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以建築資訊塑模技術實作藍綠設計之方法框架

Development of BIM-enabled Blue-Green design

framework

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本論文係郭瀚嶸君（F99521605）在國立臺灣大學土木工程學系完成之博士學位論文，於民國 107 年 8 月 7 日承下列考試委員審查通過及口試及格，特此證明

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系主任（所長）　謝尚賢

II

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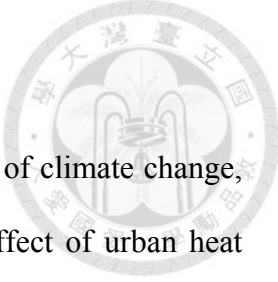感謝一路走來的友人們，在此致上最高的謝意。

<div align="right">郭瀚嶸 敬上</div>

摘要

由於近年來加劇的都市化趨勢與潛在的氣候變遷影響，都市的規劃與設計需要新的設計方法論以對應熱島效應的負面效應。藍綠設計是近年來受到矚目的都市系統設計手法，該設計手法結合水系統與綠化系統的優點，以提昇都市區域承受氣候變遷衝擊的能力，本研究針對建築設計中的藍綠設計進行探討。對於藍綠設計來說，需要專業知識以符合設計各自系統的需求。然而，設計團隊需要具備跨領域的知識與設計環境才能考量到系統之間的設計交互影響關係，以進一步量化藍綠設計的綜合效益。在考慮到設計上的挑戰，建築資訊塑模做為營建領域進行參數化與協同設計的技術，可用來解決這一層面的問題。所以，建築資訊塑模的軟體架構可作為整合設計的平台。本研究提出以建築資訊塑模技術實作藍綠設計之方法框架，提供設計團隊建構協作環境之系統方法，藉由團隊合作創造設計配套的過程以定義協作介面與流程，並可用設計配套進行藍綠設計的設計與分析操作。這套方法框架包含四套塑模準則：(1)需求塑模、(2)流程塑模、(3)系統塑模、(4)性能塑模。其四套塑模準則對應之設計配套為(1)藍綠設計需求、(2)具備流程圖與資訊交換需求之工作流程手冊、(3)建築資訊塑模之系統元件模型、(4)具備分析功能之客製化設計工具。本研究選擇綠屋頂與水箱系統作為實作設計配套的案例，並運用設計情境以展示運用設計配套的設計流程，最後採用深度訪談之方式，採訪具有建築資訊塑模設計經驗之專業建築師，以驗證方法框架的可行性。
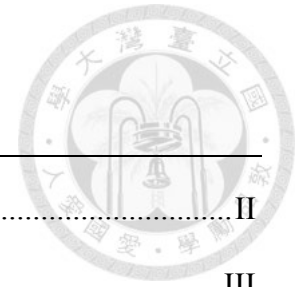

關鍵字:氣候變遷、永續設計、藍綠設計、建築資訊塑模。

Abstract

For the increasing trend of urbanization and the potential impact of climate change, it is needed to have new design approach to reduce the negative effect of urban heat island on built environment. The concept of Blue-Green design combining Blue infrastructure and Green infrastructure is proposed to improve disaster resilience of urban area with multiple benefits. The Blue-Green design in this research emphasizes on the scope of building design. For designing water system and greenery system requires multidisciplinary knowledge to clarify the design interaction between systems, there exists difficulty in evaluating the performance of the integrated system of the Blue-Green design. In order to collaborate on the multidisciplinary design approach, the Building Information Modeling (BIM) software is used as an integrated platform for design teams to create and analyze the Blue-Green design. This research proposes a BIM-enabled Blue-Green design framework for helping design teams establishing collaboration environment in design and analyzing building with the Blue-Green design in the Concept Design stage. The collaboration interface and process are clarified through the modeling approaches. Design teams can use design toolkits as modeling outcomes to conduct Blue-Green design under agreed design process. The framework includes four modeling approaches: Requirement Modeling, Process Modeling, System Modeling and Performance Modeling. The corresponding outcomes of the modeling approaches are Blue-Green requirements, workflow manual, BIM element models, and customized design tool. The case study uses green roof and water tank as an example of the Blue-Green design to implement the solution of the framework. A scenario study is used to demonstrate the design process with the solution. An in-depth interview with architect is conducted to confirm the feasibility of the framework.
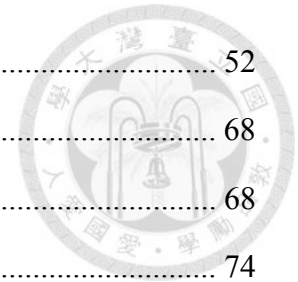
Keywords: Climate Change, Blue-Green Design, Sustainable Design, BIM

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1. Introduction

1.1 Research Background and Research Problem

Over the past decades, the pace of urbanization is fast and the impact of urbanization is huge around the world. According to United Nation's report [1], the growth of urban population is massive. Urban population comprises more and more percentage of total population since 1950. There is a continuous trend shown not only in developing countries but also in developed countries. Furthermore, there is evidence showing that urbanization results in negative environmental impact [2-6]. Concerning that more and more people live in the urban area, the living quality of the urban and the surrounding environment will become worse and worse.

In the process of urbanization (see Figure 1-1), land surface is changed and ecological resilience is destroyed. Greenery plants are replaced by grey buildings, and ground is covered by asphalt and concrete. Open watercourses are covered as sewers or even removed.

Rural Environment   Urbanization   Urban Environment
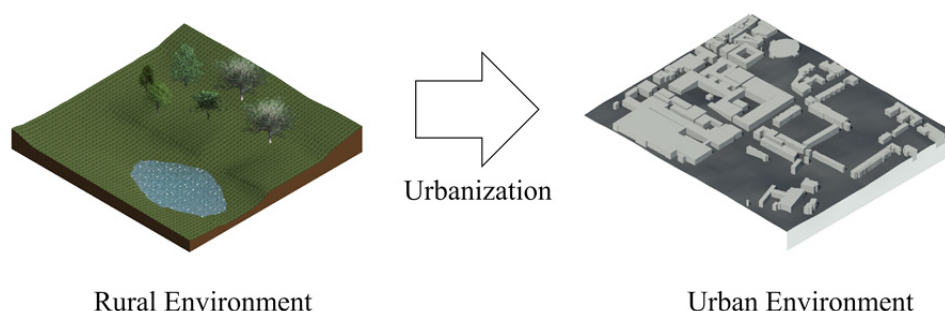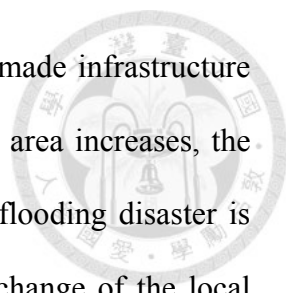
Figure 1-1. From rural to urban environment

The changes of the land surface will result in a series of problems. First, the energy and water demand of the land are increased because of high population density with corresponding human activities. Second, the risk of urban flooding is increased due to

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impervious surfaces. The original land surface is replaced by man-made infrastructure with low infiltration capability. Once the precipitation in the urban area increases, the runoff will increase to result in flooding. The potential impact of flooding disaster is huge associated with the development of urbanization. Third, the change of the local climate influences complex hazard. For the surface of high-rise building affects the effect of turbulent flow and heat storage, the phenomenon of Urban Heat Island (UHI) is generated according to these associated effects. The UHI includes a series of related effects such as urban breezes, intensive air pollution, highly probability of intense thunderstorms, discomfort in living area, disruption of human activities due to elevated temperatures, health issues, and higher energy consumption in air conditioning [2][3] [6-9]. These effects may also contributed by climate change.

For mitigating these effects, the urban area is required to be planned and developed in more sustainable and resilient way. In recent years, Blue-Green design approach [3] is proposed to reduce the negative impact of climate change in urban area. The blue (water) measures contains water supply, waste water, and rain water drainage systems. The green (vegetation) measures contains green roof, green wall and greenery space. The Blue-Green design integrated blue and green measures together to provide sustainable design with environmental resilient capacity and social benefits.

Although the concept of the Blue-Green design is straight forward, it is hard to be conducted for the complexity of multidiscipline collaboration [10] (See Figure 1-2). The Blue experts are responsible for the design of water system, and the Green experts are responsible for the design of greenery system. In conducting the Blue-Green design, it is needed to consider design interaction between Blue and Green systems for evaluating integrated performance. Therefore, the experts require multidiscipline knowledge for the design interaction. The threshold of multidiscipline knowledge is high. Following

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the mindset of work specialization, it is more applicable to establish collaboration environment for Blue and Green experts to create the project design reflecting the employer's requirements, analyze Blue-Green system with agreed approaches and review the performance of the overall Blue-Green design in consequential procedures. Concerning that traditional 2D CAD platform supports limited capability in managing the design parameters of Blue-Green system, an integrated design platform is required for the collaboration environment. Nowadays, Building Information Modeling (BIM) [11] is the promising technology used to enhance the quality of design and managing the information flow of project. With the purpose of implementing the Blue-Green design in design process, this research proposes using BIM technology creating collaboration environment to support Blue and Green experts exploring design options.

Blue expert and Green expert

Water system in building: Mechanical, Electrician and Plumbing Engineer	Green element on the building envelope: Architect, Green Roof Engineer
Water system outside the building: Urban Planner, Water Engineer	Green element around the building site: Landscape Architect, Landscape company
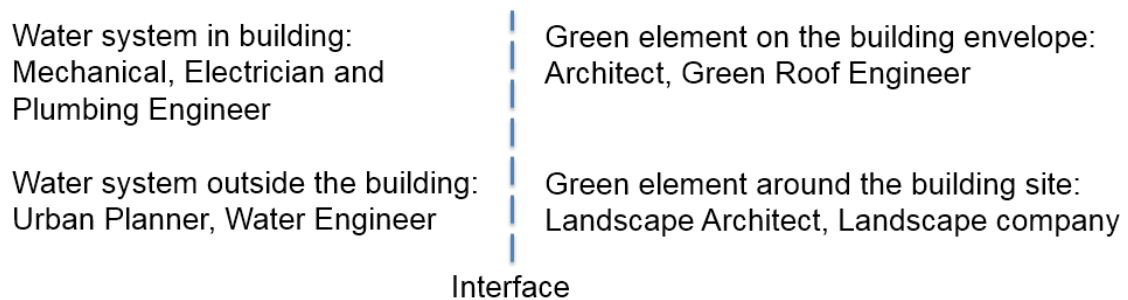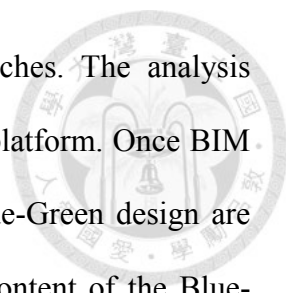
Interface

Figure 1-2. Interface between blue and green experts [10]

The challenge to couple BIM and the Blue-Green design is wrapping the content of the Blue-Green design into the design and analysis process supported by BIM [12][13]. Even the emerging BIM technology provides integration design platform, there are still lack of BIM element models represented the system of the Blue-Green design and customized design tools to evaluate the performance of the Blue-Green design to be made. The BIM element models are containers carrying product information, but seldom BIM element models are designed according to the principle of integration water and greenery system. Furthermore, Blue and Green experts should evaluate the

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performance of BIM project model with agreed analysis approaches. The analysis approaches could be formulated as customized design tool in BIM platform. Once BIM project model is analyzed and the BIM element models of the Blue-Green design are created or modified according to the analysis results, the design content of the Blue-Green design can be properly conveyed to the following designer and contractor. With the BIM element models and customized design tool prepared, Blue and Green experts can conduct design process with expected design information flow. Therefore, the collaboration interface between experts with different disciplinary expertise can be clarified, and the design content can be coordinated to maintain the design quality.

1.2 Research Objective

For the design interaction between Blue system and Green system is multidisciplinary design issue which is difficult to be evaluated, it requires holistic methodology creating collaboration environment for design teams to initiate and analyze the content of the Blue-Green design in the design process. Once the collaboration interface in collaboration environment is clarified, the integrated design outcomes of the Blue-Green design can be assessed and the overall performance of the building design can be optimized by experts with multi-disciplinary knowledge.

The major objective is to develop a BIM-enabled design framework for design team preparing collaboration environment to create the Blue-Green design solution. The framework supports design teams to analyze and form the building design in early design stage. Design teams can continuously collaborate and develop BIM project model with BIM element models of the Blue-Green design in the following design stages.

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1.3 Thesis Organization

There are six chapters with reference and appendix in this thesis. In the chapter 2, there are literature reviews on the Blue-Green design, BIM with sustainable design and current limitation. In the chapter 3, it is the methodology of this research and the structure of a BIM-enabled Blue-Green design framework is shown. In the chapter 4, it uses water tank and green roof as case study to implement the solution of design framework. In the chapter 5, it shows the scenario studies and discusses the feedback from expert interview. The conclusion of the research is stated in the chapter 6.
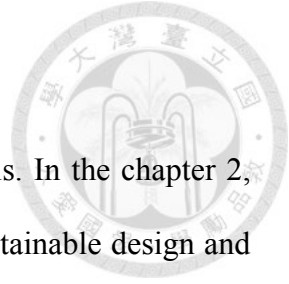
2. Sustainable Building with Blue-Green Design and BIM
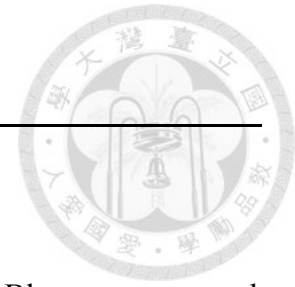
2.1 Sustainable Building Design and Blue-Green Design

The original idea of the Blue-Green design is combining the Blue measures and Green measures to provide disaster resilience of urban infrastructure to against climate change. There are several projects related to the Blue-Green design research. A research project named Green and Blue Space Adaptation for Urban Areas and Eco Towns (GRaBS) [14] is conducted to raise awareness about green and blue infrastructure. In GRaBS project, Kazmierczak and Carter [15] collected practical cases using green and blue infrastructure and listed valuable suggestion in Table 2-1-1. It is obvious that effective communication and collaboration between stakeholders are the key of success. After GRaBS project, there is a Blue-Green Cities [16] project focusing on similar topic. The Blue-Green Cities project intends to combine water management and green infrastructure to recreate water cycle. Followed by the concept of Blue-Green Cities, Hoang and Fenner [17] proposed using sustainable urban drainage systems and green infrastructure for storm water management. Almost the same time, an EU funded project called Blue-Green Dream [18] synergizes urban blue and green systems as Blue-Green solution to enhance urban environment with multiple benefits. The benefits could be air pollution reduction, biodiversity improvement, energy saving, food supply noise reduction and surface runoff delay…etc. Božović et al. [19] propose a BG systems planning methodology listed in Table 2-1-2. The scenario of the methodology is urban planning stage. In the beginning, project requirements should are defined. Then, the analysis and optimization process is the conducted with project requirements and project data. The BG Design Brief is the output of the whole process. The stakeholders include project developers, planning team, BG team, approval bodies and public.
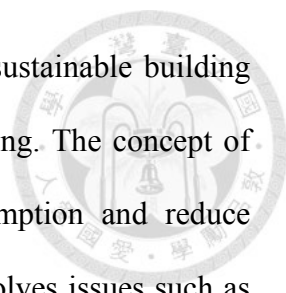
Table 2-1-1. Lessons learned from case studies [15]
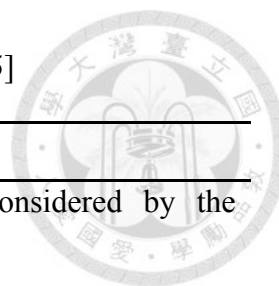
Suggestions
1. Triggers for action, or the reasons why an action is considered by the organization
2. Continuing leadership and championship
3. Raising awareness within the organization, amongst stakeholders and with the wider public
4. Collaborative working; how internal and external collaboration, and in particular cooperation with research institutes, has facilitated a stronger adaptation response
5. Learning from others, in terms of adaptation processes and/or adaptation actions
6. Developing a sound evidence base, either using in-house expertise or by outsourcing experts
7. Public engagement on adaptation issues
8. Embedding adaptation in decision making through policies, plans, regulations or incentives, and via close collaboration with developers
9. Funding for adaptation responses
10. Monitoring and evaluation of adaptation responses

Table 2-1-2. Development stages of the BG Design Brief [19]

Stages	Actions
Stage 1 - Project requirements and data collection	• Definition of project goals, performance targets and indicators. • Gathering and mapping of project requirements and design data (e.g. potential Nature Based Solutions, problems, planning opportunities, local climatic conditions and available water resources).
Stage 2 - Analysis and optimization	• Analysis and optimization. • Development of metrics for target indicators. • Analysis of potential synergy benefits between urban components. • Design of candidate solutions. • Detailed comparative analysis to develop optimized integrated solutions.
Stage 3 - Design Brief production	• BG Design Brief production. • Completion of detailed BG Design Brief, containing project requirements (based on all stakeholders' input) and agreed optimized concepts and solutions.

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In recently years, more and more studies have contributed on sustainable building [20]. In general, sustainable building is also known as green building. The concept of sustainable building is to improve efficiency in resource consumption and reduce impact on human health and environment [21]. For example, it involves issues such as energy efficiency strategy, water recycling system and renewable energy design [22]. According to an energy modeling guide [23] published by the American Institute of Architects, it suggested that architect can use energy modeling in design stage to improve the energy performance for reducing building energy usage. Another report [24] published by Royal Institute of British Architects provide guidance for architect to conduct sustainable building design along with design stage.

As mentioned above, the original idea of the Blue-Green design focuses on urban scale and the idea of sustainable building design focuses on building scale. For the common feature of these two concepts is to reduce the environmental impact, the intersection of the concepts could be made. According to the BG systems planning methodology, the BG Design Brief with urban planning requirements is formulated as output. And so forth, the building design requirement of the BG systems can be a subset of the BG Design Brief. It is assumed that buildings with the Blue-Green design can become parts of urban Blue-Green infrastructure. In this research, we emphasize on building scale to develop the Blue-Green design.

2.2 Building Information Modeling
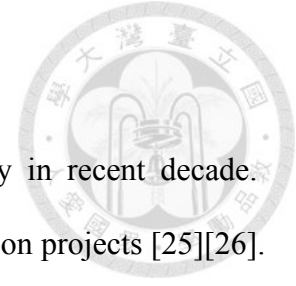
In construction industry, BIM is the most popular technology in recent decade. There are more and more countries applied BIM in public construction projects [25][26]. This trend is across North America [27], European area [28], and even Asia continent [29][30]. The concept of BIM can be traced back to the 1970s when Eastman et al. introduced the idea of "Building Description System" [31]. In 1989, the term of "Building Model" is described by Simon Ruffle [32]. Until 1992, "Building Information Model" is first time to be used in a journal paper published by G.A. van Nederveen and F. P. Tolman [33]. In 1999, Eastman published the term of "Building Product Models"[34]. After 2002, the term of "Building Information Model" and "Building Information Modeling" are widely introduced by Autodesk [35]. Compared to the terminology proposed by Autodesk, the corresponding term of Graphisoft and Bentley Systems are "Virtual Building" and "Integrated Project Models" [36][37].

Along with the development of terminology, it is shown that BIM involves the methodology for shaping and describing the information of building in the virtual world. In defining the meaning of BIM, the interpretation could be the data model contained building information or the process to create the data model. The definitions of BIM are listed Table 2-2-1 [38]. Besides the definition above, BIM could also described as "Building Information Management" which manages the process to create and share the building information across the building lifecycle [39].

According to the Macleamy curve [40], the cost of design change could be lower down when design team arrange time and effort to integrate design in the early stage of building lifecycle. Therefore, BIM is the entry point to help design team in creating and sharing design content in efficient and consistent way to avoid mistakes. The purposes of BIM use can be categorized as five types in Table 2-2-2 [41].

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Table 2-2-1. The definition of BIM (Modified from [38])

	Definition	Source
Define BIM as model	A BIM is a digital representation of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle from inception onward.	National Institute of Building Science (NIBS) [39]
	Discrete set of electronic object-oriented information used for design, construction and operation of a built asset.	PAS 1192-5:2015 [42]
	Digital representation of the physical and functional characteristics of a building over its life cycle.	BS 8536:2010 [43]
	A rich information model, consisting of potentially multiple data sources, elements of which can be shared across all stakeholders and be maintained across the life of a building from inception to recycling.	National Building Specification (NBS) [44]
	Shared digital representation of physical and functional characteristics of any built object (including buildings, bridges, roads, etc.) which forms a reliable basis for decisions.	BS ISO 29481-1 2010 [45]
Define BIM as process	Is a BUSINESS PROCESS for generating and leveraging building data to design, construct and operate the building during its lifecycle. BIM allows all stakeholders to have access to the same information at the same time through interoperability between technology platforms.	NIBS [39]
	Building Information Modelling is digital representation of physical and functional characteristics of a facility creating a shared knowledge resource for information about it forming a reliable basis for decisions during its life cycle, from earliest conception to demolition.	NIBS [46], Royal Institute of British Architects (RIBA) [47]
	The development and use of a multi-faceted computer software data model to not only document a building design, but to simulate the construction and operation of a new capital facility or a recapitalized (modernized) facility.	General Services Administration (GSA) [48]
	Construction of a model that contains the information about a building from all phases of the building life cycle.	ISO 16757-1: 2015 [49]

Table 2-2-2. BIM Uses Purposes and Objectives [41]

BIM Use Purpose	BIM Use Objective	Synonyms
Gather	to collect or organize facility information	administer, collect, manage, acquire
Generate	to create or author information about the facility	create, author, model
Analyze	to examine elements of the facility to gain a better understanding of it	examine, evaluate
Communicate	to present information about a facility in a method in which it can be shared or exchanged	exchange
Realize	to make or control a physical element using facility information	implement, perform, execute,

The five types of BIM use purpose include major activities in building lifecycle. BIM model could be the data source to organize facility information. In BIM platform, BIM project model could be created and evaluated in parametric software environment. With the outcome of the BIM project model, the building information could be shared and even fabricated. According to the BIM Project Execution planning guide [50] and the survey [51] evaluating the frequency and benefit of BIM use, 3D coordination, Design Reviews and Design Authoring are top three BIM uses. The importance of maintaining correct and consistent design information is shown.

2.3 Limitations on Current BIM-based Sustainable Building Design

BIM can be used to create design alternatives. With the use of BIM, sustainable building design concerning rainwater harvesting, solar access, and recycled content can be conducted [52]. For example, Levy [53] proposes a worksheet for designer to size green roof with rainwater harvesting calculation and BIM project model. In this scenario, designer can use existing functions of BIM platform to extract required information. Generally, most building performance analysis can be conducted with the use of Building Energy Modeling (BEM) tool [54]. In the BIM guide for energy performance [55] published by General Service Administrative of United State, it is suggested that energy analysis can be done with the use of BIM project model. Designer can transfer BIM project model into green building format as input of energy analysis software. However, there are some limitations on current approaches of BIM-based sustainable building design.

(1) User defined manual operation for sustainable building design

For there are some calculation principles of sustainable building design not included in BIM platforms or BEM tools, designer is required to define a series of operations of different software to conduct the calculation. The operations could be collecting information from web database, extracting information from BIM platform, setting calculation rules and conduct calculation in spreadsheet software. During the process of sustainable building design, it is needed to check information consistency of each manual operations. After the calculation is done, designer references the calculation results to optimize the building design in BIM platform. The feature of this approach is flexible in switching calculation principles but lack of effective mechanism in managing design information among the software. The configurations of the operations are hard to be reused.

(2) Combined operation of BIM platform and BEM tool for sustainable building design

For there are related analysis functions of sustainable building design contained in BEM tools, designer can use BIM project model as information source to export building information to BEM tool conducting analysis. In this approach, designer creates BIM project model in BIM platform, exports BIM project model from BIM platform to BEM tool, and checks the completeness of building information in BEM tool. It exists interoperability issues in exchanging information between BIM platform and BEM tool [54]. Designer is required to remodel the building geometry and reassign material properties in BEM tool. After the analysis results are obtained, designer references the analysis results shown in BEM tool and modify the BIM project model in BIM platform to process the next design iteration. Obviously, the cost of maintaining design information between BIM platform and BEM tool is high.

In designing building with the Blue-Green design, it requires a series of design activities supported by BIM to deal with multidisciplinary design requirements. For instance, the BIM element models should be created as the physical representation of the Blue measures and the Green measures. The BIM-enabled customized design tool with Blue-Green performance analysis function is also critical for handling design interaction between systems to evaluate potential benefits. Furthermore, the processes to identify the design requirements of the Blue-Green design and develop BIM project model in collaborated way play important roles in the design stage. With the above limitations and concerns, the proposed collaboration environment should support new approaches of BIM-based sustainable building design conducting the Blue-Green design.

3. Development of BIM-enabled Blue-Green Design Framework
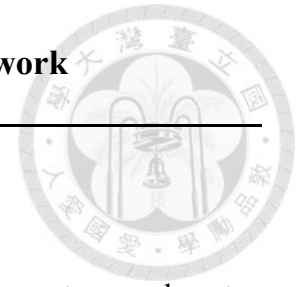
3.1 Design of BIM-enabled Blue-Green Design Framework

The feature of the Blue-Green design is to combine greenery system and water system as an integrated system. In order to design the size and the capacity of the integrated system, it is required to consider the design requirements of each sub-system and the interaction between design parameters. For the design requirements are too complex to manage design parameters, BIM software with parametric design capability is selected to support the Blue-Green design. Although BIM software can be used as an integrated design platform in designing building parametrically, a series of configuration is needed to create corresponding BIM element models of each sub-system with required design parameters. Even the BIM element models are prepared; it is still lack of analysis and design functions of the integrated system.

According to the document [41] published by Pennsylvania State University, the BIM uses purposes can be defined into five types with each BIM use characteristics. However, the design process consists of several design activities involving different BIM uses. In implementing the Blue-Green design, it shall require almost all the BIM uses listed in Tables 2-2-2. With reference to the document [41], this research proposes a BIM-enabled Blue-Green design framework for helping design teams preparing collaboration environment to analyze and design building with the Blue-Green design in the early design stage. The collaboration environment provides clear collaboration interface and process along with appropriate design solutions for design teams to conduct design.
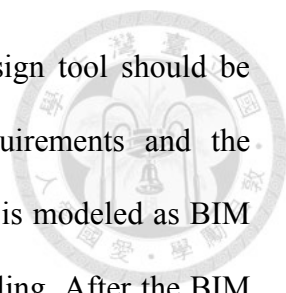
The aim of this framework is supporting Blue and Green design teams to clarify collaboration interface and process with procedures of creating the design toolkits for

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Blue-Green design. The framework considers integration and parametric design of the Blue and Green components of a building system with customized analysis functions in BIM platform.

The prerequisite of the framework is that design teams have BIM ability to collaborate building design using BIM model during design stage. The BIM ability contains the knowledge to create BIM-based customized design tool using visual programming language. The assumed research scenario is that the Blue-Green design is one of the major methodologies to be applied to fulfil the project requirements.

In selecting the BIM uses [41], the first step is to identify objectives and the second step is to determine the BIM use characteristics such as facility element, facility phase, discipline and level of development. For the BIM-enabled Blue-Green design framework, the above two steps are concerned. Furthermore, the steps to create a customized design tool and a workflow manual are defined in the framework to support the Blue-Green design. There are four modeling approaches in the BIM-enabled Blue-Green design framework shown in Figure 3-1-1. The term of "modeling" in this framework is an activity for design teams to define and describe things such as the statement of the project requirements, the representation of physical objects, the performance indicator, or the design process.

Concerning that the employer's requirement is the objective of the project, the first modeling approach of the BIM-enabled Blue-Green design framework is the requirement modeling. After the project requirements related to the Blue-Green design are defined, the candidate measures of the Blue-Green design can be chosen by design teams to fulfil the requirement. The outcome of the requirement modeling is called Blue-Green requirements. The second modeling approach is the process modeling with a workflow manual as output. The Blue-Green requirements and the potential follow-up

actions such as creating BIM element models and customized design tool should be considered in the workflow manual. With the Blue-Green requirements and the workflow manual prepared, the measures of the Blue-Green design is modeled as BIM element models containing product information in the system modeling. After the BIM element models are implemented, design teams can create a BIM project model that represents the overall building design and load the BIM element models as part of the BIM project model. In order to satisfy the threshold of the Blue-Green requirements and optimize the capability of the measures, it is required to quantify the performance of the Blue-Green design. The purpose of the performance modeling is to develop a customized design tool with analysis function to model the performance of the Blue-Green design for optimization. In the performance modeling, the key tasks to create customized design tool for the Blue-Green design are introduced. With the above modeling outcomes prepared as design toolkit, design teams could use the design toolkit conducting the Blue-Green design under clear collaboration interface and process.

The framework can be used in conducting analysis and design process in the early design stage. The four modeling approaches are interrelated with each other. The user of the framework are design teams including architects, BIM consultants or sustainability consultants representing Blue Green experts. The exact role of Blue expert or Green expert differs from project to project. Each design team may consider the Blue-Green design together in different aspects. The detailed classification of Blue expert or Green expert is not considered in this research. For the design process, it is suggested that lead designer such as architect is responsible for the requirement modeling and the process modeling. The system modeling and the performance modeling could be conducted collaboratively among design teams such as BIM consultants or sustainability consultants.

2. Process Modeling

Key Tasks:
(1) Clarify the expected workflow and information exchange for the design and analysis process

(2) Document the information using Process Maps and Exchange Requirements

3. System Modeling

Key Tasks:
(1) Collect required product information

(2) Decide appropriate behavior of BIM element model

(3) Create geometry of BIM element model

(4) Set parametric configuration of BIM element model

(5) Assemble BIM element models as whole system

BIM-enabled Blue-Green Design Framework

Workflow Manual

BIM Element Models

Blue-Green Requirements

Customized Design Tool

Outcome

Outcome

Outcome

Outcome

1. Requirement Modeling

Key Tasks:
(1) Identify the project requirement with the Blue-Green design

(2) Outline the potential measures of the Blue-Green design

4. Performance Modeling

Key Tasks:
(1) Determine the performance indicators to be checked with the inputs and the outputs of existing BEM tools

(2) Define the scope of the design tool and design the inputs and the outputs of the analysis method

(3) Develop and validate the analysis method of the tool

(4) Design and implement design tool with BIM capability

Figure 3-1-1. BIM-enabled Blue-Green Design Framework

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3.2 Key Tasks of Requirement Modeling
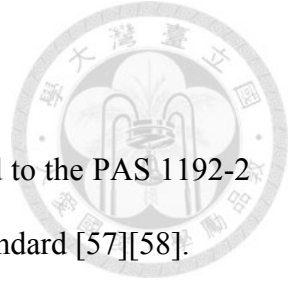
In this research, the workflow of the design process is referenced to the PAS 1192-2 document [56], which is the source of the incoming ISO 19650-1 standard [57][58].

In the beginning of a construction project which is the Strategy stage in the information delivery cycle [56] , the employer will formulate the project requirements into a Strategic Brief and an Employer Information Requirement (EIR) [42][56]. The Strategic Brief is a document written by employer to provide sufficient project information for consultant to study the feasibility of the project [59][60]. The EIR is a pre-tender document containing the information requirement towards the expected built assets of the construction project [56]. The suppliers will prepare a pre-contract Building Information Modeling Execution Plan (BEP) to demonstrate the proposed approach and the corresponding capability to fulfil the EIR [56]. After the suppliers reward the contract, they will prepare a post-contract BEP with a Master Information Delivery Plan (MIDP) to detailed defining how the suppliers and the supply chains deliver the project information [56]. In the Brief stage of the information delivery cycle, an initial Project Brief based on the Strategic Brief is coordinated by lead consultant or lead designer [61]. The Project Brief is the key document containing employer's requirement about the nature of the expected built asset [61][62]. In the Concept stage of the information delivery cycle, architect as lead designer will prepare a BIM project model, which is named Project Information Model in in the information delivery cycle [56] as an initial design response to the Project Brief [63]. The finalized Project Brief is formulated in the end of the Concept stage [61], and the BIM project model will be developed according to the Project Brief in the following stages.

In the requirement modeling, it focuses on the Concept stage in the information delivery cycle [56]. There are two modeling key tasks listed below:

(1) Identify the project requirements with the Blue-Green design

In preparing design response to the Project Brief, the sustainability targets of the project will be formulated. Design teams will review relevant international, national, and local sustainability policies to explore potential design options. The sustainability assessments such as LEED, BREEAM and Passivhaus can also be considered according to the Project Brief. With the above consideration and employer's business case, the project requirements related to the sustainability targets, which are related to the greenery or water system design, can be identified.

Besides, once there exists the previous design toolkits for similar Blue Green design project, the Blue-Green requirements can be formulated with these resources.
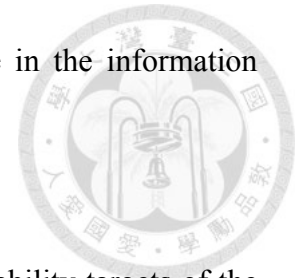
(2) Outline the potential measures of the Blue-Green design

For providing potential environmental services, there are potential services provided by the Blue measures or the Green measures [64]. The Blue measures could be water square, permeable pavement and rainwater tank. The Green measures could be green roofs, green shores and park. Each measure has advantage and disadvantage in different environmental aspect. In order to optimize the benefit of the design measures, the Blue-Green design concept is integrating the Blue measures and the Green measures in complementary way.

The scope of this framework is focusing on the design measures of building design. The Blue measures of building design could be water roof or rainwater tank. The Green measures of building design could be green roof or green wall. With the project requirements related to the Blue-Green design prepared, design teams can outline the combination of the Blue measures and the Green measures to evaluate design alternatives to fulfil the project requirements. The output of the requirement modeling are the Blue-Green requirements including the project requirements related to the Blue-Green design, the outlined Blue measures, and the outlined Green measures.

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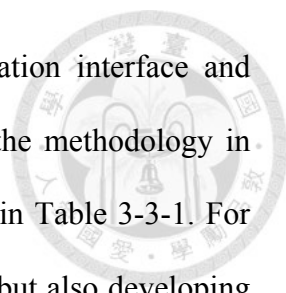
3.3 Key Tasks of Process Modeling

With the Blue-Green requirements prepared, a workflow manual is needed to describe the collaboration interface and process. This research uses two concepts describing below to support the workflow manual.

In the building design process proposed in the Figure 3-2-2, it requires Common Data Environment (CDE) as a working environment to support design collaboration. There are four phases of CDE [65]. In the CDE, a lead designer of the project will coordinate the collaboration process [66]. The first task team is usually architect team. The architect team will form an initial BIM project model in the "Work in progress" folder. After the initial BIM project model is checked by the lead designer, it can be uploaded to "Shared" folder to be shared among the project teams. The rest task teams such as landscape architect team, structural engineer team, mechanical engineer team, electrical engineer team, and plumbing engineer team can reference the initial BIM project model as a foundation to develop the content of the model. The lead designer will also check, review and approve the coordinated models before it is uploaded to "Shared" folder. When it comes to the end of design stage or the project milestone, employer will authorize the BIM project model and the corresponding design documents to be published in "Published documentation" folder. Besides, the "Archive" folder is used to record the history data of the project information at each project milestone. The CDE is an iterative process repeating above steps.

For supporting the business requirement, there is an open data format of BIM model called Industry Foundation Class (IFC) [67] designed to support all the business requirement for all project stages. In general, it is feasible to exchange information under particular business requirement during design stage [68].

Therefore, Information Delivery Manual (IDM) is a document to support the BIM

use, and the project stakeholders can use to clarify the collaboration interface and process [69]. There are international standards [70][71] to define the methodology in formulating an IDM, and there are four components of IDM listed in Table 3-3-1. For the use of IDM is not only for supporting the business requirement but also developing the software solution, there exists barriers in mapping the relationship between Process Maps, Exchange Requirements, Functional Parts and Model View Definition (MVD) which is a is a subset of IFC for particular BIM use [72][73].

In order to apply the concept of CDE and IDM to formulate a workflow manual for the Blue-Green design, there are two modeling key tasks shown below.

(1) Clarify the expected workflow and information exchange for the design and analysis process

In modeling the design process, it requires experienced consultants or designers to outline the work items for the specific design stage. The requirement identification of the Blue-Green design, the use of the BIM element models of the Blue-Green design and the customized design tool should be considered as the work items. The corresponding workflow is composed by arranging the work items and relationship between each character in the project. The structure of the workflow is developed under CDE collaboration concept. Therefore, the information exchange is clarified according to the work items in the workflow.

(2) Document the information using Process Maps and Exchange Requirements

For taking the advantage of IDM methodology, Process Maps and Exchange Requirements are used to describe expected workflow and information exchange in formal document. In creating the Process Maps, the expected workflow is illustrated in Business Process Model and Notation (BPMN) [74] format. The Exchange Requirements is formulated according to the Process Maps. It is suggested to reference existing Process Maps and Exchange Requirements in published IDM to shorten this process of documentation. Because the process modeling only focuses on satisfying the business requirement, developing IFC compatible software solution is not considered. The outcome of the workflow manual is composed of Process Maps and Exchange Requirements.

Table 3-3-1. The primary components of IDM [68]

IDM elements	Descriptions
Process Maps	A process map describes the flow of activities within the boundary of a particular topic. The purpose of a process map is to gain an understanding of the configuration of activities that make it work, the actors involved, the information required, consumed and produced.
Exchange Requirements	An exchange requirement is a set of information that needs to be exchanged to support a particular business requirement at a particular stage of a project. Typically, for IDM as presently established, the set of information should be defined within the IFC model. However, the IDM approach will also work with sets of information defined within other industry standard models such as the Geographic Markup Language (GML) as defined by the Open Geospatial Consortium (OGC). An exchange requirement is intended to provide a description of the information in non-technical terms. The principal audience for an exchange requirement is the user (architect, engineer, constructor etc.). It should however also be used by the solution provider since it provides the key to the technical detail that enables the solution to be provided.
Functional Parts	A functional part is a unit of information, or a single information idea, used by solution providers to support an exchange requirement. A functional part describes the information in terms of the required capabilities of the industry standard information model upon which it is based. For IDM as presently established, the functional parts are based on versions of the IFC model. A functional part is fully described as an information model in its own right as well as being a subset of the information model on which it is based.
Concepts	A concept is a fragment of information that can be used in a functional part (where it is bound to a release of the IFC model) or to an exchange requirement (where it is expressed in generic terms). It can be used to capture the basic functionalities within a model such as naming, identification etc. A concept does not need to be simply related to a single entity or even to a whole entity. For instance, the concept of a software identifier simply describes how a globally unique identifier attribute is asserted for an entity.

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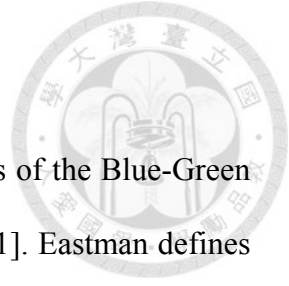
3.4 Key Tasks of System Modeling
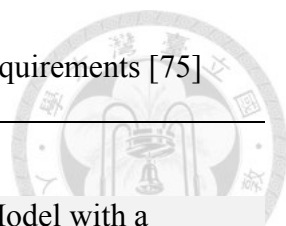
In the BIM-enabled Blue-Green design framework, the measures of the Blue-Green design are described in the form of BIM Object Models (BOMs) [11]. Eastman defines that BOMs are 2D and 3D geometrics representation of physical products. These products includes doors, windows, equipment, furniture, fixtures, walls, roofs, ceilings, floors and specific products. There are primary information content needs of BOMs listed in Table 3-4-1.

Table 3-4-1. The object specifications of BOMs [11]
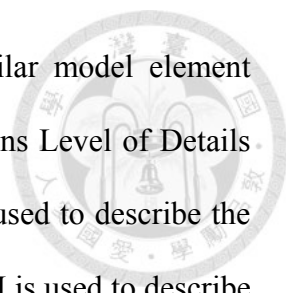
Information content
1   2D or 3D geometry (2D for carpeting, and film-like finishes)
2   Material representation, with name and model graphical finish (texture map)
3   Parametric geometry, if not fixed
4   Connection locations and requirements with other systems: electrical, plumbing, telecommunications, structural, airflow
5   Performance specifications, operating life, maintenance cycle, light transmittance, and other specs used in selection (varies by type of equipment)
6   Luminous Intensity Distribution Curve (for light fixtures)
7   Links to product distribution channels

In creating BOMs, the information content will change depending on design stage. In G202 document [75] published by the American Institute of Architects (AIA), there is a definition called Level of Development (LOD) describing the specific information content requirement and corresponding authorized uses for each model element. The meaning of "model elements" is similar to "BOMs" in the following content, and the general content requirements are listed in Table 3-4-2.

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Table 3-4-2. Level of development and model element content requirements [75]

LOD	Model Element Content Requirements
100	The Model Element may be graphically represented in the Model with a symbol or other generic representation, but does not satisfy the requirements for LOD 200. Information related to the Model Element (i.e. cost per square foot, tonnage of HVAC, etc.) can be derived from other Model Elements.
200	The Model Element is graphically represented within the Model as a generic system, object, or assembly with approximate quantities, size, shape, location, and orientation. Non-graphic information may also be attached to the Model Element.
300	The Model Element is graphically represented within the Model as a specific system, object or assembly in terms of quantity, size, shape, location, and orientation. Non-graphic information may also be attached to the Model Element.
350	The Model Element is graphically represented within the Model as a specific system, object, or assembly in terms of quantity, size, shape, location, orientation, and interfaces with other building systems. Non-graphic information may also be attached to the Model Element.
400	The Model Element is graphically represented within the Model as a specific system, object or assembly in terms of size, shape, location, quantity, and orientation with detailing, fabrication, assembly, and installation information. Non-graphic information may also be attached to the Model Element.
500	The Model Element is a field verified representation in terms of size, shape, location, quantity, and orientation. Non-graphic information may also be attached to the Model Elements.

Aside from the LOD definition from the US, there is a similar model element definition from the UK. The Level of Definition (LOD/LOI) contains Level of Details (LOD) and Level of Information (LOI) [76][77]. The LOD here is used to describe the level of geometric detail including 2D and 3D geometry, and the LOI is used to describe the level of required information according to design stage. The Level of Development (LOD) from the US is generic and flexible, and the Level of Definition (LOD/LOI) from the UK is more feasible in implementation aspect. It is suggested to consider both definition in creating model elements.

In this research, the term of "BIM element models" is used to represent the meaning of "BOMs" or "model elements" for maintaining the naming consistency. In modeling the BIM element models of the Blue-Green design, it is composed of blue (water) measures and green (greenery) measures. There are five modeling key tasks proposed.

(1) Collect required product information

Information modeling is the first step of the system modeling. For the product information is the source for information content of BIM element model such as Table 3-4-1, it is suggested to collect the product information as complete as possible. Once there is lack of information in particular area, the reference information collected from similar product cases can be used to replace the missing information. With reference to the Blue-Green requirements and the workflow manual prepared in previous paragraph, the information needed for the Blue-Green design can be outlined. Also, the LOD specification document [78] and NBS BIM toolkit [79] website are official resources contained BIM element model definitions mentioned above. For these resources provide the descriptions of specific BIM element model toward corresponding authorized uses, it indicates the descriptions of suitable information contained in BIM element model as reference for selecting needed product information. On the basis of above

considerations, the selected product information is prepared for creating the BIM element models of the Blue-Green design to convey design intent.

(2) Decide appropriate behavior of BIM element model

The process to model the behavior of BIM element model is to decide how BIM element model updates itself when its content is changed [11]. In general, BIM platform has built-in behavior defining the relationship that BIM element model adjusts itself with related BIM element models or parameters automatically. In modeling the behavior of BIM element model, it is suggested to consider the potential BIM uses. For example, Kuo [80] presented BIM-based energy analysis for BIPV building. When BIM project model of the BIPV Experiment Demonstration House is transferred to gbXML format [81] which is data schema used for energy analysis software, the BIM element model of BIPV module is not transferred to this format for interoperability issue. As a result, the BIM project model used for energy analysis could be different to the model used for construction coordination even in the same project. For there is no only guidance in creating BIM project model, it depends on the purpose of BIM use to choose suitable approach to model building elements. Designer can either choose BIM element model template of specific built-in type to create BIM element model with existing product, or use generic BIM element model template to create new BIM element model with customized parametric behavior.

(3) Create geometry of BIM element model

In modeling the geometry of the Blue measures and Green measures, the major concern is to make BIM element model in simple shape but maintain the functionality. Modeling approaches such as Constructive Solid Geometry (CSG) [82] can be used for geometry modeling. The feature of CSG is to enable modeler using Boolean operators to combine simple 3D objects into overall 3D model. It is suggested to maintain the

quantity of 3D objects and the polygons as minimum as possible. The graphical loading of computing device could be reduced when BIM element models are loaded into BIM project model.
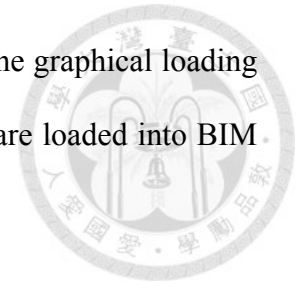
(4) Set parametric configuration of BIM element model

There are three aspects in parametric modeling. One is to set product information to parameters of BIM element model. The other one is to set constrain parameters to control geometry of BIM element model. The rest one is to set parameters according to the formula combined with information parameters or constrain parameters. The relationship created between parameters and geometry is used to design building model with versatility.

(5) Assemble BIM element models as whole system

In general, the BIM element models of the Blue measures and Green measures are created in different categories. It is required to encapsulate two kind of BIM element models as a whole system package and the parametric relationship between the Blue measures and Green measures is needed to be created. The implementation for above modeling key tasks are varied according to the feature of selected BIM platform. Therefore, the integrated BIM element models are prepared to represent the solution of the Blue-Green design.
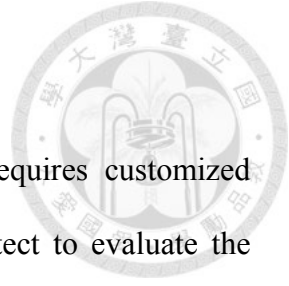
3.5 Key Tasks of Performance Modeling

In modeling the performance of the Blue-Green design, it requires customized design tool with building performance analysis function for architect to evaluate the design alternatives. There are three key tasks proposed here.

(1) Determine the performance indicators to be checked with the inputs and the outputs of existing BEM tools
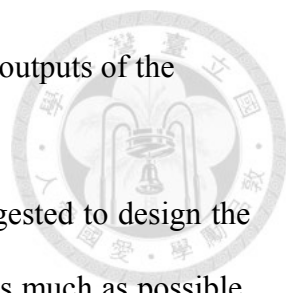
The first step is to determine the expected performance indicators of the Blue-Green design according to the Blue-Green requirements. The performance indicators and the corresponding analysis methods could be derived from urban planning policy, building regulation or self-developed calculation method.

Once the performance indicators are chosen, these indicators can be compared with the inputs and the outputs of existing BEM tools listed in Figure 3-5-1[54]. While the indicators can satisfy part of the Blue-Green requirements but not being listed in the outputs of existing BEM tools, it is recommended to implement the corresponding analysis method. In the other hand, there are circumstances that the indicators listed in the outputs of existing BEM tools worth implementing the analysis methods. Once the outputs of the BEM tools require sophisticated inputs and the indicators can aid in reducing the scope of the design variable, it is also recommended to implement the analysis method with fewer inputs to have perform instant analysis.

	eQuest	EcoDesigner	Tas V8i	Green Building Studio	Ecotect	Hevacom Simulator V8i	DesignBuilder	Visual DOE 4.0	EnergyPlus	Energy 10	IES VE	HEED
Conceptual Design												
Building geometry	■	■	■	■	■	■	■	■	■	■	■	■
Building orientation	■	■	■	■	■	■	■	■	■	■	■	■
Weather file	■	■	■	■	■	■	■	■	■	■	■	■
Building envelope constructions	■	■	■	■	■	■	■	■	■	■	■	■
HVAC type	■	■	■	■	■	■	■	■	■	■	■	■
Building type / function	■	■	■	■	■	■	■	■	■	■	■	■
Design Development												
Glazing type	■	■		■	■	■	■	■	■	■	■	■
Lighting power density	■	■		■	■	■	■	■	■	■	■	■
Equipment power density				■	■	■	■	■	■	■	■	■
Occupancy schedule	■					■		■	■	■		■
Lighting schedule	■					■		■	■	■		■
Equipment schedule	■					■		■	■	■		■
Fuel type	■	■			■				■	■	■	■
Operable windows	■	■	■		■		■		■	■	■	
Operable window schedule	■	■			■		■		■	■	■	
System energy efficiency	■	■			■				■	■	■	
Albedo (roof reflectance)	■				■				■	■	■	
User-defined glazing specifications	■	■	■		■	■	■	■	■		■	
User-defined envelope construction layers / properties	■	■	■		■	■	■	■	■		■	
Construction Documents												
MEP BIM model		■					■		■			
Water efficient fixtures	■								■			
HVAC component sizings		■	■				■		■		■	
Construction and Contracting												
Customizable occupancy schedule	■				■			■	■	■		
Customizable lighting schedule	■				■				■			
Customizable equipment schedule	■				■				■			
Plant Data		■	■			■		■	■	■		
HVAC fan power	■		■	■		■		■	■		■	
Required interior design temperatures	■		■		■		■		■		■	
Facility Management												
Energy costs	■		■	■	■		■		■		■	■
Outputs (as required by user)												
Energy analysis	■	■	■	■	■	■	■	■	■	■	■	■
Daylighting analysis		■	■	■	■	■	■	■	■	■	■	■
Natural ventilation analysis	■	■	■	■	■	■	■	■	■	■	■	■
Passive energy potential	■	■		■	■	■	■		■	■	■	■
LEED credit assistance			■	■	■			■		■	■	■
Design alternative				■					■		■	■
Carbon emissions	■	■		■	■		■	■	■		■	■
Resource management				■	■						■	
Thermal analysis	■	■	■	■	■	■	■	■	■	■	■	■
Heating / cooling load breakdown	■	■	■	■	■	■	■	■	■	■	■	■
Solar analysis	■			■	■		■		■	■	■	■
Electric lighting design		■			■			■		■	■	
Lifecycle cost analysis	■	■		■	■		■	■	■	■	■	■
Water usage	■	■		■	■			■				

Figure 3-5-1. The inputs and outputs of the BEM tools (extracted from [54])

(2) Define the scope of the design tool and design the inputs and the outputs of the

analysis method

The scope of the design tool should be well defined. It is suggested to design the

inputs of the analysis method collected from BIM project model as much as possible.

The outputs of the analysis method are the performance indicators in general.

(3) Develop and validate the analysis method of the tool

The analysis method is required to be developed and validated before published as

the core of the design tool. In case that analysis method is referenced from existing

literature, it is only needed to validate the consistency between analysis method and

implementation.

(4) Design and implement design tool with BIM capability

In designing the software architecture of the design tool, the design tool can be

formulated in different forms such as plug-in toolkit, standard software or web

service depending on different situations. Concerning that the interoperability issue

between BIM platform and BEM tools may result in rework, it is better to seek a

holistic approach to formulated the design tool. For example, Schlueter and

Thesseling [83] create an energy analysis tool using Revit Application Programming

Interface (API) to directly extract design data from BIM project model. In the other

way, Negendahl [84] reviews about building performance simulation in the early

design stage. The review paper suggests using visual programming language as

middleware to exchange and maintain consistent design data between design tool and

building performance simulation environment. Based on this suggestion, it is

applicable to take a step forward to use visual programming language in creating the

design tool with building performance analysis.

In order to determine the pros and cons between programming using BIM

platform API and programming using visual programming language, Table 3-5-1 [85] which focuses on Autodesk solutions can be referenced to show the features of both approaches. In Table 3-5-1, Revit macro represents programming using BIM platform API and Dynamo script represents programming using visual programming language. Revit Macro can provide higher efficiency in software runtime, but it is hard to be modified while Revit Macro is compiled. Dynamo provides visual programming environment for user to manipulate design data intuitively, and Dynamo script can be modified or extended with high flexibility. Considering shortening the development cycle of the design tool and maintaining flexibility in modification, this research proposes using visual programming language in implementing the analysis method.

For the design tool are used to satisfy the Blue-Green requirements and improve the nature of design performance, the outputs of the analysis method can be used to form the Blue-Green design in the BIM project model with the BIM element models prepared previously. This function can be implemented using the behaviors of the BIM element models. Therefore, the design tool can be used to connect the analysis results into design content.

Table 3-5-1. The strengths and the weaknesses of both Dynamo and Revit Macro

(modified from [85])
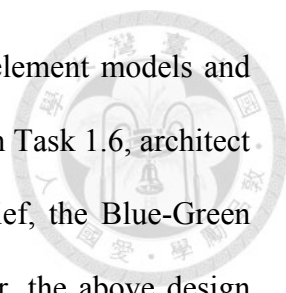
	Dynamo script	Revit macro
Fast to create	5	2
Runs Fast	2	5
Ease of Use	3	5
Ease to Modify	5	2
Few Users	5	4
Lots of Users	2	5

Note: Excellent (5) / Very Good (4) / Good (3) / Fair (2) / Poor (1)

4. Implementation of BIM-enabled Blue-Green Design Framework

In order to demonstrate the implementation of BIM-enabled Blue-Green design framework, this study presents modeling approaches in early design stage. The proposed design process is shown in Figure 4-1, which is illustrated using BPMN. There are tasks listed with index from 1.1 to 2.5 in the design process. The design iterations from Task 1.1 to 1.7 are described as design process of Brief stage under CDE, and the design iterations from Task 2.1 to 2.5 are described as design process of Concept Design stage under CDE. In general cases, design teams could be architect team, structural engineer team, mechanical engineer team, electrical engineer team, plumbing engineer team and sustainability consultant team. This proposed design process is a simplified case focusing on architect team and sustainability consultant team to emphasize the major activities of the Blue-Green design process.

When design team of architect gets contract of the project, they start to prepare initial project brief (Task 1.1 Conduct Preparation and Brief). The implementation of the requirement modeling and the process modeling can be conducted according to the initial project brief in Preparation and Brief stage (Task 1.2 Conduct Requirement Modeling, 1.3 Conduct Process Modeling). Blue-Green requirements and List of Blue-Green Design Exchange Requirement are the outputs of Task 1.2 & Task 1.3. The Exchange Requirement abbreviated as ER in Figure 4-1 is the required information to be exchanged between stakeholders. With water tank product information, green roof product information, Blue-Green requirements, List of Blue-Green Design ER presented as Appendix 2 and the workflow manual, sustainability consultant team can conduct system modeling (Task 1.4 Conduct System Modeling). Along with the Task 1.4, sustainability consultant team can reference the inputs and outputs of the BEM tools to create design tool with proposed analysis method (Task 1.5 Conduct Performance

Modeling). The output of the Task 1.4 to Task 1.5 contains BIM element models and customized Blue-Green design tool prepared for next design stage. In Task 1.6, architect team submits design data to employer. With the initial project brief, the Blue-Green requirements and the workflow manual are authorized by employer, the above design data can be published and archived as the output of design stage milestone (Task 1.7 Publish and Archive Design Report). After Task 1.7, the design process moves to the Concept Design stage and design teams start to create the BIM project model as initial respond to the initial project brief (Task 2.1 Conduct Concept Design). In Task 2.2, architect team uses the BIM project model to conduct the Blue-Green design. With the BIM element models of water tank and green roof are loaded in the BIM project model, the process of Blue-Green analysis and design can be conducted with customized design tool. After architect analyzes and designs the BIM project model, sustainability consultant team will review the BIM project model according to the Results of Blue-Green Design Exchange Requirement (Task 2.3 Review Blue-Green Design Results) along with design iterations.

The design iteration is a continuous collaboration process of design optimization. Once the design results are accepted among design teams, the prepared design data of the Concept Design will be reviewed by employer (Task 2.4 Prepare Design Data). The design data including the BIM project model containing Blue-Green measures, final project brief, preliminary cost information and project strategies will be published and archived in the end of the Concept Design stage (Task 2.5 Publish and Archive Design Report). Then, the design stage moves to Developed Design stage. The following paragraphs present the content of the BIM enabled Blue-Green design framework (Task 1.2 Conduct Requirement Modeling, 1.3 Conduct Process Modeling, Task 1.4 Conduct System Modeling, and Task 1.5 Conduct Performance Modeling).
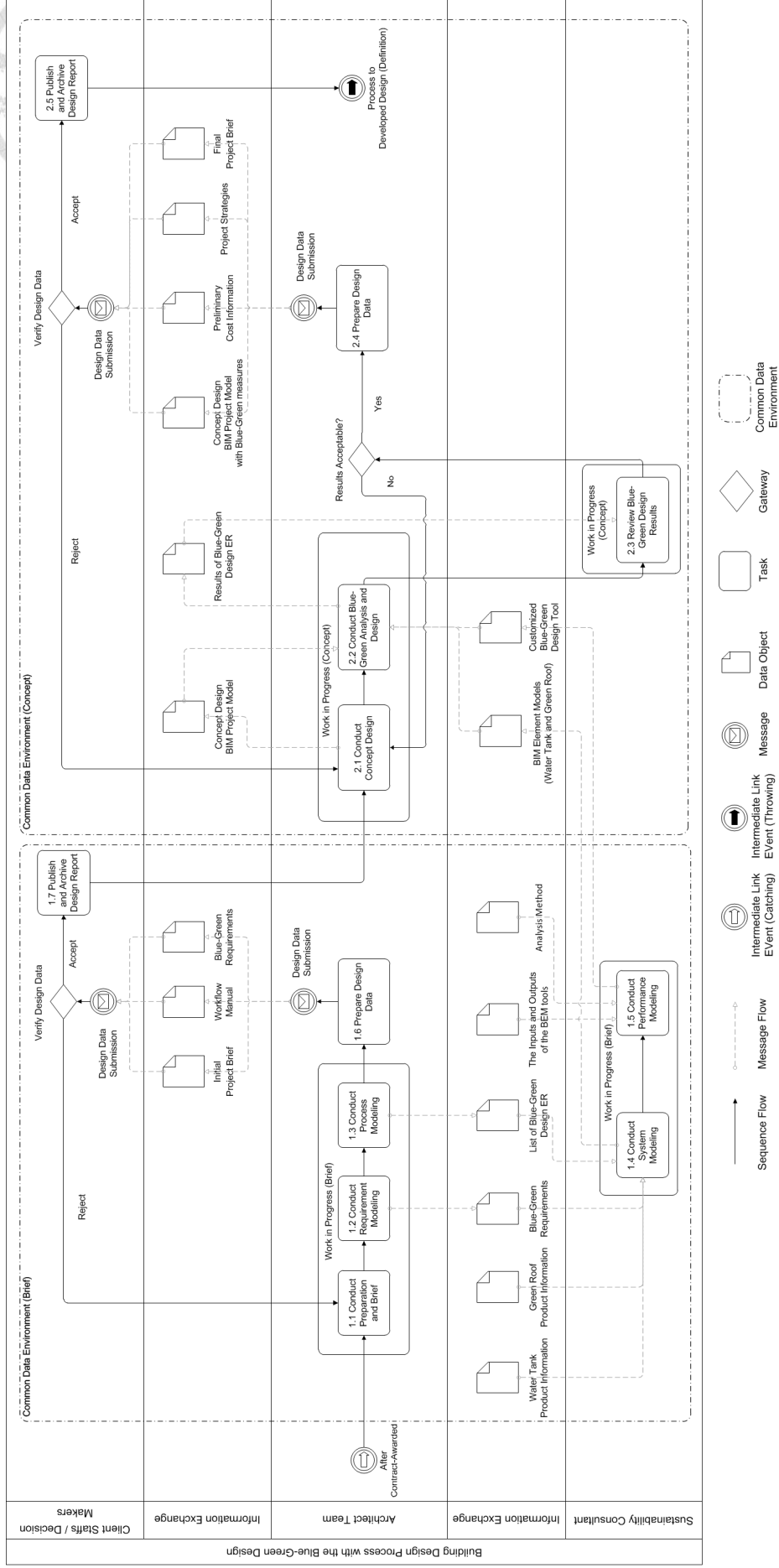
Figure 4-1. Process map for BIM-enabled Blue-Green design in early design stage

4.1 Requirement Modeling for Case Study

In Task 1.2, the purpose of the requirement modeling is creating the Blue-Green requirements containing the project requirements related to the Blue-Green design and the potential measures of the Blue-Green design. The key tasks of the requirement modeling are as follows:

(1) Identify the project requirements with the Blue-Green design

The practical project requirements are varied from project to project. There exists urban development principles of Low Impact Development (LID) [86] for water system and Biotope Area Factor (BAF) approach [15] for greenery system. In this research, it is assumed that the project requirements contain principles of LID and energy usage reduction are two major concerns. It requires that BIM project model can fulfil the minimum requirement of LID guide and the proposed green roof system with best thermal performance can be selected among available products.

The LID methodology is referenced from Taiwan's Construction and Planning Agency [86]. The calculation of LID indicator is used to size the area of greenery system and the capability of water system. The energy usage reduction is expected to be improved with better thermal performance of greenery system around building envelope.

(2) Outline the potential measures of the Blue-Green design

In order to implement the solution of the BIM-enabled Blue-Green design framework, water tank and green roof are chosen as case study of the Blue-Green design. The design of combining green roof with water tank can be used to increase the volume of water retention for LID indicator. The green roof system on top of the building can provide better insulation for improving thermal performance.
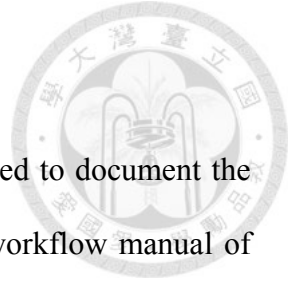
4.2 Process Modeling for Case Study

In Task 1.3, the following key tasks of process modeling are used to document the information of the design process as workflow manual. Once the workflow manual of the Blue-Green design is prepared with the Process Map and the Exchange Requirements, it could be used by design teams to describe and clarify the collaboration interface and process.

(1) Clarify the expected workflow and information exchange for the design and analysis process.

In this research, the scope of design process is from Preparation and Brief (Brief) stage to Concept Design (Concept) stage. The structure of design process and information exchange are referenced from PAS 1192-2 document [56] and RIBA plan of Work [59].

(2) Document the information using Process Maps and Exchange Requirements

The workflow manual contains Process Maps and Exchange Requirements. To document the design process, the methodology of BPMN [74] is used to illustrate the Process Map. The Process Map of the Blue-Green design process (See Figure 4-1) is developed with reference to the design process mentioned above and the Process Map proposed by Kuo et al. [87]. The concept of CDE is also embedded in the Process Map. There are expanded sub-processes named "Work in Progress" which performs the same action in CDE. The lane of information exchange can be recognized as "Shared" folder of CDE. In addition, the process to be "Publish" and "Archive" design data is the process of CDE. The Exchange Requirements of the workflow manual is "ER Blue-Green design results" shown in Figure 4-1. The content of the Exchange Requirements (See Appendix 2) is referenced from the inputs and the outs of the customized design tool and the Information delivery manual for building energy analysis [88].

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4.3 System Modeling for Case Study
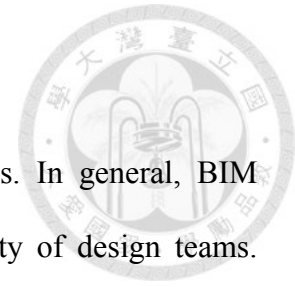
In Task 1.4, it is the process to create BIM element models. In general, BIM platform should be selected according to the technology capability of design teams. Concerning choosing BIM platform software for the system modeling in this research, there is National BIM Report 2016 [89] showing the most popular drawing tools of architecture, engineering and construction professionals in UK. The result indicates that Autodesk Revit occupied 31%, Graphisoft ArchiCAD occupied 19% and Nemetschek Vectorworks occupied 15%. Furthermore, a survey using Google Trend service shows the popularity of BIM platform software in past five years (See Figure 4-3-1). In this survey, there are five BIM platform software listed in BIM handbook. The vertical axis of Figure 4-3-1 represents the search interest for that software [90].
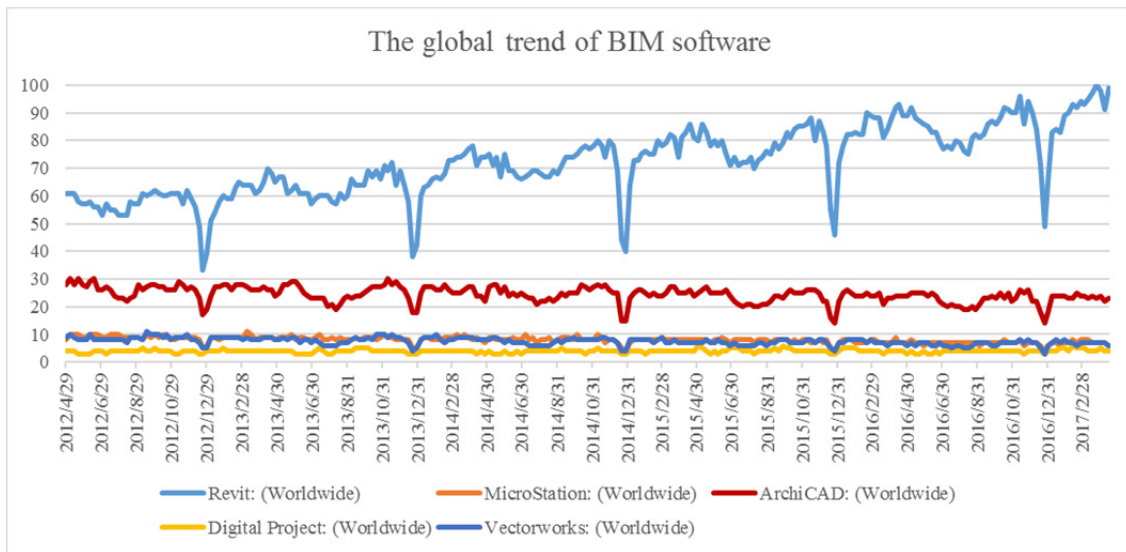
Figure 4-3-1. The global trend of BIM software [91]

For modeling the measures of the Blue-Green design, Autodesk Revit 2017 [92] is selected as BIM platform according to above survey results. In implementing BIM element models, selecting appropriate type of template as a basis to create BIM element model is important for the usability. The BIM element model of Autodesk Revit is called family [93][94]. There are three types of families listing in Table 4-3-1 [95].

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Table 4-3-1. Three Types of Revit family [95]

Family type	Description
System Families	System families create basic elements which could be assembled on a construction site such as walls, roofs, floors, ducts and pipes.
Loadable Families	Loadable families are families used to create the following: Building components that would usually be purchased, delivered, and installed in and around a building; some annotation elements that are routinely customized, such as symbols and title blocks.
In-Place Families	In-place elements are unique elements that user creates in need to create a unique component that is specific to the current project

In modeling green roof and water tank, the first step is to check the design stage and the corresponding requirement of BIM element model. The design stage of this research is focusing on Concept Design stage. For checking design requirement of the BIM project model, Table 3-4-2 can be used to have an overview on it. Since the description of LOD in AIA G202 document [75] dose not tightly couple LOD with specific design stage, the applicable scenario could be LOD 100 to 200. In this scenario, the BIM element models could be visualized in 2D symbol or 3D generic model. There are further descriptions close to the BIM element models of green roof and water tank in LOD specification [78] listing in Table 4-3-2. In general, the size, the shape and the location of the BIM element models should be modelled. The parameters of design performance could be attached to the BIM element models. Besides, the description of roofing does not exactly fit the design requirement of extensive green roof. The information about Level of Definition for extensive green roof is listing in Table 4-3-3.

Table 4-3-2. Level of Development of BIM element model with the Blue-Green design [78]

Elements	LOD 100	LOD 200
Roofing	Solid mass model representing overall building volume; or, schematic wall elements that are not distinguishable by type or material. Assembly depth/thickness and locations still flexible.	Generic assembly that contains spatial (layer) allowance for structural slab/deck and/or framing system.
Stormwater Drainage Equipment	Diagrammatic or schematic model elements; conceptual and/or schematic layout;	Schematic layout with approximate size, shape, and location of equipment; approximate access/code clearance requirements modelled;
Stormwater Drainage Piping	Diagrammatic or schematic model elements; conceptual and/or schematic layout/flow diagram; design performance parameters as defined in the BIM execution plan to be associated with model elements as non-graphic information.	Schematic layout with approximate size, shape, and location of mains and risers; shaft requirements modelled;
Facility Stormwater Drains	Diagrammatic or schematic model elements; conceptual and/or schematic layout/flow diagram; design performance parameters as defined in the BIM execution plan to be associated with model elements as non-graphic information.	Schematic layout with approximate size, shape, and location of components;

Table 4-3-3. Level of Definition of extensive green roof system [96]

Level of Definition	Description for Concept Design stage
Level of Detail	1. Requirement: Graphical representation of element, dimensionally inaccurate. 2. Purpose of information: To provide a visual indication of proposals at a Concept stage identifying key requirements such as access and maintenance zones etc. Information to be suitable for spatial coordination of primary systems / elements.
Level of Information	To provide an outline description of the deliverable. It provides the type of object to detail any design intent.

With above preparation, the process to create the BIM element models could be initiated. The detail of modeling process is shown in following paragraph:

a. Blue Measure Modeling – Water Tank

(1) Collect required product information

According to the requirements of the Blue-Green design and Table 4-3-2, the information needed for creating the BIM element model of water tank is shown as follows:

● The size and the shape of water tank

● The water storage capacity of water tank

● The weight of water tank

For the usage of BIM element model of water tank is to help architect design Blue-Green system, the above information will be encapsulated in BIM element model with parametric relationship between parameter and geometry.
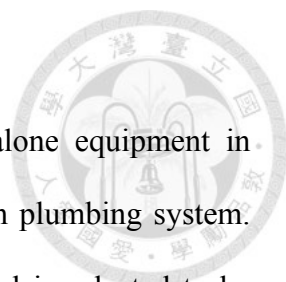
(2) Decide appropriate behavior of BIM element model

Concerning the feature of water tank, it could be a standalone equipment in installing the product. Also, water tank should be connected with plumbing system. Therefore, the family category of water tank BIM element model is selected to be plumbing fixtures and designed as loadable family in Revit.

(3) Create geometry of BIM element model

In modeling the size and shape of water tank, it is created with reference to existing water tank. In this research, the BIM element model of water tank is collected and modified from BIM element model website [97] as basic model to be further developed (See Figure 4-3-2). The major modeling approach of this BIM element model is to revolve a 2D section around the vertical axis to create model mass such as the body of water tank.
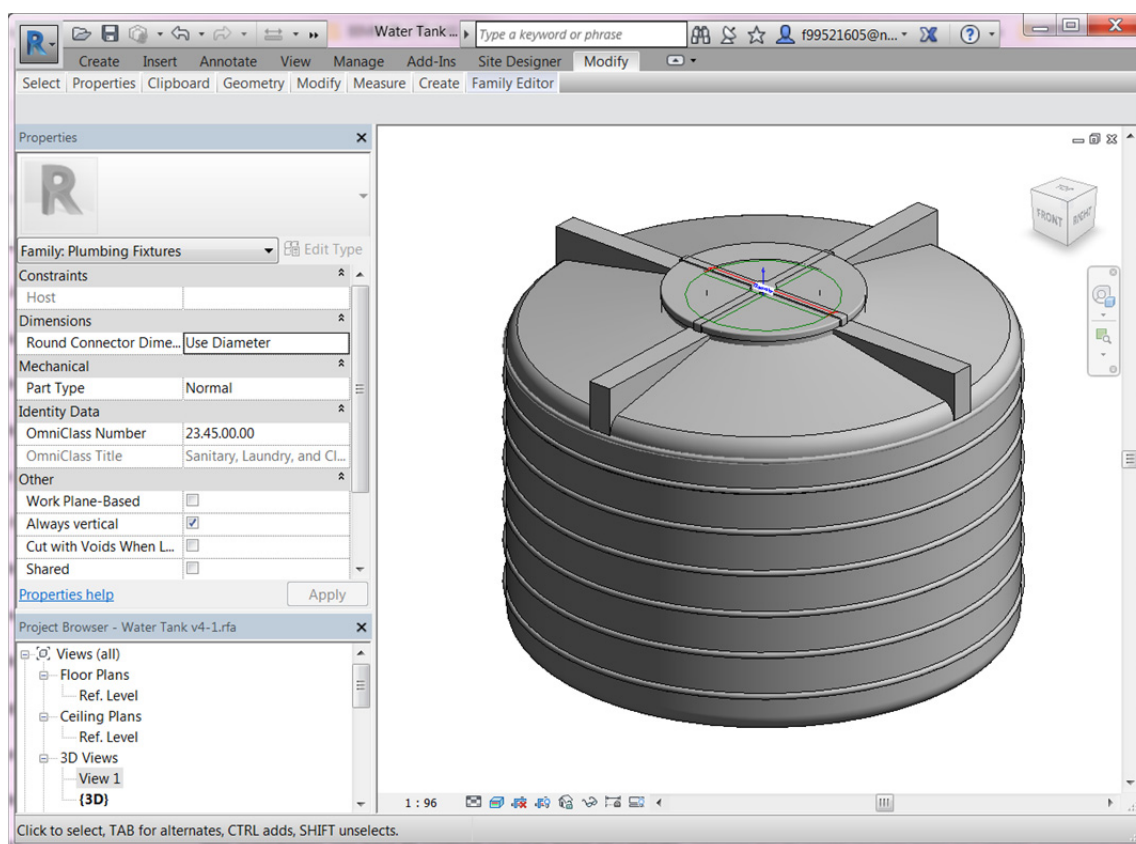
Figure 4-3-2. Revit family of water tank (modified from [97])

(4) Set parametric configuration of BIM element model

The design behavior of BIM element model is expected to be controlled and changed parametrically. Before the parameters are designed in the BIM element model, the Pipe Connector [98] which is used to connect piping system is placed on the top of water tank model (See Figure 4-3-2). Therefore, the BIM element model of water tank can be parametrically connected as part of building plumbing system in BIM project model.

There are two kinds of parameters designed in the BIM element model. One is used to constraint model geometry called constraint parameter, and the other one is used to design the content of model called design parameter in this paragraph. The constraint relationship between model geometry and reference plane is connected with parameters of family. The constraint parameters are created as instance parameter to be connected with existing constraint relationship in water tank model (See Figure 4-3-3). Therefore, the constraint parameters could be used to control the geometry of model. Besides constraint parameters, the design parameters are designed according to the combination of each parameters.

In modeling the water storage capacity of water tank, the calculation formula is designed according to the shape of water tank. It is assume that the water volume is composed of the summary volume of three truncated cones and one cylinder (See Figure 4-3-4), and this assumption is modeling in the calculation formula of design parameter called *Maximum water volume*. Concerning creating the parametric relationship between model geometry and product specification, the design parameter called *Designed water volume* is created to approximate *Maximum water volume* and control model geometry.
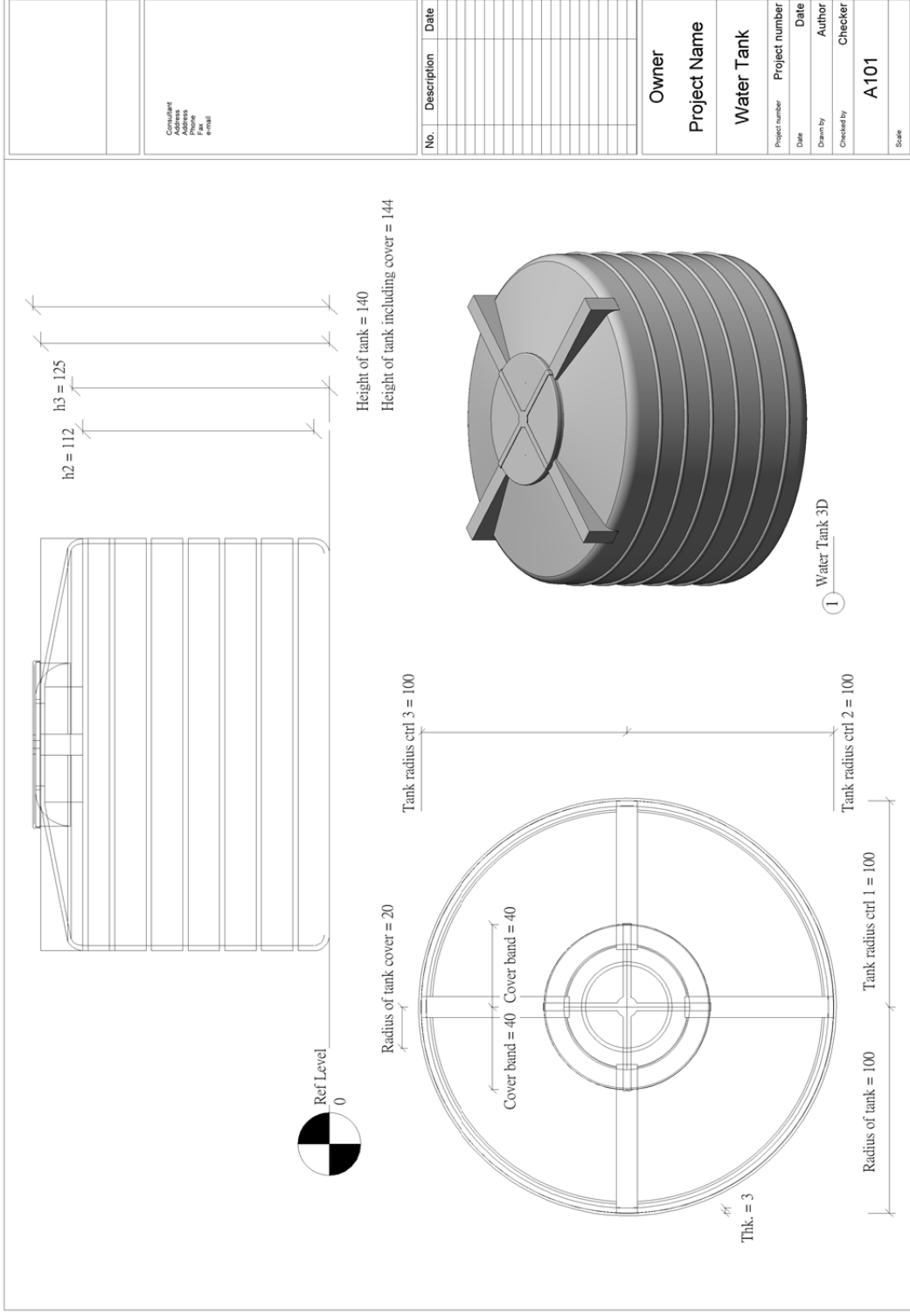
Figure 4-3-3. The section view (left) and top view (right) of water tank BIM element model (modified from [97])

The calculation formula of *Designed water volume* is assumed as single cylinder, and radius of this cylinder is *Radius of tank* which is constraint parameter. In designing the parametric relationship between *Designed water volume* and *Radius of tank*, the calculation formula is configured in the formula column of *Radius of tank* to reference *Designed water volume* as formula parameter. Therefore, designer can change the value of *Designed water volume* and trigger the transformation of model geometry instantly. The behavior of model transformation is only focused on changing the model radius, and the rest dimensions such as height of water tank are fixed.

In modeling the weight of water tank, *Weight of full water tank* is the design parameter contain *Designed water volume* and *Water tank envelope volume* to represent the specification. *Water tank envelope volume* is modelled as larger *Maximum water volume* to minus original one. The calculation formula of weight of water tank is composed of each volume multiplied with corresponding density. The overall parameters are shown in Figure 4-3-5.
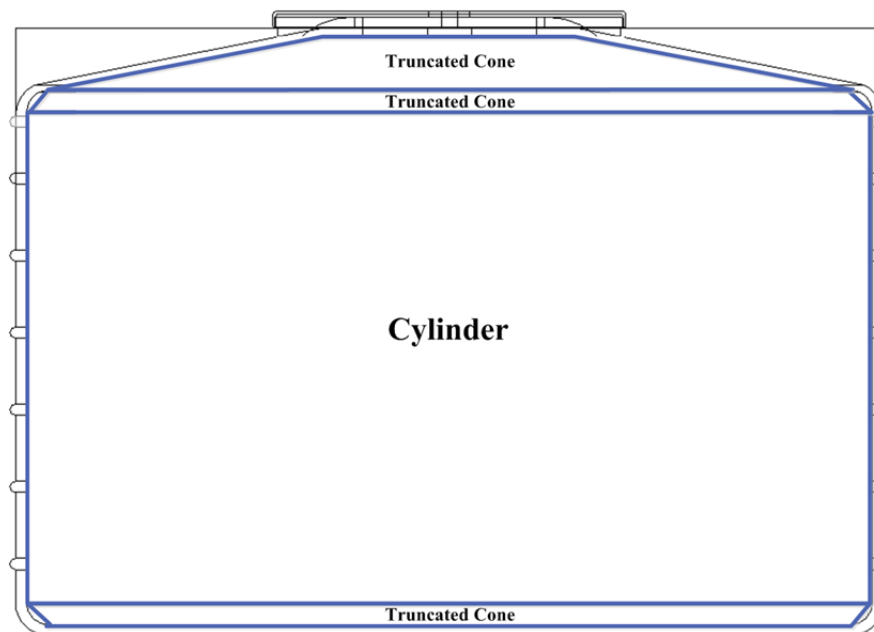
Figure 4-3-4. Modeling water volume of water tank

Family Types

Type name: Water Tank Design Model

Search parameters

Parameter	Value	Formula
Graphics		
Materials and Finishes		
hilltake tank	Plastic	=
Plumbing		
Dimensions		
Radius of tank (default)	100.04	=sqrt(Designed water vol. / ((h1 / 6 + h3) * pi0)) + Thk.
Tank radius ctrl 1 (default)	100.04	=Radius of tank
Tank radius ctrl 2 (default)	100.04	=Radius of tank
Tank radius ctrl 3 (default)	100.04	=Radius of tank
Thk. (default)	2.54	=2.54 cm
Height of tank (default)	140.00	=140 cm
Height of tank including cover (default)	143.81	=143.81 cm
Cover band (default)	40.00	=40 cm
Radius of tank cover (default)	20.00	=20 cm
h1 (default)	12.82	=12.82 cm
h2 (default)	112.06	=112.06 cm
h3 (default)	124.76	=124.76 cm
r1 (default)	29.40	=29.4 cm
r2 (default)	91.90	=Radius of tank - r3 - Thk.
r3 (default)	5.60	=5.6 cm
Mechanical		
General		
Designed water vol. (default)	3.790	=
Maximum water vol. (default)	3.824	=2 * (pi0 / 3) * r3 * ((r2 + r3) ^ 2 + (2) ^ 2 + r2 * (r2 + r3)) + h2 * pi0 * (r2 + r3) ^ 2 + (pi0 / 3) * h1 * ((2) ^ 2 + (r1) ^ 2 + r2 * (r1))
Water density (default)	1000.000000	=1000 kg/m³
Water tank envelope vol. (default)	0.286	=2 * (pi0 / 3) * r3 * ((r2 + r3 + Thk.) ^ 2 + (r2 + Thk.) ^ 2 + (r2 + r3 + Thk.) * (r2 + Thk.)) + (h2 + Thk.) * pi0 * (r2 + r3 + Thk.) ^ 2 + (pi0 / 3) * h1 * ((r2 + Thk.) ^ 2 + (r1 + Thk.) ^ 2 + (r2 + Thk.) * (r1 + Thk.)) - Maximum water vol.
Water tank envelope density (default)	1290.000000	=1290 kg/m³
Wt. of full water tank (default)	4159.069 kg	=Water tank envelope density * Water tank envelope vol. + Water density * Designed water vol.

How do I manage family types?

Manage Lookup Tables

OK   Cancel   Apply

Figure 4-3-5. Parameters of water tank

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b. Green Measure Modeling – Green Roof

(1) Collect required product information

According to the requirements of the Blue-Green design, Table 4-3-2 and Table 4-3-3, the information needed for creating the BIM element model of green roof is shown as follows:

- The size of green roof and the depth of each layer

- The thermal properties of green roof

- The weight of green roof

(2) Decide appropriate behavior of BIM element model

Concerning the feature of green roof, it could be an individual facility to be placed on the top of original roof or a part of composite roof structure. Therefore, there are two kind of modeling approaches to be considered to create green roof model. One is modeling as a loadable family, and other one is modeling as a system family. Hsu *et al*. [32] created green roof BIM element models using these two modeling approaches and made comparison results shown in Table 4-3-4.

According to the results, the BIM element model created as system family can be modeling along building envelope with built-in modeling behavior. Compared to loadable family approach, the computing loading in real-time modeling is optimized by Revit engine. Besides, the thermal properties can be imported layer-by-layer in roof system family. It is convenient to manage material data. In BIM-based energy analysis process, system family can be transferred to gbXML format. It is suggested to model green roof using system family as part of building envelope to reduce potential interoperability problem in design stage. Therefore, the family category of green roof BIM element model is selected to be roof category and designed as system family in Revit.

Table 4-3-4. Green roof modeling approach comparison [99]

Modeling approach	Loadable Family	System Family
Free form modeling	It can be used as tiles to cover the expected green roof area. It is not applicable to fitting a curved surface without reforming the model.	This is a system family with built-in model behavior, so it can be reformed using system built-in modeling behavior.
Information importing by layer	Parameters of each green roof layer can be configured as parameters of the whole BIM element model.	Green roof information can be imported by layer.
Layer control	Layers cannot be changed without modification of the original model structure.	Layers can be added or deleted.
Model display	Model can be created in high polygon and displayed with detailed geometry representation and texture.	Model appearance is shown without layer texture.
Memory usage	Heavy	Light
Model sharing	Loadable family model can be saved in family format (.rfa) and can be loaded directly into different projects.	System family model cannot be loaded into templates and projects, but it can be copied and pasted among projects.
Applicable Scenario	Model can be used for display.	Model can be used for analysis.

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(3) Create geometry of BIM element model

In modeling the size of green roof, it is the design content arranged by designer during design stage and it can be achieved by using Revit built-in behavior of roof system family. In modeling the depth of each green roof layer, it is created with reference to existing green roof. In this research, the BIM element models of green roof are collected and modified from 15 BIM library websites [100] (See Figure 4-3-6). In order to make each case comparable, the settings of the structure layers for all cases are assigned to the same concrete material with 20 cm thickness.
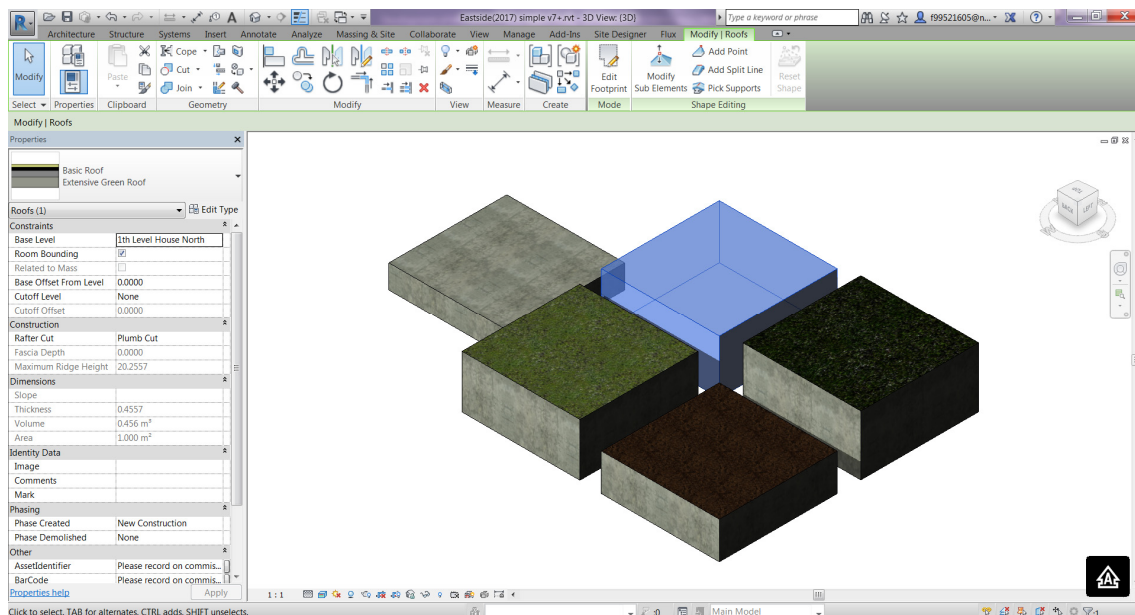
Figure 4-3-6. Four BIM element model types of green roof and concrete roof

(4) Set parametric configuration of BIM element model

In modeling the thermal properties of green roof, it required the product information provided by manufacturer. The BIM element models of green roof collected contains thermal properties. For some layers of green roof assigned with wrong material, it is corrected by assigning corresponding materials from the Revit built-in material library (See Appendix 1). In modeling the weight of green roof, the unit weight can be calculated according to physical properties of green roof.

c. Assemble BIM element models as whole system

In order to use the BIM element models of the Blue-Green design in the BIM project model, it is required to make two kind of BIM element model as a package. The water tank BIM element model is created in loadable family, but the green roof BIM element model is created in system family which cannot be directly loaded into project. Therefore, the solution is to load the water tank BIM element model to the Revit project file containing the green roof BIM element model. Then, the BIM element model of drain [97] can be collected from website to be placed on the green roof BIM element model. With use of the piping function in Revit under "Plumbing & Piping" classification, the elements of the water tank and the drain can be connected using "Flex Pipe" shown in Figure 4-3-7. The Revit project file with these BIM element models is an integrated package. When user open the BIM project model file and the package file at the same time, and user can select all the BIM element models using "Copy to Clipboard" function in the package file and use "Paste from Clipboard" in the BIM project model file. As a result, the integrated package can be applied to different BIM project model to be used without the limitation of model category.
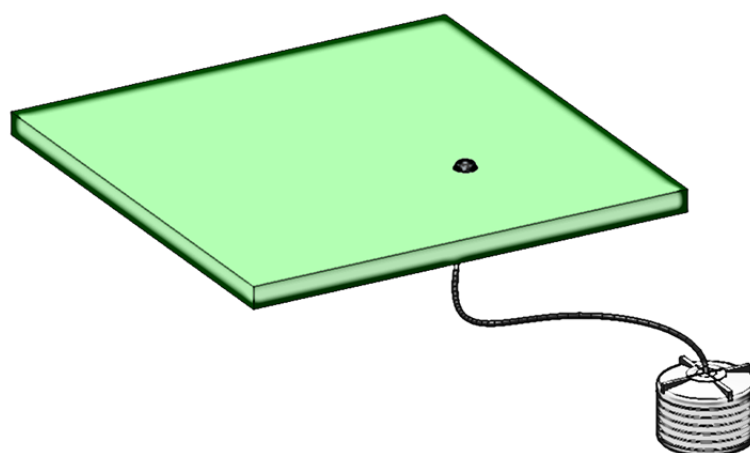
Figure 4-3-7. The BIM element models containing the green roof and the water tank

4.4 Performance Modeling for Case Study

In Task 1.5, the purpose of performance modeling is creating customized design tool for the Blue-Green design. Concerning there are two kind of sub-systems in the Blue-Green design, it requires analysis functions to evaluate the performance of the sub-systems and design functions to integrate the sub-systems as whole system according to the analysis results. The following paragraphs show the implementation of a design tool containing analysis functions. In this design tool, two analysis functions are implemented for green roof and water tank. Low Impact Development (LID) [86] analysis function is used to size the green roof and water tank. Thermal analysis function is used to evaluate the thermal performance of green roof.

4.4.1 Development of Low Impact Development Analysis Function

(1) Determine the performance indicators to be checked with the inputs and the outputs
    of existing BEM tools

For the size of green roof and water tank is related to the ability of collecting water, the calculation of water retention is selected as an indicator of the analysis function. There is a concept called LID [86] to reduce the impact of land development by optimizing water conservation. Thus, the idea of LID can be connected to the implementation of the Blue-Green design. The method to calculate water retention comes from the operation manual for Low Impact Development facility [101] published by Taiwan's Construction and Planning Agency in Ministry of the Interior.

By looking up the inputs and outputs of the BEM tools (See Figure 3-5-1), it is shown that water efficient fixtures and water usage are two factors related to water aspect. Therefore, the calculation method of water retention is not implemented in the mainstream BEM tools. The method is called LID analysis in the following paragraph.

(2) Define the scope of the design tool and design the inputs and the outputs of the
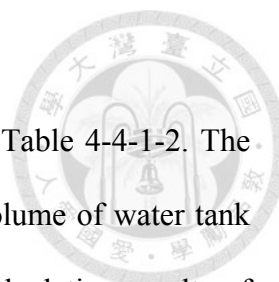
analysis method

The scope of the proposed design tool is aimed to help architect designing green roof and water tank according to the official analysis method and the thermal performance analysis in Concept Design stage. The LID analysis function is proposed to analyze the required water retention of the project site to size the green roof and water tank. The assumption of this research to use the LID analysis method is that green roof and water tank are the first priority of the LID facility design.

Input Data

The input variables of the LID analysis method are shown in Table 4-4-1-1. The input variable such as the project site area A and the designed green roof area A_{gr} can be collected from BIM model. The required water retention depth of the project site S_d is referenced from Table 4-4-1-3. The default value of the unit water retention capability of green roof GR_c, water tank WT_c and permeable pavements PP_c are defined according to the operation manual [101].

Table 4-4-1-1. Input variables of the LID analysis method

Input type	Input variable	Description	Unit	Default Value
1. The inputs are extracted from BIM model.	A	The project site area	m^2	-
	A_{gr}	The designed green roof area	m^2	-
2. The inputs are default value.	S_d	The required water retention depth of the project site	m	(See Table 4-4-1-3)
	GR_c	The unit water retention capability of green roof	m^3/m^2	0.3 [101]
	WT_c	The unit water retention capability of water tank	m^3/m^3	1 [101]
	PP_c	The unit water retention capability of permeable pavements	m^3/m^2	0.075 [101]

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Output Data

The output variables of the LID analysis method are shown in Table 4-4-1-2. The volume of water retention SE is the LID indicator. The designed volume of water tank V_{wt} and the designed area of permeable pavements A_{pp} are the calculation results of LID analysis method.

Table 4-4-1-2. Output variables of the LID analysis method

Input variable	Description	Unit
SE	The volume of water retention (LID indicator)	m^3
V_{wt}	The designed volume of water tank	m^3
A_{pp}	The designed area of permeable pavements	m^2

(3) Develop and validate the analysis method of the tool

For the development and the validation of the LID analysis method is conducted by the research project of the Ministry of the Interior [85], this research focuses on the implementation of the LID analysis method. With defining $\sum_{i=1}^{n} LV_i$ as the total amount of the volume of water retention collected by each LID facility to fulfil the requirement of the project site, the formula of the LID analysis method is referenced from the operation manual [101] as follows:

$$SE = \sum_{i=1}^{n} LV_i \geq S_d \times A \tag{1}$$

Concerning the LID facilities listed in Table 4-4-1-3, there are two kinds of design requirements. The LID design using bio-retention cell, tree box filters, green roof, grass swales or permeable pavements is required to fulfil the 80% of the required water retention depth of the project site. Besides, there is no requirement on LID design of water tank, infiltration well or infiltration gutter.

In calculating the formula, it is required to define the land use of the project to obtain the required water retention depth S_d (See Table 4-4-1-3). To multiply S_d with the project site area, the required volume of water retention for the project site is

obtained. Then, the area of green roof A_{gr} can defined by architect. To multiply A_{gr} with GR_c , the volume of water retention contributed by green roof is obtained. Once the design of green roof cannot fulfil the 80% of the water retention for the project site, the design of permeable pavements are used to compensate the rest difference in the 80% of the volume of water retention ($A_{gr} \times GR_c + A_{pp} \times PP_c = S_d \times A \times 80\%$). In the end, the 20% of the water retention for the project site is satisfied by the design of water tank ($V_{wt} \times WT_c = S_d \times A \times 20\%$). Therefore, the formula of the LID analysis is:

$$SE = \sum_{i=1}^{n} LV_i = A_{gr} \times GR_c + A_{pp} \times PP_c + V_{wt} \times WT_c \geq S_d \times A \qquad (2)$$

Table 4-4-1-3. The required water retention depth of the project site with LID [101]

| Land Use		Housing district	Business district (Others)	Business district (No.4/No.5)	Industrial district
		Required water retention depth			
LID water retention capability analysis		6.0 cm	5.0 cm	4.0 cm	5.0 cm
LID facility	Bio-retention Cell				
	Tree Box Filters				
	Green Roof	4.8 cm (>=80%)	4.0 cm (>=80%)	3.2 cm (>=80%)	4.0 cm (>=80%)
	Grass Swales				
	Permeable Pavements				
	Water tank Infiltration Well/ Infiltration Gutter	(There is no required water retention depth for these facilities)			
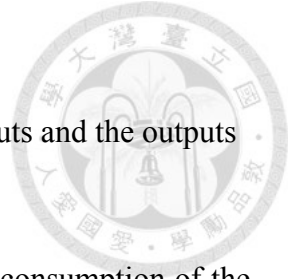
4.4.2 Development of Thermal Analysis Function

(1) Determine the performance indicators to be checked with the inputs and the outputs

of existing BEM tools

The thermal performance of the green roof affects the energy consumption of the whole building. Therefore, the thermal performance such as temperature or heat-flux can be indicators to design green roof. With reference to the inputs and outputs of the BEM tools (See Figure 3-5-1), there are some inputs (albedo, user-defined envelop construction properties and plant data) and outputs (energy analysis, thermal analysis and) related to the thermal analysis of green roof. Although there exist BEM tool with thermal analysis function, the cost to transfer BIM model into BEM tool is still high due to interoperability issue. This research implements a thermal analysis function to help architect evaluating the thermal performance of green roof without spending much efforts on transferring model.

(2) Define the scope of the design tool and design the inputs and the outputs of the

analysis method

The core of the thermal analysis function in design tool is the physical model of the thermal behavior. Because there is a green roof module [102] in EnergyPlus with plenty of laboratory parameters, this research focused on developing efficient thermal models with physical parameters provided by the manufacturer that can be extracted from the BIM element model. In addition, unlike the detailed energy modeling in EnergyPlus, the thermal model should perform simple thermal functions to simulate design performance rapidly.

The thermal models in this study are developed in a multi-paradigm numerical computing environment - MATLAB [103]. Two thermal models are implemented. The thermal model using the finite difference method is used to validate the
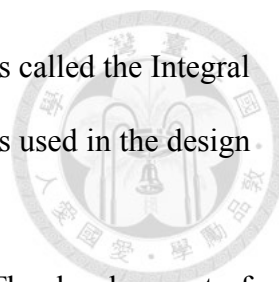
performance of the thermal model developed in this study, which is called the Integral Model. After validation of the thermal model, the Integral Model is used in the design tool.

The thermal model of a roof is described in Figure 4-4-2-1. The development of the thermal model in the following paragraph is referenced from Kuo *et al*. [104] and the major contribution is made by Mr. Ivo Suter and Dr. Maarten van Reeuwijk. The thickness of the roof is *d*, and *z* is unit length from the bottom of the roof to the top of the roof. The heat flux of solar radiation is divided into shortwave radiation $S_\downarrow$ and longwave radiation $L_\downarrow$. The longwave radiation transmitted from the roof to the air is $L_\uparrow$. Besides, the roof has the sensible heat flux *H* and the evaporative flux *E* from roof to air. The value of *H* could be negative when the heat flux is transferred from air to roof. ϕ_b is the heat flux into the building. T_s is the surface temperature of the roof. T_a is the temperature function of time, which represents atmospheric temperature. $T(z,t)$ is the temperature function of time within the roof at a height of *z*. T_b is the temperature of the building, which is fixed in this research.

$$\left(\rho c_p\right)_e \frac{\partial T}{\partial t} = \lambda_e \frac{\partial^2 T}{\partial z^2}$$
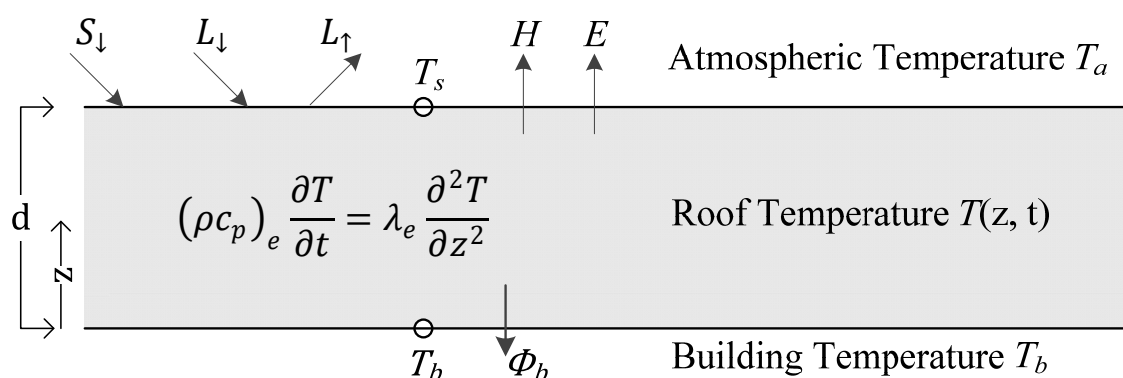
Figure 4-4-2-1. Roof profile and the thermal model

Governing Equation Assumption:

The thermal model assumptions are as follows:

1. Roof materials, which include plants and soil, are treated as a single homogeneous material.

2. The heat transferred within the roof is diffused vertically, and horizontal heat transport is not considered in this study.

3. Chemical reactions and physical factors of the green roof material resulting in heat transfer are ignored.

For developing the thermal model, it is assumed that the heat transfer of the roof can be modelled using the heat diffusion equation. The heat diffusion equation is supposed to have a T function to model temperature change with time through the roof structure. The heat transfer through the roof can be described with

$$\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial z^2} \tag{3}$$

where $T(z, t)$ is the roof profile temperature, κ is thermal diffusivity, z is unit length of roof depth, and t is time. Therefore, the major issue of the roof model is to solve the heat diffusion equation, which is a one-dimensional partial differential equation.

Concerning that green roof is composed of multi-layer, the properties of the green roof are calculated as effective values in the equations. Substitute equation (3) with equation (4), the heat equation (5) is obtained with the effective thermal conductivity λ_e and the effective volumetric heat capacity $(\rho c_p)_e$.
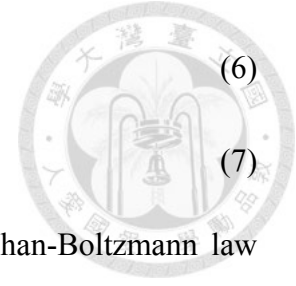
$$\kappa_e = \frac{\lambda_e}{(\rho c_p)_e} \tag{4}$$

$$(\rho c_p)_e \frac{\partial T}{\partial t} = \lambda_e \frac{\partial^2 T}{\partial z^2} \tag{5}$$

Therefore, the boundary condition of the roof bottom and the rooftop can be denoted in equation (6) and equation (7).

$$\lambda_e \frac{\partial T}{\partial z}(0, t) = \phi_b \tag{6}$$

$$\lambda_e \frac{\partial T}{\partial z}(d, t) = S_\downarrow + L_\downarrow - L_\uparrow - H - E \tag{7}$$

In equation (7), longwave radiation is denoted using the Stephan-Boltzmann law with parameters such as the emissivity ε and the Stefan-Boltzmann σ [105]. The sensible heat flux H is modeled using convective heat transfer coefficient h [105] and the evaporative flux E is modeled with the Bowen ratio $Bo = H/E$ [106]. As a result, the equation (7) can be written in equation (8).

$$\lambda_e \frac{\partial T}{\partial z}(d, t) = S_\downarrow + \varepsilon\sigma T_a^4 - \varepsilon\sigma T_s^4 - \left(1 + \frac{1}{Bo}\right)h(T_s - T_a) \tag{8}$$

Input Data

The input variables of the Integral Model are shown in Table 4-4-2-1. In addition, the value used for validating the Integral Model are referenced from the physical properties and listed in the table.

Table 4-4-2-1. Input variables of the thermal model

Input type	Input variable	Description	Unit	Value used for validation
1. The inputs are extracted and calculated from BIM model.	d	Roof thickness	m	0.05-1
	R	Thermal resistance	$(m^2 \cdot K)/W$	0.11-2.22
	λ_e	Thermal conductivity	$W/(m \cdot K)$	0.45
	$(\rho c_p)_e$	Volumetric specific heat capacity	$J/(m^3 \cdot K)$	2.43×10^6
	κ_e	Thermal diffusivity	m^2/s	1.85×10^{-7}
2. The inputs are default value.	h	Convective heat transfer coefficient	$W/(m^2 \cdot K)$	16
	ε	Emissivity	-	0.85
	α	Albedo	-	0.4
	Bo	Bowen ratio	-	2
	T_b	Building temperature	K	295
3. The inputs are extracted from weather data.	$S_\downarrow$	Shortwave radiation	W/m^2	(Equation (11))
	T_a	Atmospheric temperature	K	(Equation (12))

The input variable such as roof thickness d, thermal conductivity λ_e, volumetric specific heat capacity $(\rho c_p)_e$, and thermal diffusivity κ_e are designed to be collected from BIM model. The roof thickness d and the thermal resistance R can be directly extracted from the green roof BIM element model. With using the equation (9), the thermal conductivity λ_e can be obtained.

$$R = \frac{d}{\lambda_e} \tag{9}$$

For the volumetric specific heat capacity $(\rho c_p)_e$, it can be calculated according to the thermal properties of each green roof layer. Assuming that the green roof is composed of n layers with d_i and $(\rho c_p)_i$, $(\rho c_p)_e$ can be obtained with equation (10). After the thermal conductivity λ_e and the volumetric specific heat capacity $(\rho c_p)_e$ are prepared, the thermal diffusivity κ_e will be calculated using equation (4). The input variable such as convective heat transfer coefficient h, emissivity ε, albedo α, Bowen ratio Bo and building temperature T_b are default value in the design tool. The rest input variable such as air temperature and shortwave radiation are collected according to the weather data of the project site.

$$(\rho c_p)_e = \frac{\sum_{i=1}^{n} d_i (\rho c_p)_i}{d} \tag{10}$$

For validation the thermal model, the values of the input variables are referenced from the physical properties. Concerning that heat transfer process is driven by time-varying atmospheric forcings, an idealized forcing strategy [107] is applied in the validation. The shortwave radiation $S_\downarrow$ and the atmospheric temperature T_a will be described using sinusoidal functions. Assuming that the shortwave radiation $S_\downarrow$ is zero during nighttime, it is defined using positive part of sinusoidal function in equation (11). For setting the variables, $S_{\downarrow,0}$ is $700 \frac{W}{m^2}$ and ω is angular frequency in rad/s.

$$S_\downarrow(t) = (1 - \alpha) \max\left(S_{\downarrow,0} \sin(\omega t) + \frac{S_{\downarrow,0}}{2}, 0\right) \tag{11}$$

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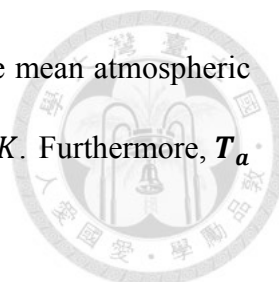
The atmospheric temperature T_a is defined in equation (12). The mean atmospheric temperature $\overline{T}_a$ is $298K$ and the daily temperature variation $\widehat{T}_a$ is $5K$. Furthermore, T_a is assumed that there is three hours time-lag compared to $S_\downarrow$.

$$T_a(t) = \overline{T}_a + \widehat{T}_a \sin(\omega(t - 3h)) \tag{12}$$

Output Data

The output variables of the Integral Model are shown in Table 4-4-2-2. The surface temperature T_s and the average temperature inside the wall T_w are used to indicate the temperature profile of the green roofs. Besides, the heat-flux into the building ϕ_b is an indicator to show the quantity of heat-flux to be transmitted into the building.

Table 4-4-2-2. Output variables of the thermal model

Input variable	Description	Unit
T_s	Surface temperature	K
T_w	Average temperature	K
ϕ_b	Heat-flux into the building	W/m^2

(3) Develop and validate the analysis method of the tool

This research develops the Integral Model, which is a trinomial function to analyze roof performance. The other one is the finite difference method. With the initial condition and boundary conditions, solution can be obtained. The solution of the Integral Model will be compared with the solution of the finite difference method to conduct validation (See Fig. 4-4-2-2).
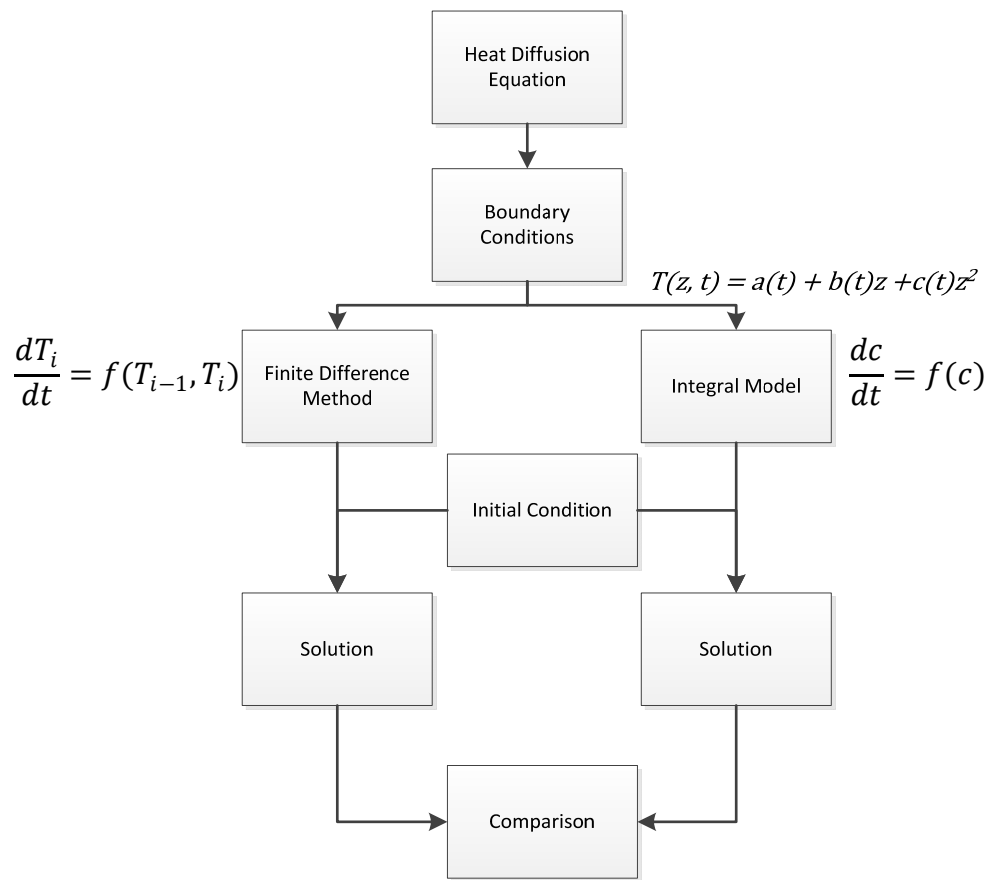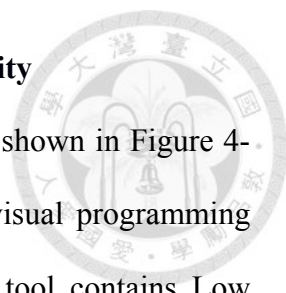

Figure 4-4-2-2. Developing and validation process

4.4.3 Development of Blue-Green Design Tool with BIM Capability

The system design of a BIM-enabled Blue-Green design tool is shown in Figure 4-4-3-1. In this research, the BIM platform and the corresponding visual programming environment are Revit 2017 and Dynamo 1.3 [108]. The design tool contains Low Impact Development analysis function and thermal analysis function. The implementation of the design tool is a set of Dynamo scripts with external library resources. The Dynamo scripts contains following customized nodes: LID Analysis Node, Green Roof Filter Node, Data Processing Node, Weather Data Processing Node, Green Roof Thermal Analysis Engine Node, Design Respond Nodes and Excel Output Nodes. The terms of "node" is an operation object of Dynamo to form a visual program. The built-in nodes preform basic Dynamo functions. The customized nodes are formulated with a group of built-in nodes and scripts to perform specific functions. Besides, the external library resources are Green Roof Thermal Performance Chart Library (dynamic link library, dll) and Integral Model (Matlab script). The methodology of Low Impact Development analysis is implemented in the LID Analysis Node, and the methodology of thermal model is implemented in a Matlab script.
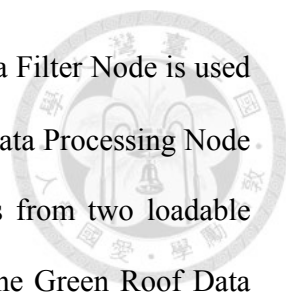
When launching the design tool, the input interface of the design tool shows up for user to assign related information for the LID Analysis Node. After the results of the LID analysis are obtained, a windows form pop up to display the results. Once user accepts the results, the process move to the Data Processing Node and the Green Roof Filter Node to collect the thermal properties of green roof in the BIM project model. At the same time, The Weather Data Processing Node is activated to extract weather data of project site. The thermal properties of green roof and the weather data are the input to the Green Roof Thermal Analysis Engine Node to call external library resources for thermal analysis. In order to conduct thermal analysis, the Green Roof Thermal

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Analysis Engine Node calls the Integral Model through the Green Roof Thermal Performance Chart Library with Matlab API. The thermal analysis results are displayed in the green roof thermal analysis chart. User can select preferred type of green roof listed in the chart. Then, the Design Respond Nodes collect LID analysis results to modify the properties of the BIM element model of water tank and uses the type of green roof to create the BIM element model of green roof with assigned area. The design data could be exported in Excel format using the Excel Output Nodes.

There are different concerns in implementation the design tool. In order to have an input interface for user, a download package called data-shapes [109] is used in LID Analysis Node. The inputs are "Land Use", "Site Area", "Floor Area", "GR Area", "GR Level", "Water Tank" and "File Paths" (See Table 4-4-3-1). The "Land Use" is used to select the corresponding parameters of the LID analysis. The "Site Area" and the "Floor Area" are used to calculate building coverage ratio and floor area ratio. The "GR Area" and the "GR Level" are used to create preferred green roof. The "Water Tank" is used to assign the BIM element model used of water tank to be designed. The "File Paths" is used to assign the file path of the excel file for data record.

Table 4-4-3-1. The variables of the user input of the design tool

Input variable	Description	Unit	Input Type
Land Use	The input is used to assign required water retention depth of the project site.	n/a	Drop-down list with user defined default value
Site Area	The total area of the project site. User should select corresponding topography object in Revit.	m^2	Revit element selection
Floor Area	The floor area of the BIM project model.	m^2	Revit face selection
GR Area	The designed green roof area.	m^2	Revit face selection
GR Level	The designed green roof elevation.	n/a	Drop-down list with elements of Levels category
Water Tank	The BIM element model used of water tank.	n/a	Revit element selection
File Path	The file path of the excel file to output data.	string	File path

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For filtering multiple model elements as a list, the Green Roof Data Filter Node is used to filter thermal properties data of single BIM element model and the Data Processing Node is used to process data with a for-loop script. The customized nodes from two loadable packages called SteamNodes [110] and Lunchbox [111] are used in the Green Roof Data Filter Node to filter the thermal properties in the material layers of BIM element model. For obtaining the weather data of the project site, the Weather Data Processing Node is established to extract solar radiation and environmental temperature from Autodesk database [112]. For conducting the thermal analysis, the Python script in the Green Roof Thermal Analysis Engine Node calls the Integral Model using Matlab API through the Green Roof Thermal Performance Chart Library. The Green Roof Thermal Performance Chart Library written in C# using .Net framework contains a Data Handler and Windows Form to deal with windows form event of the Green Roof Thermal Performance Chart. For implementing the design respond in BIM platform according to the analysis results, the Design Respond Nodes collect the design decision to modify the properties of the selected BIM element model of water tank. The modified property is the designed volume of water tank. In addition, a new BIM element model of green roof can be created with selected roof type, designed roof area and roof elevation. For the record function, the Excel Output Nodes are created with built-in nodes to export data as excel file. The overall system architecture of BIM-enabled Blue-Green design tool is shown in Figure 4-4-3-1, and the layout of the design tool is presented in Figure 4-4-3-2.
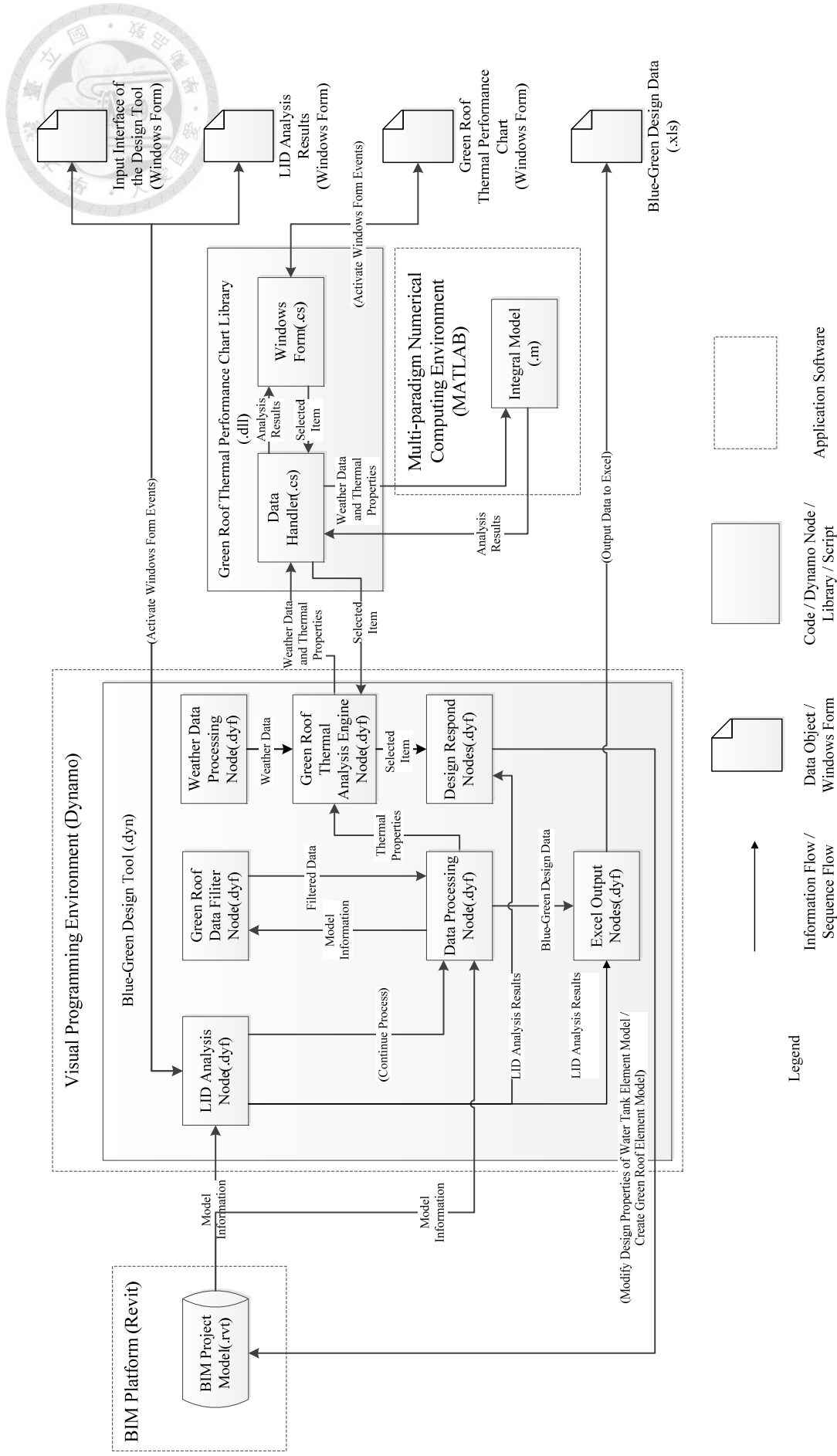
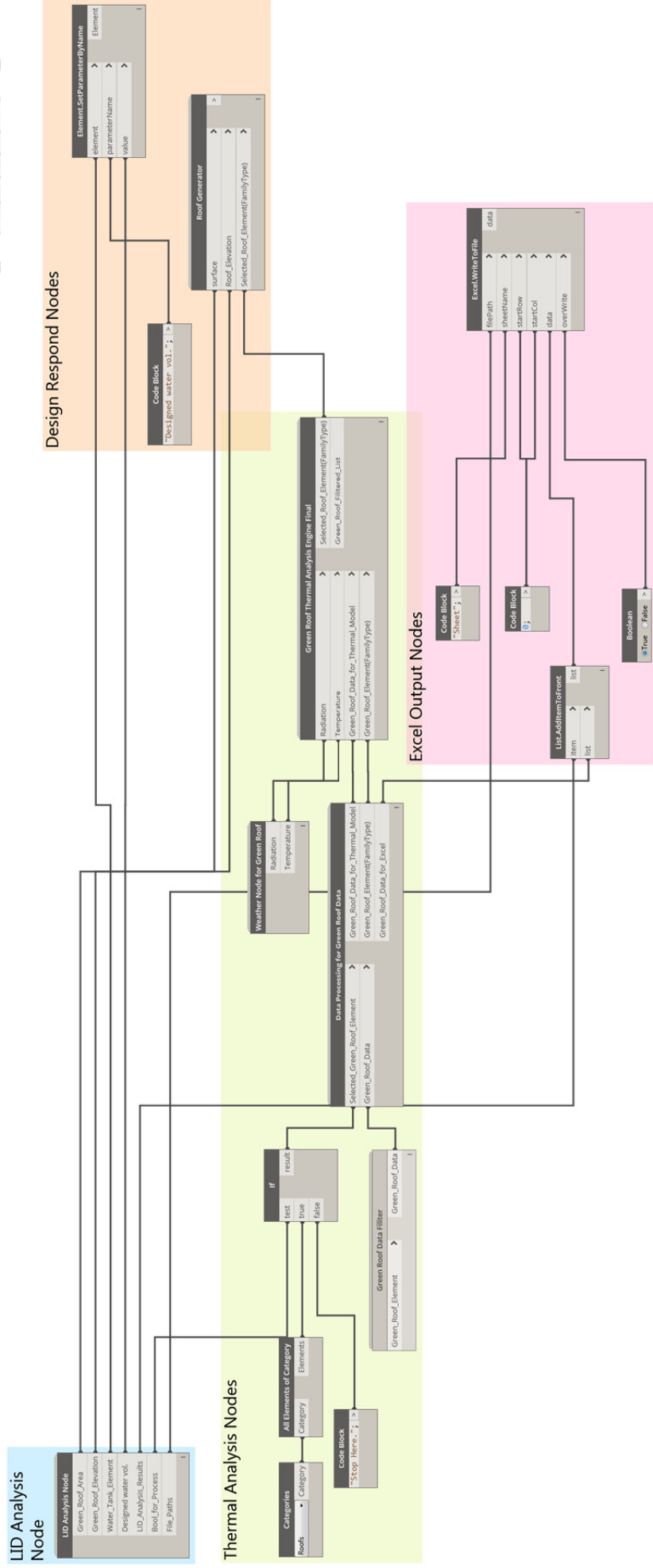Figure 4-4-3-1. System architecture of BIM-enabled Blue-Green design tool

Figure 4-4-3-2. Dynamo script layout of BIM-enabled Blue-Green design tool

5. Demonstration and Expert Interview

5.1 Demonstration using Scenario Study

In order to demonstrate a design process with design toolkits of the BIM-enabled Blue-Green design framework prepared in previous chapter, the following paragraph presents the procedure of Task 2.1 Conduct Concept Design and Task 2.2 Conduct Blue-Green Design and Analysis. A campus building of National Taiwan University (See Figure 5-1-1) is used for scenario study. The Civil Engineering Research Building (CERB), which belongs to the department of civil engineering, is a nine-story building with one basement floor. For the design scenario is in the Concept Design stage, the architect identifies the project requirements with the Blue-Green design and propose green roof with water tank combined design as principal measure of the Blue-Green design.

Figure 5-1-1. Case study - Civil Engineering Research Building and its BIM model.

The building mass model of CERB is created using Conceptual Mass function in Revit, and the project site area is created using Topography function in the same software. The mass floor is configured with reference to the information collected from shop drawings. The setting of project location, orientation and weather station is configured in the BIM platform. For preparing the analysis and design process, the

integrated package contained green roof and water tank BIM element models is required to be used in the building mass model (See Figure 5-1-2). The other BIM element models of green roofs collected from the BIM library websites are also applied to the building mass model for thermal analysis.
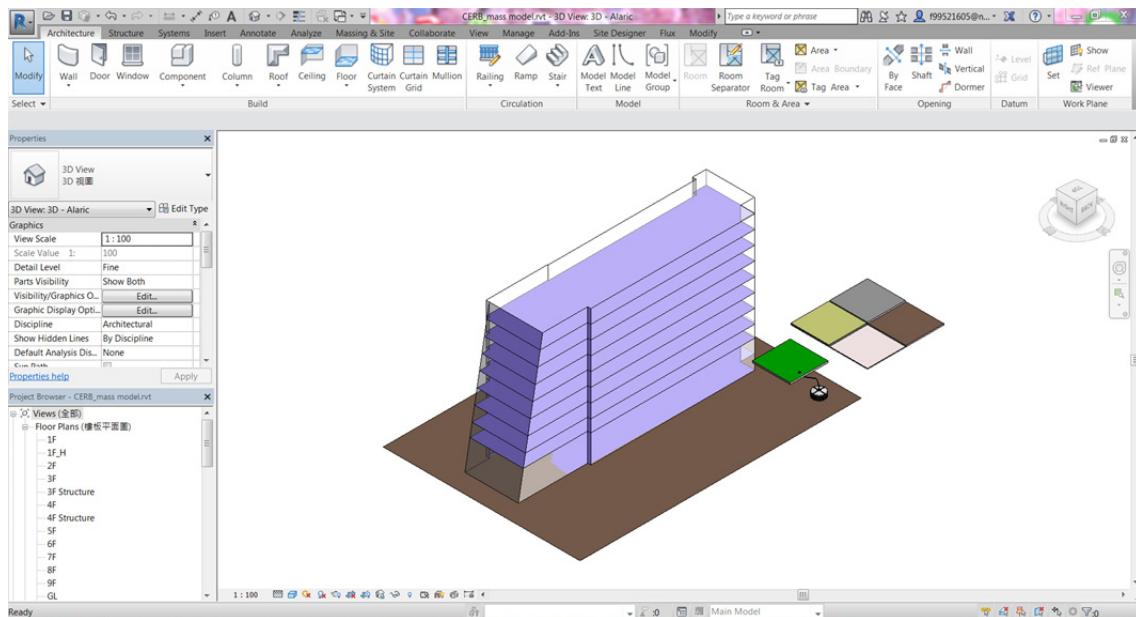
Figure 5-1-2. The building mass model of CERB and the BIM element models.

With building mass model prepared, the architect opens Dynamo to launch the Dynamo script: Blue-Green design tool. The Blue-Green design tool is used to analyze the potential water retention strategy of the project and the thermal performance of the green roof. When the Blue-Green design tool is launched, the windows form is pop out for user to select appropriate information as input. User can select suitable information from the drop down menu of the "Land Use" column. For the "Site Area", user just need to click the topography surface and finish the selection. For the "Floor Area", it is required to select every enclosed area in each floor. For the "GR Area" and "GR Level", user can select the proposed green roof area and elevation. For the "Water Tank", the BIM element model of water tank is the corresponding option. For the "File Path", it is used to output analysis information in excel format. While the above inputs are assigned, user can click "Set value" bottom to continue the next step.

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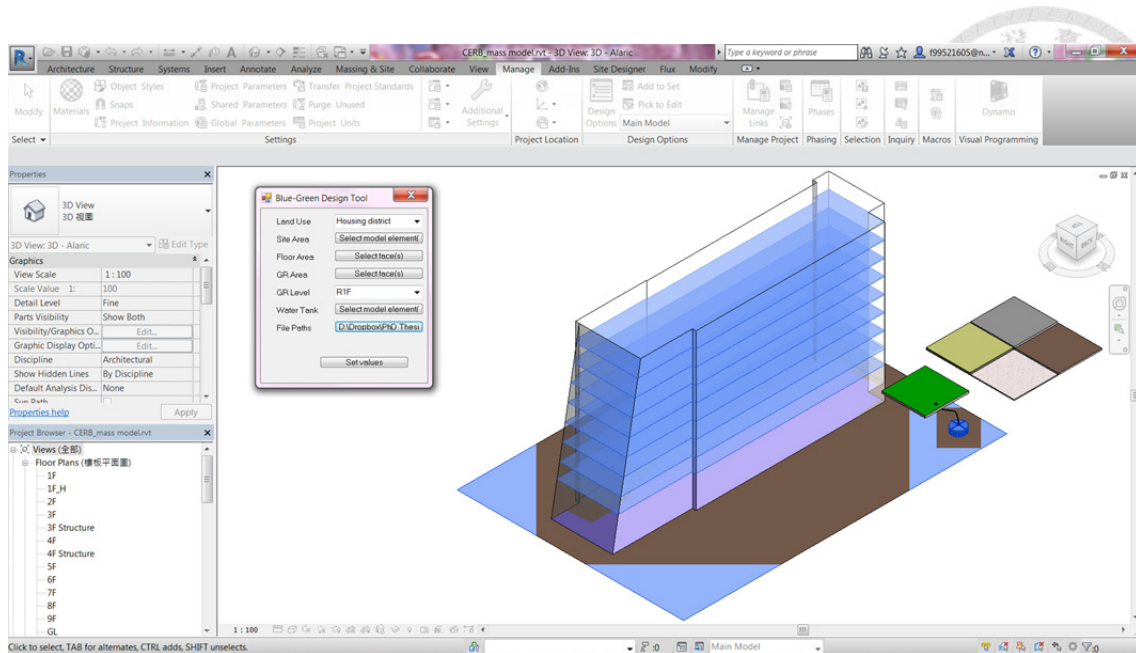
Figure 5-1-3. The input interface of the Blue-Green design tool.

The calculation of LID analysis is conducted, and the analysis results are shown in the windows form (See Figure 5-1-4). Once the architect does not satisfy with the analysis results, the architect can click "NO" bottom to terminate the design tool and prepare another design scheme for the LID analysis. While the analysis results are acceptable, the architect can click "OK" bottom to conduct the thermal analysis. It shows that the design results of BIM project model satisfy the requirements of LID analysis (Housing type in Table 4-4-1-3) in Figure 5-1-4.
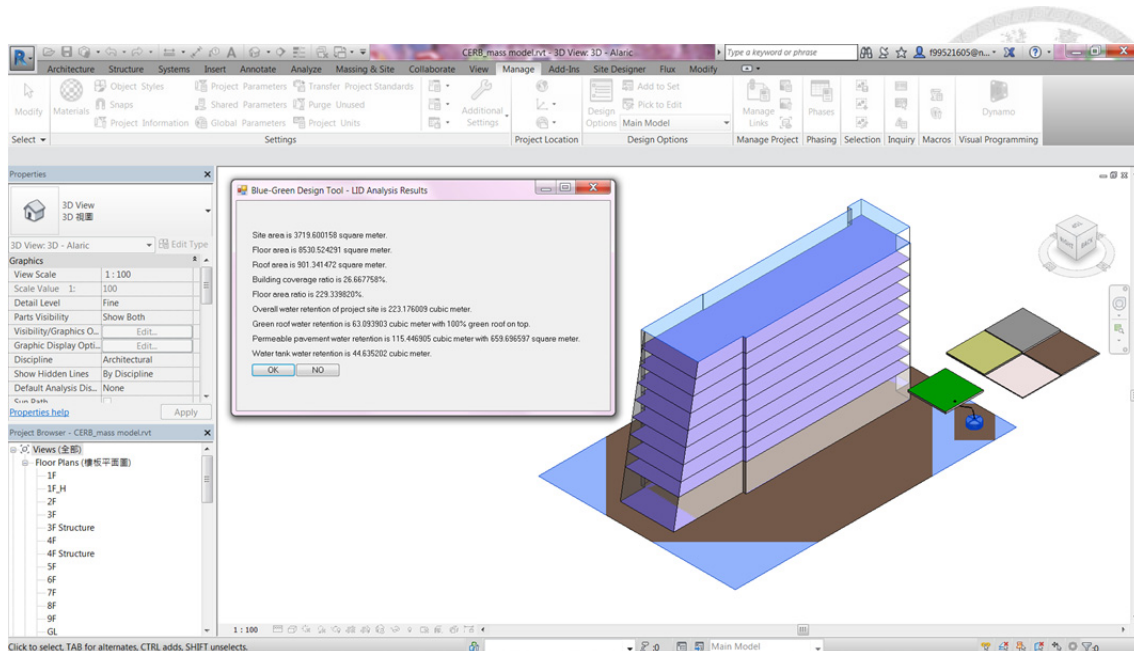
Figure 5-1-4. The windows form of LID analysis results.

In processing the thermal analysis, the Integral Model is used for the thermal performance simulation. The Integral Model requires thermal properties of green roof BIM element model and the weather data of the project site. The weather data is collected from web database of Revit according to the project location. There is an assumption that the building temperature is fixed at 22 ºC in the thermal simulation. The simulation time span is configured in July. The last day of the simulation time span is used to represent the simulation results.

Once the simulation of the thermal analysis is done, the results are shown in the windows form with multiple plots (See Figure 5-1-5). These plots are "Roof Temperature", "Atmospheric Forcings" and "Building Heat Loading". In the "Roof Temperature" plot, the surface temperatures and average temperatures of roof cases are presented. The higher surface temperatures and average temperatures indicates that more heat storage is captured within the roof case. In the "Atmospheric Forcings" plot, the weather data including solar radiation and atmospheric temperature is shown. In the "building heat loading" plot, the heat-flux which transmits from the roof to the

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building is the performance indicator. The higher heat-flux represents worse insulation performance. With the above indicators, the thermal performance of a green roof can be evaluated.

The architect can select preferred type of green roof from a list in the windows form. A dialog window will pop-up to show a message for user. After the decision is made with best performance in Figure 5-1-5, the architect can click "OK" bottom to process the design feedback according to the analysis results. The selected type of green roof BIM element model is created in Revit with assigned parameters such as area and elevation (See Figure 5-1-6). The size of water tank BIM element model is changed by overwriting the *"Designed water volume"* parameter. The value of the "Designed water volume" parameter is defined according to the LID analysis results. The analysis results are exported in the spreadsheet format using assigned file path.

In the beginning of the project, the Blue-Green requirements should be defined. The BIM element models, the design tool and the working manual of the Blue-Green design are prepared for the design process. The working manual is a reference for the other design team in different disciplinary to realize the design information within the BIM model. In this demonstration, the architect can design green roof and water tank with LID analysis and thermal analysis. With the BIM element models and design tool prepared, the iteration of the design process can be conducted earlier. For the analysis results are used as design indicators, the architect can explore the Blue-Green design with quantitative feedback. The design information of the green roof with water tank combined design can be properly presented in the BIM model. With the use of the working manual, the process map and the information exchange are clearly defined. Thus, the BIM model contained the Blue-Green design can be further developed in the following design stage.
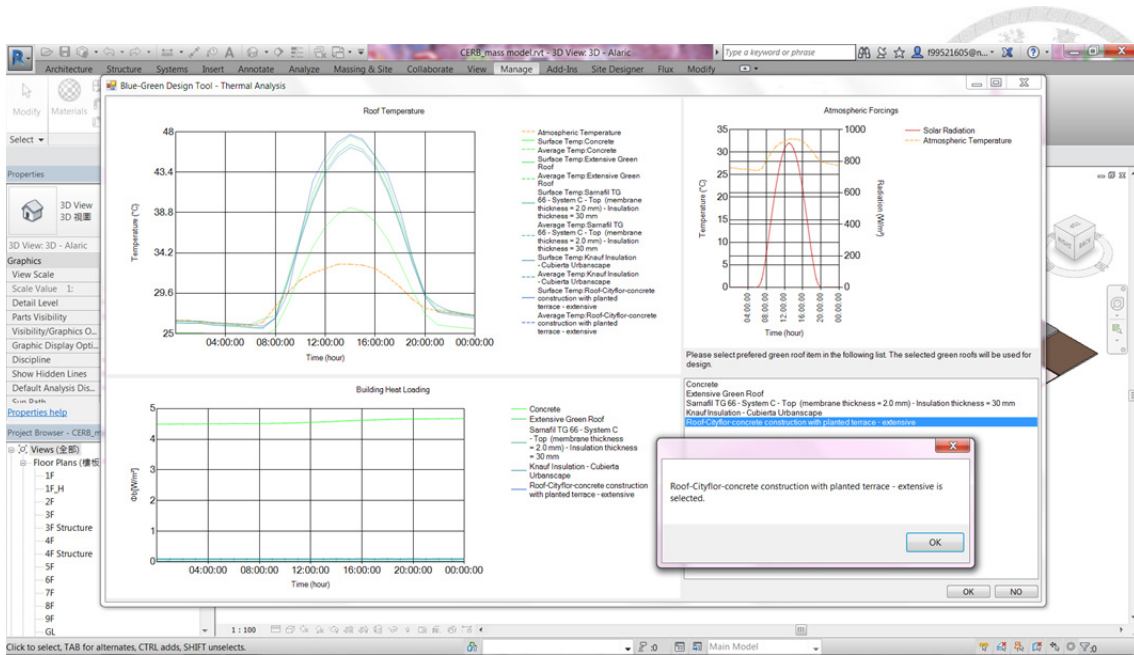
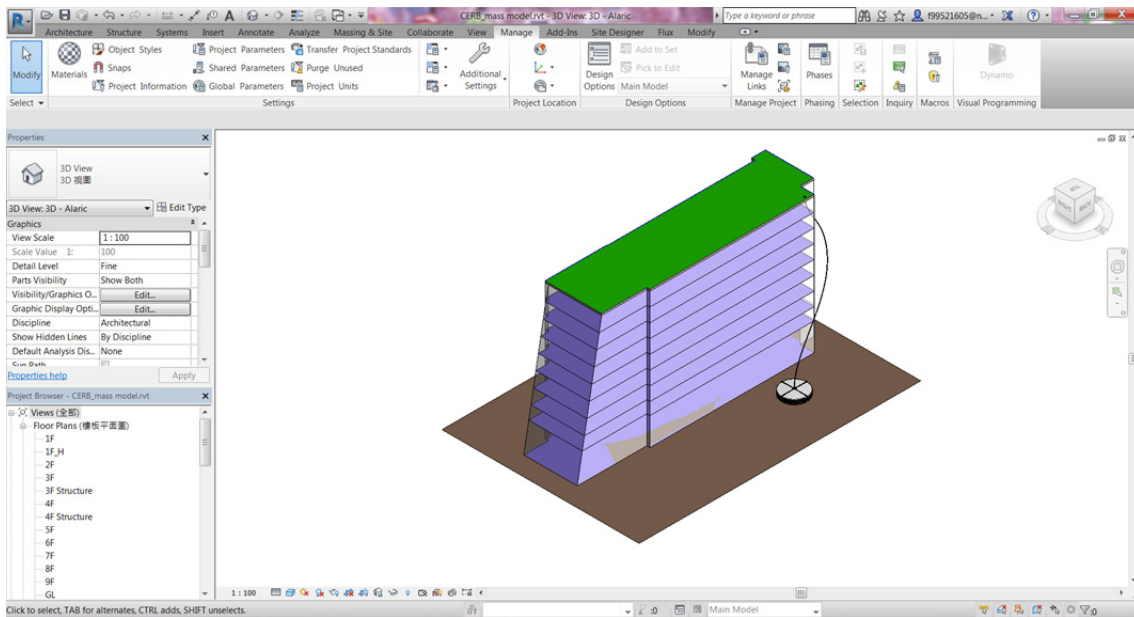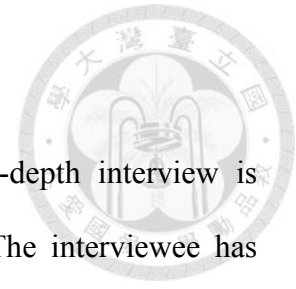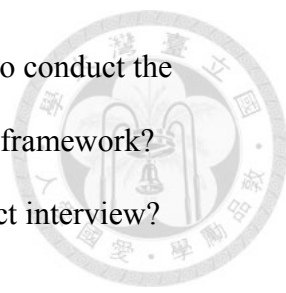Figure 5-1-5. The windows form of thermal analysis results

Figure 5-1-6. The BIM project model contained the Blue-Green design

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5.2 Feedback of Expert Interview and Discussion

In order to validate the feasibility of the framework, an in-depth interview is conducted with an architect who has expertise in BIM design. The interviewee has complete project experience in designing building in BIM platform, optimizing building energy performance and collaborating building design with construction team with BIM model. The detailed record is shown in Appendix 3. The interview questions are shown as follows:

(1) In the chapter of the requirement modeling, there are modeling key tasks for transferring owner's project requirement into the Blue-Green requirements. Is there any gap between the statements and the design process in practice?

(2) In the chapter of the system modeling, the concept of LOD is used as reference to create BIM element models. Will this step arouse controversy in implementation? Is there any further key tasks required in the chapter?

(3) In the process of implementing the performance modeling, Dynamo is used to create design tool with analysis function. Is it possible for architect to use Dynamo scripts to analyze BIM project model? What is the bottleneck of this idea?

(4) In the assumption of the process modeling, design teams collaborate on developing BIM project model using CDE methodology. The key point of the process modeling is to describe how design teams analyze and design BIM project model in the process of the early design stage. With above considerations and case study in this research, what are the practical factors required in the early design stage?

(5) In the BIM-enabled Blue-Green design framework, the output of four modeling key tasks are Blue-Green requirements, BIM element models, customized design tool and workflow manual. Is it applicable for architect to conduct the Blue-Green design with a toolbox containing the above items?

(6) Concerning the architect with BIM expertise in the local market to conduct the Blue-Green design, is there any statement needed to improve the framework?

(7) Do you suggest other Green BIM experts from industry to conduct interview?

Feedback of Expert Interview

The feedback statements of expert interview are summarized as follows:

(1) Response for question (1)

It should be fine. The purpose of this description is ok.

(2) Response for question (2)

The LOD is a good tool to interpret BIM project model. In using the LOD to describe the development of BIM project model, there are three concepts needed to be mentioned in the statement. First, the LOD should be used to describe the design stages in developing the BIM project model. Then, the design stages represent the developing process to refine a building design. Lastly, the maturity of the BIM project model should be mapped with the corresponding development of geometry and information. In supporting the specific BIM use, it is required to find out the essential information to be loaded to the BIM project model. The key concept to use the LOD is describing the BIM use with the corresponding information in each design stage.

(3) Response for question (3)

There is a need of simple interface and user manual of the customized design tool. According to the demonstration of the customized design tool, the strength of the design tool is visualization. It is possible for architect who is familiar with Dynamo to use this design tool in practice. For the interface of Dynamo is hard for general architects to realize, it is suggested to have simple interface of customized

design tool to lower the learning curve. Furthermore, a user manual is needed not only for the beginners, but also for the experts of Dynamo to have overview of the tool.
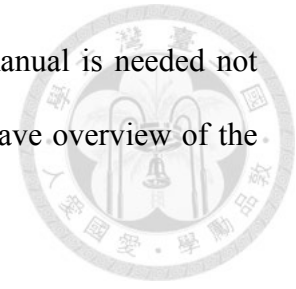
(4) Response for question (4)

The land developing intensity and the building acts are the first concern in the beginning of the project. The certificate of green building will be concerned after Concept Design stage. In the planning stage (such as strategy definition stage to preparation and brief stage in RIBA plan of work [59]), architect will deal with the land developing intensity and building acts first. For the owner focuses on the development intensity of the project site, architect needs to clarify the restriction of the project site according to the building acts to define the quantity of building mass. In the following design stage, the green building analysis could be considered for the project requirements such as applying the certification of green building.

There are different patterns of practical operation in land development. In some official and large development project, there is a building programming stage in the beginning of the project. The contracted consultancy company will define a design brief according to the project requirements in building programming stage. In defining the design brief, there are many design factors to be concerned. The design factors include the land developing intensity, the building acts, the spatial function, the certification of green building, and financial condition of the project. After the design brief is formulated, the owner will invite architects to participate the tendering process according to the design brief.

(5) Response for question (5) and (6)

The design objectives should be clear. As an architect with a certain understanding about BIM, there is no problem in using the tool. The design objectives are the most important thing. For the demonstration case is lack of design objectives, it is hard to realize the purpose of the design. In contrast, it could be acceptable in the condition that the objective values of input and output are clear.

(6) Response for question (7)

(The suggested Green BIM experts from industry are listed in Appendix 3.)

Discussion

The responses to the feedback are summarized as follows:

For using the LOD to interpret BIM project model, the detailed modeling key tasks are listed in the system modeling. The LOD is used as reference to create BIM element models with corresponding purpose instead of describing an overall BIM project model.

For the simple interface of the customized design tool, there is an enhancement mentioned in chapter 4.4.3. After user opens Dynamo and launch the Dynamo scripts of the design tool, the windows form of user interface will pop up for user to input corresponding information. Therefore, user can use the design tool without manipulate the Dynamo scripts. For the user manual of the customized design tool, there could be some replacement alternatives. Once architect uses the framework to implement the design tool, there could be not necessary to prepare the user manual as extra work. In addition, once sustainability consultant uses the framework to implement the design tool for architect, the operation instruction could be embedded in the user interface of the design tool as software wizard.

Concerning the land developing intensity and the building acts are important issues in the beginning of the project, the content of the design tool is modified with the concerns. In the input of the design tool, "Land Usage", "Site Area" and "Floor Area" are related design factors. In the windows form of the LID analysis results, the building coverage ratio and floor ratio are required information of the land developing intensity and the building acts.
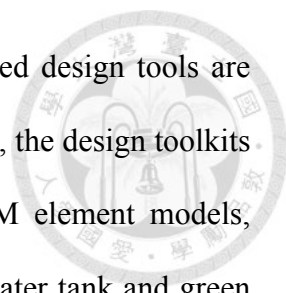
In order to clarify the design objective, the modeling key tasks of the requirement modeling is enhanced. For the example of implementation, the input and output information are mentioned in chapter 4.4. In addition, the Exchange Requirements are shown in Appendix 2.

6. Conclusions and Future Works

For mitigating the Urban Heat Island effect, the Blue-Green design integrating Blue measures (water system) and Green measures (greenery system) was proposed in building design. It requires different experts to co-work in a collaboration environment to create and evaluate the Blue-Green design for optimizing the performance. This research develops a BIM-enabled design framework to support the collaboration environment of the Blue-Green design. The contribution of this design framework is to provide a systematic approach for design teams, consisting of both green and blue experts, to formulate design toolkits in BIM platform to support the collaboration interface and process needed. The design toolkits can be also used by the design teams to conduct, evaluate and review multidisciplinary design in an agreed design process. The design requirements and parameters of the water system and the greenery system can be considered in an integrated manner through the framework.

The BIM-enabled Blue-Green design framework contains four modeling approaches: the requirement modeling, the process modeling, the system modeling, and the performance modeling. The requirement modeling focuses on capturing project requirements and selecting the potential Blue-Green design measures. The process modeling states the key tasks in preparing workflow document for design team members to collaborate on BIM project model with the Blue-Green design in design iterations. The workflow document defines the collaboration interface with exchange requirements and the collaboration process with process map. The system modeling describes the key tasks in creating BIM element models of each systems with required design parameters in appropriate BIM element model type. The performance modeling outlines the considerations in creating new design tool with customized performance analysis function using visual programming language. The BIM element model is a

static representation of the Blue-Green system, while the customized design tools are dynamic ones for evaluating various design performance. As a result, the design toolkits for the Blue-Green design includes Blue-Green requirements, BIM element models, customized design tool and workflow manual. This research uses water tank and green roof as outlined Blue Green measures in case study. A workflow manual is drafted concerning water tank and green roof cases and the customized design tool. The BIM element models of water tank and green roof are created with reference to existing cases. A customized design tool is created with two analysis functions – the Low Impact Development analysis and the thermal analysis.
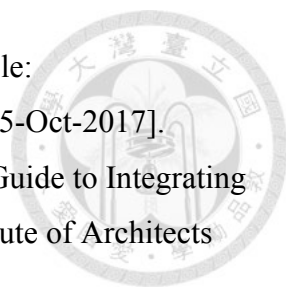
The demonstration case under the collaboration environment conforming to the workflow manual is presented to satisfy the initial project requirements. For validating the feasibility of the framework, an expert interview is conducted.

For the future work, it is suggested to apply the BIM-enabled Blue-Green design framework to design greenery systems and water systems and to conduct further validation from urban planning to building design in practice. In order to support data-driven Blue-Green design, it requires a systematic method to create parametric BIM element models with real physical properties. Besides, the algorithm of analysis function concerning multiple design interaction among building systems and urban infrastructure should be developed to support the Blue-Green design of the building and surrounding area. Furthermore, an AI programming algorithm can be trained and validated with numerous study cases to support urban planners and building designers exploring the Blue-Green design automatically.

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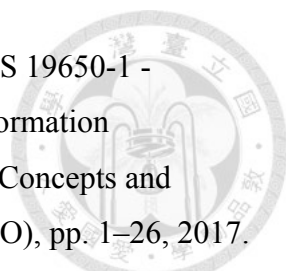
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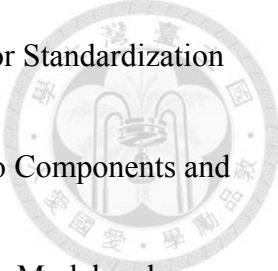
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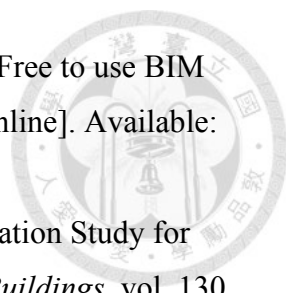
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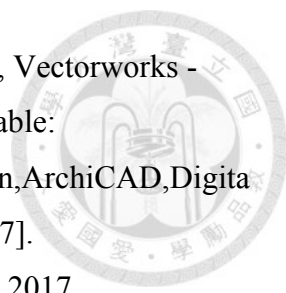
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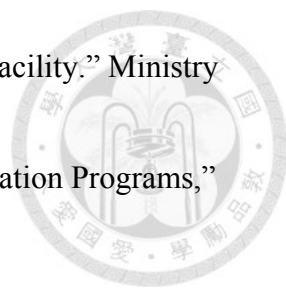
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Appendix

Appendix 1. Green Roof Thermal Properties

Table 8-1-1. Thermal data of green roof case one

Family and Type : Basic Roof: Extensive Green Roof				
Thermal Resistance (R) : 4.1507 (m²·K)/W				
Default Thickness : 0.455				
Layer Name	Thickness (m)	Density (kg/m³)	Specific Heat (J/(g·°C))	Thermal Conductivity (W/(m·K))
Pre-Planted Vegetation Blanket - Extensive Green Roof - (60mm)	0.06	1300	1.046	0.837
ALKORPLAN Green Roof Substrate - AlkorPlus (81017) - (50mm)	0.05	1300	1.046	0.837
Polypropylene Water Retention Geotextiles - AlkorPlus (81016) - (2.75mm)	0.0028	930	2.092	0.138
Polypropylene Geotex - AlkorPlus Filter/ Drainage Layer (81015) - (8mm)	0.008	930	2.092	0.138
Polypropylene Geomembranes - AlkorPlus Slip Layer (81014) - (1.6mm)	0.0016	930	2.092	0.138
ALKORPLAN Roofing Membranes - LA membrane (35177) - (3.3mm)	0.0033	930	2.092	0.138
PIR Polyisocyanurate Insulation (130mm)	0.13	23	1.47	0.035
PLEASE SELECT VCL LAYER FROM MATERIAL LIBRARY	0	930	2.092	0.138
Bitumenous Primer (for use with SK self adhesive VCL 81002 on timber/masonry substrate only)	0	930	2.092	0.138
Concrete	0.2	2300	0.657	1.046
Proofcoat emulsion - CITYFLOR® - Axter®	0	1	0.84	1.15

Table 8-1-2. Thermal data of green roof case two

Family and Type : Basic Roof: Sarnafil TG 66 - System C - Top (membrane thickness = 2.0 mm) - Insulation thickness = 30 mm

Thermal Resistance (R) : 1.5500 (m²·K)/W

Default Thickness : 0.3122

Layer Name	Thickness (m)	Density (kg/m³)	Specific Heat (J/(g·°C))	Thermal Conductivity (W/(m·K))
Soil with plants/vegetation	0.08	1300	1.046	0.837
Sarnavert Aquadrain 550	0	855	1.925	0.25
Sarnafil TG 66-15 loosely laid/Beige	0.0022	1500	1.674	0.167
Sarnatherm PIR GT	0.03	32	0.92	0.024
Sarnavap-3000 E	0	920	2.092	0.331
Concrete	0.2	2300	0.657	1.046

Table 8-1-3. Thermal data of green roof case three

Family and Type : Basic Roof: Knauf Insulation - Cubierta Urbanscape

Thermal Resistance (R) : 1.2427 (m²·K)/W

Default Thickness : 0.445

Layer Name	Thickness (m)	Density (kg/m³)	Specific Heat (J/(g·°C))	Thermal Conductivity (W/(m·K))
Urbanscape Sedum-mix PDS	0.2	800	1.046	0.837
Urbanscape Green Roll (HTC GR)	0.02	110	0.71	0.04
Urbanscape Drainage System with buffer	0.025	1050	1.3	0.08
Urbanscape Root Membrane	0	930	2.092	0.331
Impermebilizante	0	2330	1	0.5
Concrete	0.2	2300	0.657	1.046

Table 8-1-4. Thermal data of green roof case four

Family and Type : Basic Roof: Roof-Cityflor-concrete construction with planted terrace - extensive

Thermal Resistance (R) : 6.1841 (m²·K)/W

Default Thickness : 0.5053

Layer Name	Thickness (m)	Density (kg/m³)	Specific Heat (J/(g·°C))	Thermal Conductivity (W/(m·K))
Soil with vegetable	0.05	1300	1.046	0.837
Filter layer	0	855	1.925	0.25
Drainage layer	0.04	855	1.925	0.25
Absorbent Material	0	920	2.092	0.331
FORCE® 3000 TRAFIC-CITYFLOR® - Axter®	0.003	950	2.301	0.502
HYRENE® 35 PY-CITYFLOR® -Axter®	0.0035	920	2.092	0.331
CITYFLOR ST ® - CITYFLOR® - Axter®	0.0026	1500	1.674	0.167
Insulation	0.2	23	1.47	0.035
HYRENE® 35 PY-CITYFLOR® -Axter®	0.0035	920	2.092	0.331
HYRENE® 25/25 TS - CITYFLOR® - Axter®	0.0027	1500	1.674	0.167
Proofcoat emulsion - CITYFLOR® - Axter®	0	1	0.84	1.15
Concrete	0.2	2300	0.657	1.046

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Appendix 2. Exchange Requirements of the Workflow Manual
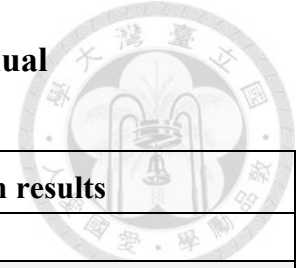
Name		Exchange of Blue-Green analysis and design results		
Identifier		ER Blue-Green design results		
Change Log				
<2017-11-08>		< Initial version , adapted from BPEA IDM developed by GSA and OGC >	<Han-Jung Kuo>	
Project Stage	0	Portfolio requirements		
	1	Conception of need		
	2	Outline feasibility		
	3	Substantive feasibility		
	4	Outline conceptual design		✓
	5	Full conceptual design		✓
	6	Coordinated design and procurement		
	7	Production information		
	8	Construction		
	9	Operation and maintenance		
	10	Disposal		

Overview

The scope of this exchange requirement is the exchange of information about the design content of the Blue-Green design. The purpose of the exchange requirement is to support the design collaboration of the Blue-Green design to satisfy the Blue-Green requirements. The exchange requirements are contained in the building model of the concept design with green roof and water tank system.

Exchange Requirements - Blue-Green design results

Type of Information	Information Needed	Required	Optional	Data Type	Units
Blue-Green Design	The following properties should be included:				
	o The type of Land Use	X		String	n/a
	o The project site area	X		Real	m^2
	o The volume of water retention (LID indicator)	X		Real	m^3
	o The designed volume of water tank	X		Real	m^3
	o The designed area of permeable pavements	X		Real	m^2
	o The designed green roof area	X		Real	m^2
	o The thickness of green roof	X		Real	m
	o The thermal resistance of green roof	X		Real	$(m^2 \cdot K)/W$
	o The thermal conductivity of green roof	X		Real	$W/(m \cdot K)$
	o The volumetric specific heat capacity of green roof	X		Real	$J/(m^3 \cdot K)$
	o The thermal diffusivity of green roof	X		Real	m^2/s
Project	The following properties should be included:				
	o Identification	X		String	n/a

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Type of Information	Information Needed	Required	Optional	Data Type	Units
	o Owner/Client information		X	String	n/a
	o Model Author		X	String	n/a
Site	The following properties should be included:				
	o Address	X		String	n/a
	o Global Coordinates	X		(2) triples	deg/min/sec
	o Site Elevation	X			m
	o 2D Geometry		X	Geometry	varies
	o 3D Geometry		X	Geometry	varies
Site Context	The following properties should be included for existing buildings adjacent to the subject building:				
	o Identification	X		String	n/a
	o 3D Geometry	X		Geometry	m
Building	The following properties should be included (if not known then probable values should be used):				
	o Identification	X		String	n/a
	o Global Coordinates	X		(2) triples	deg/min/sec
	o Functional Classification (OmniClass)		X	String	n/a
	o Orientation (deviation of building grid from true north, clockwise)	X		Real	Angular Degrees
	o Elevation (relative to the site datum)	X		Real	m
Building Stories	The following properties should be included (if not known then probable values should be used):				
	o Identification	X		String	n/a
	o Elevation(relative to the building datum)	X		Real	m
Spaces	The following properties should be included:				
	o Identification	X		String	n/a
	o Description		X	String	n/a
	o Inside or Outside space	X		Boolean	
	o Functional Classification - OmniClass Table 13		X	Relationship	n/a
	o Functional Classification – Client Space Type	X		Relationship	n/a
	o 2D Geometry		X	Geometry	varies
	o 3D Geometry	X		Geometry	varies
	o Links to Space Boundaries	X		List of Relationships	n/a
2nd Level Space Boundaries	The following properties should be included for 2nd level space boundaries:				
	o Space Boundary Type (1=internal, 2=external, 3=virtual)	X		Enum	n/a
	o Space Boundary Tag (2nd level, "face")	X		String	n/a
	o 3D planar geometry	X		Geometry	m
	o Link to Space	X		Relationship	n/a
	o Link to Building Element	X		Relationship	n/a

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Type of Information	Information Needed	Required	Optional	Data Type	Units
Building Elements (General)	The following properties should be included (if not known then probable values should be used):				
	o Building Element Type (wall (exterior/interior), curtain wall, roof, floor, ceiling, window, door, shading device)	X		Enum	n/a
	o Construction type (e.g. wall type, door type, window type, shading device type, etc.) Window constructions from Window 6, opaque constructions from ASHRAE Fundamentals.	X		String	n/a
	o Classification - UniFormat		X	String	n/a
	o 3D Geometry	X		Geometry	varies
	o Exterior or Interior Element (i.e. Is Exterior)	X		Boolean	n/a
	o Link to Space Boundary	X		Relationship	n/a
Building Elements (Opaque-Wall, Roof, Floor, Ceiling, Door)	Added to the list above, the following properties should be included for opaque building elements (e.g. walls, floors, ceilings, roofs, doors, etc.):				
	o Link to Material Layer Set	X		String	n/a
Building Elements (Glazing-Curtain Wall, Glazed door, Skylight, Window)	Added to the Building Elements list above, assigns thermal information to building elements to enable energy analysis. The following properties should be included for glazed building elements (e.g. windows, curtain walls, glazed doors, and skylights):				
	o Window Assembly Exterior Surface Color of Glass (clear, bronze, silver, gold, copper, blue, green, gray, mirror)		X	Enum	n/a
	o Window Assembly Interior Surface Color of Glass (clear, bronze, silver, gold, copper, blue, green, gray, mirror)		X	Enum	n/a
Material (Opaque)	A building material (e.g. wood, concrete, steel, etc.):				
	o Identification	X		String	n/a
Material Layer (Opaque)	An individual building layer in a material layer set:				
	o Identification	X		String	n/a
	o Description	X		String	n/a
	o Material	X		String	n/a
Material Layer Set	An ordered list of material layers used in a building element construction:				

Type of Information	Information Needed	Required	Optional	Data Type	Units
(Opaque)					
	o Identification	X		String	n/a
	o Description	X			
	o List of material layers	X		List of String	n/a

Appendix 3. The Record of Expert Interview (In Chinese)

專家訪問紀錄

專家背景：

陳清楠 建築師/台灣建築資訊模型協會第五屆理事長/LEED AP

時間規劃：

訪問日期為 2017 年 04 月 18 日下午 14:00-16:00

14:00-14:30 介紹以 BIM 實作藍綠設計之方法框架

14:30-14:45 解釋與確認研究內容細節

14:45-15:45 訪問開始

15:45-16:00 緩衝

訪問問題：

1. 在需求塑模的內容當中，將業主的專案需求轉換為設計需求的描述，是否與實務有很大出入?

2. 在系統塑模中，運用 LOD 的描述進行元件建置的參考，這部份是否會造成爭議的問題點? 除此之外，設計用元件是否有哪些需要考量的重點是在簡報內容中未提及的?

3. 在性能塑模的過程中，採用 Dynamo 為分析工具建置的環境，若是將分析工具與相關說明都準備好，則建築師有可能使用 Dynamo 腳本進行模型分析嗎? 技術困難點可能出現在哪裡?

4. 在流程塑模部分，在協作部分是假設採用 CDE 方式，而此框架重點在於進行 CDE 前期的基礎設計模型的分析與設計。想請問一般在規劃設計流程的部分，最需要優先考量的關鍵因子是哪個層面?

5. 在方法框架中，提出四個塑模方法所對應產出為需求列表、模型元件、分析工具與設計流程。那麼於概念設計階段，若具備這些配套，建築師是否可能應用此方法進行藍綠設計? 若不會，有那些問題點待克服或是需要增加探討那些因素?

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6. 若以國內的設計情況，假設建築師具備 BIM 能力，那麼以上的框架需要增加那些調整?

7. 依您的專業判斷，是否仍需要訪問國內哪些專家以完備研究的論述?

訪問內容：

郭瀚嶸: 我目前要問七個問題這樣，我前面有四個問題主要有關我四個塑模的狀況。我在
講到專案需求轉換到設計需求的描述，基本上與實務的部份會不會落差很大?

陳清楠: 塑模其實我有個地方不太懂，元件行為塑模是什麼意思阿 ?

郭瀚嶸: 就是有點像是說，我們要來決定這個元件是怎麼樣的行為。這個行為其實指得就
是說，我們一般來說，它都會有一個互相的關係。像是我們今天的屋頂，下面會
有一些支撐的構件，或是說門在牆上面這種，就算是它這樣的行為。算是有點這
樣是說，軟體定義元件之間怎麼互動、怎樣處理資料的部分，Revit 裡面當然有
一些已經設定好的類別，我之後要做哪些東西而決定去 model 它。我在這裡面比
較直接一點的差別像是在屋頂的部分，我可以分為做得比較細或是綠屋頂的部分
不是一整層，而是一個單元一個單元的，甚至可能拿來做載入式元件，可以刻得
比較完整。如果今天一開始我希望是做一個很快的限定範圍或是留下來後面去用
已經是屋頂的類別繼續做分析，我就會決定這個元件要怎麼設計它，就像做元件
我決定它拿的類別的部分。

陳清楠: 應該還好，目的性都還 OK。

郭瀚嶸: 正如我前面所說，我會分為比較大尺度、政策面的要求到綠建築的指標以及業主
本身的偏好，這部分比較抽象，恐怕無法實做。另外，剩下實際上設計時遇到的
問題，包括需要陽光的地方、需要澆灌的需求、或者是後面結構的分析等等。水
的部分也較類同。這問題比較偏向我收集這些狀況，把它們轉化為設計的條件。

陳清楠: 第一個沒有問題。

郭瀚嶸: 第二個部分在系統塑模的部分，其實我用了 LOD 做了一個參考，在台灣一般來

說，我目前知道大家對於 LOD 不太接受的原因之一，是因為寫專案要求的人其

實對 LOD 的認知並不清楚，反過來造成有些地方過度要求。我是一開始要做設

計元件，我是依照那個階段的需求來推出元件要長到什麼地步，這部分是不是一

個適當的方法？

陳清楠: 其實我一直覺得 LOD 是一個對 BIM 模型很好的詮釋的詞，只是大家有時候很容

易把它簡化成細緻度這件事情，我覺得要講這件事情沒有關係，但要講清楚。其

實 LOD 應該是要涵蓋三個概念，第一個：我認為 D 是發展、發展階段的意思，

發展階段要用一百、兩百、三百…我覺得無所謂，或者是你用設計階段、基本設

計概念階段來描述。接下來，發展階段代表是一個設計的成熟度發展的歷程，接

下來你要談去對應它的模型的成熟度，可能就是一定要用細緻度與資訊量一起來

描述去做它的對應關係，這樣會比較合理。比如說你在概念設計階段，你的模型

可能是一個幾何抽象的模型，需不需要有資訊？比如說你需要版位的資訊，到了

基本設計，這個成熟度你需要做哪些設計決策，模型的細緻度需要深化到哪個程

度，資訊量為了要輔助你的 BIM 使用，哪些資訊需要再加進來？我會比較期待

除了幾何的說明之外，這個階段要做甚麼事情？那它所必須夾帶的資訊等等，需

要再做補充，這樣會比較完整。我不曉得這個部分你有沒有寫到？

郭瀚嶸: 其實我是寫後面的，我前面參考既有的，後面才列舉設計的因子，並歸納它的行

為以及幾何怎麼建。

陳清楠: 我覺得 LOD 善用它是不錯的詮釋工具。

郭瀚嶸: 第三個問題，是要使用 Dynamo 做為分析工具建置的環境，假設是說一方面我比

較容易去客製，因為不管是說專門在做這部分的顧問公司的人，或者是建築師自

己日後要 tune 這件事情也好，比較容易去處理接下來，我可以用它把設計的過

程回饋到模型裡面，所以這是為什麼我選擇 Dynamo 做為一個分析工具建置的原

因，現在有一個問題，假如說我都準備好這些東西了，假如建築師建置 BIM 模

型的部分，他對 Dynamo 的使用有我教他去點選一些功能，你覺得他是不是比較

有信心把它拿來做應用？

陳清楠: 因為你剛才的操作過程感覺就是視覺化的部分很清楚，我覺得建築師當然是有可

能實用，如果說在使用介面上稍微再簡化一點，因為 Dynamo 的介面我發現不是

一般建築師可以理解的，像我去上過課才知道哪裡有哪些選項或功能，但一般人

看到這個會傻眼，到底它的流程是甚麼？除非你要搭配一個手冊，去說明第一個

步驟要做甚麼、第二個步驟要點甚麼諸如此類。或是建築師在使用它會更容易些。

我覺得要給使用者使用的話，可能要有另外一本說明手冊，但這樣的工具給專業

人員來使用是沒問題的，像是上過 Dynamo 的課程，再跟大致我解釋這個程式的

邏輯，自己稍微熟悉一下大概會知道要怎麼使用。但對於一個沒有接受過

Dynamo 訓練的人，他看到這樣接過來接過去，會不知道要從何開始。

郭瀚嶸: 第四個問題在流程塑模的部分，前面我先假設建築師是第一個把設計需求轉化成

模型的人，在做後面較複雜的協作之前，我先進行分析，後面假設是做 CDE 的

部分，在實際上規劃流程的部分，你們優先考慮的因子有哪些層面？我在這部分

只有參考過去文獻，關於有哪些 milestone 之類的而已。

陳清楠:通常在前期規畫階段，建築師面對的是開發強度與法規檢討，一定是這兩者優先，

因為客戶會關心自己的這塊地可以蓋多少，這又會牽扯到法規，甚至是開發的量、

高度、或是有沒有其他法規的限制條件等等，這些一定是第一個層面。進到基本

設計階段，才有可能因為這個案子要申請綠建築以及目標是甚麼？這時候才會去

做綠建築的分析。只有在這個階段才會開始去做能源模型或是 Ecotect 的簡單幾

何分析模型。

郭瀚嶸: 之前我看到的一些文獻提到，最前面的階段稱之為準備階段（Preparation），再

過來是概念階段，之後是 SD 或其他等等。在我的假設中，有的概念設計階段是

把前面準備的一些需求條件轉成模型，我可能會提出二至三個方案，目前只有初步認知到這樣。

陳清楠: 在實際操作上有許多模式，像我剛才所提到的是比較私人的建設公司，而比較嚴謹或官方的大型開發計畫，它前面可能會有一個建築企劃，甚至會委託前期規劃的廠商，規劃廠商做的事情可能不只剛剛講的，還有綠建築、甚至是空間定性定量這些要求等等都會幫忙訂出來，業主再根據這些需求去招下一標的建築師，比較嚴謹的案子才會有經費做這些事情，不然在一般小案子，可能也只有內部幾個承辦人員去訪問需求。大案子中綠建築分析也跑不掉，像中興以前一些 PCM 的案子會包含前期規畫設計，他們要做的就是那些事情，例如：法規、案子會蓋甚麼大小，再去了解業主的需求，排一排幾種可能性，初步去安排甚麼樣的配置是合理的。我剛到中興做機場捷運線的影響評估，我們總顧問含基本設計，基本設計應該算是概念設計、規劃設計，機場捷運要怎麼走？哪一個點要設站？站內有那些機電空間的需求？排起來會長甚麼樣子？然後以我們的成果招標去做後續的細部設計，設計是重做的，他們只是參考空間的定性定量，還有軌道高程等等與機電相關的條件，造型幾乎是重頭設計。關於規劃設計要考慮的因子，像是剛才較嚴謹的案子，綠建築一直都是公部門關心的重點，可能是法規、開發量、空間機能、綠建築分析、財務，這幾點是目前主要的因子，通常在前期規劃也要考慮財務，確定這個方案不會超過業主預算，業主才能往下進行，並甄選後續的廠商。

郭瀚嶸: 第五個問題，在看過這些配套之後，建築師有可能會利用這些配套來做設計嗎？我還有哪些問題點需要克服來使建築師比較能夠使用這些東西？幫我做這些配套的角色還未確定，有可能是一個 BIM 顧問公司，需求會有轉化，回饋到建築師如何設計，另外，我幫你準備元件、分析方法與設計流程，除此之外，這樣是否足夠？還要增加哪些項目嗎？

陳清楠: 以建築師來說，如果對 BIM 有一定了解，他使用上基本不會有問題，主要還是

在於目的性，例如檢討指標就有一個明確的目標，有目標就知道要拿甚麼東西來

用、或期待有甚麼結果。現在的案例比較沒有目的性，所以會不知道做這件事情

的企圖心在哪，如果說你 input 與 output 的目標值都很明確的話，我覺得就沒關

係。

郭瀚嶸: 謝謝，第六個問題回答與第五個差不多。

郭瀚嶸: 最後，依你目前的判斷，這個配套仍需要訪問哪些專家學者讓論述更加完備呢？

陳清楠: 郭榮欽老師？

郭瀚嶸: 下禮拜六會問他。

陳清楠: 若要找有在用 BIM 做設計的專家，像是汪孟欣、張淳榕或是九典建築師事務所

等等，我知道有一些做綠建築標章申請的公司，他們很期待用 BIM 幫他們做一

些事情，但對 BIM 又不太了解，現在很多案子要申請容積獎勵與保證金，如果

沒有達標，保證金會被沒收，他們只許成功、不許失敗，所以他們會特別去拜託

申請綠建築標的公司，這些公司的人員曾表示過他們想學習 BIM，像是許書

豪，建築中心開課他們也有派人去上課。