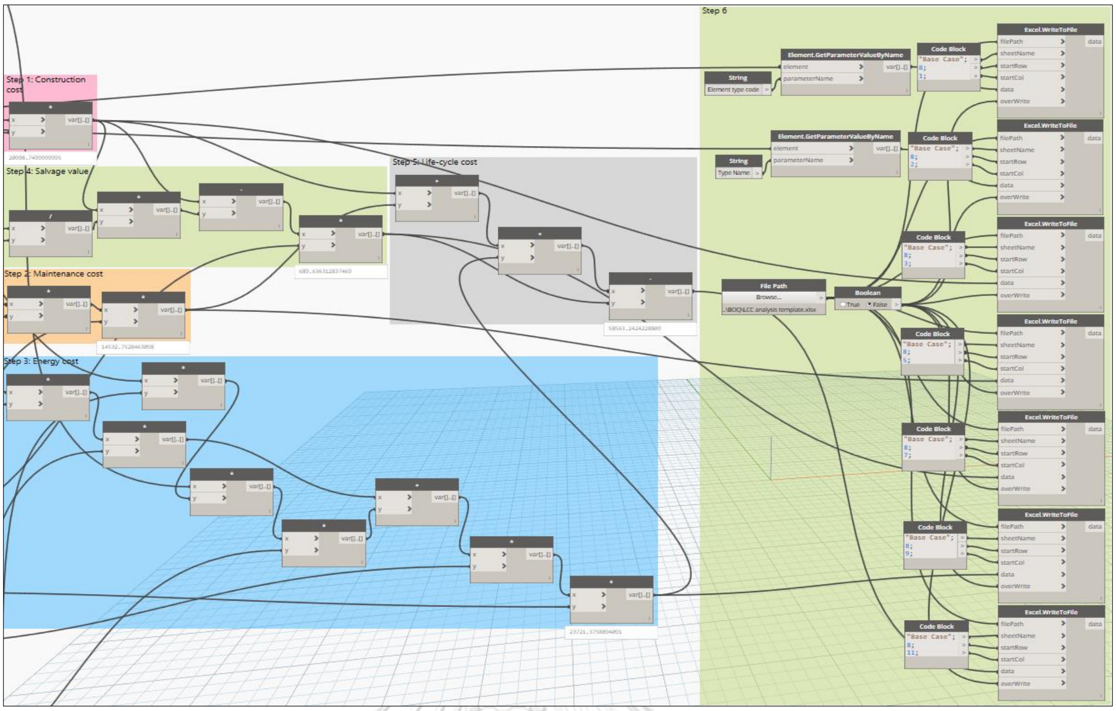
Export LCC results of Exterior metal-glazed window W1’” type



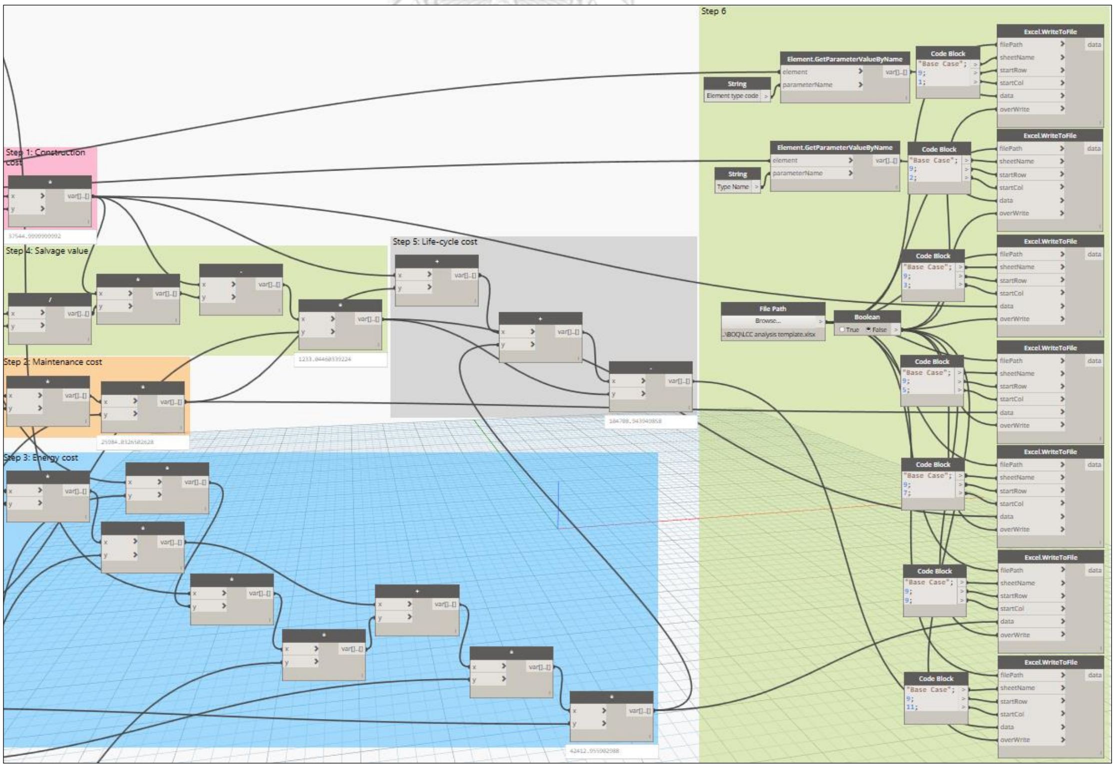
Export LCC results of Exterior metal-glazed window W1”” type



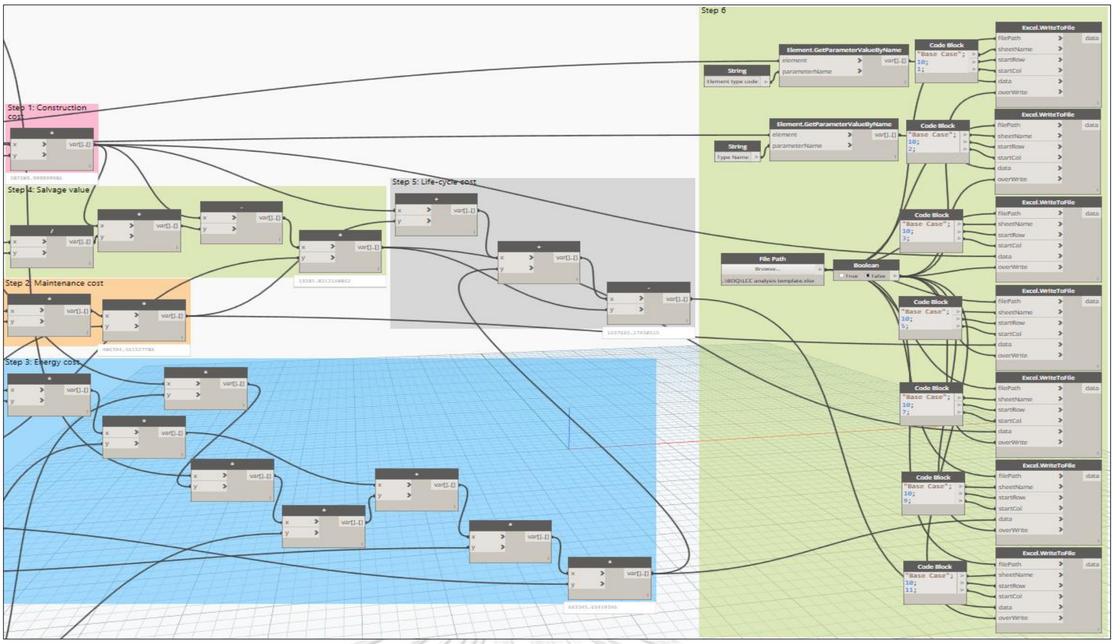
Export LCC results of Exterior metal-glazed window W4’ type



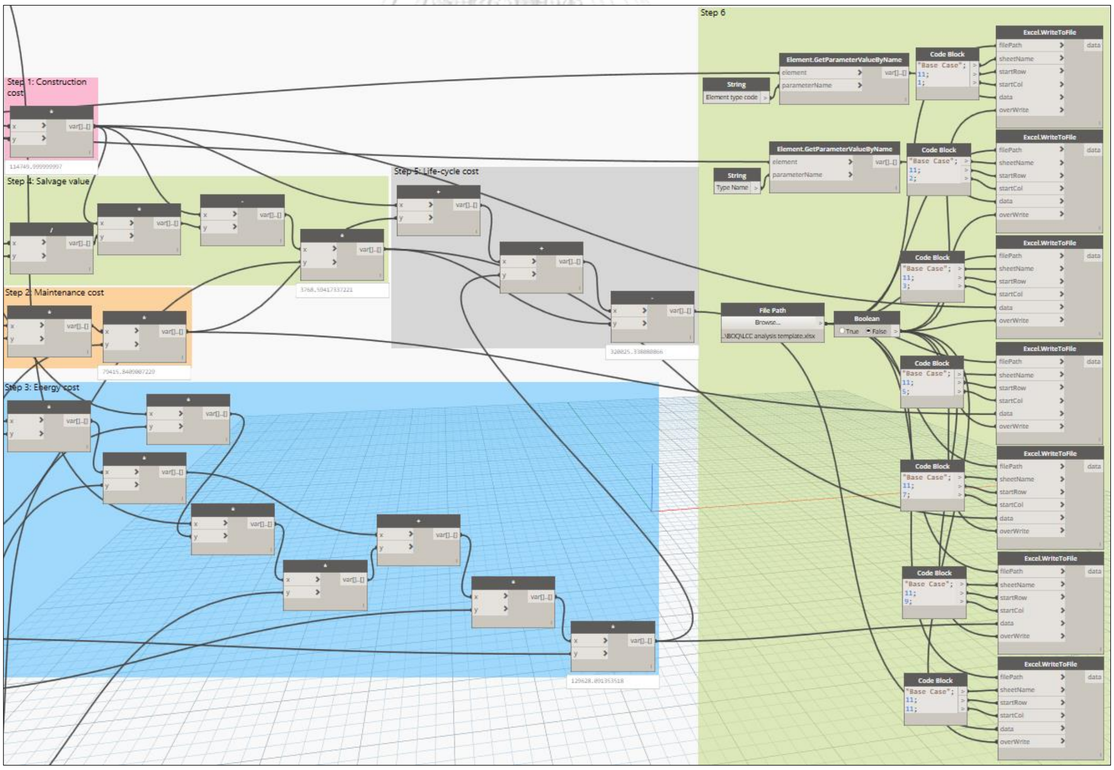
Export LCC results of Exterior metal-glazed window W4” type



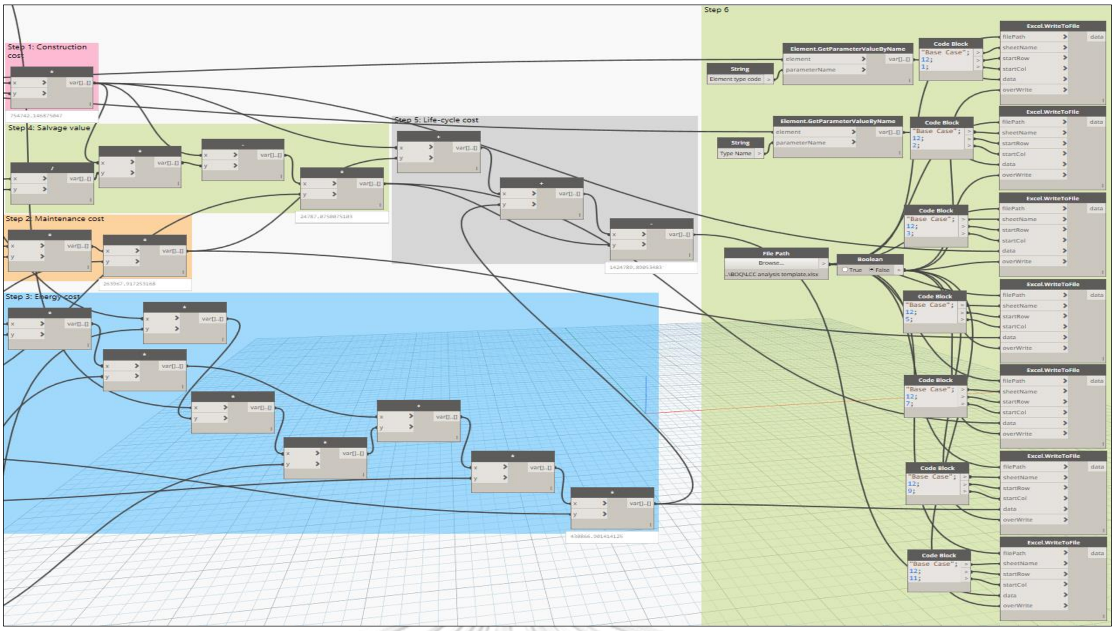
Export LCC results of Exterior metal-glazed window W4”’ type



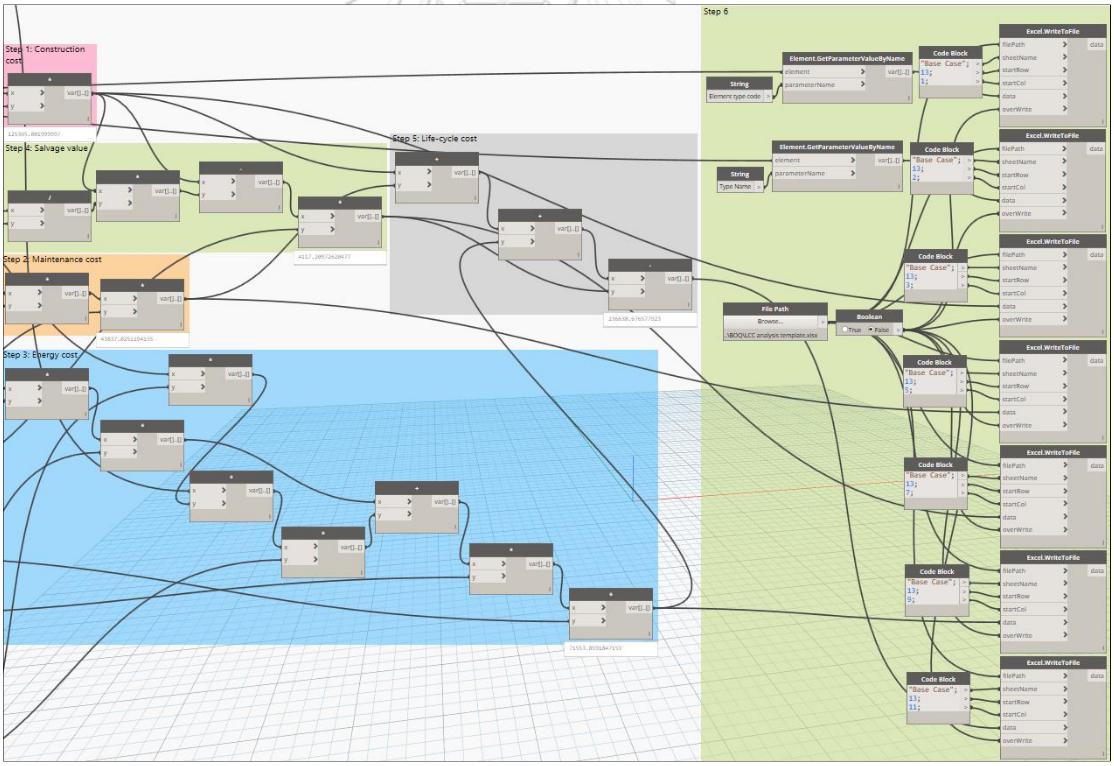
Export LCC results of Exterior metal-glazed window W5’ type



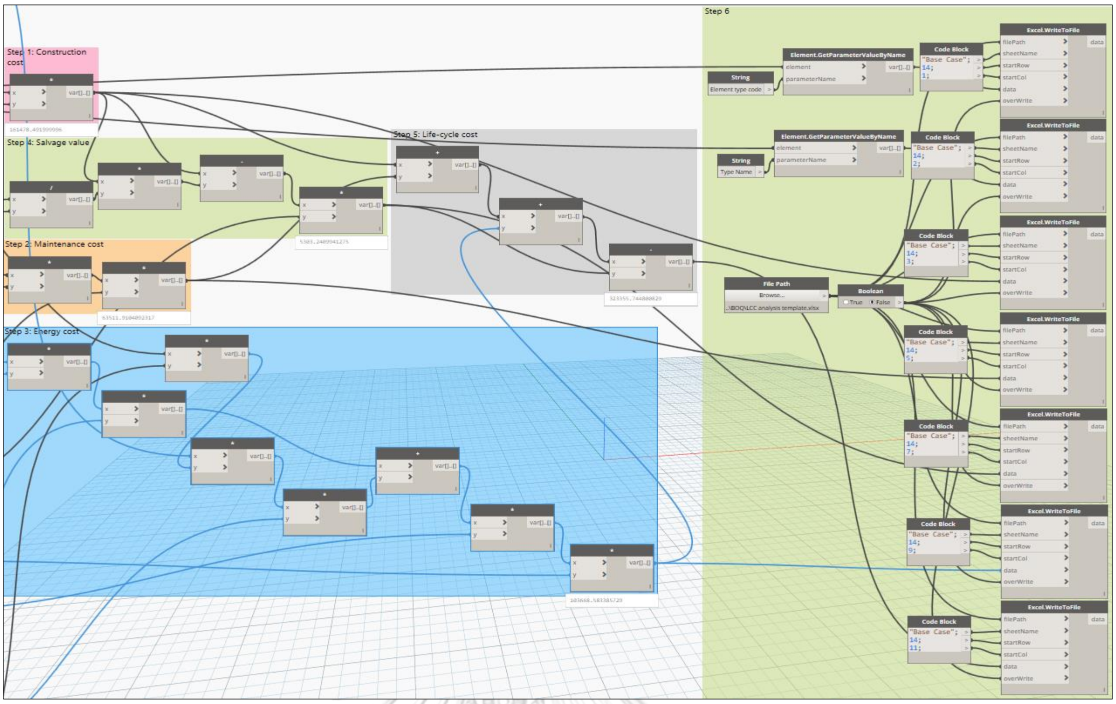
Export LCC results of Exterior metal-glazed window W5” type



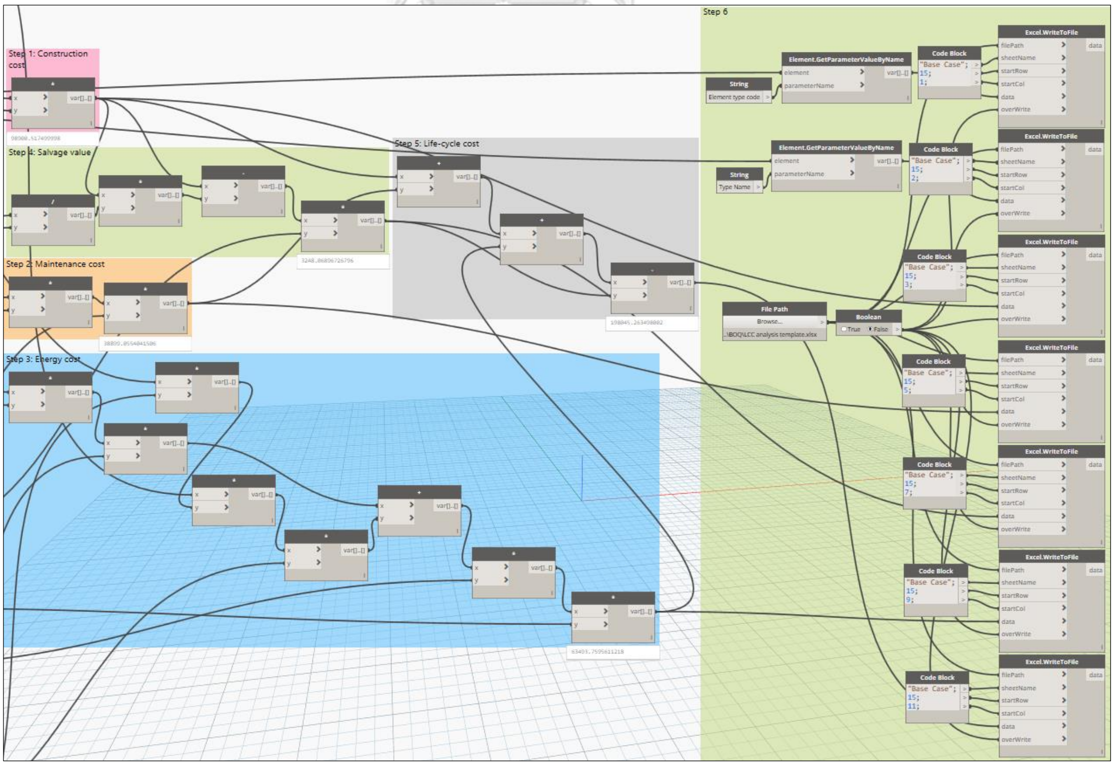
Export LCC results of Exterior frosted glazed window W2 type



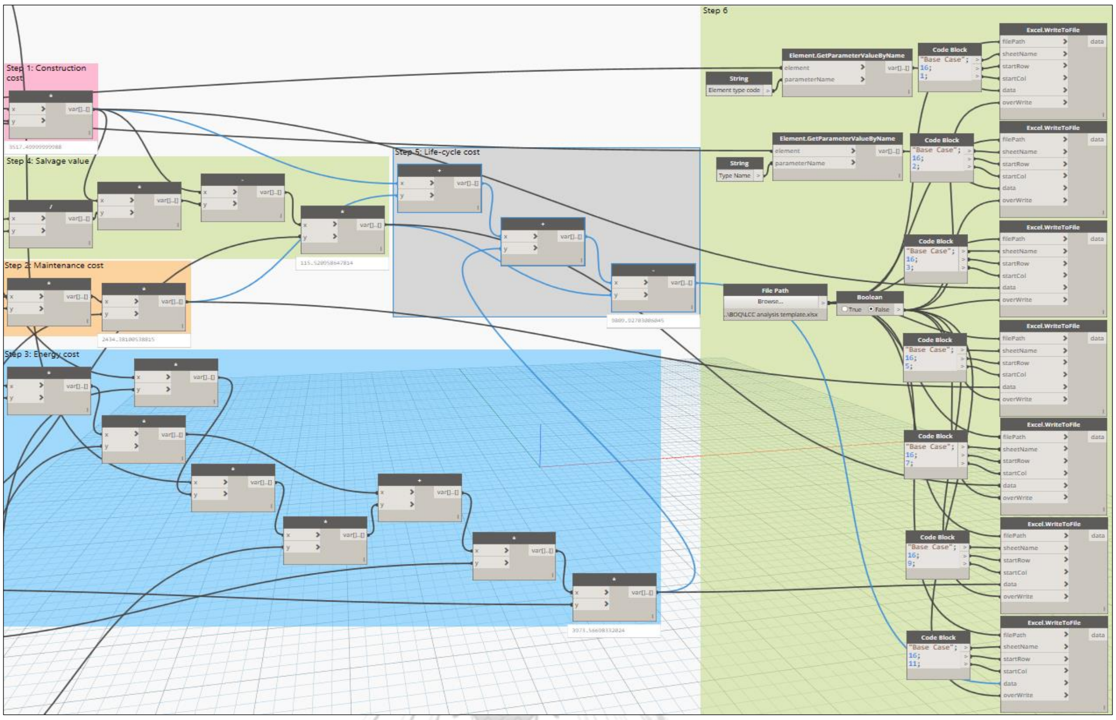
Export LCC results of Exterior glazed window W2’ type



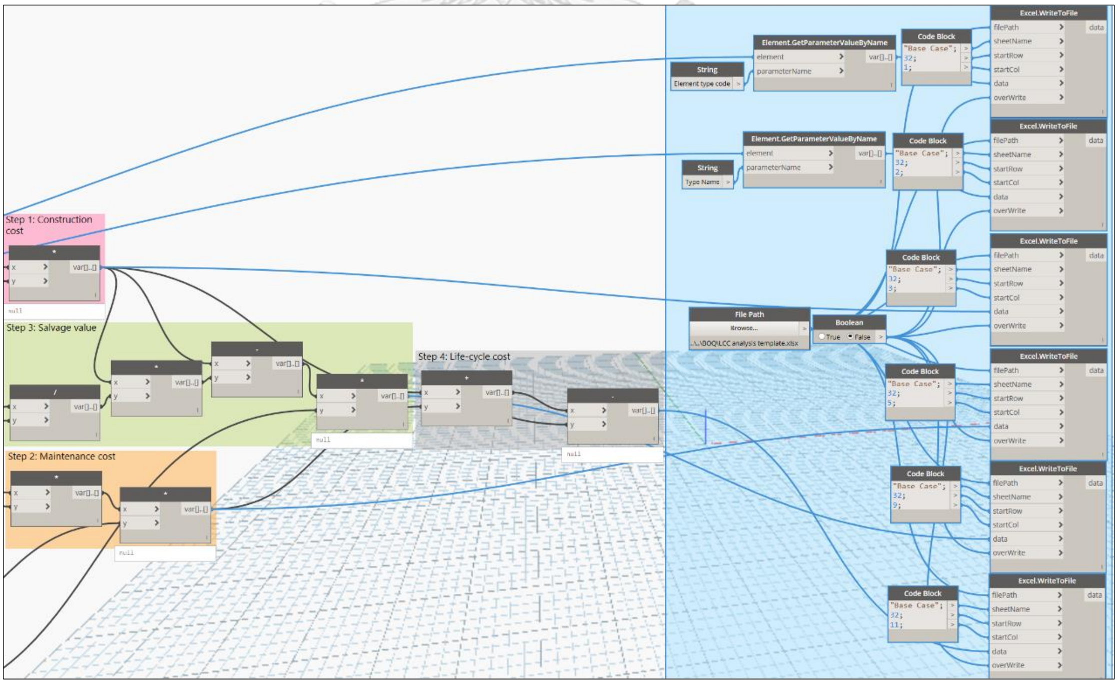
Export LCC results of Exterior glazed window W3 type



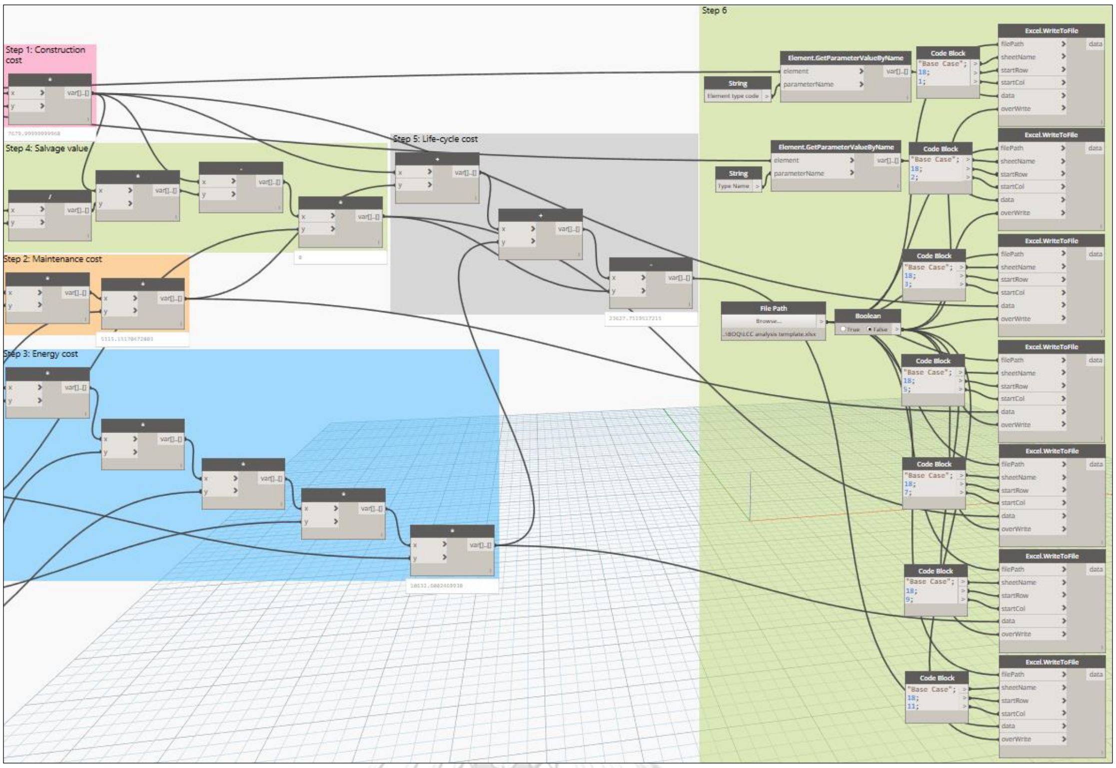
Export LCC results of Exterior glazed window W3’ type



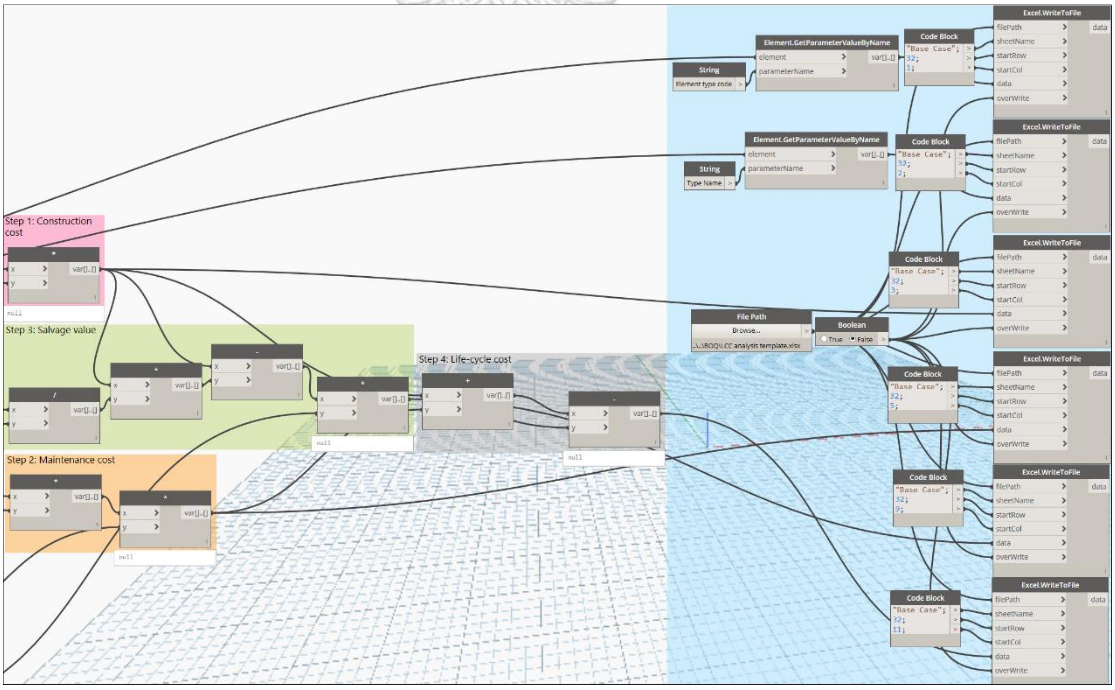
Export LCC results of Exterior metal window W10 type



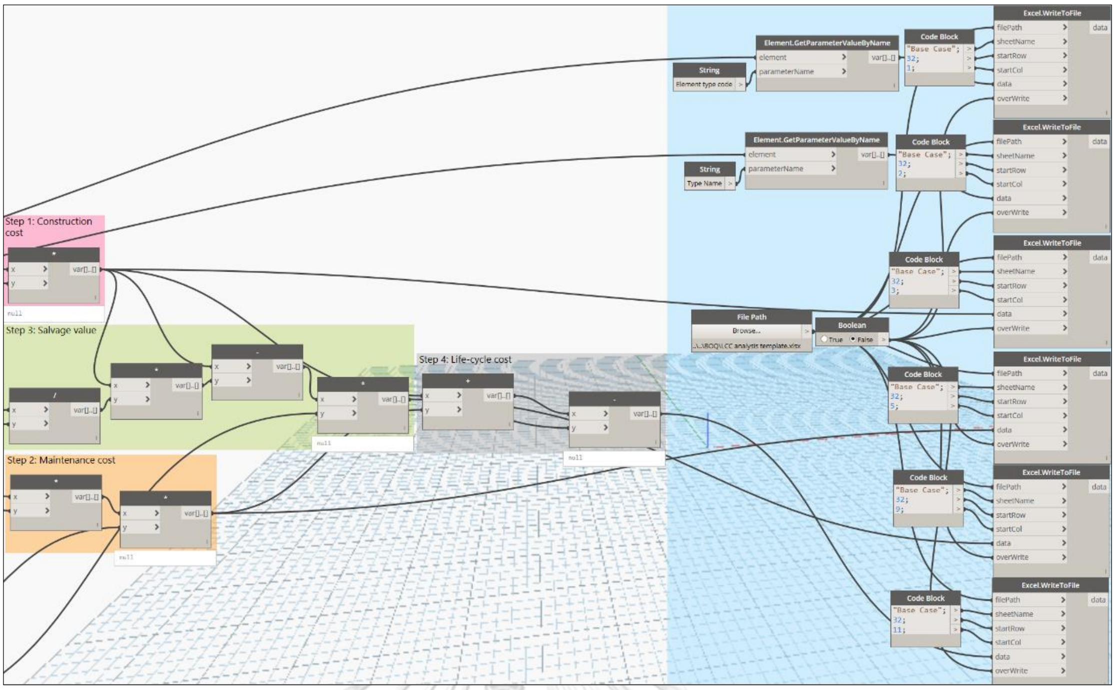
Export LCC results of Interior glazed window W7 type



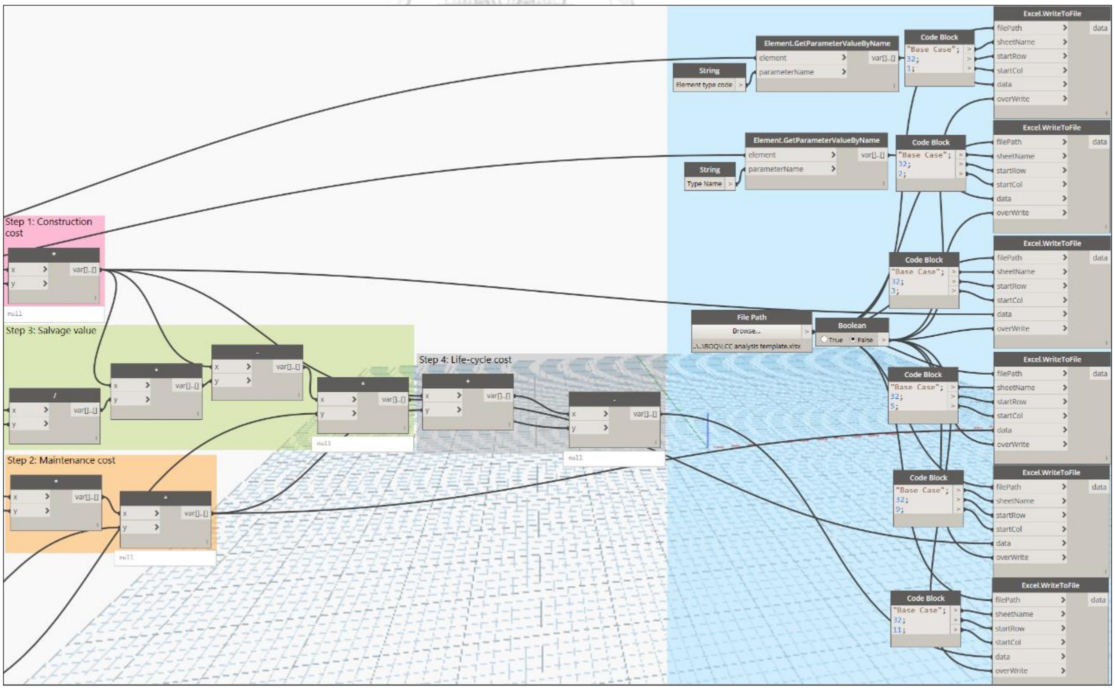
Export LCC results of Interior glazed window W7' type



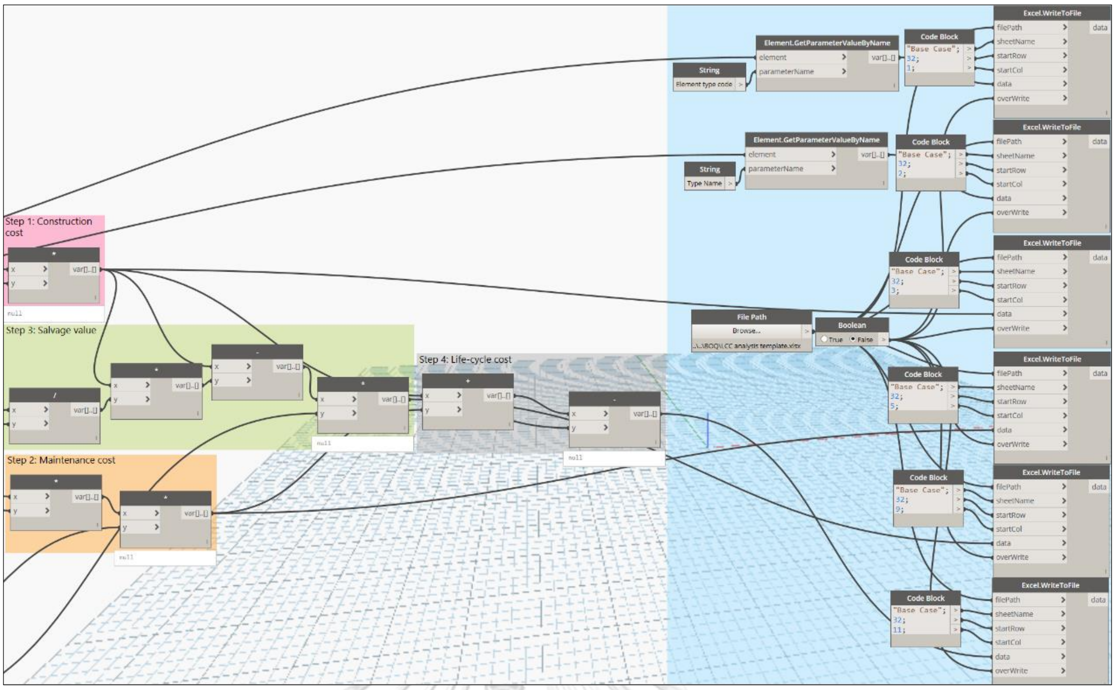
Export LCC results of Interior glazed window W8 type



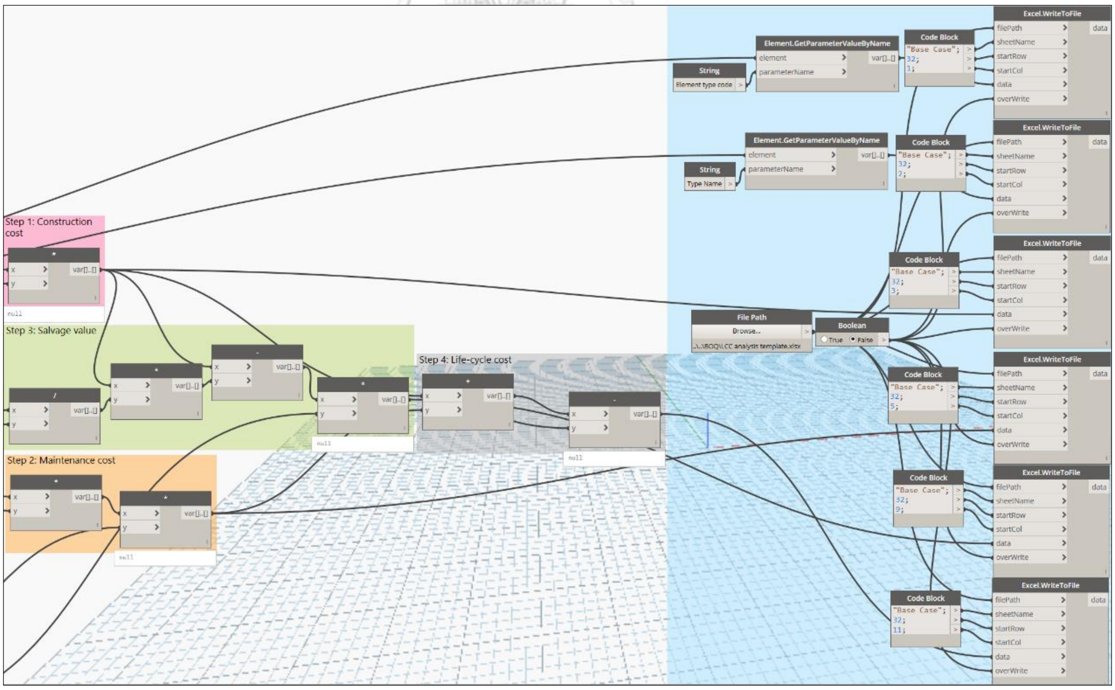
Export LCC results of Exterior metal-glazed double door D1 type



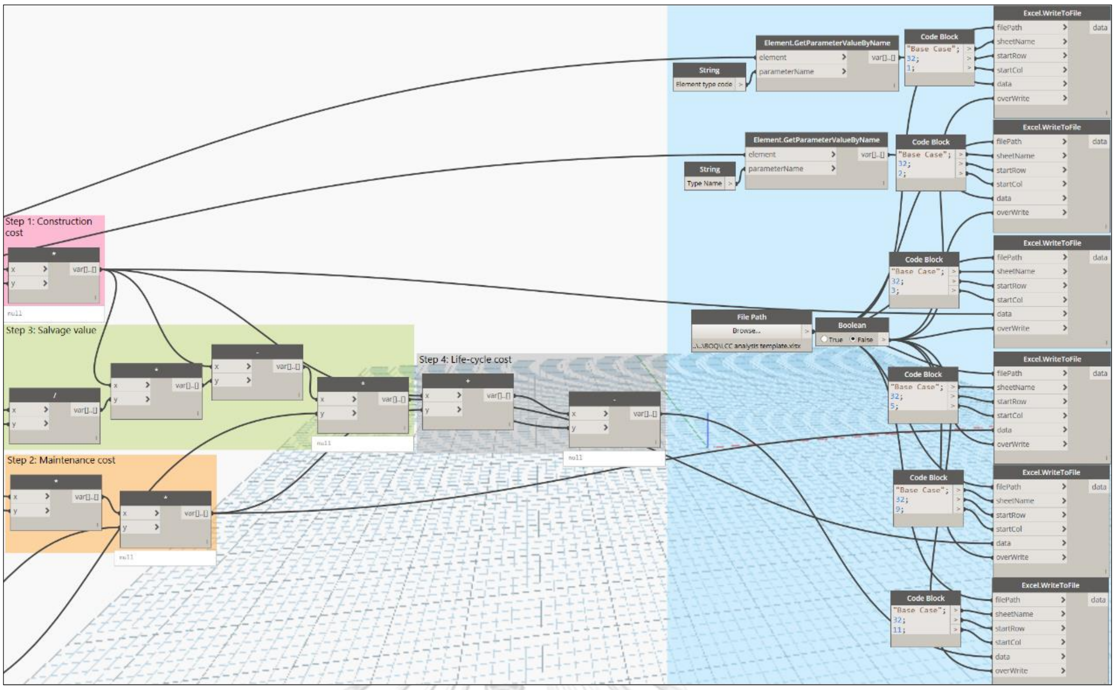
Export LCC results of Exterior metal single door D4 type



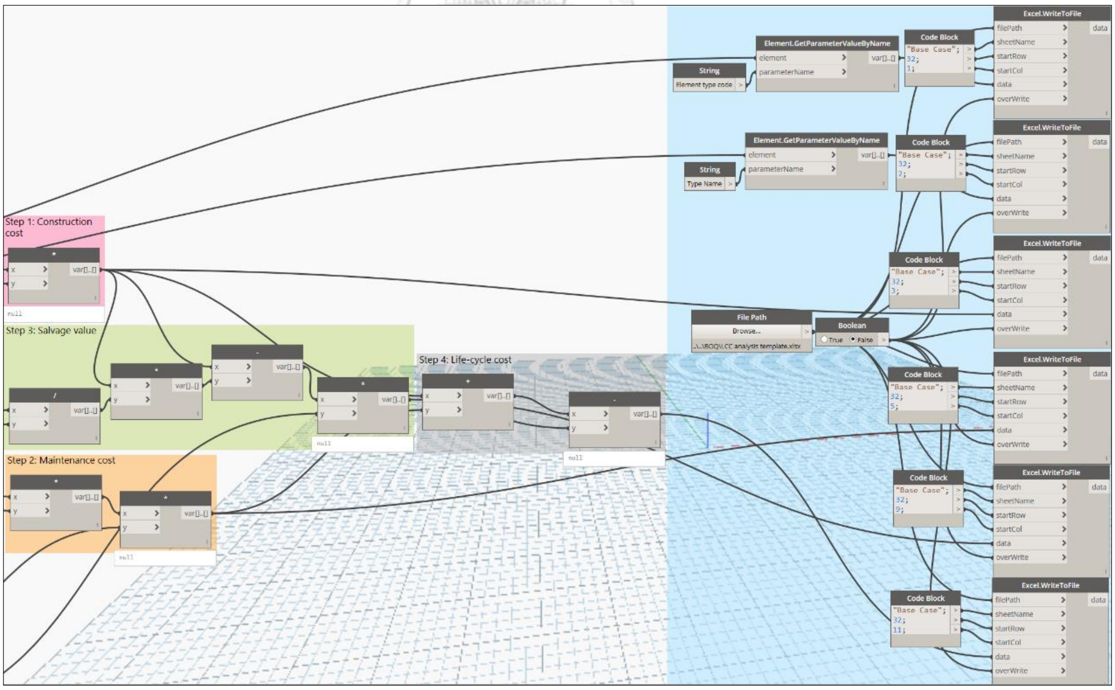
Export LCC results of Exterior plywood double door D9 type



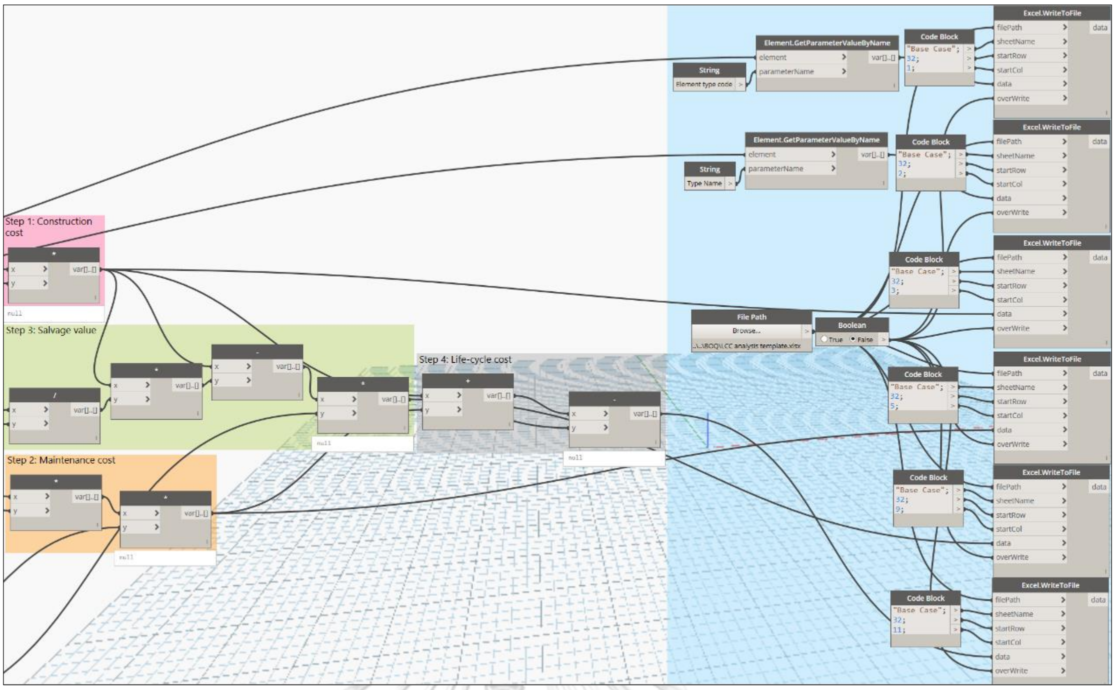
Export LCC results of Interior metal-glazed double door D2 type



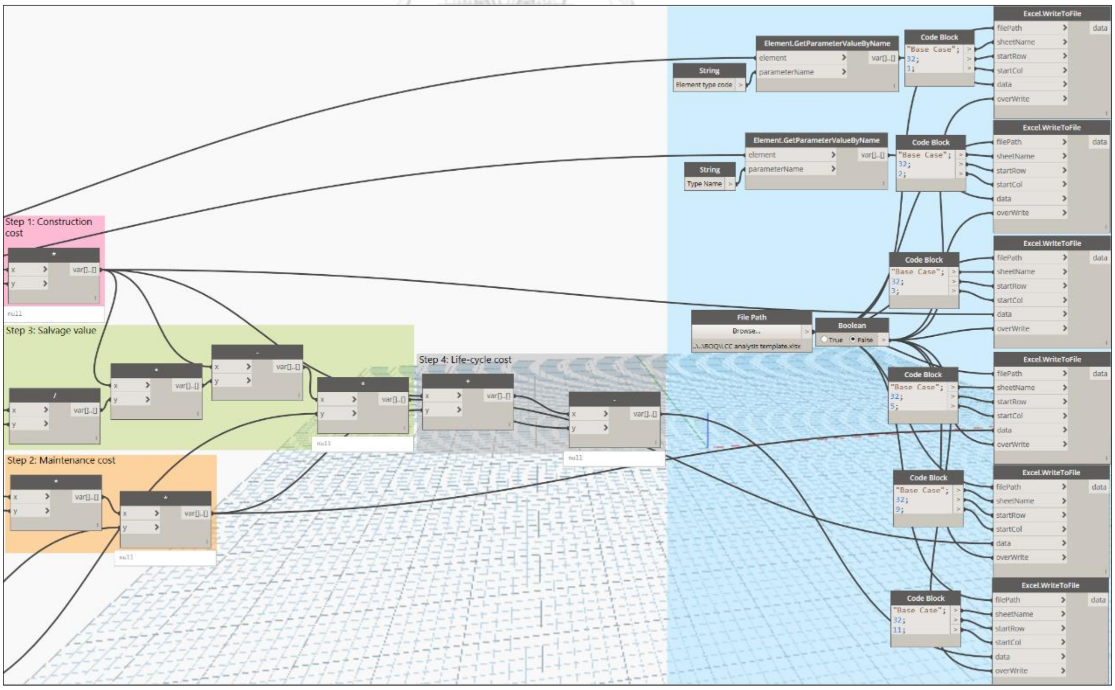
Export LCC results of Interior metal-glazed single door D3 type



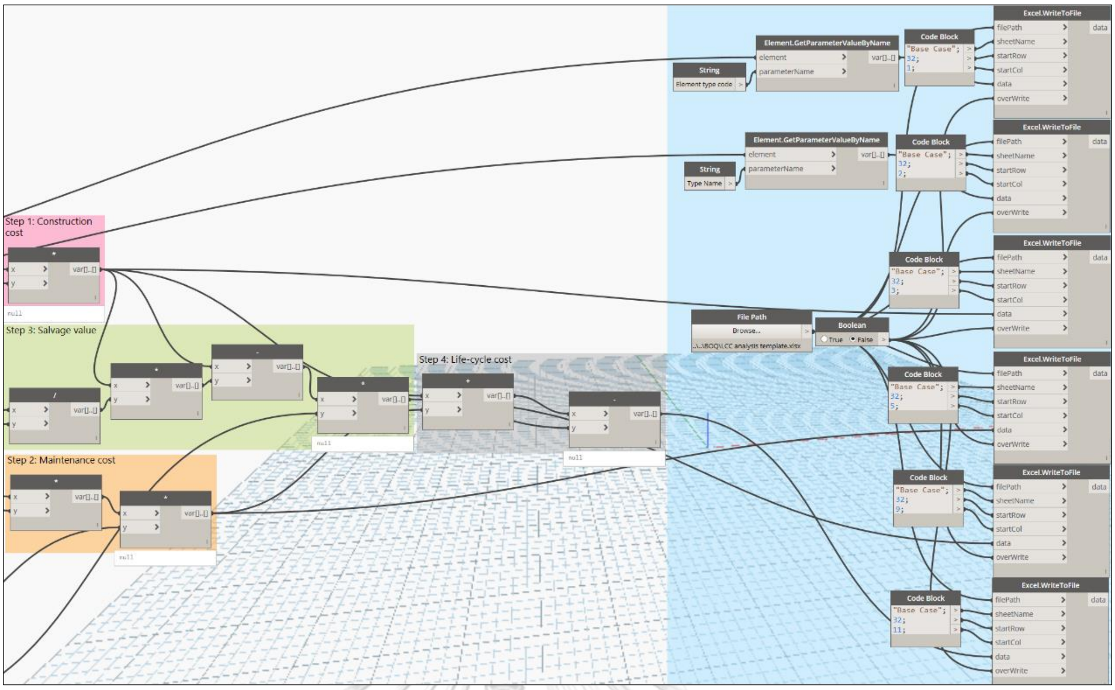
Export LCC results of Interior metal-glazed double door D10 type



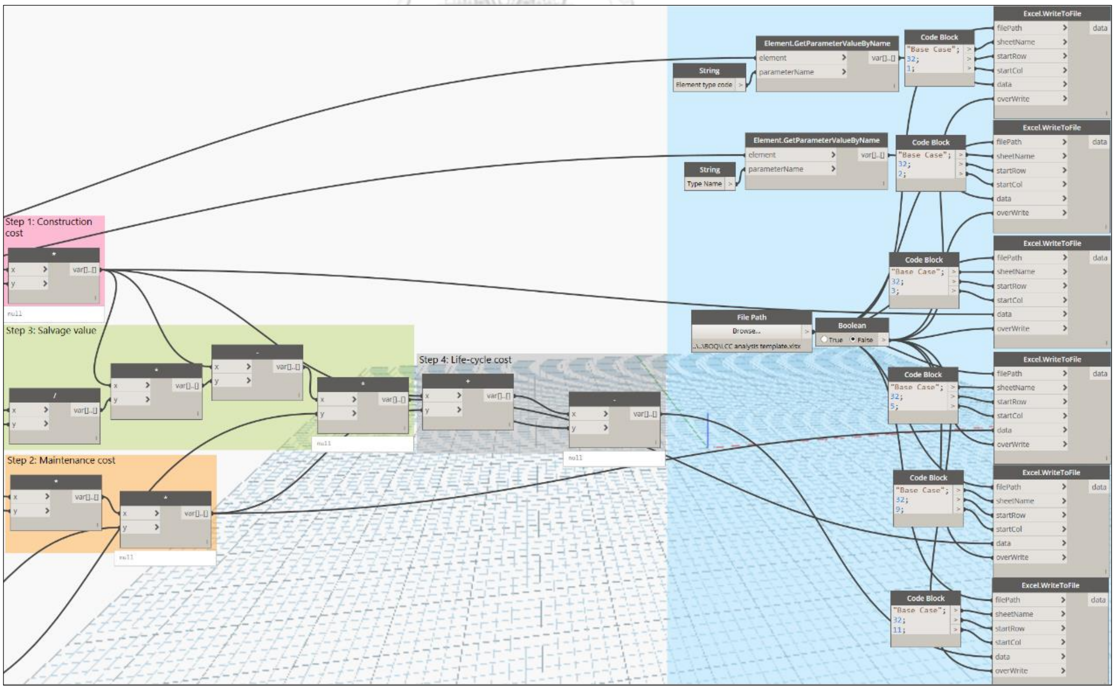
Export LCC results of Interior wood single door D5 type



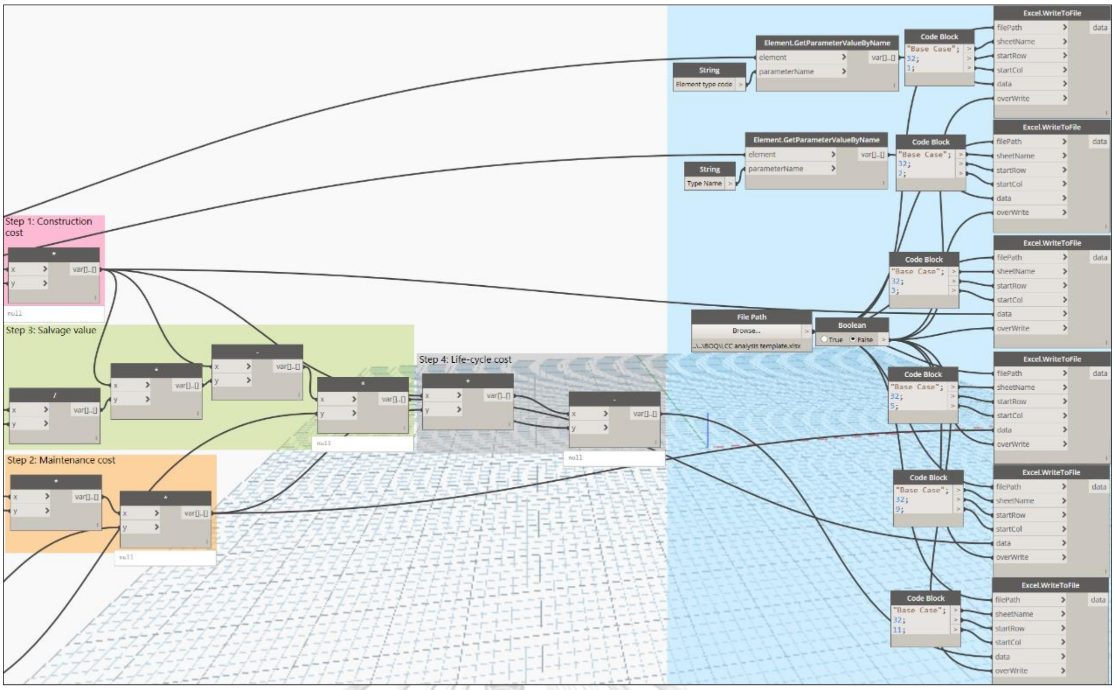
Export LCC results of Interior wood single door D7 type



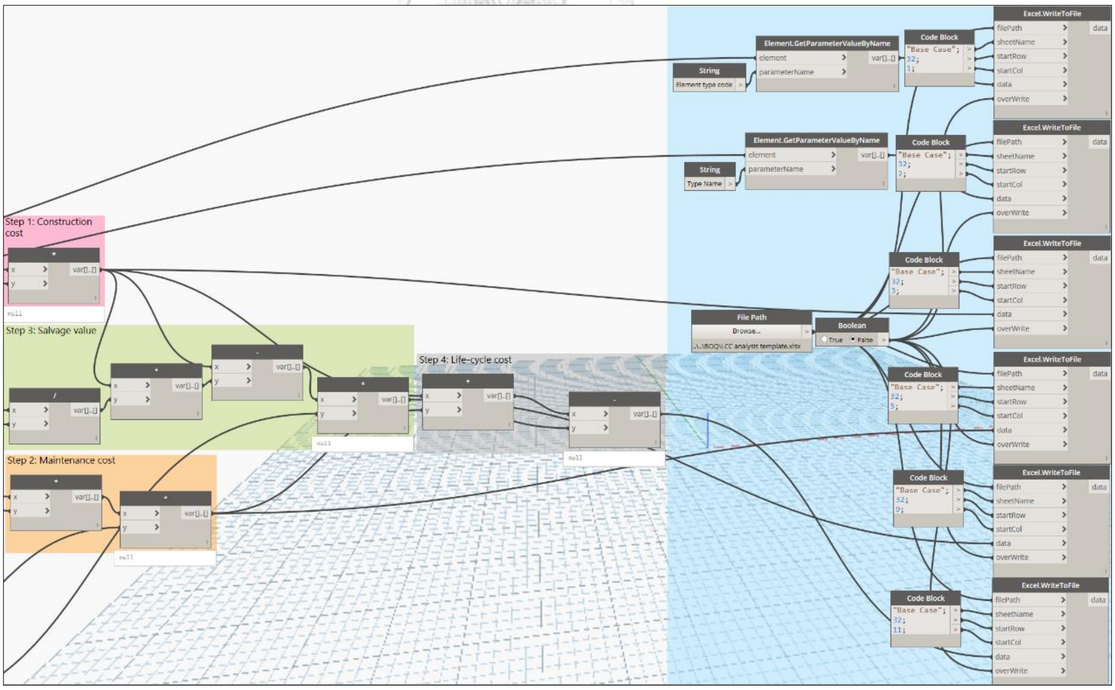
Export LCC results of Brick wall W11 type



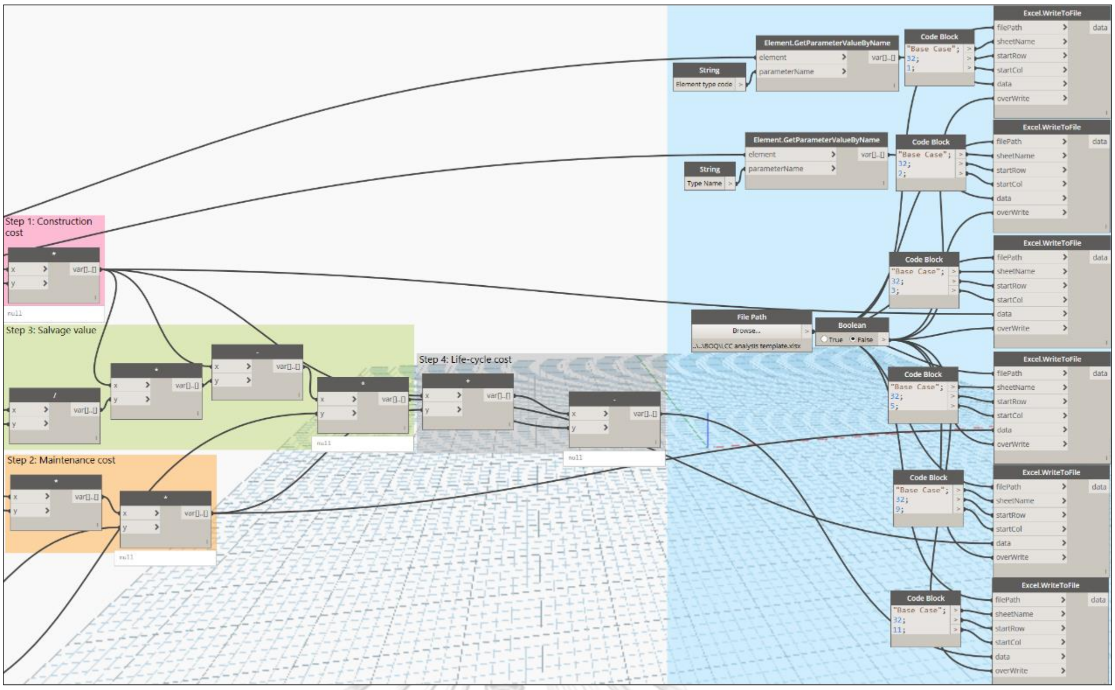
Export LCC results of Gypsum wall W55 type



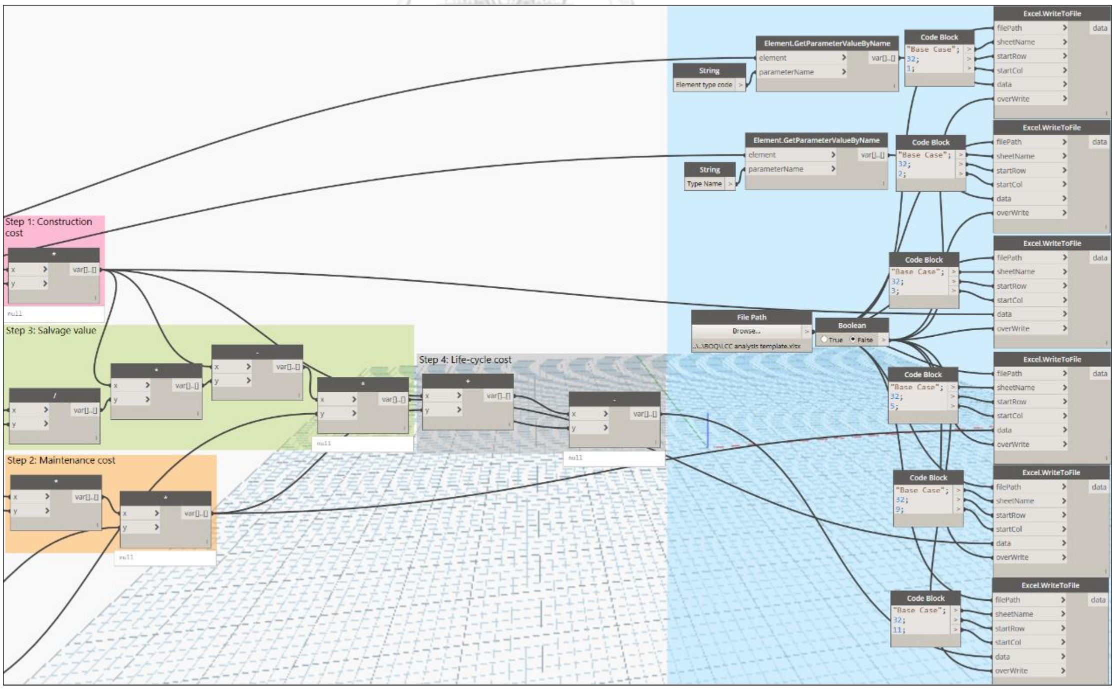
Export LCC results of Cladding tile 12x12 wall W3 type



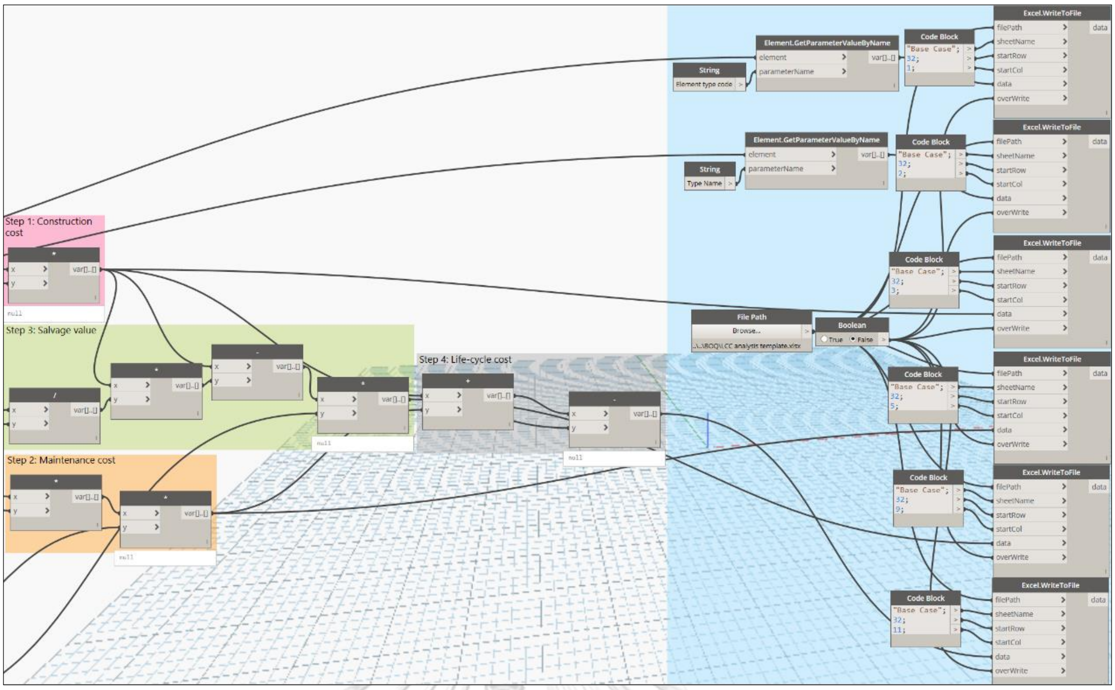
Export LCC results of Brick and cladding tile 12x12 wall W13 type



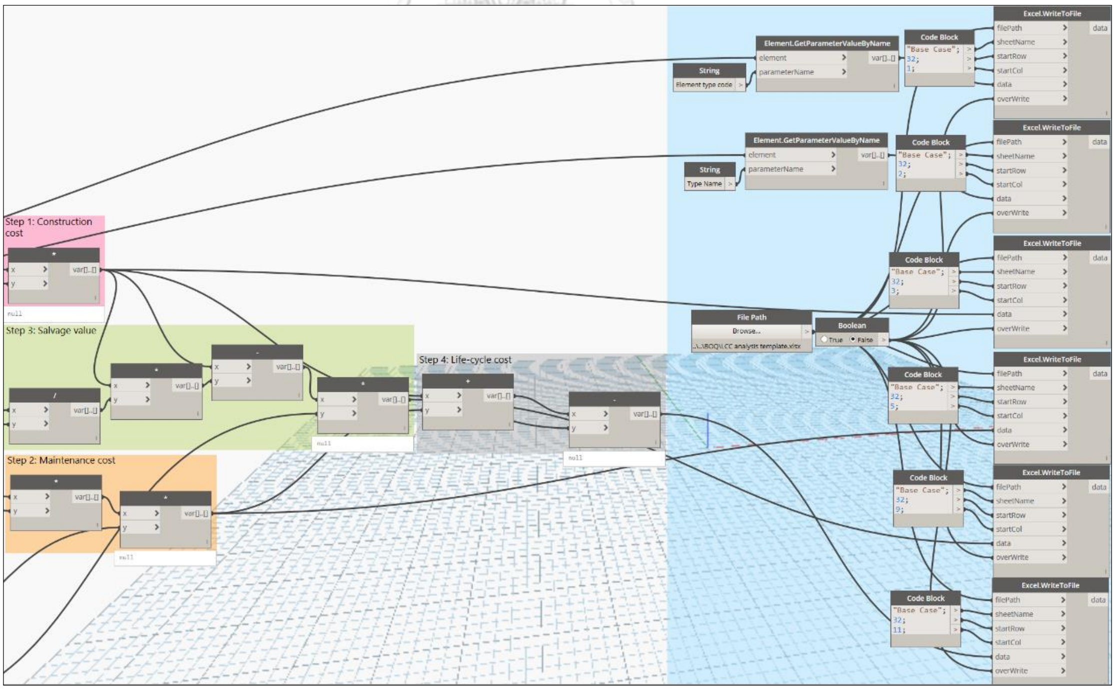
Export LCC results of Gray stone floor F1 type



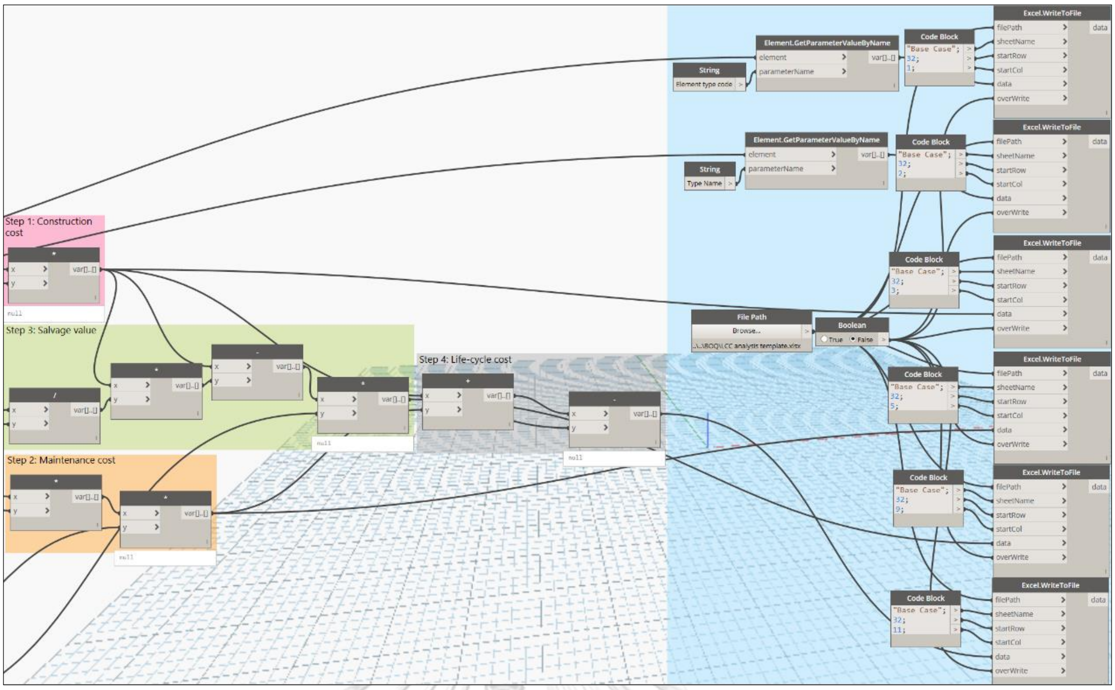
Export LCC results of Gray tile floor F2 type



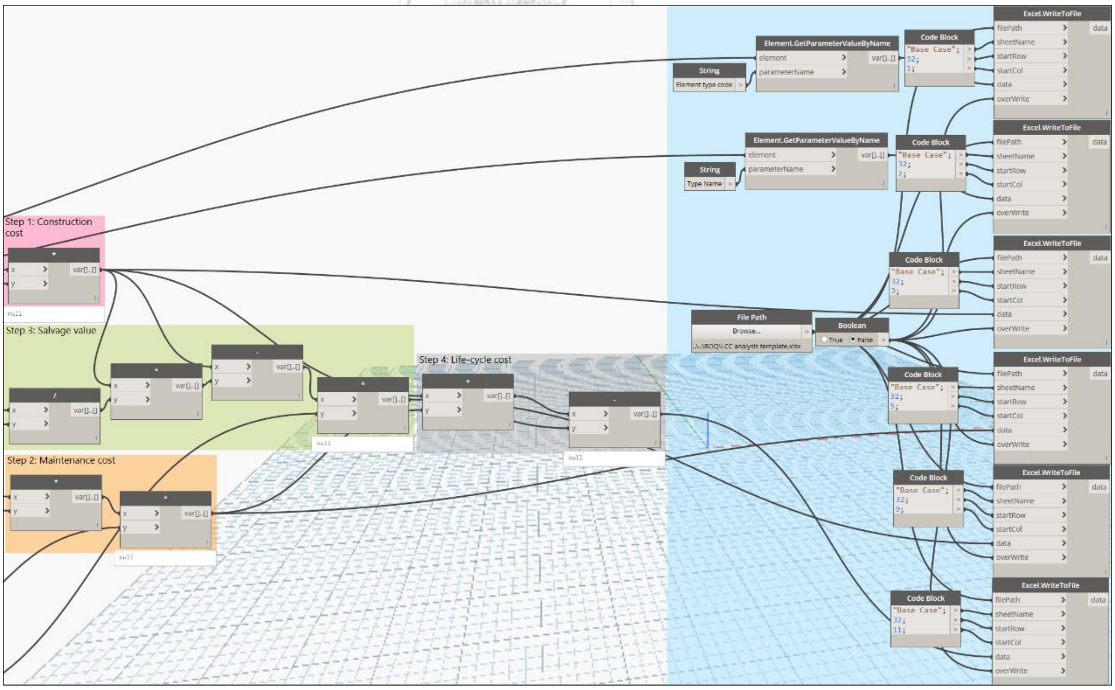
Export LCC results of Ceramic tile floor F3 type



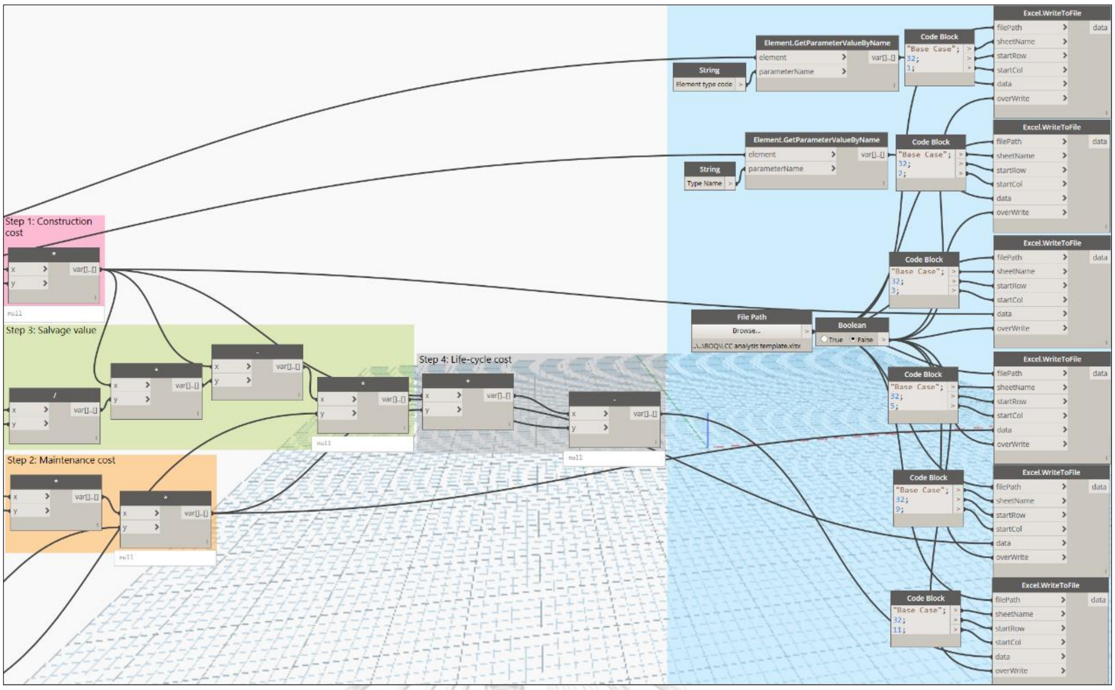
Export LCC results of White-gray terrazzo floor F5 type



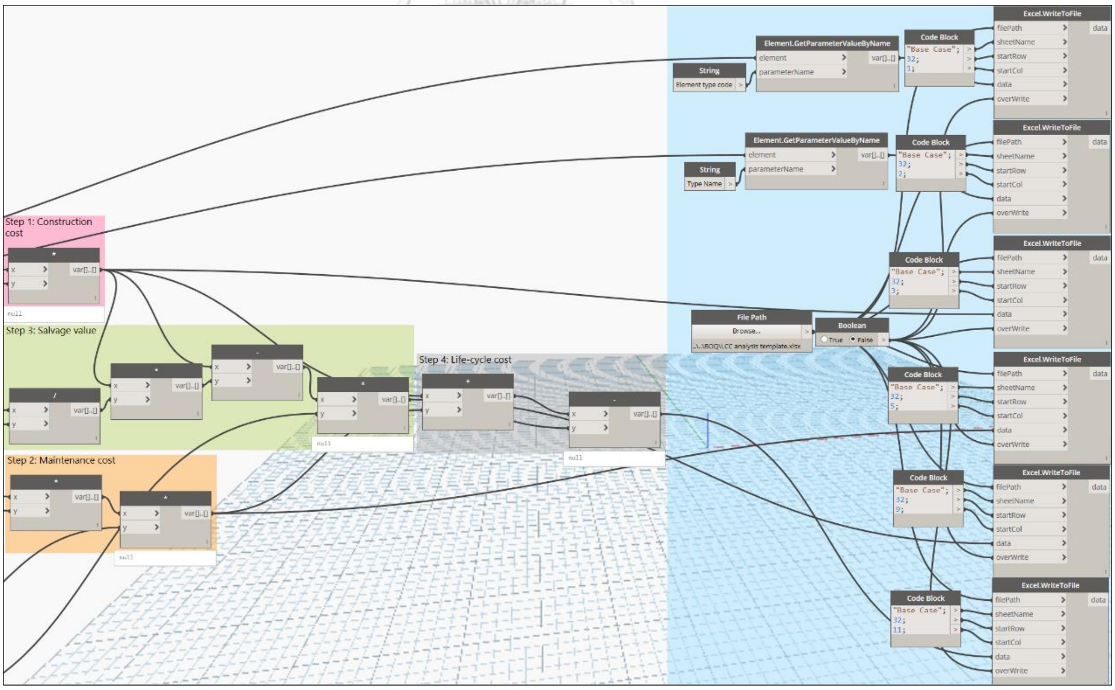
Export LCC results of Concrete floor F6 type



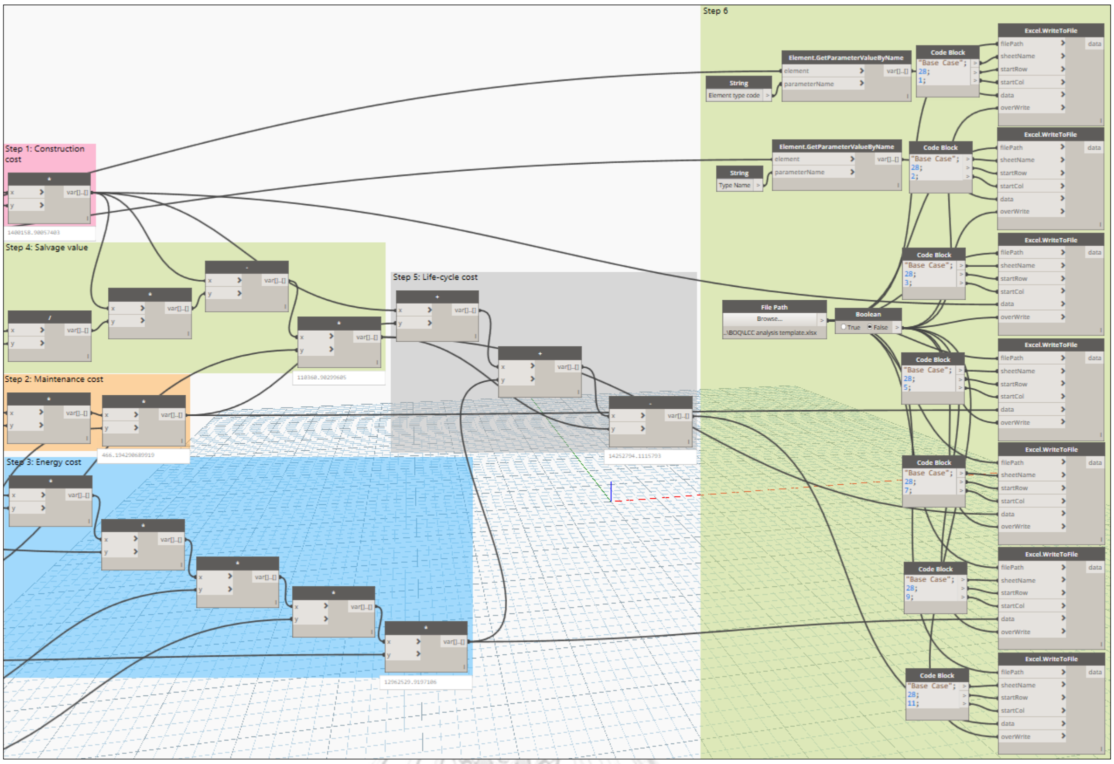
Export LCC results of Gray tile floor F2’ type



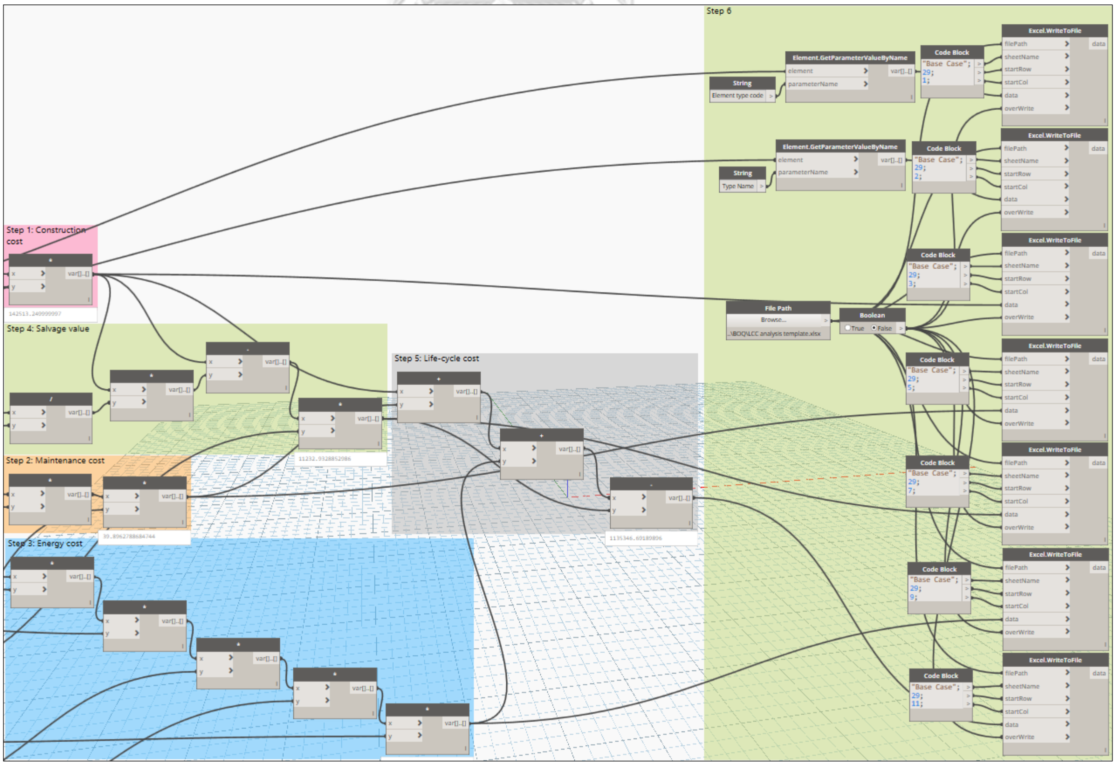
Export LCC results of Gray stone floor F1’ type



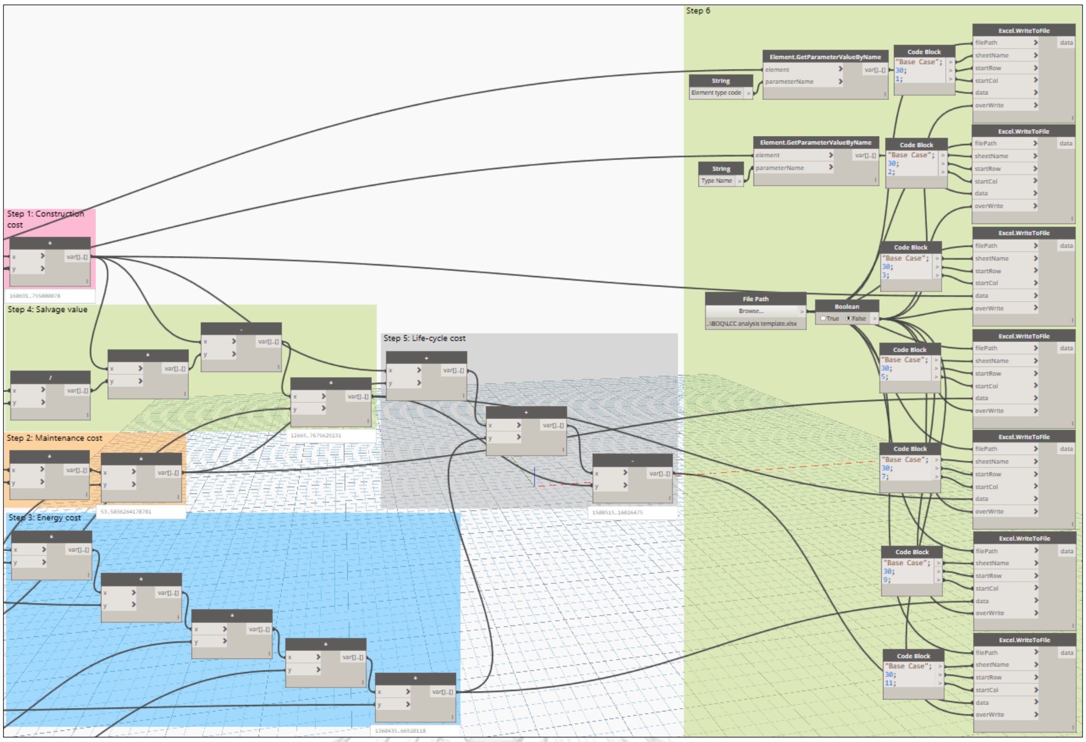
Export LCC results of Concrete floor F6’ type



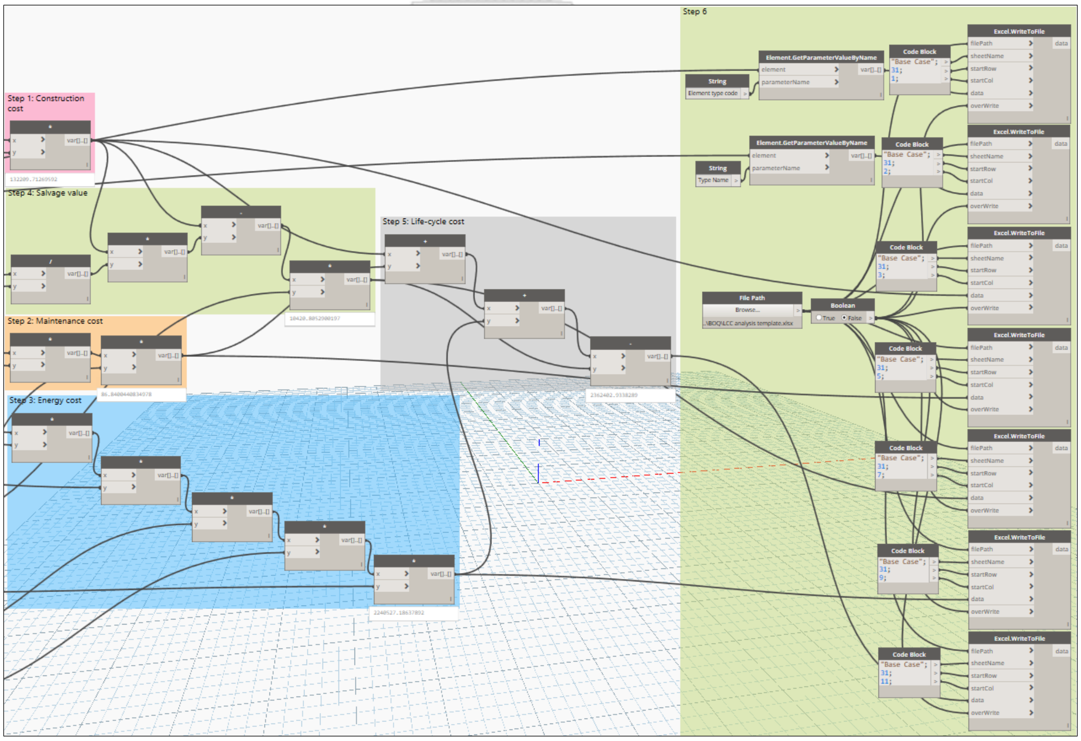
Export LCC results of Red ceramic tile 4x8 wall W66 type



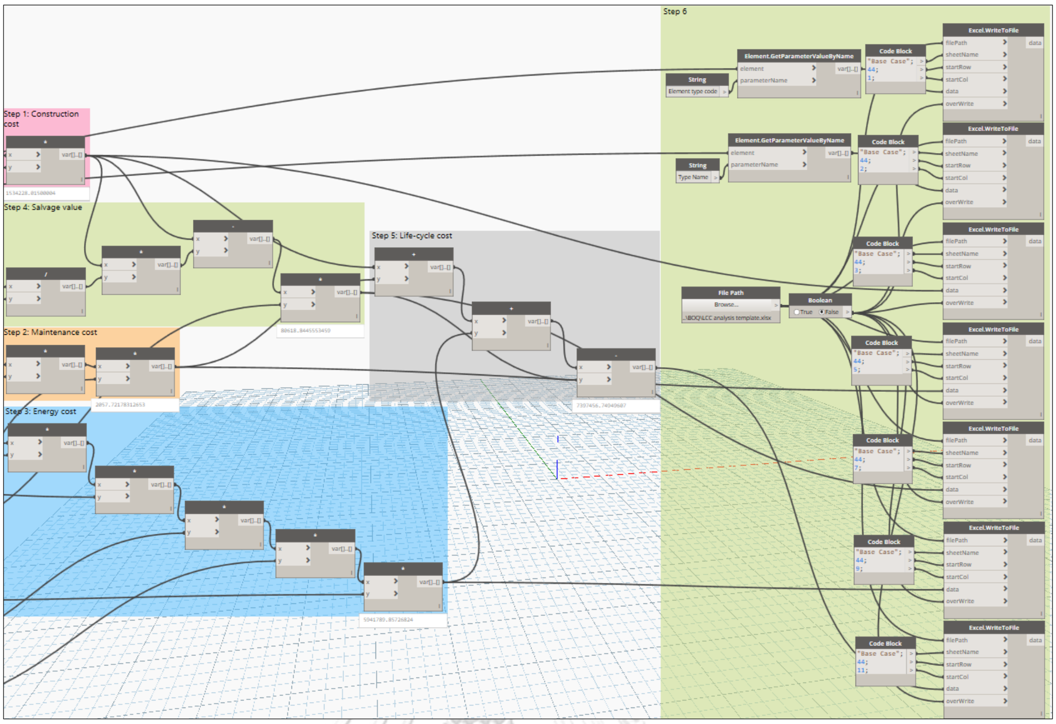
Export LCC results of Cladding tile 12x12 and red ceramic tile 4x8 wall W36 type



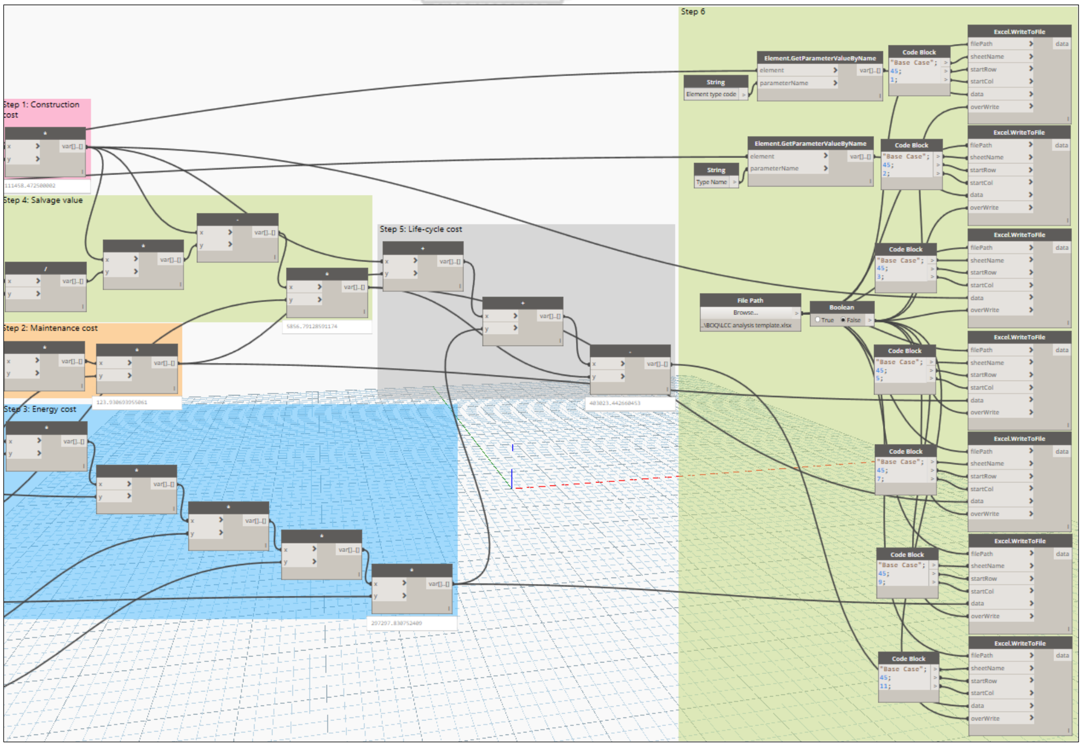
Export LCC results of Brick and red ceramic tile 4x8 wall W16 type



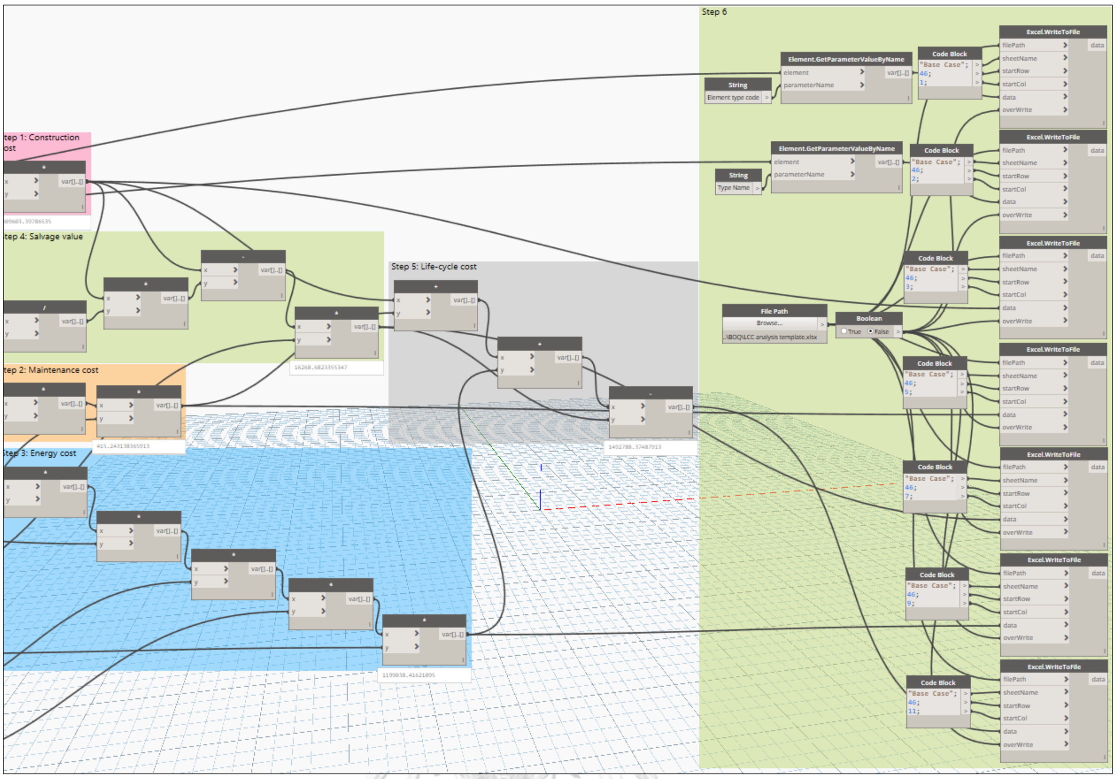
Export LCC results of Balcony wall W8-1 type



Export LCC results of Concrete roof with waterproofing F4 type



Export LCC results of Gray tile roof F2’ type



Export LCC results of Concrete roof F6' type

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