Integrating BIM and Decision-Making System for HVAC Design of Low Rise Green Buildings

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Abstract

During the past decade, building energy consumption has risen significantly. Meanwhile, the building area is being increased at a high speed. The conflict between high building energy consumption and low energy efficiency has attracted great attention in the construction industry. HVAC system contributes to most of the whole building energy consumption. Thus, it is imperative to study and analyze the means of HVAC system’ s energy conservation. This study aims at addressing two specific challenges: (1) the lack of knowledge to know the kind of HVAC performance that can be evaluated as the criteria for decision making; and (2) the lack of efficient methods for collecting HVAC system and equipment data to comprehend the information used by decision makers.

An effective way to minimize these challenges is to predict the HVAC performance of a new building at the conceptual design stage through the application of energy simulation tools. However, the development process of these tools is usually isolated, which results in having the information of a building model that is created by other tools cannot be shared. On another side, there is a need to establish an energy conservation expert system to use during the design of the HVAC systems for buildings.

Based on the above, this study integrates Building Information Modeling (BIM) and decision-making system to select HVAC systems for buildings. First, the basic of HVAC components and systems are collected and stored in specific database that will be used for the optimization of HVAC design. Various types of heating/cooling equipment are presented based on ASHRAE standards. Second, the environmental, economic, technical performance and green building rating system are summarized as the criteria for evaluating HVAC performance. Then a combined AHP (Analytic Hierarchy Process) and Entropy structure for HVAC system is introduced as the Decision-making method. Finally, the interoperability of BIM tool is developed to bridge the connection between BIM tool and the HVAC decision making systems through the whole life cycle of buildings. The entire model is coded in Visual Studio via C#. The model is tested through a project to prove its workability and dependency.

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Acronyms

BIM	Building Information Model
USGBC	United Stated Green Building Council
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCC	Life Cycle Cost
EER	Energy Efficiency Ratio
AHU	Air Handle Unit
LEED	Leadership in Energy and Environmental Design
MCDM	Multiple Criteria Decision-Making
MADM	Multi Attribute Decision Making
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
AHP	Analytic Hierarchy Process

Chapter One

Introduction

1.1 General

Energy is an important component for the development of economy and society. With the development of technology and economy, the demand for energy is increasing at a large scale, while the energy scarcity has attracted lots of attentions. Therefore, energy savings became a global problem.

Energy consumed by buildings accounts for the largest proportion of the total energy consumption all over the world, the ratio is more than 60% of the total energy consumption in developed countries, and 40% in developing countries. Hence, to ensure the rapid development of the society and the continuous improvement of the people's living standards, it is of great importance to study how to reduce the energy consumption of buildings.

Since the energy consumption of buildings make up the largest part of the total energy consumed by societies, the energy consumption of HVAC systems is the highest consumer of building' s energy, which accounts for more than 60% of it. Therefore, it is at most importance to optimize the energy saving of the HVAC systems.

1.2 Research Objectives

Until now, most of the evaluation methods of HVAC systems focus on how to improve their technical performance to reduce their operating cost, while the environmental impacts caused by them are usually neglected. Although some researches illustrated the relationship between HVAC design and the environment, but there is still a lack in the methods currently used to integrate them via one single model. Therefore, the main objective of this study is to develop an integrated model that relates BIM with a DSS in order to select efficient HVAC systems while designing sustainable buildings at the conceptual stage. The sub-objectives are as follows:

- Search and understand the characteristics of HVAC system for green buildings;
- Identify and outline the methodologies for evaluating HVAC system performances;
- Create a database that stores collected information about a wide range of commercial HVAC products available in the market;
- Apply BIM tools (i.e., Revit) for the evaluation of HVAC system performance to simplify the decision-making process;
- Automate the selection of the appropriate factory-assembled HVAC products for green buildings through the use of new plug-in that will be developed and inherited into BIM tool.

The decision-making model will be applied for the selection of the primary system of HVAC. All the HVAC systems that are in the scope of the decision-making model are assumed to meet the cooling and heating load of the building and satisfy the indoor thermal comfort requirements.

1.3 Methodology Overview

The study follows a methodology that is divided into series of steps to be followed in order to achieve the above listed objectives. Those steps include the following:

1.3.1 Literature Review

A comprehensive literature review will be conducted to identify the recent implementations and gaps that exist in the integration of BIM and HVAC design at the conceptual stage. As well the benefits of using decision support systems to select efficient HVAC systems for sustainable buildings. This step is important because of its contribution in refining the methodologies.

1.3.2 Data Collection

The proposed model requires the design and implementation of a database to store the collected information needed while selecting HVAC products, which will be considered as alternatives to stimulate energy analysis. The collected data is pertained to decentralized HVAC systems' factors that contribute to the evaluation of HVAC performances. The reliability of the data is imperative for the evaluations. Thus, the data is acquired from the catalogues published by main HVAC manufacturers.

1.3.3 Model's Development and Integration

Based on the literature review, the proposed models will consist of the following five modules: 1) A 3D BIM module; 2) An energy analysis module; 3) An equipment and system selection module; 4) A HVAC performance module; and 5) A decision making system module. Once all of those modules are developed, they will be all integrated in a way that follows the logical sequence in designing HVAC systems. This will enhance the model's overall capabilities and will make it a user-friendly model in relation to the process of HVAC design.

1.4 Thesis Organization

This thesis consists of the following six chapters:

Chapter Two: Introduction

Chapter Two, Literature Review, covers the conducted literature review that defines the terminologies and concepts used in relation to BIM and HVAC. Even though the reviewed studies lack the evaluation of the methods used for HVAC design, however they indicated that the way to integrate them via BIM environments is still a major gap that needs to be solved.

Chapter Three, Methodology, it outlines the methodology used to develop the integrated model with its five modules. For each module a description of its development process is detailed including its analysis tools and explains how it is linked to the model. Furthermore, the model's development flowchart and the components are presented.

Chapter Four, Model Development, it illustrates the steps of developing the integrated model and its five modules.

Chapter Five, Model Testing, it presents the capabilities of the developed model by stimulating the HVAC design of a real project.

Chapter Six, Conclusion and Future Work, it describes the study's conclusion and identifies how the developed model contributes to the HVAC design for green buildings at the conceptual stage. Moreover, it lists the model's limitations and lists the recommendation for further development and enhancement.

Chapter Two

Literature Review

2.1 Introduction

Recent studies on HVAC optimization systems will be reviewed in this chapter by discussing the typical HVAC systems as characterized by ASHRAE, including the decentralized system and centralized system. Moreover, this chapter outlines the different assessment methods used to evaluate the technical, environmental and economic performances of HVAC systems. The technical performance includes effectiveness, reliability, maintainability and spatial requirement for HVAC design. Life cycle assessment (LCA) is used to evaluate the environmental performance of the HVAC systems. Life cycle cost analysis (LCCA) is the method used for evaluating the economic performance of the selected HVAC systems. While LEED rating system is elected to evaluate the sustainability of buildings after selecting the HVAC systems. Finally, the benefit of applying BIM tools during the design of HVAC is reviewed.

2.2 Optimization of HVAC

Presently, the optimization of HVAC system is a topic of high importance to researchers who are concerned to minimizing the energy consumptions in buildings. HVAC is an assembly system that includes fans, surface cooling devices, pumps, refrigerators and cooling towers, which are interconnected and constrained by each other. Therefore, modeling and optimizing the HVAC equipment is the basis for the system optimization.

Many scholars have conducted in-depth studies on modeling and optimizing HVAC equipment. In terms of cooling coil, series of studies conducted by W. J. Cai (2004), concluded that the model of cooling coil is nonlinear. The earlier model set up was either a linear or a complex nonlinear one. Based on that, a simple and accurate engineering model routed on the principle of heat balance and heat transfer is established, which can also be applied to other HVAC heating equipment (Wang et al., 2004). On that basis, W. J. Cai (2004) established a dynamic model for the cooling coil. If compared with the previous described model, the dynamic model has more practical implementations, in addition to modeling the cooling tower. This model is simpler, more accurate, easier to implement, and it can predict the working state of the cooling tower in real time (Jin, et al., 2007). The dynamic model not only can achieve the purpose of reducing energy consumption, but it can also improve the indoor air quality (Tashtoush, et al., 2005). Because of the complexity of the HVAC system, modeling and optimizing the HVAC equipment could not achieve the best state of operation, which means it cannot obtain the maximum energy saving. Therefore, in order to optimize the HVAC system, one must treat this comprehensively and systematically. With an increased development of the optimization of HVAC equipment, more and more studies have been done. Some scholars started to study the various circuits of the HVAC system based on studying the equipment model. The cooling towers have been the focus of studies done by in S. V. Shelton (Anon, 1988), J. E. Braun (Braun &

Diderrich, 1990) and F. T. Morrison's research. They all have optimized the cooling water circuit. On this premise, H. Crowther (2004) optimized the refrigerators and cooling towers. Since then studies on the optimization of HVAC system have been highly developed. W. J. Cai (2004) made series of studies on the HVAC system optimization. He established the model of cooling water loop and improved the genetic algorithm to get the optimal set point of the equipment. The simulation results showed that the strategy can significantly reduce the energy consumption of the cooling water loop.

2.3 HVAC Components and Systems

Typical HVAC systems contain a cooling plant, heating plant and air distribution systems. In most cases, the cooling or heating water is pumped from chiller/boiler to the Air Handling Unit (AHU). In the AHU, fresh air is introduced for ventilation requirement and mixed with return conditioned air. The mixed is conducted into heat transfer with cooling/heating water through coils and is distributed to the conditioned space (Bhatia, 2015).

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) is a global professional association seeking to advance heating, ventilating, air conditioning and refrigerating (HVAC&R) systems design and construction. The standards and handbooks published by ASHRAE are used worldwide. ASHRAE 62.1 (ASHRAE, 2016b) is the ventilation standard for acceptable indoor air quality including requirement for minimum airflow rate. ASHRAE 90.2 (ASHRAE, 2018) is the energy standard for low rise residential buildings, which establishes the minimum energy efficiency requirements for buildings. ASHRAE 189.1 (ASHRAE, 2015) is the standard for high performance green buildings. While ASHRAE HVAC Systems and Equipment handbook (ASHRAE, 2016a) summarizes all types of components and systems of HVAC. In this study, the literature review related to the HVAC components and systems will mainly follow ASHRAE standard.

2.3.1 HVAC Component

HVAC system's components can be grouped into three functional categories: 1) source components; 2) distribution components; and 3) delivery components. Source components provide or remove heat and moisture. Distribution components convey a heating or cooling medium from a source location to the conditioned space of a building. Delivery components serve as an interconnection between the distribution system and occupied spaces. Systems that are designed to condition multiple spaces in a building usually have distinctly different equipment elements for corresponding function (Grondzik & Furst, 2008).

2.3.2 Decentralized System

A decentralized HVAC system serves a single thermal zone and has its major components located within that zone, on the boundary between the zone and the exterior environment, or directly adjacent to the zone. In general, space conditioning energy from a decentralized system will not pass through another zone on its way to the space being conditioned (ASHRAE, 2016a). There is several advantages associated with the use of decentralized HVAC systems, it provides greater reliability than centralized systems. Because decentralized systems are seemed to be of small capacity and are not interconnected with other units, the maintenance of local systems tends to be simple. In a building where a large number of spaces that may be unoccupied at any given time, such as a dormitory or hotel, decentralized systems may be totally shut off in unused spaces, thus providing potential energy savings (ASHRAE, 2016a).

However, decentralized system units cannot be easily connected. They can usually be centrally controlled with simple on-off functions, where complicated control is not possible. Decentralized systems seemed to be not economic. The coefficient of performance (COP) of a refrigeration system generally increases with capacity, but since each separated unit is normally with low capacity, therefore, the whole system COPs are relatively low. Since decentralized system maintenance may often be relatively simple, therefore such a maintenance may have to occur directly in occupied building space (ASHRAE, 2016a).

2.3.3 Centralized System

A centralized HVAC system may serve one or more thermal zones and its major components are located either outside or inside the building. Compared to the decentralized system, space conditioning energy from a centralized system must pass through zone boundaries, which on its way to the space or spaces being conditioned. If conditioning is transferred only by means of heated or cooled air, the system is termed as an all-air system. If conditioning is transferred only by means of hot or chilled water, the system is termed as an all-water system. If conditioning is transferred by a combination of heated/cooled air and hot/chilled water, then the system is termed as an air-water system (ASHRAE, 2016a).

There is several advantages of the centralized HVAC systems. Centralized systems allow major equipment components to be isolated in a mechanical room, which is more convenient for maintenance and yet it can reduce the noise impact on occupant. Centralized HVAC systems are usually considered to be of high efficiency. Larger capacity refrigeration equipment is usually more efficient than smaller capacity equipment. Larger systems can utilize cooling towers, which would improve the system’s efficiencies. Centralized systems can also utilize smarter control strategy, which can reduce the building’s energy consumption (ASHRAE, 2016a).

On the other hand, Centralized HVAC systems have some disadvantages. For instance, as a non-distributed system, failure of any major equipment component (such as a pump or chiller) may affect the entire building. Whereas system size and sophistication increase, maintenance may become more difficult. Large, centralized systems tend to be less intuitive than the smaller, decentralized systems. Also larger duct’ s sizes may require more space to set ductwork (ASHRAE, 2016a).

Generally, all-air systems are the most commonly used centralized HVAC systems in buildings. Unfortunately, air is not an efficient heat transfer medium because it requires big volume to build the ductwork. Sometimes, where ductwork cannot be reasonably accommodated in the building design, air-water or all-water system may be considered. Another concern that should be considered is the air quality of all-air system. Air-water systems are more popular in renovation projects for the improvement of indoor air quality (ASHRAE, 2016a).

2.4 Life Cycle Assessment (LCA)

In the 60s, the Mid West Research Institutes was commissioned by the Coca-Cola incorporation to conduct a research on beverage containers, which began the work about life cycle assessment. Then number of institutions in Europe also implemented series of similar studies for packaging.

In the 70s, the objectives of the study were changed from packaging to raw materials, as well as the exploitation and use of energy (Frischknecht et al., 2007). People started to realize the significance of life cycle assessment in energy consumption, where some international organizations tried to use this method to evaluate some existing products.

Since 1980, because of the scarcity of energy that became a global problem, more countries around the world, including organizations and enterprises commenced to focus on life cycle assessment. In 1990, the society of Environmental Toxicology and Chemistry (SETAC) was the first to host an international seminar about LCA (Gray A., 1991). Subsequently, ISO formally drafted sections about life cycle assessment into their system. Since then, the theory of life cycle assessment has been rapidly developed. The basic concept of LCA has been widely used in many studies and became an important mean for environmental evaluation. There are many LCA tools that can be used to measure the environmental impact, such as KCL-ECO; LCAiT; PEMS; SimaPro; and TEAM (Osman & Ries, 2007).

ISO made some changes to the framework of SETAC and finally published ISO 14040. Life cycle assessment is divided into four main parts, namely: a) goal definition and scope; b) inventory analysis; c) impact assessment; and d) interpretation. The interconnection of them is shown in figure 2.1 as per Cabeza et al, (2014). Different from the framework published by SETAC, improvement assessment was replaced by interpretation (ISO, 1999a); (ISO, 1999b); (ISO, 2000a); (ISO, 2000b).

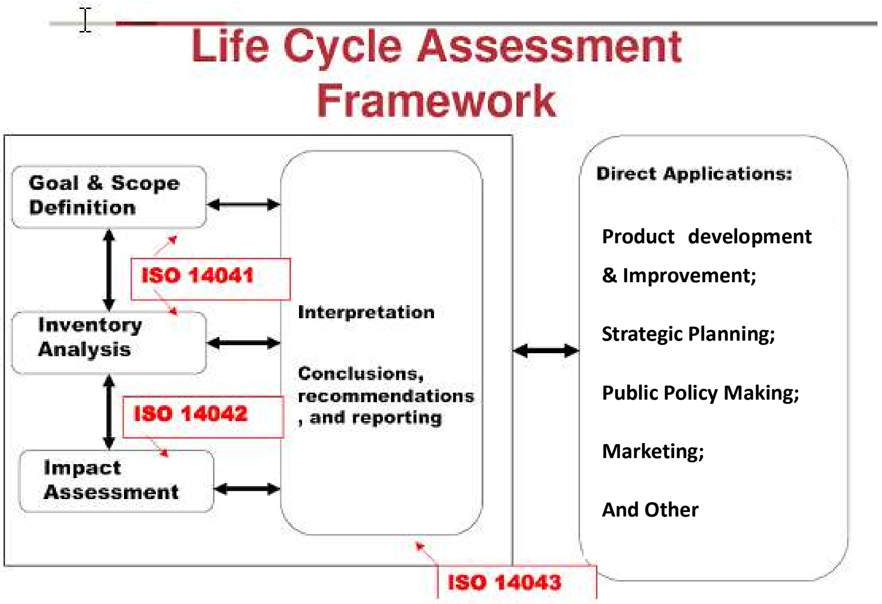


Figure 2.1 The framework of LCA (Cabeza et al, 2014)

2.4.1 Goal definition and scope

The first step of a life cycle assessment study is to define its scope. It mainly includes defining the objective of the study; determining the system boundaries; and listing the assumptions and data requirement.

2.4.2 Inventory Analysis

Life cycle inventory (LCI) is a process of data collection of all emissions and consumptions for each step of the life cycle assessment. It requires a lot of data for each element in the inventory analysis, such as raw materials, energy consumptions and environmental emissions that must be quantified. In most cases, that data cannot be obtained from the literature, yet it has to be supplied by manufacturers . Reusing data from other studies can be considered but the quality of that data is of great significance, therefore one must be very careful in using such data. There are several databases that are commonly used (Reiter, 2010):

1) Ecoinvent database, which is used in various LCA studies on buildings,
2) SimaPro database,
3) Worldwild LCI Database for Steel Industry Products, and
4) US Life cycle inventory database.

The results of the environmental impact may vary depending on the database used for the inventory inputs and outputs.

2.4.3 Impact Assessment

Life cycle impact assessment (LCIA) aims at evaluating the conversion of emissions into environmental and health impacts of a product, system or service using the results of the life cycle inventory analysis.

2.4.4 Interpretation

Interpretation is the final phase of the LCA in which the results of the inventory analysis and the impact assessment are combined in order to reach further conclusion.

2.5 Life Cycle Cost Analysis of HVAC Systems

Presently, life cycle cost of HVAC system is one of the most important factors that determine the HVAC design. In previous years, the cost of HVAC systems mainly focused on the initial investment while neglecting the operating, maintenance and demolition costs of the systems, so that the overall benefits of the HVAC systems are not enough. At present, with the increased attention to sustainable development and green buildings, life cycle cost analysis became a hot research spot for scholars. The National institute of Standards and Technology(NIST) Handbook (Butcher, et al., 2015) defined life cycle cost as: an economic method of project evaluation in which all costs arising from owning, operating, maintaining, and ultimately disposing of a project are considered to be potentially important to that decision.

2.6 Leadership in Energy and Environmental Design (LEED)

LEED standard is a series of building energy conservation and environmental protection certification system formulated by the United States Green Building Council (USGBC) (Kubba, 2015). The USGBC, which is a third-party organization, will make a comprehensive investigation of the projects in the areas of sustainable site selection; water resources use; energy and atmosphere; resources and materials; and indoor environmental quality; etc. The major means of investigation is the relevant green building where engineers submit a variety list of materials that can prove that the building meets the corresponding standards. At the end, the council examines the score points, to define the level of certification, which are divided into platinum grade (more than 80 points), gold grade (60 $\leqslant$ 79 points), silver grade (50-59 points) and certified grade (40-49 points).

The latest versions of the standard are LEED-V4 for buildings, LEED system is divided into: New Construction; Existing Buildings; Homes; Schools; Healthcare; Retail; Commercial Interior; and Core& Shell. For the whole life cycle of buildings, LEED-V4 standard mainly aims at different evaluation systems in building design and construction, operation and maintenance, interior design and construction, etc. In this study, the energy saving project is a commercial building, which belongs to the building design + construction (BD+C) in LEED certification.

LEED-BD+C v4 has 7 categories: Sustainable Sites; Water Efficiency; Energy & Atmosphere; Material & Resources; Indoor Environmental Quality; Innovation in Design and Regional Priority (Kubba, 2015). It has 100 base credits in total. Also, there are 6 possible points related to Innovation in Design and 4 credits for Regional Priority.

2.7 Multiple Criteria Decision-Making (MCDM)

Since 1960, MCDM was a popular research theme. MCDM methods was designed to generate an optimal alternative, classify alternatives in different categories, and rank alternatives by subjective preference (Mardani, et al., 2015). By using MCDM, one can solve complex problems by breaking them into different objectives. After weighing some considerations and making judgements about objectives, those objectives are rebuilt for decision-makings. MCDM consists of two main categories: 1) Multi-Objective decision making (MODM), where the objectives are not predetermined, but arise from the optimization. 2) Multi-Attribute decision making (MADM), where the objectives are always predetermined and a small subset is evaluated against a set of attributes (Anil, et al., 2016). For both methods, when comparing the ranking of each attribute's combination, the best alternative will be chosen. The methods that are widely used in MADM include: TOPSIS; VIKOR; AHP; DEMETEL; ELECTRE; and PROMETHEE etc.

Traditionally, experts choose materials that their characteristics are known by either using trial and error techniques or by employing their previous experiences, which may cause multiple problems related to the expectations, standards, and companies' budgets. The deficiency of this traditional method can be prevented by using the MADM, which is basically based on a complex comparison between available alternatives (Mardani et al., 2015).

Based on a study by Ayşegül Tuş Işık and Esra Aytaç Adalı (2017), ROV and Entropy methods where used to select apple. Modanloo et al. (2016) chose TOPSIS and MOORA methods for the selection of sheet hydroforming process parameters (Modanloo, et al., 2016). Anil et al., (2016) proposed to combine entropy and AHP-TOPSIS methods for the evaluation of internet shopping malls and solution optimality. Chuansheng et al., (2012) combined AHP and Entropy methods to evaluate the safety of smart grid. Huang (2012) utilized AHP and Entropy methods to determine the establishment of green building technology cost.

2.7.1 Analytic Hierarchy Process (AHP)

AHP is a scientific evaluation method that combines qualitative and quantitative analysis put forward by American operational research scientist T.L. Saaty (2008) when people's evaluation of decision-making is not scientific due to many influencing factors and unable to quantify the importance of each factor. It represents an accurate approach for quantifying the weights of decision criteria (Mardani, et al., 2015). Individual experts' experiences are utilized to estimate the relative magnitudes of factors through pair-wise comparisons. The basic steps of AHP method to solve HVAC design problem are listed in methodology.

2.7.2 Entropy Weighting Method

The entropy weighting method is an important information weight model that has been extensively studied and practiced (Liu, et al., 2010). Compared with various subjective weighting models, the biggest advantage of the entropy weighting is the avoidance of the interference of human factors on the weight of indicators, thus enhancing the objectivity of the comprehensive evaluation results (Ding, et al., 2017). Therefore, the entropy weighting method has been widely used in decision-making in recent years. For example, Wang et al. (2009) developed fuzz multi-criteria model to make a comprehensive assessment on HVAC schemes, six HVAC systems are evaluated and compared in multi-criteria. Based on entropy weighting method, Liu (2017) created an evaluation index system of green building energy-saving technology.

2.7.3 TOPSIS Method

Since the AHP-Entropy method cannot process the normalization of the performance value of each criterion, the TOPSIS method is introduced to integrate the criteria and rank alternatives. TOPSIS was originally developed by Ching-Lai Hwang and Yoon (1981) with further developments by Yoon (1987). And it is based on the idea that the best alternative should have the shortest distance from an ideal solution. To achieve the goal, we need to find the farthest distance from the negative ideal solution and the closest distance from the positive ideal solution. The steps of TOPSIS method are listed in methodology.

2.8 Building Information Modeling (BIM)

2.8.1 The Concept of BIM

In 1975, Chuck Eastman of Carnegie Mellon University was the first to propose the concept of green building. In 1986, Robert Aish for the first time put forward the concept of Building Modeling in his article. In 1997, the first edition of the Industry Foundation Classes (IFC) for information transfer was published (Laiserin, 2003). Although many software and applications were developed based on IFC, which obtained some achievements, the model is not widely used (Laiserin, 2003). In 2002, Autodesk officially submitted an application to AIA (American Institute of Architects) in order to define BIM.

The National Building Information Model Standard (NBIMS) defines BIM as: A digital representation of the physical and functional characteristics of a facility. It serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions made during its life cycle.

Since the 21st century, computer science is highly developed, which provided a solid foundation for the application of BIM technology and the relevant studies on BIM have also been greatly increased.

2.8.2 BIM's Application

The concept of BIM originates from the US, and now it is widely used in Europe and Asia. Being the first country to use BIM, the United States is ahead of other countries in the world in the research and development of BIM.

In 2003, the General Services Administration (GSA) implemented the 3D-4D BIM program, which is intended to satisfy the request of customers for the management of design, construction and maintenance (Nachtigall et al., 2006). In fall 2006, USACE established a conference with Academia, and Legal firms to conduct discussions on BIM issues. According to a survey by McGraw-Hill survey (Bernstein et al., 2012), the proportion of BIM-based projects in North America rose from 17% in 2007 to 49% in 2009 and 71% in 2012.

In 2012, the Office for National Statistics of England published a survey report for BIM, which collected professional suggestions from 1,000 construction engineers. The result showed that 78% of them agreed that BIM is the future of construction projects, 31% of them are using BIM in their projects, 75% of them believed that they would use BIM technology in some projects by the end of 2012 and nearly 95% of them plan to use BIM within the next five years (Johnston et al., 2018).

2.8.3 Characteristics of BIM

Compared to CAD 2D plane drawing, BIM occupies absolute advantages. That is the reason why BIM can be admitted and highly supported by various countries. With the continuous update of BIM tools, BIM currently has five main characteristics:

1) 3D Visualization: The designed building is in three dimensions (3D), so that the architectural design can be visualized, and the designed building model can also be rendered to form some very realistic drawings. For plumbing and electric engineering, 2D drawings can demonstrate simple ducts and water pipes work. However, for more complicated projects, if one continues to cut through the pipeline to check them, it will bring a lot of workload to engineers, which will lead to errors that cannot be tested. The 3D visualization capability of BIM can solve those type of problems. For the later operating and maintenance stage when the pipeline needs to be repaired, with the 3D model, it will be very fast to find the location of the faulty pipeline, which may avoid looking for it in the thick 2D drawings.

2) Improvement of Collaboration: The traditional process of engineering design is usually initiated with the architectural and structural design. Based on the preliminary design, electrical, heating, pipe and plumbing engineers finish their conceptual design independently and separately. Architectural engineers modify the design drawings according to the problems put forward by different engineers. The revised drawings are sent to different engineers again. During the design stage, different engineers will contact each other pairwise to adjust their design. For engineering design that occupies large space, such as HVAC design, it is necessary to check the complex overlapping parts to see if there are any problems in the pipeline. If omissions in the process of inspection cannot be discovered, it will result in extra costs and prolonged construction period. However, BIM is quite different from the traditional design method. After the preliminary model is completed under the cooperation of architectural and structural engineers, the model is saved in the main server. The other engineers can directly link their design model to the preliminary model. If any part of the design is updated, it can be discovered by others. Through collaborative design, the communication of different engineers is reduced, and the design time is saved. Through 3D views, it will be easy to check the overlapping areas. The result of collaborative design is to avoid the redesign, which can save cost and shorten construction period.

3) Simulation: The model built within BIM environment can be used not only for design, construction and operation, but also for sun analysis, outdoor air flow simulation and heat conduction simulation during the early stage of design. During the construction stage, construction simulation (3D model + time) can be carried out to guide the construction. During the operation stage, fire smoke and evacuation can also be simulated. The above-mentioned simulations can be conducted through several software, but all of the simulations are based on the original BIM model, which avoids the need of re-modeling in the other software, this will reduce the workload.

4）Parameterization: It is one of the important characteristics of BIM. In the process of designing and modeling, designers use parameterized components to build their models. Each component in the model is digitized, such as flow or velocity in air ducts and water pipes, material composition and material characteristics of walls and structures.

5) Software Development: The function of BIM is very powerful, but there is no software that can independently manage and share the information of the whole life cycle of BIM. BIM tool has application programming interface (API). Through the development of API, the modeling work can be transferred automatically, which improves the efficiency of modeling. Similarly, the functions of other software can be centralized into BIM tool.

2.9 Information Transmitting in BIM

Autodesk is a design software and service company, and its products for drawing and modeling are widely used by researchers and designers, such as AutoCAD and Revit. DXF and DWG are both compatible with AutoCAD, DXF carries 2D information and

DWG carries 3D information. The Green Building XML schema (gbXML) is an open schema developed to facilitate transfer of building data stored in BIM models. The Industry Foundation Classes (IFC) data model is intended to describe the building and construction industry data.

DXF and DWG: AutoCAD DXF (Drawing Interchange Format, or Drawing Exchange Format) is a CAD data file format developed by Autodesk for enabling data interoperability between AutoCAD and other software. DWG is used for storing two- and three- dimensional design data and metadata. In addition, DWG is supported by many other CAD applications.

gbXML: gbXML is the underlying architecture of Autodesk's Green Building Studio commercial on-line energy analysis product (Cheng, 2010), it is the main export option for energy analysis. gbXML can carry construction information for single or multiple buildings. It is widely applied in the data exchange of Autodesk, Graphisoft, Bentley and so on. Figure 2.2 shows how building’s information can be transferred by gbXML (Jalaei, 2015).

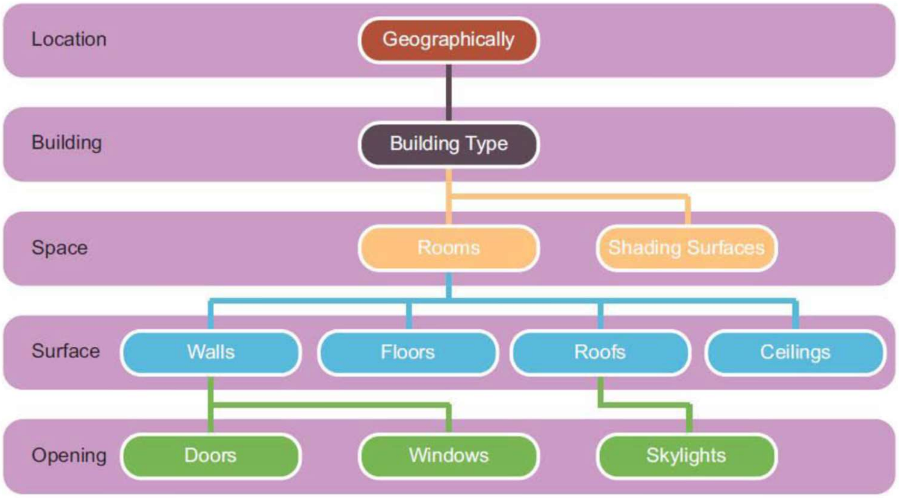


Figure 2.2 Hierarchy diagram of the gbXML schema (Jalaei, 2015)

Industry Foundation Classes IFC: IFC is an open file format. It is developed by buildingSMART (International Alliance for Interoperability, IAI) to facilitate interoperability in the architecture, engineering and construction (AEC) industry. It is a format commonly used as a collaboration format in BIM based projects. The rule of IFC model is similar to STEP, which utilizes the same EXPRESS (Liu, 2011).

2.10 Functionality of Revit for 3D Design

Autodesk Revit as a BIM tool includes many functionalities that enable the creation of a comprehensive 3D building information model, which consists of the whole building systems including architectural, structural and MEP components.

All components of the model built in Revit are based on categories of objects, which are known as families in Revit terminology. Each family has its own size, shape, materials, components and parameters. Families in Revit can be divided into three categories (Laiserin, 2003):

- System Families, such as walls, floors, roofs and ceilings, which are built inside a project.
- Loadable Families / Components, which are built with primitives (extrusions, sweeps, etc.) separately from the project and loaded into a project when needed.
- In-Place Families, which are built in-situ within a project with the same toolset as loadable components

Each family in Revit has its own instance parameters and type parameters. Instance parameter enables designers to modify the parameter value separately for every instance. Whereas, type parameter enables designers to modify the parameter value, that is applied to all elements of the family type. Type parameter will affect all existing instance in the model. However, instance parameter will only affect the designated families.

ODBC (Open Database Connectivity): ODBC is a standard application programming interface for accessing data management system (Jalaei, 2015). For the convenience of managing the parameters of families, all the information of a model built in Revit can be connected with an external database (Excel, Access) for exporting and importing data through ODBC.

2.11 Energy Analysis in BIM

Energy simulation and analysis tools are often applied to design sustainable and Energy efficient buildings, such as Ecotect, IES (VE), e Quest, Energy Plus, DOE - 2, the Design Builder, HEED, etc., including sound, light, heat, gas, solar Energy, computational fluid dynamics (CFD) analysis and so on. These tools are usually used in the design phase to identify whether the energy design decisions are appropriate. However, creating models by using these tools takes a lot of time. Therefore, BIM and its interoperability can reflect one of the advantages; the model can directly be imported into these tools.

Ecotect is a typical simulation program, which will be discussed later on. IES is an embedded energy analysis tool that can be integrated into BIM environment. These tools eliminate the work of importing and exporting the geometry information of a model. IES (VE) is a powerful energy analysis tool that can be integrated into Revit, which can independently run the load calculation and system simulation as well.

Ecotect: Ecotect is a building design and environmental analysis tool that includes a variety of simulation and analysis functions to help users to understand how buildings operate. It enables designers to use the analysis functions in a 3D interface. It provides solar, lighting, sound environment analysis, thermal analysis, ventilation and air distribution analysis, and other functions.

The simulation engine of Ecotect follows CIBSE (Chartered Institution of Building

Services Engineers) rule to determine the internal temperature and heat load. The algorithm is more flexible, faster and contains a lot of useful information. Under rule, temperature and load calculation can be divided into two separate processes. When the internal temperature is provided, the calculation of thermal load can be obtained.

There is a lot of files format that can be imported or exported via Ecotect, including simulation program Radiance (RAD, OCT) for luminous, POV Ray (POV), VRML models (WRL), and EnergyPlus (IDF) for thermal simulation. Ecotect can also import geometry information, including files from AutoCAD (DXF), Lightscape (LP), Lightwave (LWO), and VRML (WRL), etc.

IES-VE: IES Virtual Environment (VE) is an energy analysis and performance modeling software that offers a variety of custom modules designed to address different building performance workflows. IES-VE can help users to incorporate sustainable building approaches and analysis into BIM projects.

IES-VE includes integrated data model, which contains various information of architecture and geographic information. 3D model can be directly imported into CAD or Revit via gbXML format.

Default building templates can be applied in IES, and users can also import their own database of construction materials, building control strategy, surface color and the like. Location and weather data can be selected from a database called "Apache", which is specifically designed to simulate HVAC systems.

The thermal analysis of IES-VE is based on the heat balance model, which is proposed by ASHRAE, where the principles of calculation are:

- Use the heat loss of the stable thermal area to predict the heating requirement.
- Use the thermal load to predict the cooling requirement.

The calculation of heating and cooling load can be daily, monthly or yearly. However, Ecotect only provides the yearly thermal calculation yearly and the maximum value of thermal load. Different from Ecotect, IES-VE is not able to support various files format. It mainly applies gbXML where the model built into the IES is usually stored in the independent VE files. The degree of interoperability of IES is very high. For example, integrated data model can be used to make thermal environment simulation, as well as air conditioning heating and cooling load calculation. The application of conveying size model can also be used to predict the ventilation efficiency. The thermal environment impact can also be imported from the Sun Cast application options to improve the thermal load calculation.

2.12 Revit API

As a tool that contributes to the entire life cycle of BIM, Revit has a powerful modeling capability in the construction industry, and its operation can meet almost all the modeling requirements. With the development of architecture and MEP design, Autodesk also introduces new versions every year to update their features and functions. However, it does not mean that the updated Revit tool is efficient. Revit's commands are cumbersome, modeling is step-by-step. Such cumbersome operations bring unnecessary workload to designers, reducing efficiency and indirectly inhibiting the development of BIM technology. Therefore, Revit is not perfect enough, which force researchers to modify it and optimize both its functions and operations.

After Autodesk purchased the software from Revit Technology Corporation, it began packaging the API with its products, allowing developers to get access to secondary development. With API, Revit can own functions of third-party software, providing different projects with Plug-ins at different stages of the life cycle. For example, the world-renowned structural analysis software ETABS developed CSIxRevit by API, which can carry out the load analysis of a building into Revit model. Whereas Affinity, which is developed by Trelligence, can take out the room information from the Revit model in real time by avoiding the heavy investment in modeling and data management. It is directly developed by API and installed in the Revit platform. In year 2017, the Autodesk App Store shows that the amount of Revit secondary developments for architectural design and building performance analysis is 342, and the amount of Revit secondary developments for structural design and mechanism simulation analysis is 132. There are more than 71 plug-ins for the electrical，water supply and drainage design. For instance, Dynamo is added to Revit in 2017, which is a powerful plug-in for the visual programming.

2.13 Summary

This chapter reviews the literature about the traditional optimization methods of HVAC design and the concept of BIM to be integrated it into the HVAC design for green building. Various HVAC systems are basically designed for suiting different buildings. The requirements from building owners are not only about the technical running condition of HVAC, but also the incurred environmental impact and economic cost. These criteria for evaluating HVAC are reviewed, including technical performance of different types of HVAC system based on ASHRAE, life cycle cost, life cycle assessment and LEED rating system for green building. Then, to determine the weightings of these criteria, MCDM method is reviewed and introduced. Since BIM is a process supported by different tools, the function of BIM tools for HVAC design and the possible way to bridge connection among them are reviewed in details.

Chapter Three

Methodology

3.1 Introduction

This chapter describes the methodology that will be used to develop the proposed model, which integrates BIM with HVAC design at the conceptual stage. The proposed model includes five modules that will be developed and interrelated to each other, which are: 1) 3D design module; 2) Energy analysis module; 3) Equipment and system selection module; 4) HVAC performance module; and 5) Decision-making system module. The development of each module will follow a series of steps that are identified from the literature review to simplify the process of designing HVAC for green buildings.

3.2 Proposed Model' s Component

The proposed model will be developed based on the above listed five modules. The 3D design module will be integrated with the energy analysis module since it will rely on BIM tool (i.e., Revit) to extractt the building information. The energy analysis module will be used to make the necessary preparations for the evaluation of the system HVAC performance. The equipment and system selection module will provide numbers of appropriate HVAC alternatives for the optimal selection, it will allow users to customize suitable HVAC products based on what is stored in the database. The HVAC performance module will use three approaches for the evaluation of the HVAC system performance, including: 1) technical performance; 2) economic performance; and 3) environmental performance. The decision-making system will use the AHP-Entropy and TOPSIS methods to develop a way to rank the appropriate HVAC alternatives. The established link between the modules will allow the information to be transmitted in an efficient and quick manner. Figure 3.1 illustrates the components of the proposed model.

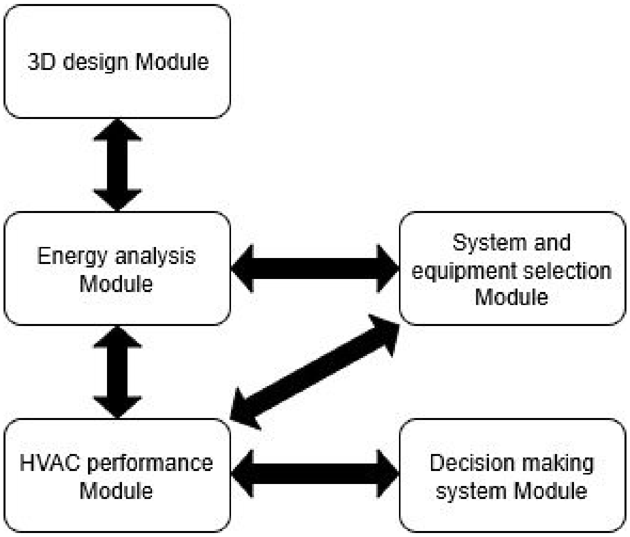


Figure 3.1 Proposed Model's Component Modules

The development of the proposed modules will follow a logical flowchart reflecting the conceptual design of HVAC in real life. Figure 3.2 shows the flowchart of the proposed model.

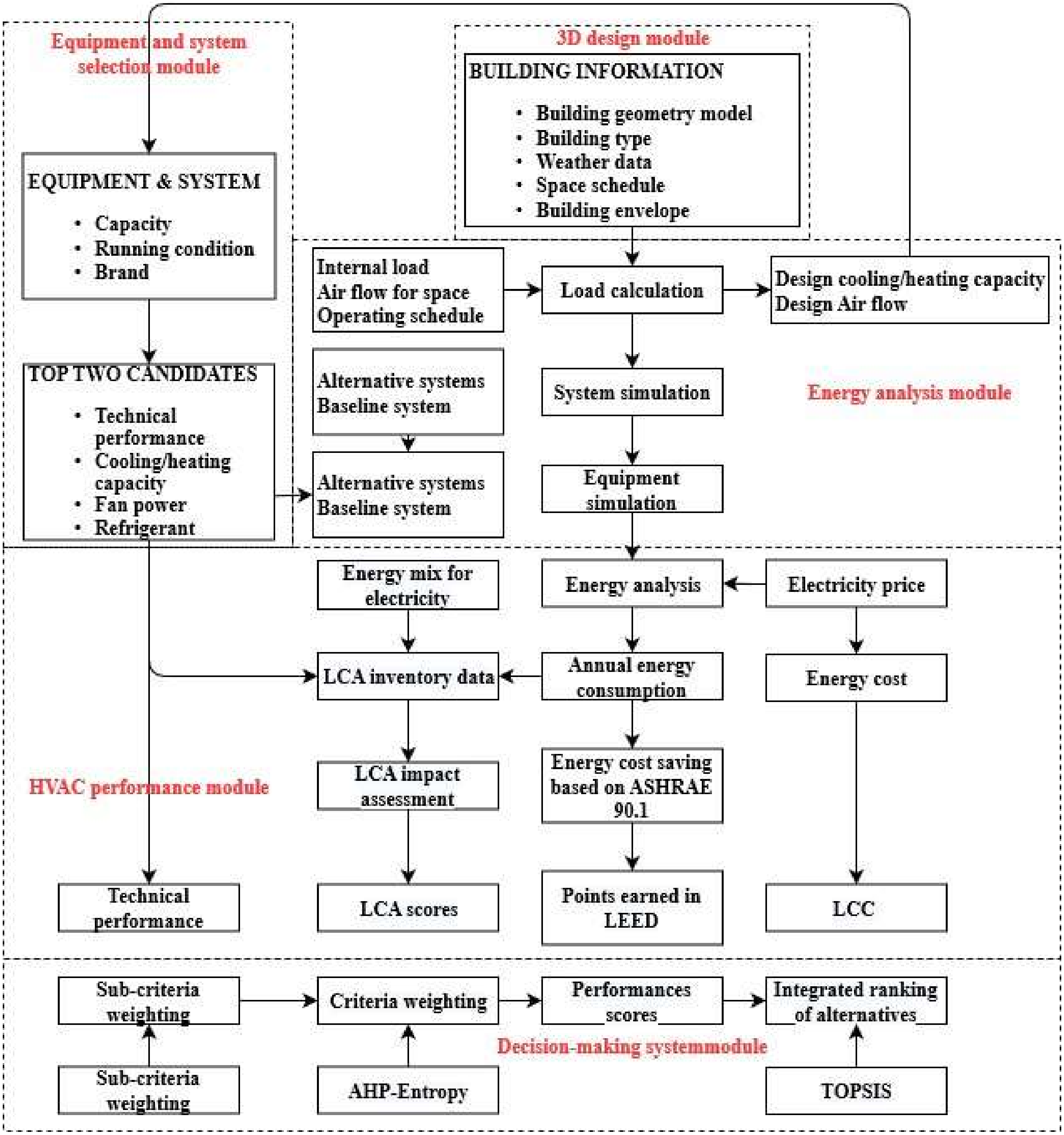


Figure 3.2 The flowchart of overall model

3.3 3D Design module

To guarantee the interoperability of BIM, it is decided to integrate the 3D design module, which is used to model proposed buildings, with the other modules. The entire proposed model is coded in Visual Studio and thus it is better to choose a modeling software that is compatible with the selected programming language (i.e., C#). After considering multiple options, Autodesk Revit is chosen as BIM tool due to its flexibility and capability. Furthermore, Autodesk Revit is a convenient software for 3D construction design, and it is the most commonly used by engineers.

3.4 Energy Analysis Module of HVAC system

Energy analysis is the key to evaluate the performance of HVAC systems. To run a comprehensive energy analysis, a building's design model will be exported from Autodesk Revit and imported into an energy simulation tool. The inputs for load calculation and system simulation include the building information (location, type, weather data, definition of zone and building envelopes) and the design requirements for comfortable indoor environment (internal load, air flow requirement, and space schedules). The energy analysis module will then calculate the required cooling capacity, heating capacity and air flow for specific HVAC systems, which will be provided to users for selecting the factory that assembled HVAC equipment retrieved from the equipment database as will be described later. Since the capacity of an equipment is sized by the energy analysis tool, the result may not reflect the real condition of the energy consumption. Thus, the information of the suggested HVAC equipment will be reloaded into the energy analysis tool in order to generate the annual energy consumption report, which will be used to evaluate the environmental impacts and economic of the proposed system. Those will be used to calculate the potential points that can be earned based on LEED certification system as well as the associated costs.

3.5 Equipment and System Database Module

To establish the connection between the proposed model and the available products in the market, a detailed database that stores information related to the HVAC equipment and systems will be created based on ASHRAE classification for the different types of HVAC. Since the objective of this study is to recommend the appropriate HVAC products from major manufactures to designers, then the information of some decentralized systems is collected and stored in that database, including packaged terminal air conditioner, packaged rooftop system and split system, which are described as follow:

Packaged Terminal Air conditioner: A Packaged Terminal Air Conditioner (PTAC) is a type of self-contained heating and air conditioning system commonly used for hotels, motels, senior housing facilities, hospitals, condominiums, apartment buildings, add-on rooms & sunrooms (ASHRAE, 2016a). Many of those are designed to go through a wall, and having vents and heat sinks both inside and outside.

Packaged Rooftop Air Conditioner: Packaged rooftop air-conditioner may function as a decentralized air-conditioning system if it is not connected to substantial distribution ductwork. A rooftop unit typically consists of a vapor compression refrigeration cycle and a heat source, an air handler, and control devices (ASHRAE, 2016a). The typical capacity of a rooftop packaged unit is greater than the PTAC or unitary air-conditioner. Packaged rooftop units are also commonly used with distribution ductwork in centralized systems.

Residential and Light Commercial Split System: The split system contains two parts of unit, an indoor unit and an outdoor unit. The evaporator and condenser components in small-scale systems often restrict many architectural applications. For example, PTAC systems and unitary units must penetrate vertical elements of the building envelope. Having all system components in a single location would also limit the installation flexibility (ASHRAE, 2016a). A PTAC, for example, can only be installed where a wall is available. Rooftop units work well for low-rise buildings but are not good for high-rise buildings. The split system provides a solution to those potential problems.

Several HVAC systems, from the developed database will be selected as candidates for energy analysis. The information of the factory that assembled the HVAC equipment, including the cooling capacity, heating capacity, AHRI rated air flow, air distribution method, heating method and applied refrigerant are fully stored in the database. From the HVAC database, the module will locate the appropriate equipment for each candidate based on the capacity requirement for each alternative and the designer's preference. After that, the suggested HVAC systems and corresponding equipment will be reloaded into the energy analysis module in order to correct the result of the energy consumption.

3.6 HVAC Performance Analysis Module

The performance analysis module contains the following four criteria for evaluating the performance of HVAC systems: 1) technical performance; 2) environmental performance; 3) economic performance; and 4) LEED performance, and each criterion contains corresponding sub-criteria. The performance value of each criterion will be an input for the decision-making system module for grading.

3.6.1 Technical Performance (P_T)

The purpose of HVAC system is to provide thermal comfort and acceptable indoor air quality. It requires not only the energy efficient operation, but also how reliable and convenient the HVAC system is. In accordance with the criterion for selecting HVAC systems as summarized in ASHRAE Handbook for selecting HVAC systems and equipment, technical performance is determined through 4 sub-criteria: a) energy efficiency ratio; b) reliability; c) constructability; and d) spatial requirement(ASHRAE, 2016a).

Energy Efficiency Ratio (EER): One of the most common efficiency factors to evaluate the effectiveness of the cooling equipment (mostly chillers) is EER. It is expressed as the power into the compressor motor divided by the cooling produced. A lower EER indicates a higher efficiency of the equipment.

$$EER = \frac{Capacity\ (BTUH)}{Power\ Input\ (Watts)} \qquad \text{Equation 3-1}$$

Reliability: Reliability is the probability that a system will perform its function without failure over a specific period of time when used under specific conditions. The achievable points of alternatives is based on the description of reliability of different HVAC systems in ASHRAE standard (ASHRAE, 2016a).

Spatial Requirement: The performance of the spatial requirement of an equipment depends on the real area it occupies. The smaller the room's area of the equipment is, the better the spatial requirement will be. For a centralized system, the equipment room is normally needed, and it is located outside of the conditioned area. The additional cost should be considered to install a secondary equipment for the air/water distribution. However, the decentralized system requires less space for the installation, operation and maintenance. This is because the decentralized system is normally installed separately for both outdoor part and indoor part, while the condenser, evaporator and air conditioning unit can be factory-assembled in one box, which will efficiently reduce the spatial requirement of the equipment.

Constructability: HVAC designers should take the HVAC constructability into account before the project moves to the construction stage. Some of these restrictions will significantly affect the success of the project. Compared with the decentralized system, centralized system requires more coordination for the installation.

To quantify the performance results for later calculation, the performance values (PV) are introduced. Table 3-1 lists the technical performance value (PV_T) for different types of HVAC system on a scale of "poor, fair, good, and excellent" based on the ASHRAE standard (ASHRAE, 2016a), while the corresponding performance value is set on a scale of 1 to 4.

Table 3-1Technical performance value (PV_T) for alternatives

	Packaged rooftop system	Split system	Packaged terminal air conditioner
Energy efficiency	Good (3)	Good (3)	Fair (2)
Reliability	Good (3)	Good (3)	Good (3)
Constructability	Excellent (4)	Good (3)	Excellent (4)
Spatial requirement	Excellent (4)	Excellent (4)	Excellent (4)

3.6.2 Environmental Performance （P_E）

Environmental performance is a criterion aiming to evaluate the environmental impacts that are generated during the life cycle of the HVAC system. Since LCA is a quantitative method, this study completely follows the steps of LCA in order to understand the relationship between the environmental impact and the products. Life cycle assessment (LCA) aims at evaluating the impact and emissions of a product (inventory data) on the environment, system or service. Natural resource inputs and emission represent the amount of emissions created during the production process.

Based on the literature reviews (Ragheb, 2011; Calm, 2002), the green gases generated by refrigerant in the HVAC systems commonly contribute the most to the global warming and ozone depletion. Table 3-2 lists the global warming potential and ozone depletion potential of refrigerant.

Table 3-2 Global warming potential and ozone depletion potential of refrigerant (Calm, 2002)

Refrigerant	Global Warming Potential ($lbCO_2/lb$r)	Ozone Depletion Potential ($lbCFC11/lbr$)
R12	2400	1.00
R22	1700	0.05
R32	650	0.00
R134a	1300	0.00
R152a	120	0.00
R404A	3300	0.00
R407C	1600	0.00
R410A	1900	0.00

There are no globally accepted methodologies to be used for linking inventory data to specific damage categories, which are the sub-criteria of the environmental performance. In this study, BEES+ (as LCA database) will be applied to characterize the impact and damages into Global warming; Acidification; Human Health cancer; Human Health noncancer; criteria air pollutants; Eutrophication; Ecotoxicity; Smog; Natural resource depletion; Indoor air quality; Habitat alteration and Water intake and Ozone depletion. After characterization, the inventory data will be classified into different impact damages (Lippiatt, 2007). For example, CO_2 is classified into the global warming impact. However, other green gases will still impact the global warming. To quantify the damages, all green gas emissions are converted into an equivalent amount of CO_2 emission. Thus, the impact of the product on global warming can be calculated. To comprehensively present the whole environmental impact of a product, the normalization and weighting process of different damage categories is needed (Cooper, 2007). These weighting factors are calculated by using the AHP approach by investigating stakeholder's preferences. The environmental performance value of each criterion will be converted into one-point unit (pt), which represents the individual's annual share regardless if that individual participated in the economy's environmental impacts directly or indirectly. The total of these points will be added together as environmental performance value (PV_E).

Because of the limited and shaded information provided by the manufactures on the composition of raw materials of the equipment, also with the proof of low environmental contribution of that equipment during the production phase over the whole life cycle, the contribution of manufacture production and disposal phase of the HVAC systems is neglected.

3.6.3 Economic Performance （P_C）

The estimated costs of HVAC over its whole life cycle refers to the sum of all the expenses incurred within the whole life cycle of the HVAC starting from the design, through construction, passing by operation and maintenance, and ending by the demolition. That total cost includes the cost of design, construction and installation, operating energy, equipment maintenance, and demolition. The diagram of the cost breakdown is shown in figure 3.3.

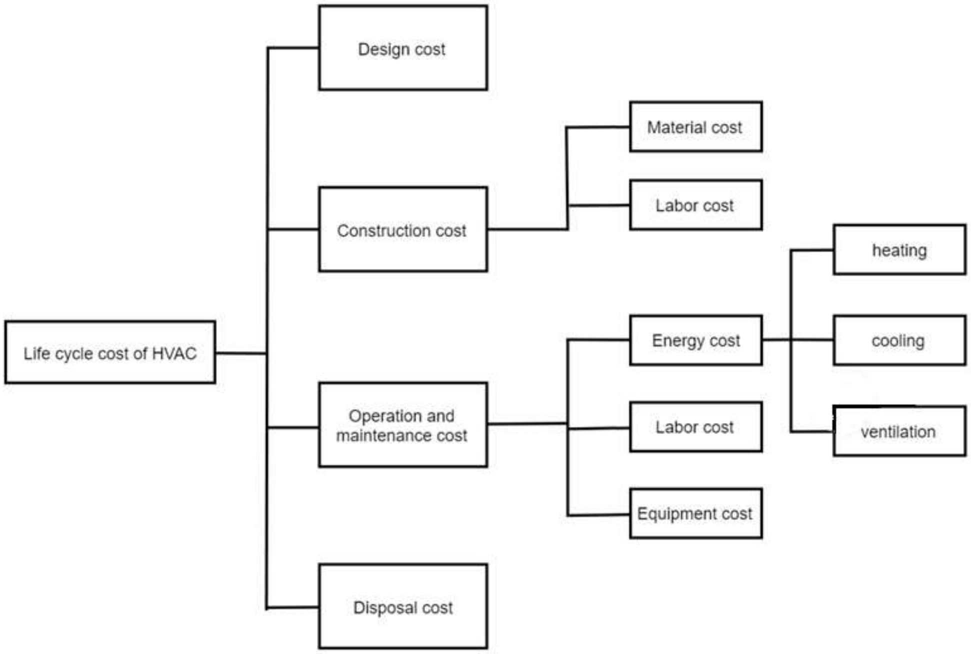


Figure 3.3 The whole life cycle economic cost of HVAC (Chen, 2018)

The mathematical model for calculating life cycle cost (LCC) of HVAC can be expressed by both equation 3-2 and equation 3-3, which are adopted from Xu (2007) study:

$$\mathrm{LCC} = C_0 + \sum_{t=0}^{T} O \times PV_t + \sum_{t=0}^{T} M \times PV_t - S \times PV_T \qquad \text{Equation 3-2}$$

$$PV_t = \frac{1}{(1+r)^t} \qquad \text{Equation 3-3}$$

Where, "C_0" is the initial cost of HVAC system, including the cost for cooling equipment, heating equipment, cooling and heating distribution equipment, air handling and distribution equipment, controls, design, construction, energy and fuel services, mechanical room, electrical service cost, fuel service cost and associated overhead costs;

"O" is the operating cost, the main operating costs are the electricity and other fuel energy usage cost; "M" is the maintenance cost; "PV_t" is the present value of year t. "T" is the length of study period; "r" is the discount rate. Similar, to the process of evaluating the environmental performance, the manufacturers of HVAC are not willing to provide all the necessary information of their products, even for educational purpose, the initial and maintenance cost of the equipment is not be accessible. RS Means cost database (2011) is used to obtain the total cost including overhead and profit for installing the different types of HVAC system. The operating cost, which includes the energy consumption cost, can be obtained by multiplying the local utility energy charge. The whole life cycle cost represents the economic performance value（PV_C）.

The traditional calculation of the construction cost is to calculate the total cost according to the 2D CAD drawing, that is, the unit cost multiplied by the associated quantities. First, there is no doubt that this method is very tedious and error-prone, and as the project becomes more and more complex, a large number of components need to be counted. Second, neither the traditional manual calculation nor the mainstream single cost software can update the changes of the quantities in real time. Nor do the statistics of the project's whole process. If the construction model includes the MEP design, with the emergence of BIM technology, fine cost statistics is possible, because BIM technology can store information about the design planning, construction, management and so on. At the same time, the collected information from the BIM model can reach the component level and can be synchronized with the 3D model. Therefore, regardless of the HVAC or other materials, as long as the BIM model exists, the components' database will be generated, and the quantity will change synchronously with any change made to the design at any time.

3.6.4 LEED Performance（P_L）

LEED is a green building rating system that is used worldwide. LEED raised several requirements for the whole energy consumption and environmental impacts, however the focus of this study will be on the Energy and Atmosphere criterion. There are four prerequisites for Energy & atmosphere (EA) in LEED-BD+C V4, which are:

1）Fundamental commissioning and verification,

2）Minimum energy performance,

3）Building-level energy metering, and

4）Fundamental refrigerant management.

The prerequisites #2 and #4 are mainly related to the HVAC systems. Minimum energy performance requires that the whole building energy simulation of proposed buildings demonstrates an improvement of 5% for new construction, 3% for major renovations, or 2% for core and shell projects in the proposed building performance rating if compared with the baseline building performance rating (Kubba, 2015). Fundamental refrigerant management states that there should be no chlorofluorocarbon (CFC)-based refrigerants used in new heating, ventilating, air-conditioning, and refrigeration (HVAC&R) systems or in a phase-out plan for renovation of existing buildings with CFC refrigerants. The credits for EA, which relate to most of the HVAC systems are: EAc1 Optimize Energy Performance, and EAc4 Enhanced refrigerant management.

EAc1 (Optimize Energy Performance): Optimize Energy Performance follows the criteria in EA Prerequisite Minimum Energy Performance to demonstrate a percentage improvement in the proposed building performance rating compared with the baseline. Points are awarded according to Table 3-3. This process will need the annual energy consumption of a building to be calculated by the energy analysis module.

Table 3-3 Points for percentage improvement in energy performance (Kubba, 2015)

New construction	Major renovation	Points (except Schools and health care)
6%	4%	1
8%	6%	2
10%	8%	3
12%	10%	4
14%	12%	5
16%	14%	6
18%	16%	7
20%	18%	8
22%	20%	9
24%	22%	10
26%	24%	11
29%	27%	12
32%	30%	13

35%	33%	14
38%	36%	15
42%	40%	16
46%	44%	17
50%	48%	18

EAc4 (Enhanced Refrigerant Management): EA credit 4 can be earned by any of the following two options: Option1, where there are no refrigerants or low-impact refrigerants (1 point) or Option 2, where the refrigerants used in the HVAC systems minimize or eliminate the emission of compounds that contribute to ozone depletion and climate change.

For Option 2, the refrigerants must comply with the following equations:

$$LCGWP + LCODP \times\ 10^5\ \leq 100 \qquad \text{Equation 3-4}$$

Where,

$$LCODP = [ODPr \times (Lr \times Life + Mr) \times Rc]/Life \qquad \text{Equation 3-5}$$

$$LCGDP = [GWPr \times (Lr \times Life + Mr) \times Rc]/Life \qquad \text{Equation 3-6}$$

LCODP = Lifecycle Ozone Depletion Potential (lbCFC11/Ton-Year) Equation 3-7

LCGWP = Lifecycle Direct Global Warming Potential (lbCO_2/Ton-Year) Equation 3-8

ODPr = Ozone Depletion Potential of Refrigerant (0 to 0.2 lb CFC11/lb refrigeration),

GWPr = Global Warming Potential of Refrigerant (0 to 12,000 lb CO_2/lb refrigeration),

Lr = Refrigerant Leakage Rate (0.5% to 2.0%; the default is 2%),

Mr = End-of-life Refrigerant Loss (2% to 10%; the default is 10%),

Rc = Refrigerant Charge (0.5 to 5 lb of refrigerant per ton of cooling capacity),

Life = Equipment Life (20 years; default based on equipment type).

The points earned in EAc1 and EAc4 will be added together as LEED performance value PV_L and input in the decision-making module.

3.7 Decision Making System Module

The decision-making system module will directly output the comparison results of alternatives, the one with the highest score will be the optimal selection. The combination of AHP-Entropy methods will be applied to weight the criteria and sub-criteria of performances, and the results of each alternative will be ranked by TOPSIS method.

3.7.1 Analytic Hierarchy Process (AHP)

1) The hierarchical structure of AHP

An AHP hierarchy is a structured means for modeling the decision between hand. It consists of an overall goal, a group of options or alternatives for reaching the goal, and a group of factors or criteria that relate the alternatives to the goal. The criteria can be further broken down into sub-criteria, sub-sub-criteria, and so on, in as many levels as the problem requires.

a) In general, the highest layer represents the problem of using the analytical method to study the solution, that is, the goal layer.

b) The middle layer is the criteria layer, which refers to the intermediate link needed to achieve the final goal, which can be broken down into sub-criteria layers based on the study.

c) The lowest layer is the alternative layer, which represents the chosen alternatives chosen to be evaluated.

Figure 3.4 shows the hierarchy structure for choosing the appropriate HVAC system. The goal layer is to select one HVAC system, which is the purpose of the decision-making model. The criteria layer contains four performances for evaluating HVAC system, including technical performance; economic performance; environmental performance and LEED performance. Technical performance is further developed into four sub-criteria in the sub-criteria layer, including EER, reliability, spatial requirement and constructability.

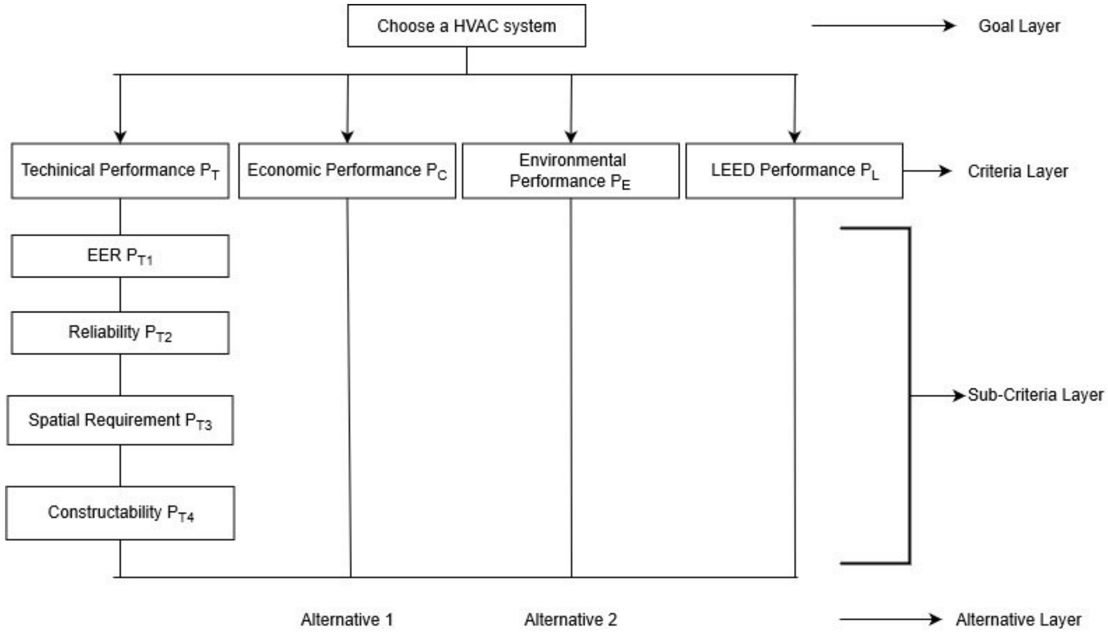


Figure 3.4 Hierarchy structure for choosing the appropriate HVAC system

2) The judgment matrix

According to the hierarchical model, the criteria of each level are compared. By the pairwise comparison of HVAC performances based on the preference of the decision maker, the relative importance of the criteria is obtained, and the value is assigned. In order to quantify the importance of one criterion over another, the importance intensity is introduced as shown in Table 3-4.

Table 3-4 Importance scale for pairwise comparison

Importance scale	Description
1	Two criteria are equally important to the preference
3	One criterion is moderately important than the other
5	One criterion is strongly important than the other

7	One criterion is very strongly important than the other
9	One criterion is extremely important than the other
2, 4, 6, 8	Intermediate values between two adjacent importance judgment

Figure 3.5 list an example of the importance scale for pairwise comparison of HVAC performance based on the decision maker's preference.

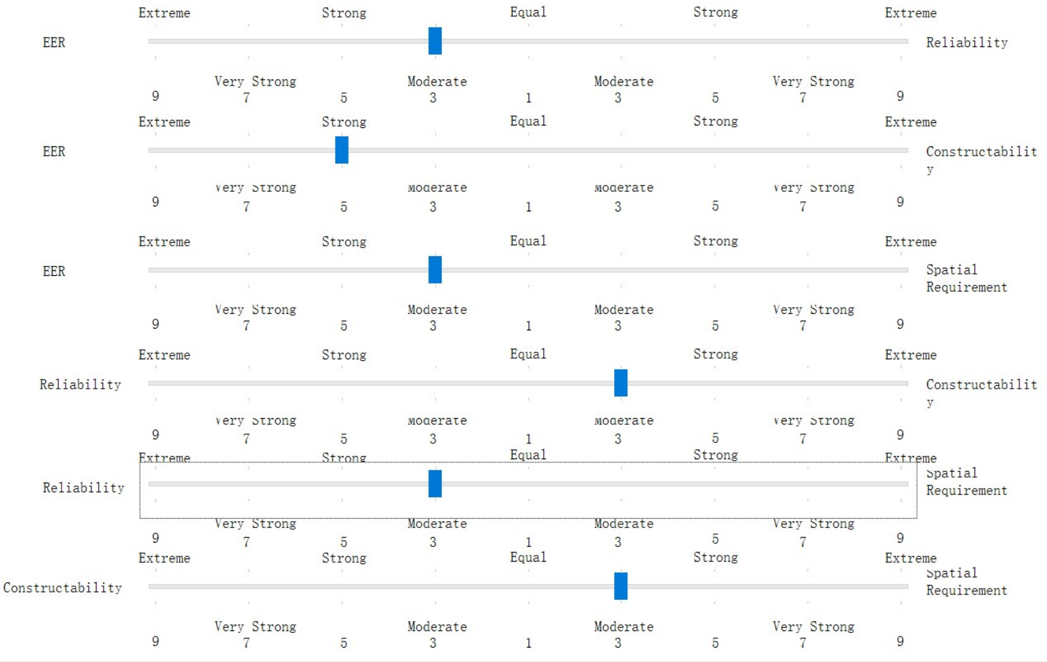


Figure 3.5 Pairwise comparison of HVAC performance

After identifying the pairwise comparison for each two HVAC performance of each layer, the judgement matrix of the pairwise comparison can be expressed as shown in table 3-5.

Table 3-5 Pairwise comparison matrix

	Technical Performance P_T	Environmental Performance P_E	Economic Performance P_C	LEED Performance P_L
P_T	p_{TT}	p_{ET}	p_{CT}	p_{LT}
P_E	p_{TE}	p_{EE}	p_{CE}	p_{LE}
P_C	p_{TC}	p_{EC}	p_{CC}	p_{LC}
P_L	p_{TL}	p_{EL}	p_{CL}	p_{LL}

The properties of the matrix are as listed:

$p_{ij} \neq 1/p_{ij}$,

$p_{ii} = 1$.

p_{ij} represents the importance of criteria P_i over criteria P_j , $1/p_{ij}$ represents the importance of criteria P_j over criteria P_i .

3) Weighting of HVAC performance

The weighting for the criteria P_i is calculated based on equations 3-9. The sum of the weightings in each layer should be equal to 1. The weighting factor of criteria P_i is calculated as:

$$w_{P_i} = \sqrt[4]{p_{i1} \times p_{i2} \times p_{i3} \times p_{i4}} \qquad \text{Equation 3-9}$$

For example, the weighting factor of technical performance can be calculated as by using Equation 3-10:

$$w_{P_T} = \sqrt[4]{p_{TT} \times p_{TE} \times p_{TC} \times p_{TL}} \qquad \text{Equation 3-10}$$

3.7.2 Entropy Weighting Method

The Entropy method can be easily adopted because it is highly reliable in information measurement. First, the decision matrix of multi criteria problem with alternative HVAC systems and criteria is shown in Table 3-6 in which " PV_{ij} " represents the performance value of the alternative i to the criteria j (Anil et al., 2016).

Table 3-6 Decision matrix of multi criteria problem

	Criteria			
Alternatives	Technical Performance Value PV_T	Environmental Performance Value PV_E	Economic Performance Value PV_C	LEED Performance Value PV_L
Residential and Light Commercial Split System	PV_{1T}	PV_{1E}	PV_{1C}	PV_{1L}
Packaged rooftop air-conditioner	PV_{2T}	PV_{2E}	PV_{2C}	PV_{4L}

In order to obtain dimensionless values of different criteria to make comparison among them, the matrix should be normalized by using equation 3-11:

$$q_{ij} = {PV_{ij}}\Big/{\sum_{i=1}^{2} PV_{ij}} \qquad \text{Equation 3-11}$$

Then, calculate the entropy values (e_j) are determined for each criterion by using equation 3-12:

$$e_j = -k\sum_{i=1}^{2}(q_{ij}\ln q_{ij}) \qquad \text{Equation 3-12}$$

Where,

$$k = \ln\frac{1}{2} \qquad \text{Equation 3-13}$$

The divergence (d_j) of the intrinsic information for each criterion is calculated by using equation 3-14:

$$d_j = 1 - e_j \qquad \text{Equation 3-14}$$

The higher "d_j" is, the more important the criterion j is for the purpose. The weighting for each criterion can be obtained from equation 3-15:

$$w_j = \frac{d_j}{d_T + d_E + d_C + d_L} \qquad \text{Equation 3-15}$$

3.7.3 The combination of AHP and Entropy evaluation model

The weightings of each criterion determined by the entropy method are entirely based on the relationship of the data. However, sometimes the objective weights are different from reality. Whereas, the weights determined by AHP are obtained based on people's preference, which usually ignores the data information. So, the subjective weighting method AHP and the objective weighting entropy method are combined. This study determines the overall weights by using the following equation 3-16:

$$w_j = \frac{w_j^A \times w_j^E}{w_T^A \times w_T^E + w_E^A \times w_E^E + w_C^A \times w_C^E + w_L^A \times w_L^E} \qquad \text{Equation 3-16}$$

where, "w_j^A" is the weight of criteria j obtained via AHP method and "w_j^E" is the weight of criteria j obtained through entropy method.

3.7.4 TOPSIS Method

Since the AHP-Entropy method cannot process the normalization of the performance value of each criterion, the TOPSIS method is introduced to integrate the criteria and rank alternatives. Technique for order performance by similarity to ideal solution (TOPSIS) method is based on the idea that the best alternative should have the shortest distance from an ideal solution. The decision matrix of TOPSIS will be the same matrix as listed in Entropy weighting method. The steps of this method are summarized as follow based on (Anil et al., 2016) and (Roszkowska, 2016):

Step 1: Construct the normalized decision matrix. The normalization of the decision matrix is performed by using Eq. 3-17.

$$r_{ij} = {PV_{ij}}\Big/{\sum_{i=1}^{2} PV_{ij}} \qquad \text{Equation 3-17}$$

Where, "r_{ij}" is a dimensionless number representing the normalized performance value of alternative i on criteria j.

Step 2: Construct the weighted normalized decision matrix. The columns of the normalized decision matrix are multiplied by the related weights (w_j) obtained from equation 3-18. The weighted normalized decision matrix is defined as:

$$V_{ij} = r_{ij} \times w_j \qquad \text{Equation 3-18}$$

Step 3: The ideal and negative ideal solutions are determined respectively, as follows:

$$\{V_1^+, V_2^+, \cdots, V_n^+\} = \left\{\left(\left(\max_i V_{ij} \,\middle|\, j \in K\right), \left(\min_i V_{ij} \,\middle|\, j \in K'\right) \,\middle|\, i = 1, 2, \ldots, m\right)\right\} \qquad \text{Equation 3-19}$$

$$\{V_1^-, V_2^-, \cdots, V_n^-\} = \left\{\left(\left(\min_i V_{ij} \,\middle|\, j \in K\right), \left(\max_i V_{ij} \,\middle|\, j \in K\right) \,\middle|\, i = 1, 2, \ldots, m\right)\right\} \qquad \text{Equation 3-20}$$

Where, "K" and "K'" are the index set of benefit criteria and the index set of cost criteria, respectively.

Step 4: Compute the distances from the ideal and negative solutions. These two Euclidean distances for each alternative are calculated by using equations 3-21 and 3-22:

$$S_i^+ = \left\{\sum_{j=1}^{n}\left(V_{ij} - V_j^+\right)^2\right\}^{0.5} \quad i = 1, 2, \ldots, m; \quad j = 1, 2, \ldots, n \qquad \text{Equation 3-21}$$

$$S_i^- = \left\{\sum_{j=1}^{n}\left(V_{ij} - V_j^-\right)^2\right\}^{0.5} \quad i = 1,2,\dots,m; \quad j = 1,2,\dots,n \qquad \text{Equation 3-22}$$

Step 5: Calculate the relative closeness to the ideal solution. The relative closeness of an alternative to the ideal solution is indicated by "C_i" and calculated by using equation 3-23

$$C_i = \frac{S_i^-}{S_i^- + S_i^+} \qquad i = 1,2,\dots,m; 0 < C_i < 1 \qquad \text{Equation 3-23}$$

The appropriate HVAC system is determined by the one with the highest C_i value.

3.8 Summary

This chapter presented the methodology that will be used to develop the integrated model, which includes the following modules: 1) 3D design module; 2) energy analysis module; 3) equipment and system selection module; 4) performance analysis module; and 5) decision-making module. The building model is created in the 3D design module by using Revit as BIM tool. The energy analysis module receives the geometry and information of the 3D building model from Revit and conducts energy analysis of the selected HVAC. The project information including the building information and design requirements need to be collected and fed as inputs. The outputs of the energy analysis module contain the basic capacity requirement of the equipment for selecting the appropriate HVAC products, and annual energy consumption for evaluating the environmental impacts, estimated cost and sustainability. The equipment and system selection module will create a general database that collects the HVAC products of major manufactures. This database is to provide the appropriate HVAC equipment for alternative systems based on the energy analysis results. The performance analysis module will evaluate the technical, economic, environmental, and sustainable performance of HVAC, as outlined by the literature reviews. The technical performance of different HVAC systems is embedded in the products database. The environmental performance uses the annual energy consumption to quantify and calculate the environmental impacts via LCA tool. The annual energy consumption will be multiplied by the local energy price to calculate LCC, which represents the economic performance of HVAC. LEED as a rating system for evaluating the sustainability of green buildings, the points that are related to HVAC design are gathered. After that, to recommend the best HVAC system and equipment to users, the decision-making module is established. The weighting of criteria is conducted by AHP-Entropy method, and the ranking of alternatives is realized by TOPSIS method.

Chapter Four

Proposed Model Development

4.1 Introduction

In this chapter, the process of developing the proposed model will be introduced and the integration of each module will be outlined separately. As the key to evaluating the HVAC performance, the energy analysis module will be integrated with BIM tool through a plug-in that will be created and linked to Revit. Equipment and system selection module will be integrated via ODBC in order to link the equipment information to the calculation. The integration of the performance analysis module will be achieved by using the compiled formulas and by directly obtaining the results from the analysis tools. The decision-making system module is developed to carry out all the necessary calculations and to help in selecting the most appropriate system. The integration between all the modules will be accomplished by using Visual Studio platform and C# codes .

4.2 The Preparation for Revit Secondary Development

Since Revit 2013 was released, Revit LT has been integrated with Revit API (application programming interface), which is automatically installed when Revit is installed. Revit secondary development can be compiled by using either C#

programming language or VB.Net language. The programming environment of Revit APIs varies with different versions. Revit 2014 is based on .NET4.0, Revit 2015 is based on .NET4.5, while Revit 2016 is based on .NET 4.5.2.

Revit SDK can be found in the installation folder of Revit. Revit SDK is a comprehensive library file that is provided by Autodesk. It contains a lot of case code for secondary development. Users can use this case code, or modify it to fit their own needs.

Add-In Manager (plug-in manager) and Revit Lookup are important plug-ins for assisting secondary development of Revit. The installation of Add-In Manager can be added directly by copying the “Autodesk.AddInManager.addin” file and pasting the “Addins” folder under the Revit installation directory, such as C:\ProgramData\Autodesk\Revit\Addins\2016. After the installation is completed, the “Add-In” and “External Tools” button appear in the Revit function bar, as shown in figure 4.1.

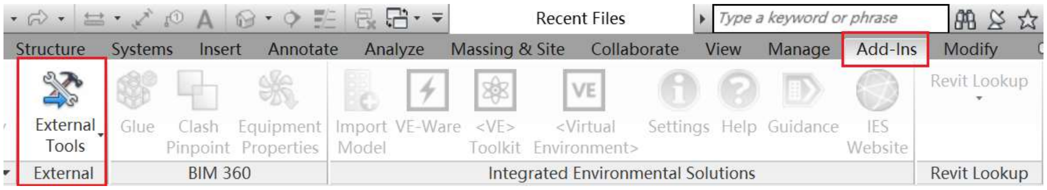


Figure 4.1 The Revit interface with Add-In manage

Add-In Manager is a “dll” file format that can be loaded in Visual Studio with C#. It allows users to load the plug-in code without restarting Revit again, making the loading of both external applications and plugins flexible and convenient. The installation of Revit Lookup is like the installation of the Add-In Manager. As shown in figures 4.2 and 4.3, Revit Lookup allows users to directly view or modify the information of objects without writing code.

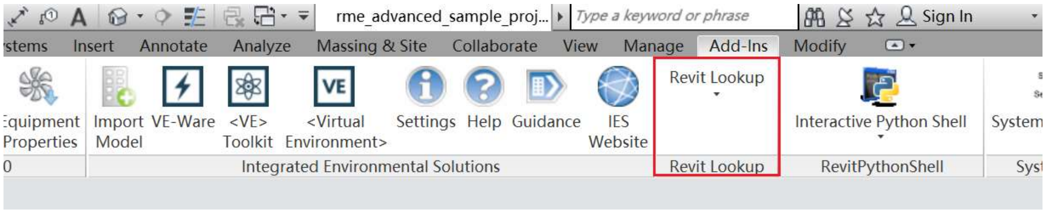
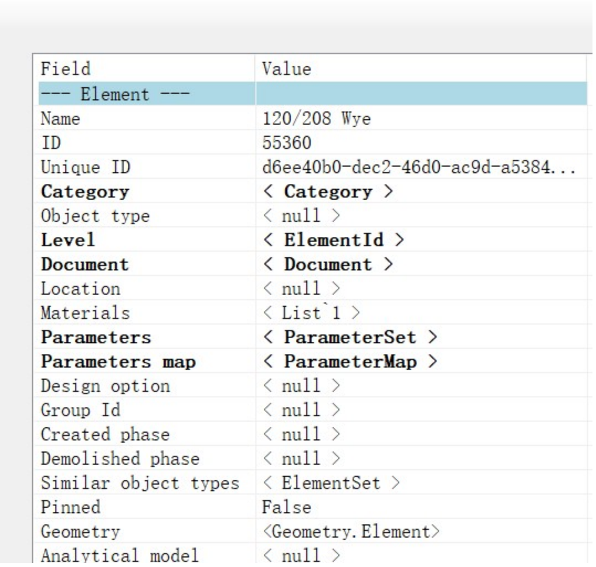


Figure 4.2 Revit interface with Revit lookup



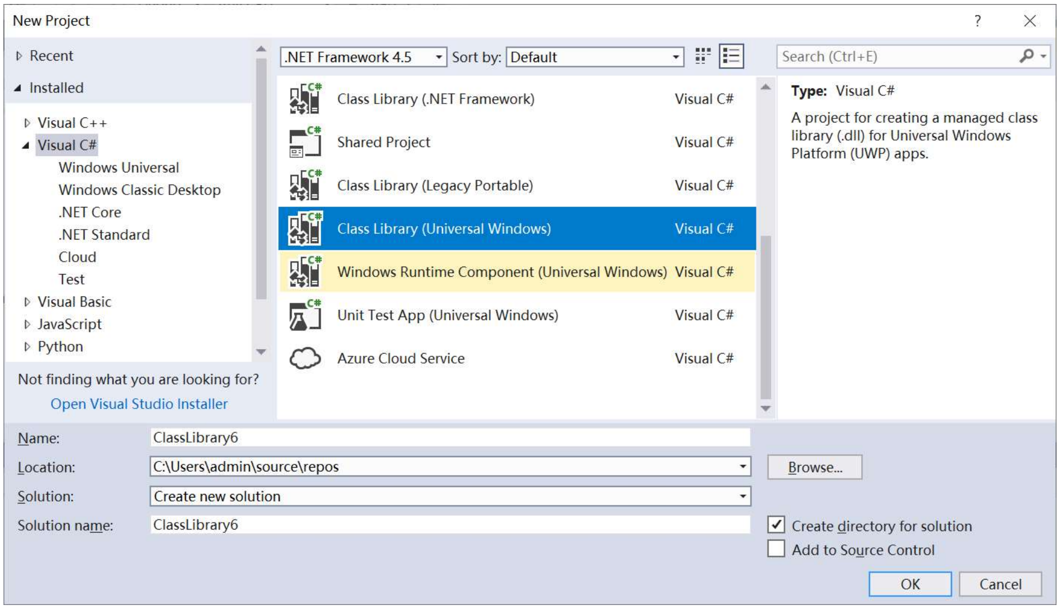
Field	Value
--- Element ---	
Name	120/208 Wye
ID	55360
Unique ID	d6ee40b0-dec2-46d0-ac9d-a5384...
Category	**< Category >**
Object type	< null >
Level	**< ElementId >**
Document	**< Document >**
Location	< null >
Materials	< List`1 >
Parameters	**< ParameterSet >**
Parameters map	**< ParameterMap >**
Design option	< null >
Group Id	< null >
Created phase	< null >
Demolished phase	< null >
Similar object types	< ElementSet >
Pinned	False
Geometry	<Geometry.Element>
Analytical model	< null >

Figure 4.3 Using Revit Lookup to check the equipment information

By completing these four forehand steps, the preparation of Revit secondary development is completed. With the help of these external tools and Revit Lookup, the secondary development efficiency is enhanced.

4.3 The Process of Revit Secondary Development

Create new project: As shown in figure 4.4, in Visual Studio2017, "File"-"New"-"Project", select "Visual C#"-"Windows"-"Class Library" in the "Project type" drop-down list and modify the plug-in name, finally click "OK" to complete it.



Class Library (.NET Framework)	Visual C#
Shared Project	Visual C#
Class Library (Legacy Portable)	Visual C#
Class Library (Universal Windows)	Visual C#
Windows Runtime Component (Universal Windows)	Visual C#
Unit Test App (Universal Windows)	Visual C#
Azure Cloud Service	Visual C#

Type: Visual C#

A project for creating a managed class library (.dll) for Universal Windows Platform (UWP) apps.

Name: ClassLibrary6
Location: C:\Users\admin\source\repos
Solution: Create new solution
Solution name: ClassLibrary6
☑ Create directory for solution
☐ Add to Source Control

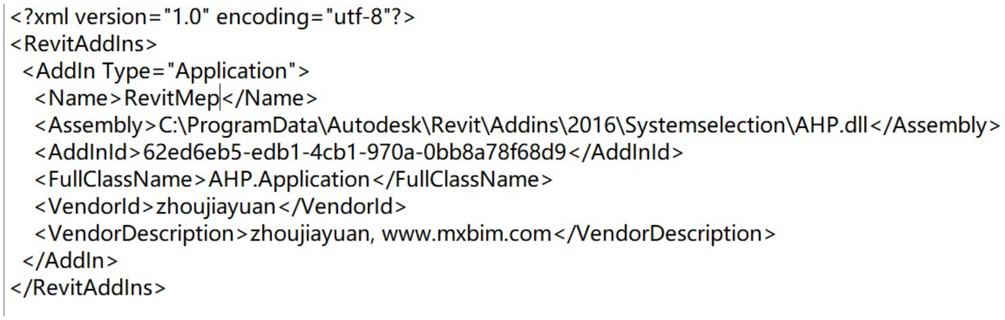
Figure 4.4 Create a new project in Visual Studio

Add reference: Add "RevitAPI.dll" and "RevitAPIUI.dll" to reference, which are in the Revit installation directory. After adding the reference, set “Copy Local” to "False". This process is to avoid copying many reference files into the output directory during the compilation process.

Compile code: The programming code is the most important part of the entire development process, while can be written in languages such as C# or VB.NET, C++, and CLI.

Debug plug-in: During the coding and running process, break point debugging is required to check the state between the objects and the variables, to locate the question and to avoid possible problems.

Registration: To run the plug-in in Revit, the registration file is required to be edited by Notepad as shown in figure 4.5 and to be placed in the following directory: C:\ProgramData\Autodesk\Revit\Addins\2018.



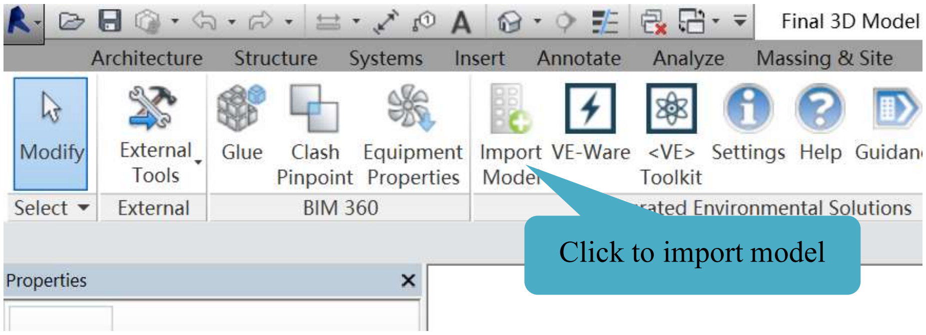
```
<?xml version="1.0" encoding="utf-8"?>
<RevitAddIns>
  <AddIn Type="Application">
    <Name>RevitMep</Name>
    <Assembly>C:\ProgramData\Autodesk\Revit\Addins\2016\Systemselection\AHP.dll</Assembly>
    <AddInId>62ed6eb5-edb1-4cb1-970a-0bb8a78f68d9</AddInId>
    <FullClassName>AHP.Application</FullClassName>
    <VendorId>zhoujiayuan</VendorId>
    <VendorDescription>zhoujiayuan, www.mxbim.com</VendorDescription>
  </AddIn>
</RevitAddIns>
```

Figure 4.5 The add-in file for plug-in registration

4.4 Integration of 3D design Module

Revit is a powerful modeling tool used in the construction industry, and its capability can meet almost all design requirements. Meanwhile, Revit API allows developers to get access to secondary development, which can provide different projects with plug-ins at different stages of the life cycle. In this study, the IES-VE plug-in has been already packaged in the installation file. It allows the information of 3D building model to be automatically exported from Revit and imported into IES-VE via gbXML file format. Figure 4.6 shows the developed plug-in icon of IES-VE in Revit.

To guarantee the accuracy of the transmitted information of the building model, the geometry of the building envelope (wall, roof, floor, doors and windows) should be assigned correctly before importing the model.



Click to import model

Figure 4.6 IES-VE plug-in in Revit

4.5 Integration of Energy Analysis Module

In this study, the energy analysis of HVAC system is carried out by IES-VE. After importing the 3D model from Revit, users should follow the ASHRASE guidance for designing the HVAC system to assign main parameters of the construction, and then run the load calculation and system simulation to generate the reports. The main steps include weather and location assignment, thermal properties of envelops assignment, and space assignment, as shown in figure 4.7. The room load calculation will calculate the peak cooling/heating load and required supply air flow of the building, and the system simulation will calculate the energy cost of the selected HVAC system. The reports of room load and energy simulation of the building can be found in Appendix F and Appendix G.

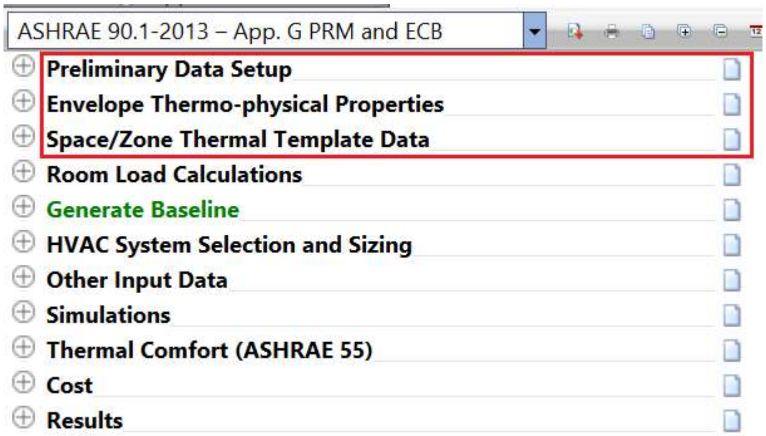
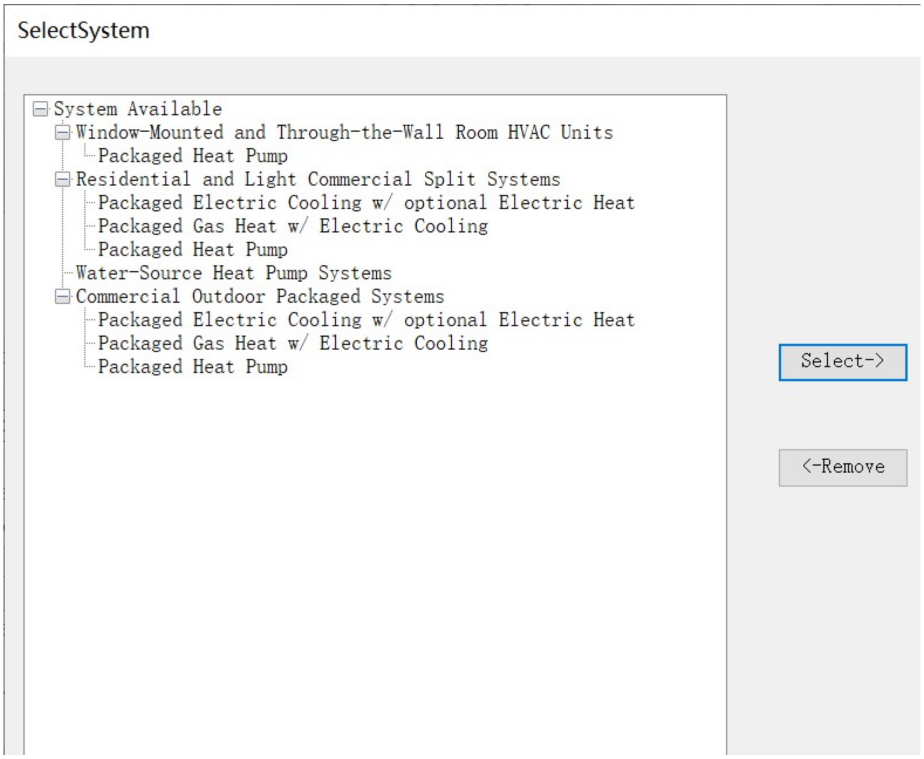

ASHRAE 90.1-2013 – App. G PRM and ECB
Preliminary Data Setup
Envelope Thermo-physical Properties
Space/Zone Thermal Template Data
Room Load Calculations
Generate Baseline
HVAC System Selection and Sizing
Other Input Data
Simulations
Thermal Comfort (ASHRAE 55)
Cost
Results

Figure 4.7 The ASHRAE guidance on the design of HVAC system

4.6 Integration of Equipment and System Selection Module

Information about around 500 products are collected and stored in the database. The equipment can be classified into three types of HVAC systems: Package rooftop system, light commercial split system and PTAC. First, the module gives users the ability to select the candidates of HVAC system for their design, which will be used later for the energy analysis. After loading the project in Revit, users can use the plug-in from the add-in manager. Figures 4.8 and 4.9 illustrate the interface for the system selection.



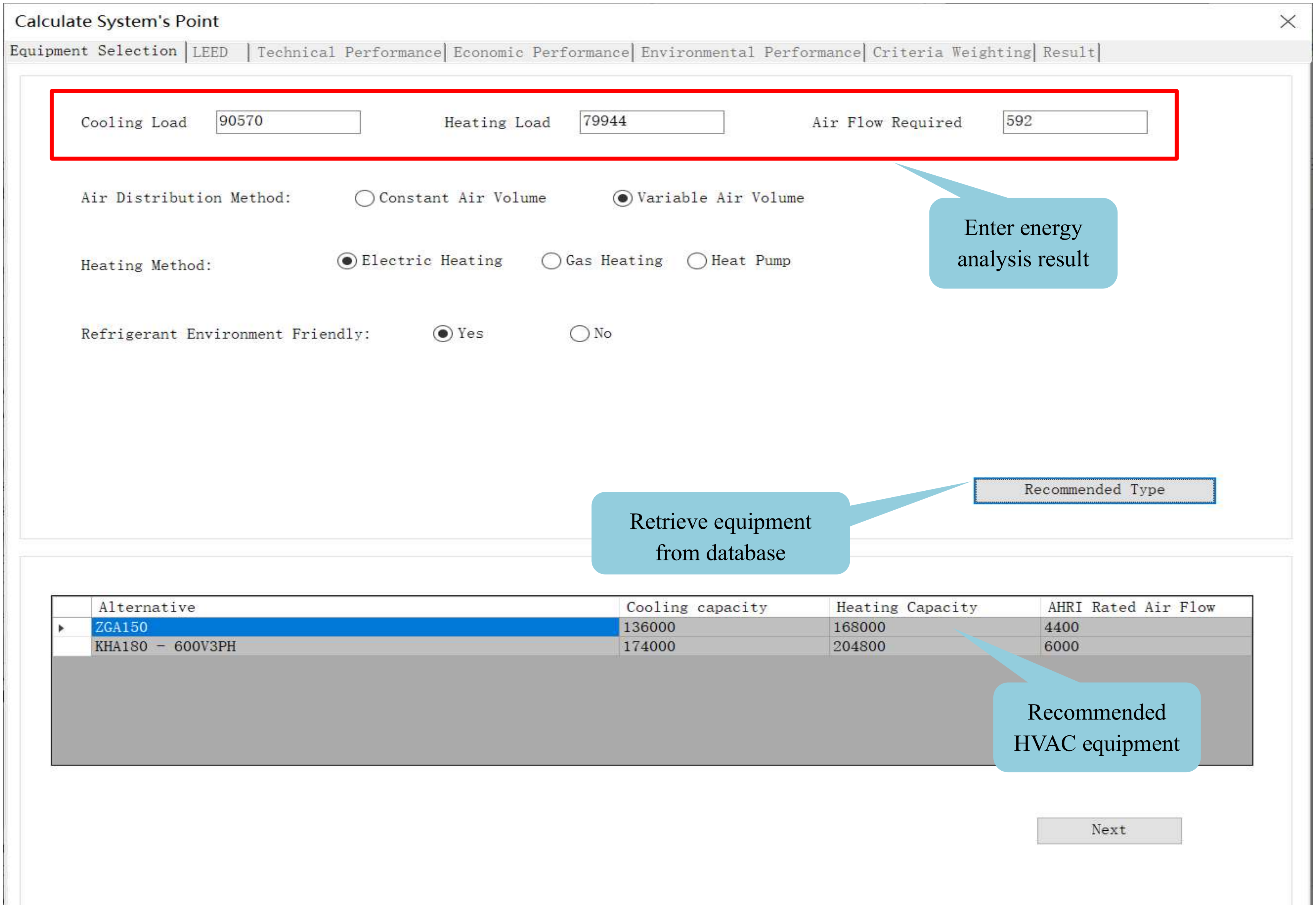
SelectSystem

- System Available
  - Window-Mounted and Through-the-Wall Room HVAC Units
    - Packaged Heat Pump
  - Residential and Light Commercial Split Systems
    - Packaged Electric Cooling w/ optional Electric Heat
    - Packaged Gas Heat w/ Electric Cooling
    - Packaged Heat Pump
  - Water-Source Heat Pump Systems
  - Commercial Outdoor Packaged Systems
    - Packaged Electric Cooling w/ optional Electric Heat
    - Packaged Gas Heat w/ Electric Cooling
    - Packaged Heat Pump

Figure 4.8 System Selection Interface

From the supplied tree diagram, users will be required to select at least two HVAC systems for further comparison. Due to the limitation in the collected data from the website of the factory-assembled HVAC products, only three kinds of HVAC systems are used in this study. Based on the reviews, these three kinds of HVAC systems are applied in most of the small building projects around the world.

The next plug-in interface, which is shown in figure 4.9, is for the equipment selection. Users will be required to manually enter the cooling load, heating load and required airflow of the building into the assigned text boxes. Based on the building type and users' preference, it can be decided if constant air volume distribution or variable air volume distribution will be applied. Depending on the local condition of energy, heating method can be chosen from electric heating, gas heating and heat pump. Since the proposed HVAC system is expected to have low effects on the environment, the refrigerants will be suggested to be environmentally friendly. Then, the HVAC equipment of each system will be recommended respectively.



Cooling Load 90570

Heating Load 79944

Air Flow Required 592

Air Distribution Method: ○ Constant Air Volume ● Variable Air Volume

Heating Method: ● Electric Heating ○ Gas Heating ○ Heat Pump

Refrigerant Environment Friendly: ● Yes ○ No

Alternative	Cooling capacity	Heating Capacity	AHRI Rated Air Flow
ZGA150	136000	168000	4400
KHA180 – 600V3PH	174000	204800	6000

Enter energy analysis result

Retrieve equipment from database

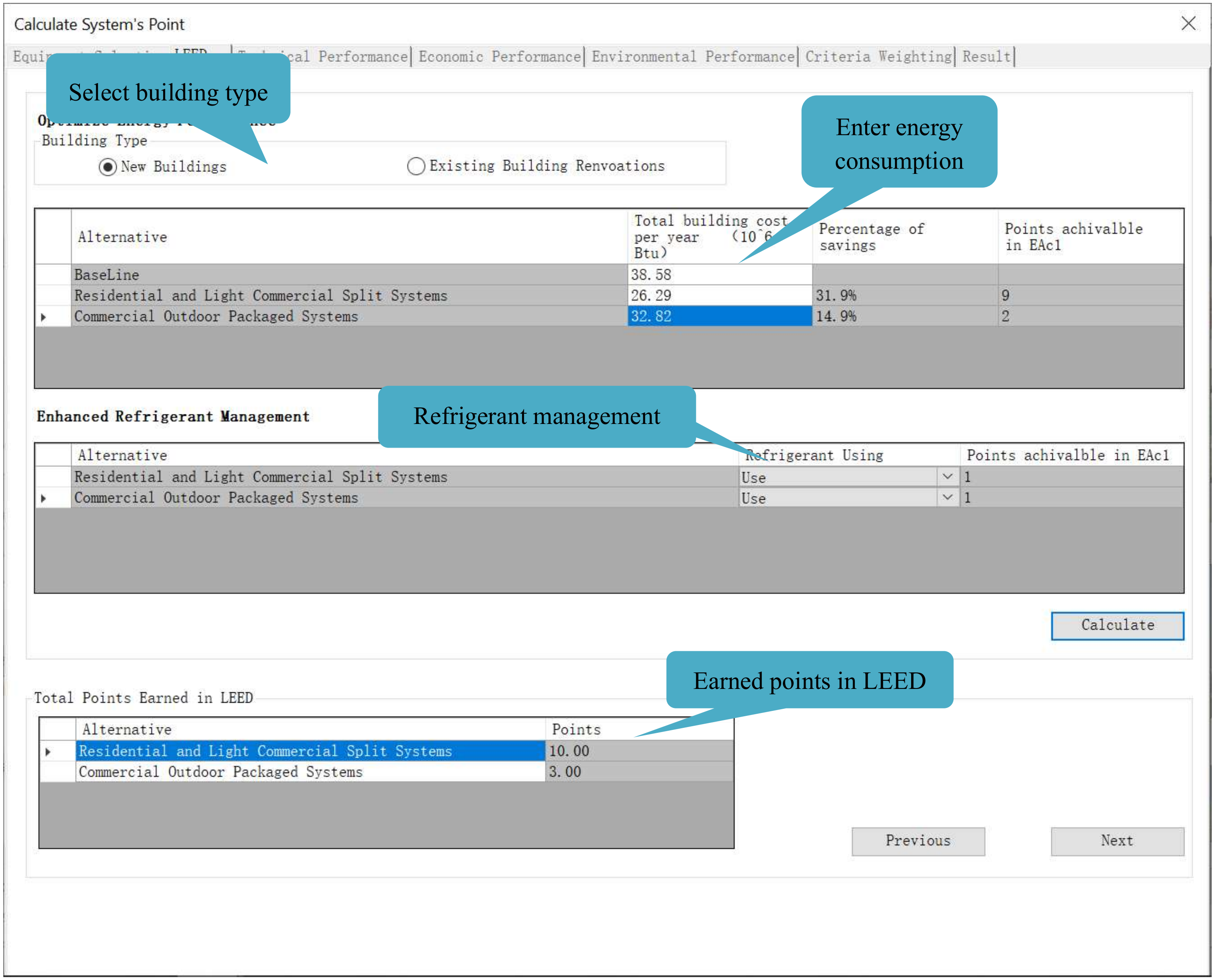
Recommended HVAC equipment

Figure 4.9 Equipment Selection Interface

4.7 Integration of Performance Analysis Module

As discussed in the methodology, the evaluation of HVAC performance consists of 4 criteria, which include: LEED; technical; economic; and environmental performance.

There are two credits related to HVAC in LEED. To calculate EAc1, as shown in figure 4.10, users are required to first select the building type. Since the focus of this study is on the conceptual design stage, the HVAC design is for new buildings by default. Then, the annual energy consumption of alternatives and baseline are required to calculate the percentage of energy saving. Depending on if the refrigerant is used in HVAC system and on the type of refrigerant, EAc4 can be calculated. The establishing code and equations used to calculate the LEED points can be found in Appendix C.



Select building type

Enter energy consumption

Refrigerant management

Earned points in LEED

Building Type

● New Buildings ○ Existing Building Renvoations

Alternative	Total building cost per year (10^6 Btu)	Percentage of savings	Points achivalble in EAc1
BaseLine	38.58		
Residential and Light Commercial Split Systems	26.29	31.9%	9
Commercial Outdoor Packaged Systems	32.82	14.9%	2

Enhanced Refrigerant Management

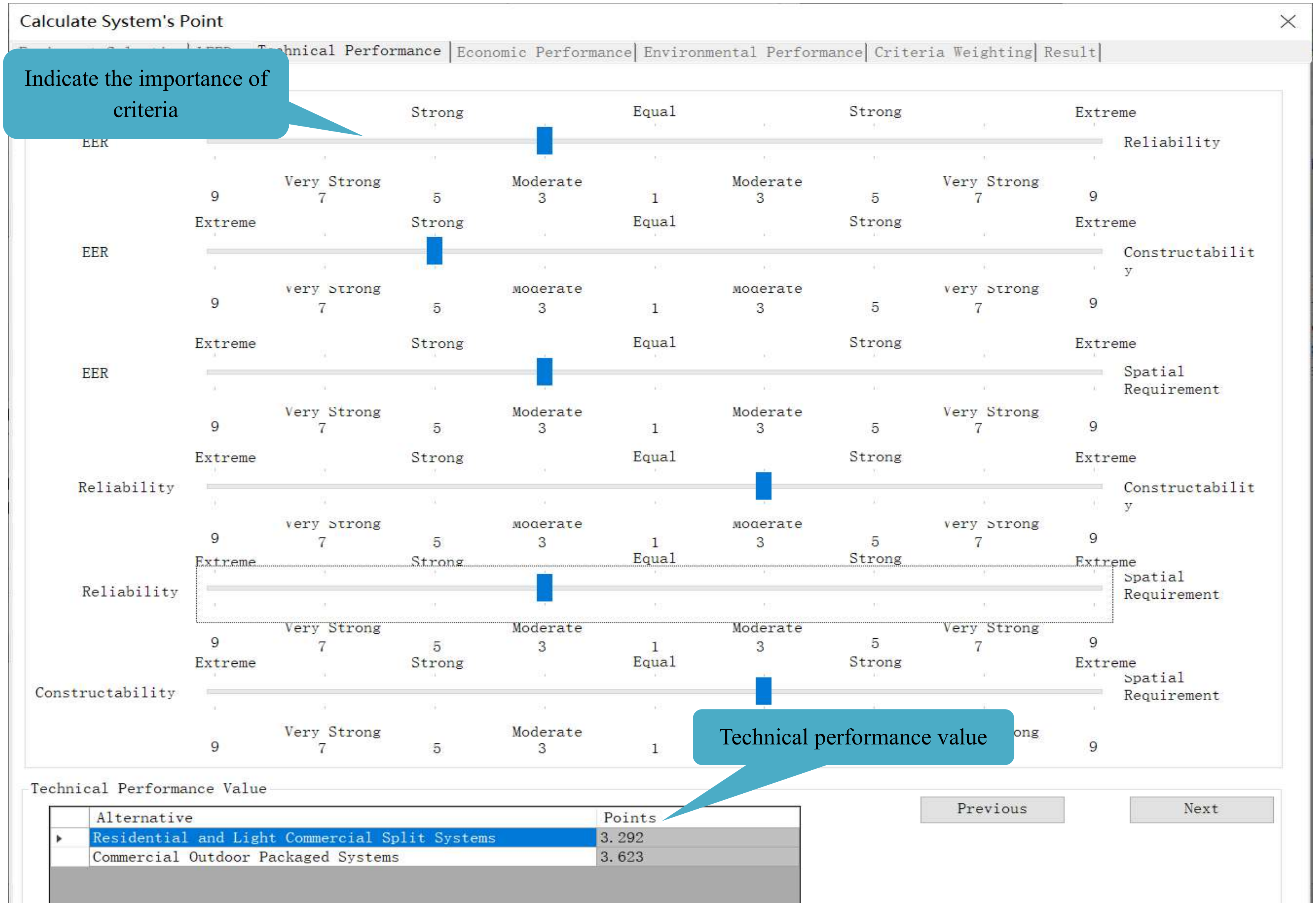
Alternative	Refrigerant Using	Points achivalble in EAc1
Residential and Light Commercial Split Systems	Use	1
Commercial Outdoor Packaged Systems	Use	1

Total Points Earned in LEED

Alternative	Points
Residential and Light Commercial Split Systems	10.00
Commercial Outdoor Packaged Systems	3.00

Figure 4.10 Calculate points earned in LEED

There are 4 sub-criteria under technical performance, which include EER; reliability; constructability; and spatial requirement. As shown in figure 4.11, the scroll bars are constructed into a window form to make pairwise comparison between criteria. For example, the first scroll bar in the figure shows that the EER is moderately favored over the reliability. The established code and equations used for evaluating the technical performance are presented in Appendix D.



Indicate the importance of criteria

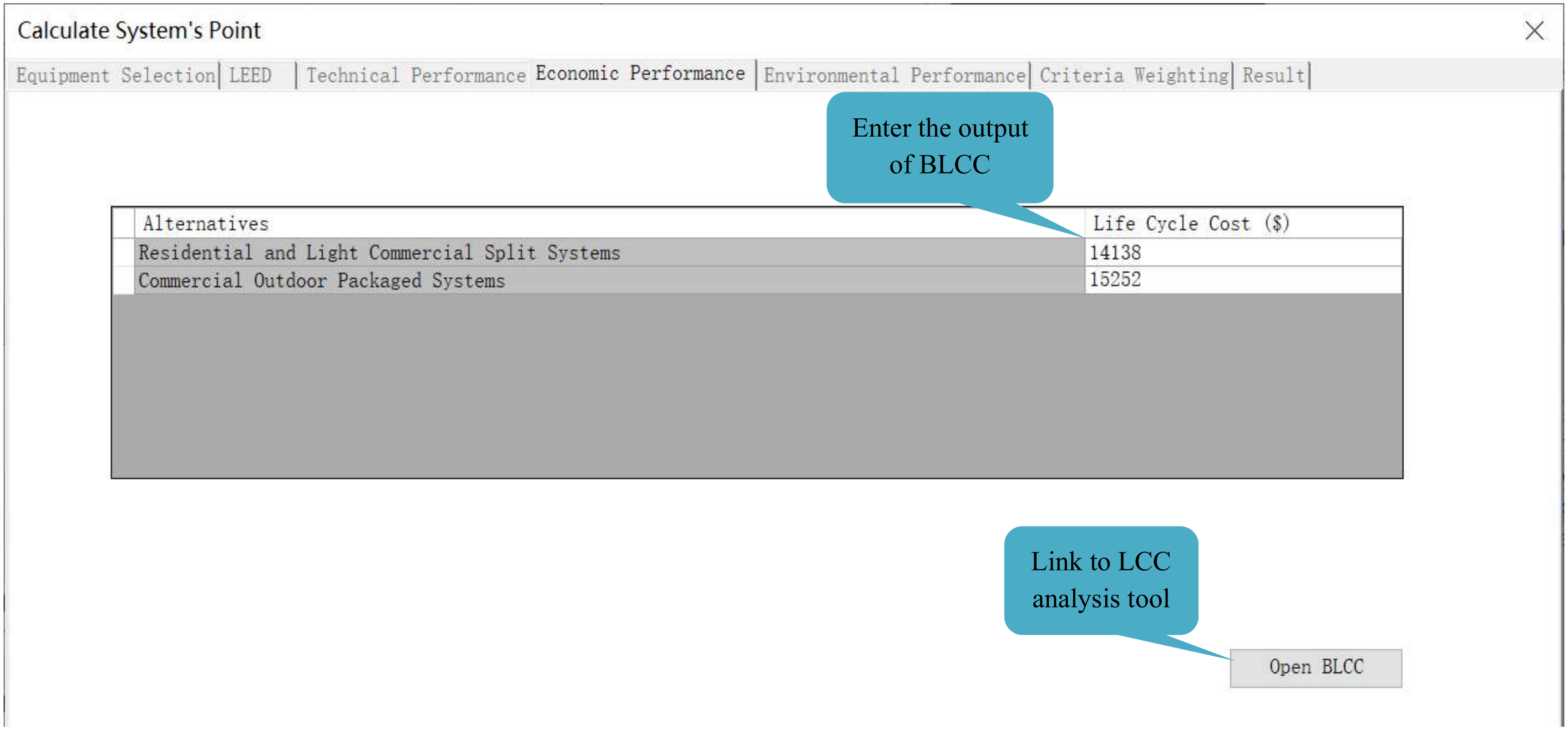
Technical performance value

Technical Performance Value

Alternative	Points
Residential and Light Commercial Split Systems	3.292
Commercial Outdoor Packaged Systems	3.623

Figure 4.11 Pairwise comparison of sub-criteria under technical performance

The economic performance is evaluated based on BLLC 5, as shown in figure 4.12. The utility rate for electricity consumption, electricity demand from the utility companies at the building location and the initial cost of HVAC equipment are retrieved from RS Means cost database, which will be required to calculate the annual energy cost. Please refer to Appendix A to check RS Means cost database that used in this study for HVAC equipment.



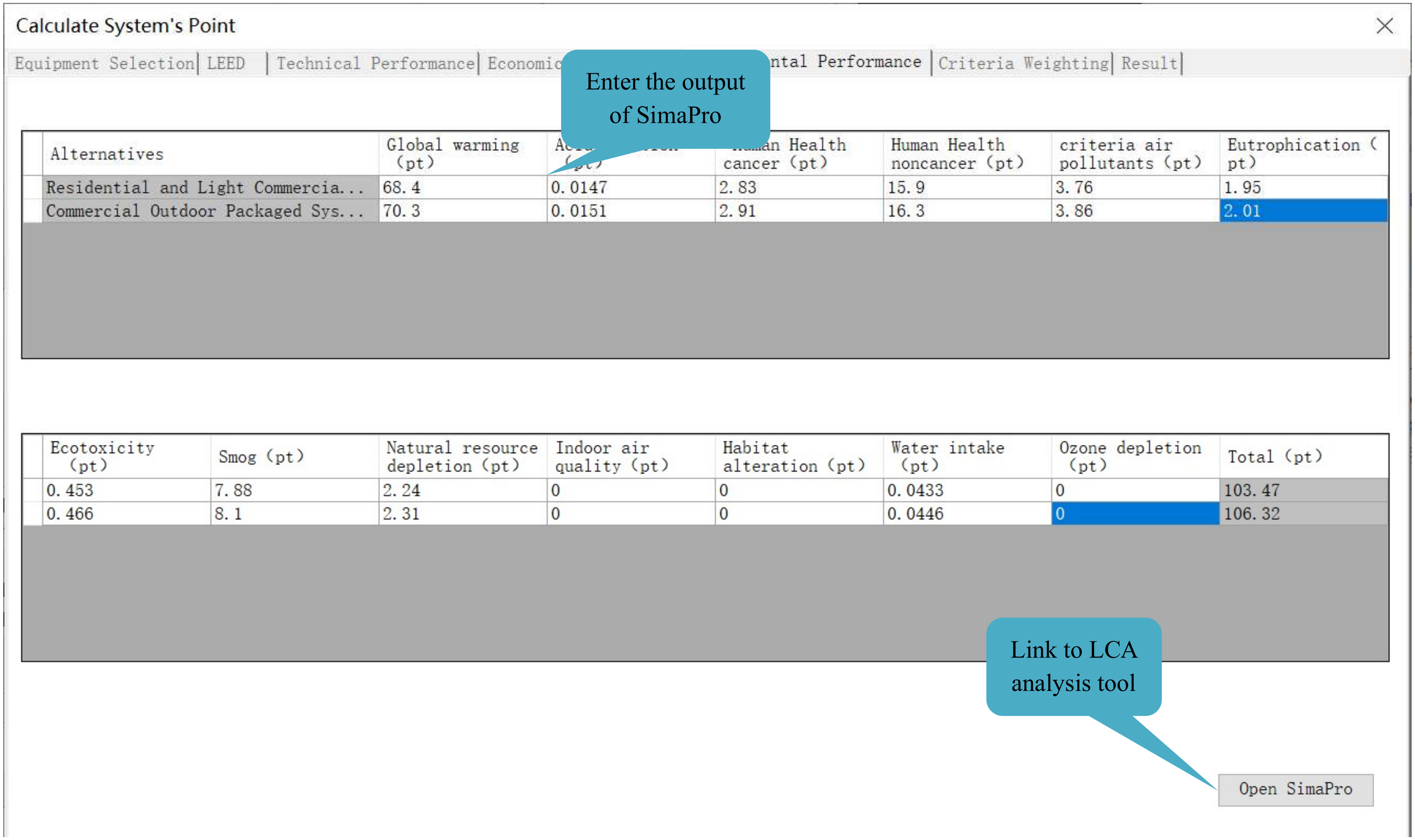
Enter the output of BLCC

Alternatives	Life Cycle Cost ($)
Residential and Light Commercial Split Systems	14138
Commercial Outdoor Packaged Systems	15252

Link to LCC analysis tool

Figure 4.12 Calculating LCC with BLLC 5

Similarly, to evaluate the environmental performance, another link to SimaPro is created as shown in figure 4.13. Annual energy consumption data, the electricity fuel mix of the region and the management of refrigerant will be imported into an inventory database to calculate the converted emissions of alternatives during the life cycle period. After that, the converted emissions will be evaluated by BEES+ to obtain the environmental impact points.



Enter the output of SimaPro

Alternatives	Global warming (pt)	Ac (pt)	an Health cancer (pt)	Human Health noncancer (pt)	criteria air pollutants (pt)	Eutrophication (pt)
Residential and Light Commercia...	68.4	0.0147	2.83	15.9	3.76	1.95
Commercial Outdoor Packaged Sys...	70.3	0.0151	2.91	16.3	3.86	2.01

Ecotoxicity (pt)	Smog (pt)	Natural resource depletion (pt)	Indoor air quality (pt)	Habitat alteration (pt)	Water intake (pt)	Ozone depletion (pt)	Total (pt)
0.453	7.88	2.24	0	0	0.0433	0	103.47
0.466	8.1	2.31	0	0	0.0446	0	106.32

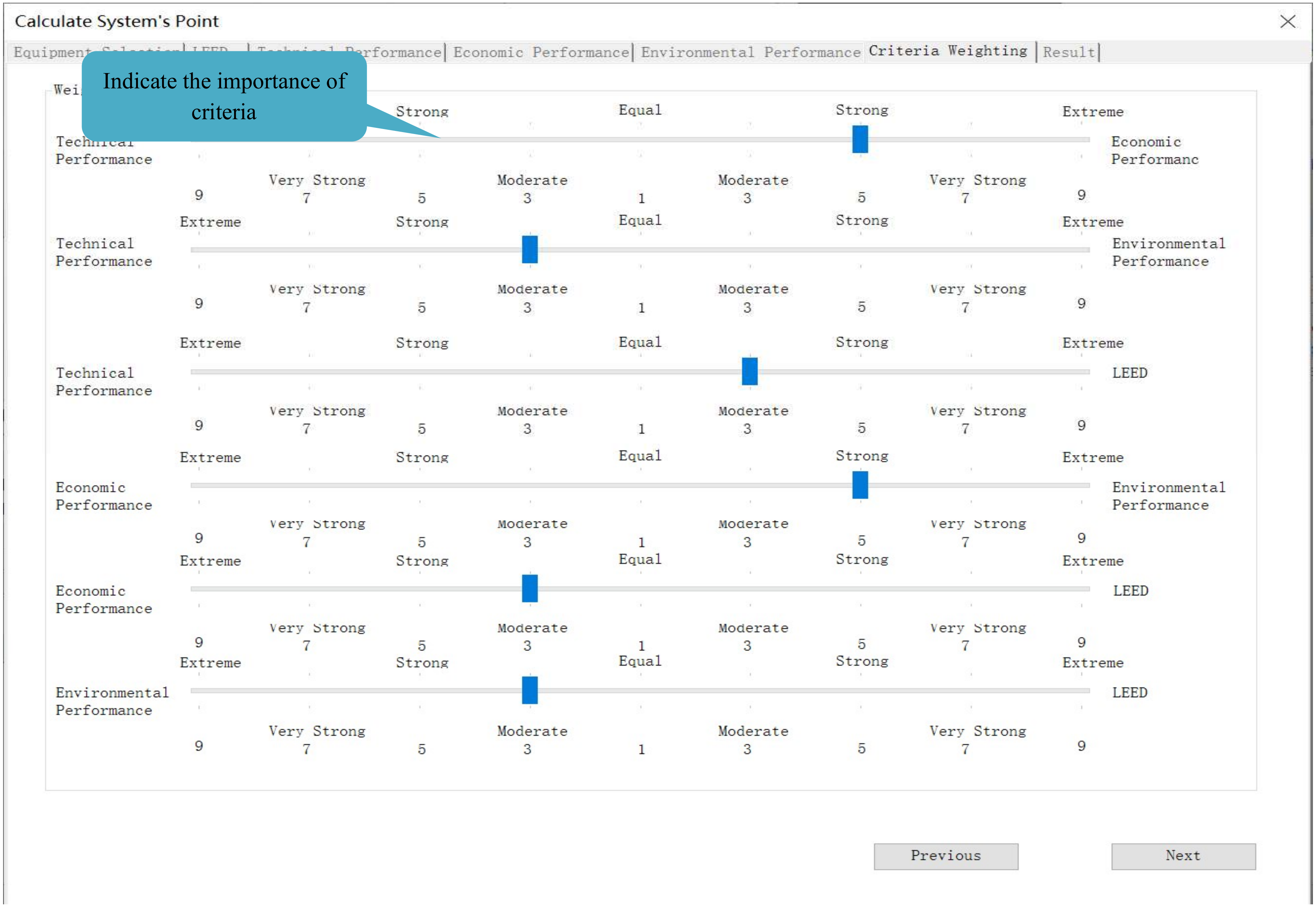
Link to LCA analysis tool

Figure 4.13 Calculating LCA with SimaPro

In conclusion, technical Performance of alternatives and the achieved points in LEED EAc4 credit can be directly obtained from the equipment and systems database, and LEED EAc1 credit, economic and environmental performance are calculated based on the energy consumption obtained from the energy analysis module.

4.8 Integration of Decision-Making System Module

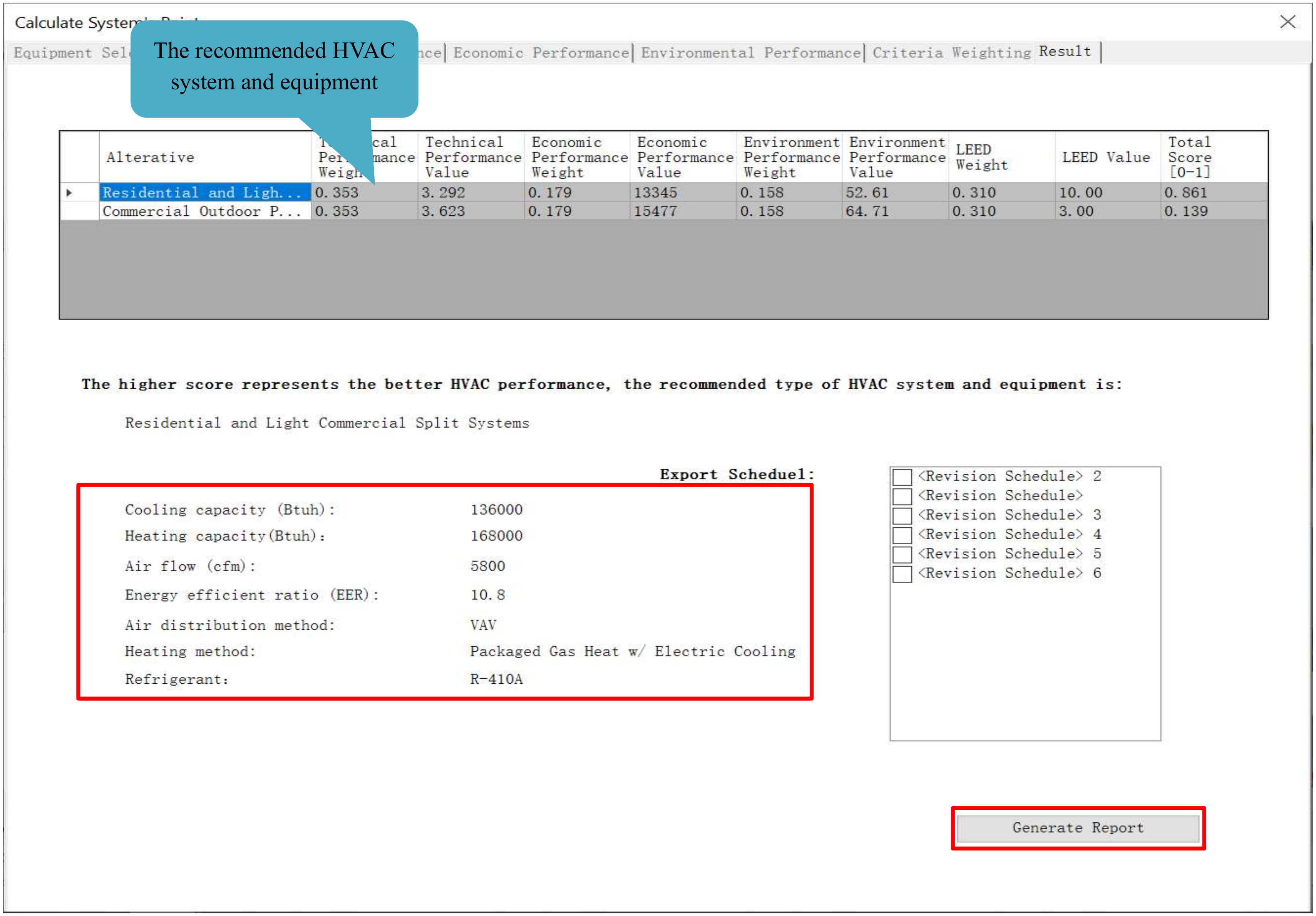
As described in chapter 3， the development of the decision-making system consists of criteria weighting (AHP-Entropy) and ranking (TOPSIS). The criteria for evaluating HVAC systems are divided into four categories: technical performance; economic performance; environmental performance; and sustainability (LEED). The performance values of each criterion can be obtained from the performance analysis module. Figure 4.14 illustrates the scroll bar used to determine the weighting factors via AHP method. Users should give their preference on the level of importance of each criterion by the pairwise comparison. For example, the first scroll bar in the figure represents that the economic performance is strongly favored over the technical performance.



Indicate the importance of criteria

Figure 4.14 Pairwise comparison of performance criteria

Once the required data is fed, the data is transferred to the coded formulas to execute the calculations. Then the result is sent back to the plug-in and displayed as shown in figure 4.15. Users can also transfer the information to a spreadsheet for further review and to generate reports.



The recommended HVAC system and equipment

	Alterative	T cal Per mance Weigh	Technical Performance Value	Economic Performance Weight	Economic Performance Value	Environment Performance Weight	Environment Performance Value	LEED Weight	LEED Value	Total Score [0-1]
▸	Residential and Ligh...	0. 353	3. 292	0. 179	13345	0. 158	52. 61	0. 310	10. 00	0. 861
	Commercial Outdoor P...	0. 353	3. 623	0. 179	15477	0. 158	64. 71	0. 310	3. 00	0. 139

The higher score represents the better HVAC performance, the recommended type of HVAC system and equipment is:

Residential and Light Commercial Split Systems

Export Scheduel:

Cooling capacity (Btuh):	136000
Heating capacity(Btuh):	168000
Air flow (cfm):	5800
Energy efficient ratio (EER):	10. 8
Air distribution method:	VAV
Heating method:	Packaged Gas Heat w/ Electric Cooling
Refrigerant:	R-410A

☐ <Revision Schedule> 2
☐ <Revision Schedule>
☐ <Revision Schedule> 3
☐ <Revision Schedule> 4
☐ <Revision Schedule> 5
☐ <Revision Schedule> 6

Figure 4.15 Output recommended HVAC system and equipment

4.9 Summary

This chapter explained the development process of the proposed model and showed how the four modules (Energy analysis module, Equipment and system module, Performance module and Decision making module) are dynamically integrated. The energy analysis module uses Revit plug-in to transmit the information of construction and calculates the energy consumption of HVAC system. The equipment and system selection module establishes a general database accessing to HVAC products from manufactures and suggests the appropriate products to match the requirements of thermal capacity and users' preference. The performance analysis module divides the HVAC performance into 4 categories. Among them, the calculations of technical performance and LEED points are coded via Visual Studio. Environmental and economic performances are evaluated via LCA and LCC tools, respectively. The decision-making system weights the criteria of HVAC performance via AHP-Entropy method, and the alternatives selected by designer are ranked via TOPSIS method. After executing all the necessary calculations, the model will display the recommended HVAC system and equipment based on the users' preference.

Chapter Five

Model's Testing

5.1 Introduction

The purpose of this chapter is to test the developed model. Due to the lack in the literature about matured studies that covered the use of multiple-criteria decision analysis for HVAC design, we were not able to find a real case project to use in order to test the model's results. Therefore, the workability of the model in terms of the inputs and outputs will be tested. Since the purpose of the model is to select the appropriate HVAC products at the conceptual design stage, the testing process is not based on an actual existing project but yet through a hypothetical one. Since the developed model is not set for a specific location or construction site, the 3D construction model of a 2-story building located in Boston is randomly downloaded from Autodesk Revit's website. The 3D construction model of a 2-story building located in Boston, is downloaded from Autodesk Revit's website. According to ASHRAE 90.2, the climate zone of Boston is 5A. The project information is listed in Table 5-1 and figure 5.1 shows the project's 3D model.

Table 5-1 Information of the building project

Weather Data	Summer outdoor	Summer outdoor	Winter outdoor	Summer outdoor	Winter outdoor	Summer outdoor	Winter outdoor

	dry bulb （℃）	wet bulb （℃）	dry bulb （℃）	air speed (m/s)	air speed (m/s)	air pressure (kPa)	air pressure (kPa)
	35.4	26.9	-5.1	1.6	2.1	98.82	100.9
Gross Area	1st floor (m^2)			2nd floor (m^2)		Total (m^2)	
	188			127		315	

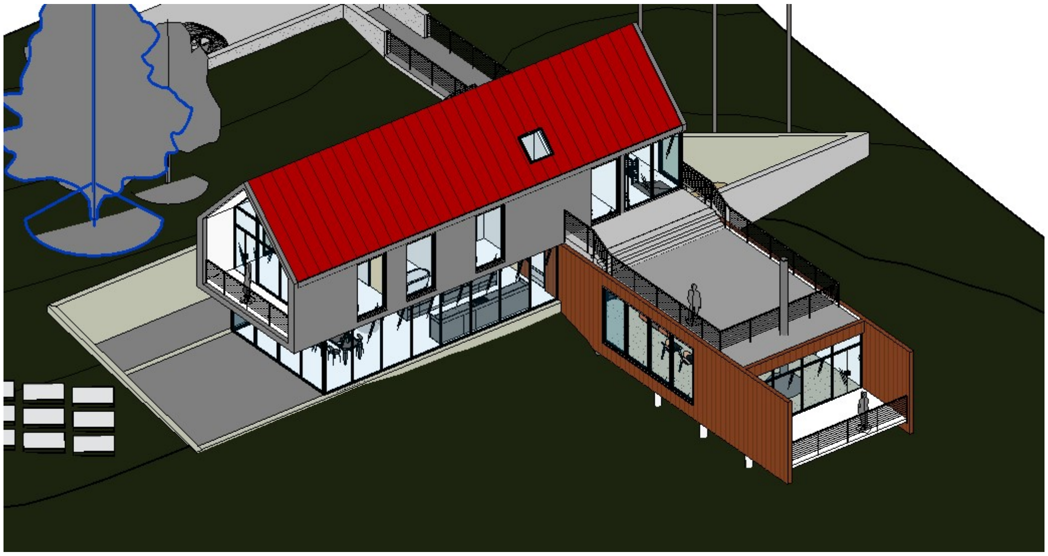
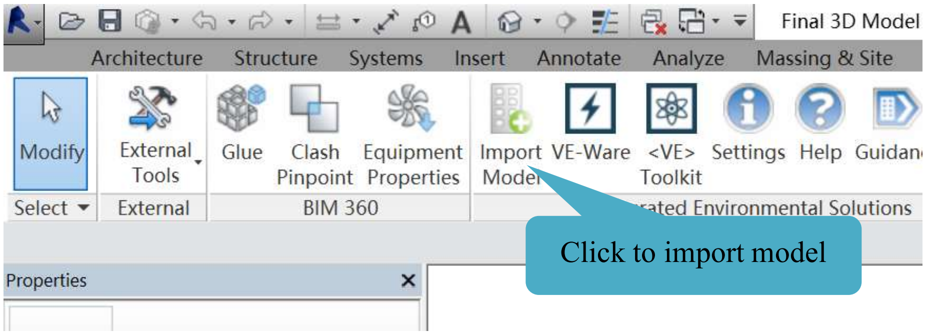


Figure 5.1 3D Model of Building

Information of the building envelopes, space schedule and operation schedule follow the requirements of ASHRAE 90.2-2016 on different building types, and the required air flow are designed based on the requirement of indoor air quality as described in ASHRAE 62.1-2016.

5.2 Transmitting the 3D Building Model Information

The first step is to transmit the building information from Revit 3D model to IES. As shown in figure 5.2, the developed plug-in allows the 3D building model to be efficiently imported from Revit into IES via gbXML file. To make sure the information is accurately transmitted, the geometry of the building envelope (wall, roof, floor, doors and windows) should be assigned correctly before importing the model. Figure 5.3 shows the transmitted building model in IES.



Click to import model

Figure 5.2 IES-VE plug-in in Revit

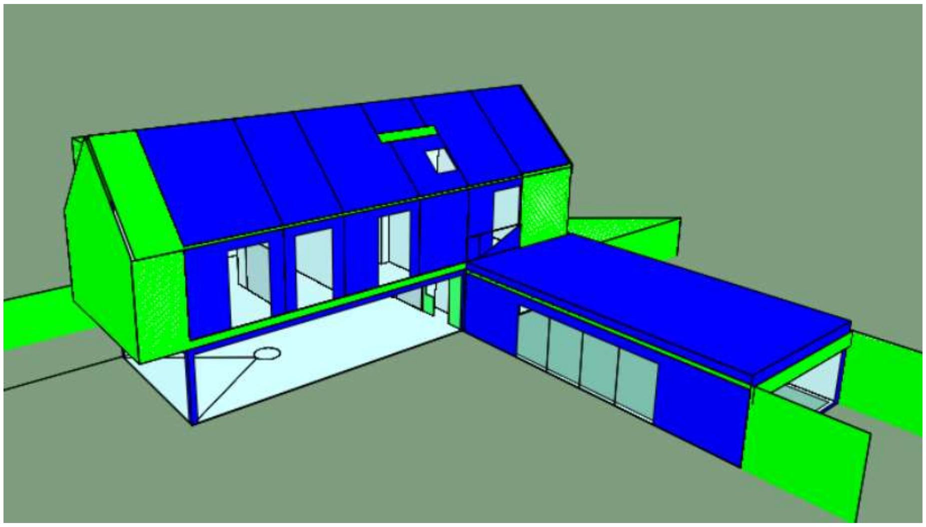
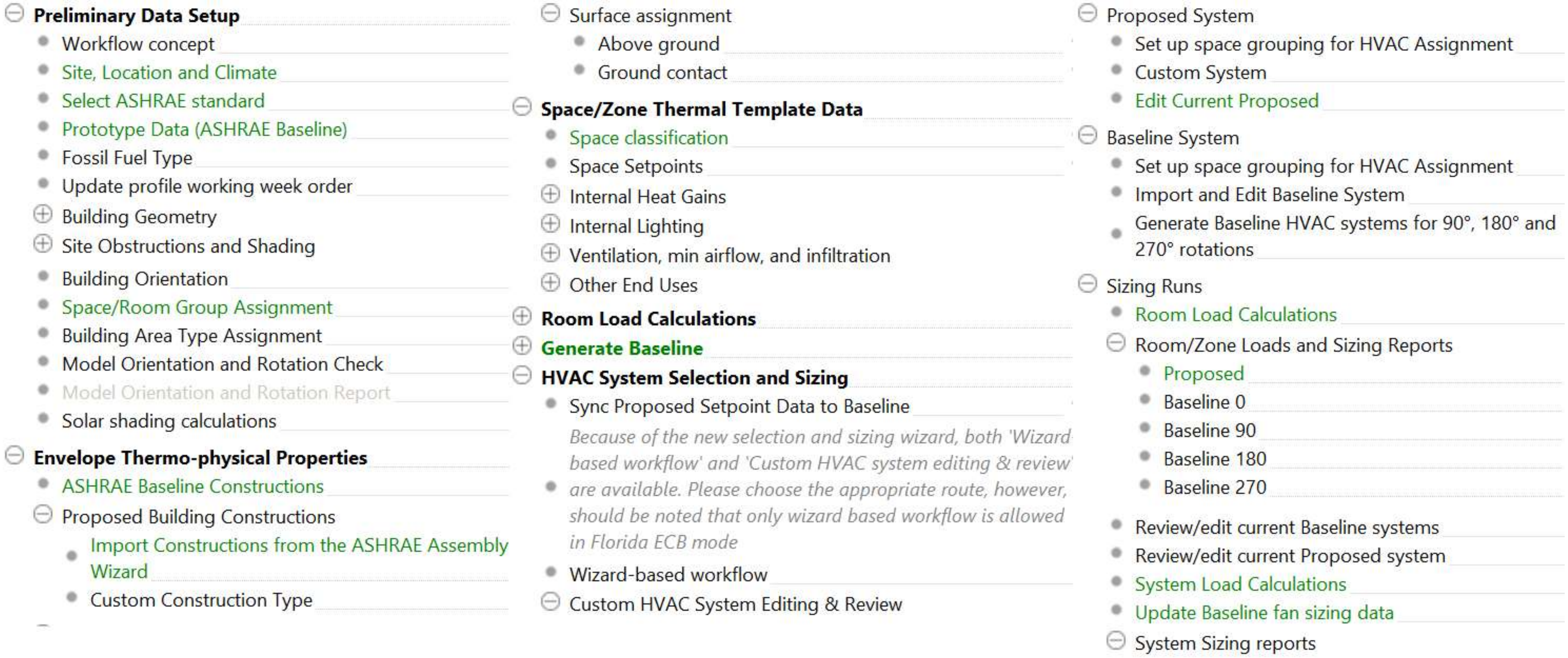


Figure 5.3 Transmitted 3D Model in IES-VE

5.3 Energy Analysis

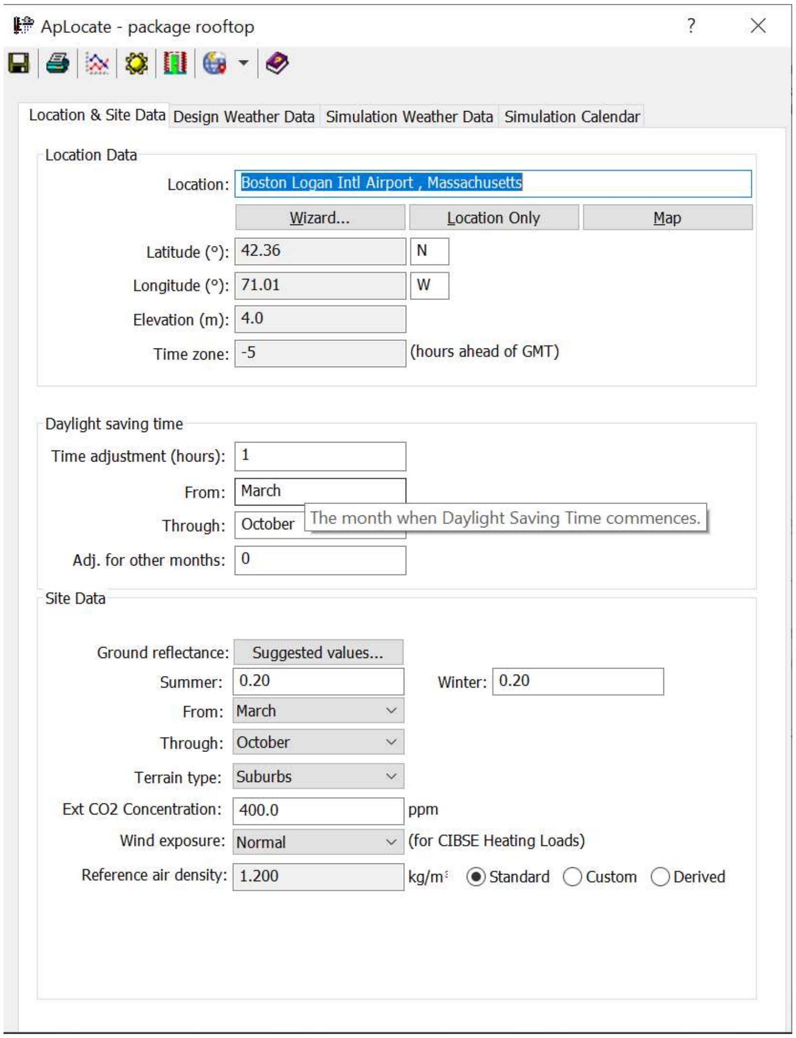
The next step is to run the energy analysis of the building model, which is done by IES-VE. After importing the 3D model, users should follow the ASHRAE 90. 1 2013 Navigator for designing HVAC system to assign the main parameters of the building, and then run the load calculation and system simulation to generate the energy reports. The main steps include weather and location assignment, thermal properties of envelops assignment, space assignment, and HVAC system editing as shown in figure 5.4. The highlighted steps in the navigator are applied in this research. Users are required to click the marked buttons step by step to finish the simulation of proposed HVAC system.



- **Preliminary Data Setup**
  - Workflow concept
  - Site, Location and Climate
  - Select ASHRAE standard
  - Prototype Data (ASHRAE Baseline)
  - Fossil Fuel Type
  - Update profile working week order
  - Building Geometry
  - Site Obstructions and Shading
  - Building Orientation
  - Space/Room Group Assignment
  - Building Area Type Assignment
  - Model Orientation and Rotation Check
  - Model Orientation and Rotation Report
  - Solar shading calculations
- **Envelope Thermo-physical Properties**
  - ASHRAE Baseline Constructions
  - Proposed Building Constructions
    - Import Constructions from the ASHRAE Assembly Wizard
    - Custom Construction Type
  - Surface assignment
    - Above ground
    - Ground contact
- **Space/Zone Thermal Template Data**
  - Space classification
  - Space Setpoints
  - Internal Heat Gains
  - Internal Lighting
  - Ventilation, min airflow, and infiltration
  - Other End Uses
- **Room Load Calculations**
- **Generate Baseline**
- **HVAC System Selection and Sizing**
  - Sync Proposed Setpoint Data to Baseline
  - *Because of the new selection and sizing wizard, both 'Wizard based workflow' and 'Custom HVAC system editing & review' are available. Please choose the appropriate route, however, should be noted that only wizard based workflow is allowed in Florida ECB mode*
  - Wizard-based workflow
  - Custom HVAC System Editing & Review
    - Proposed System
      - Set up space grouping for HVAC Assignment
      - Custom System
      - Edit Current Proposed
    - Baseline System
      - Set up space grouping for HVAC Assignment
      - Import and Edit Baseline System
      - Generate Baseline HVAC systems for 90°, 180° and 270° rotations
    - Sizing Runs
      - Room Load Calculations
      - Room/Zone Loads and Sizing Reports
        - Proposed
        - Baseline 0
        - Baseline 90
        - Baseline 180
        - Baseline 270
      - Review/edit current Baseline systems
      - Review/edit current Proposed system
      - System Load Calculations
      - Update Baseline fan sizing data
      - System Sizing reports

Figure 5.4 ASHRAE design navigator for designing HVAC system

The first step is to acquire the weather information related to the project location. IES-VE helps user to collect the global location of the building, external design conditions and simulation weather files automatically as shown in figure 5.5.



Location Data

Location: Boston Logan Intl Airport , Massachusetts
Latitude (°): 42.36 N
Longitude (°): 71.01 W
Elevation (m): 4.0
Time zone: -5 (hours ahead of GMT)

Daylight saving time

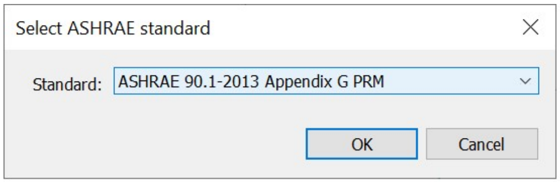
Time adjustment (hours): 1
From: March
Through: October
The month when Daylight Saving Time commences.
Adj. for other months: 0

Site Data

Ground reflectance:
Summer: 0.20 Winter: 0.20
From: March
Through: October
Terrain type: Suburbs
Ext CO2 Concentration: 400.0 ppm
Wind exposure: Normal (for CIBSE Heating Loads)
Reference air density: 1.200 kg/m³ ● Standard ○ Custom ○ Derived

Figure 5.5 Site, location and Climate setup

The next step is to select ASHRAE Standard. To select the ASHRAE Standard user should select from the dropdown, the options relevant to the version of the Navigator currently being used as shown in figure 5.6. For example, the ASHRAE 90. 1 2013 Navigator offers option of 90. 2013 app. G PRM or else 90.1 2013 ECB method. Since the project in located in North America, ASHRAE 90.1 2013 app is applied in this study.

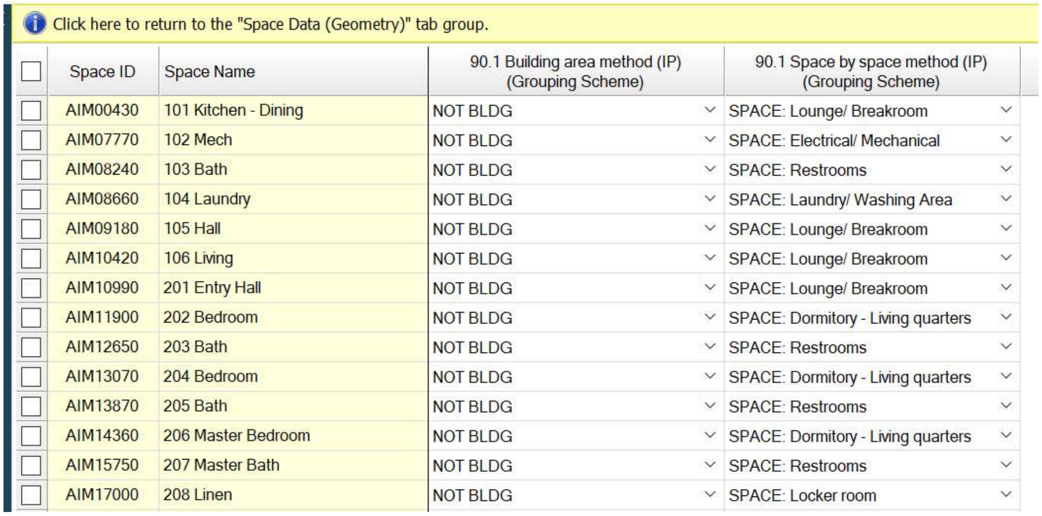


Standard: ASHRAE 90.1-2013 Appendix G PRM

Figure 5.6 Selection of ASHARE standard

The third step is to acquire the prototype data for ASHRAE baseline system, which can activate the software automatically to import a range of default ASHRAE data in a fully functional VE format. This includes: 1) ASHARE 90.1 thermal templates (by building or space type); 2) ASHRAE 90.1 internal gains; 3) ASHRAE outdoor fresh air rates; 4) ASHRAE schedules; 5) ASHRAE 90.1 envelope data and 6) ASHRAE 90.1 baseline systems.

The fourth step is to assign the space type for the rooms of the building as shown in figure 5.7. When the prototype's data is imported into the working model, it contains series of thermal room group based on ASHRAE 90.1 "Building area" and "Space by Space" methods. The prototype data also contains some additional grouping schemes that may be relevant to the users' needs.

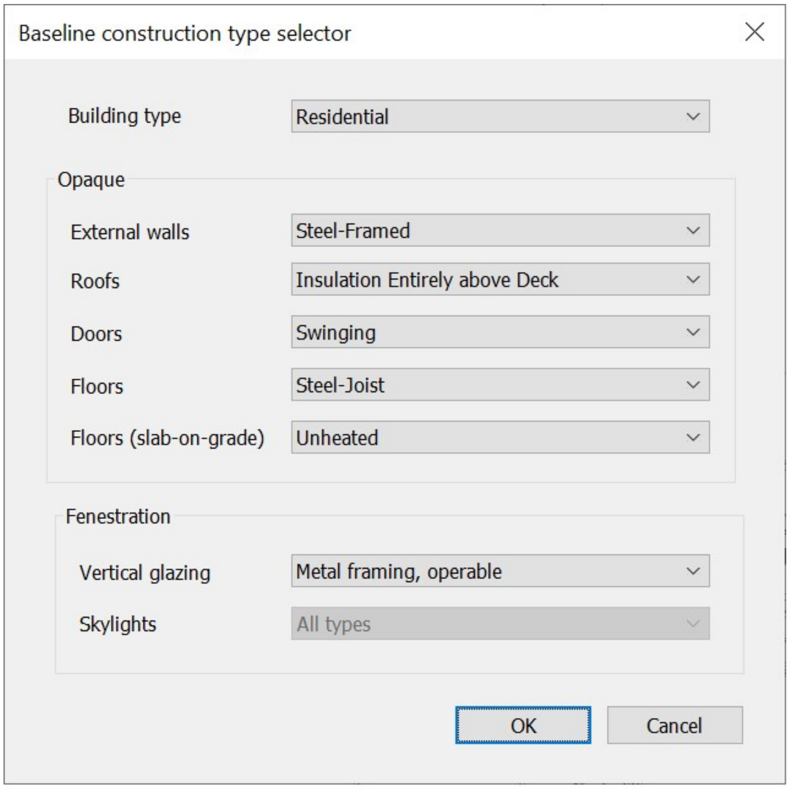


Click here to return to the "Space Data (Geometry)" tab group.

☐	Space ID	Space Name	90.1 Building area method (IP) (Grouping Scheme)	90.1 Space by space method (IP) (Grouping Scheme)
☐	AIM00430	101 Kitchen - Dining	NOT BLDG	SPACE: Lounge/ Breakroom
☐	AIM07770	102 Mech	NOT BLDG	SPACE: Electrical/ Mechanical
☐	AIM08240	103 Bath	NOT BLDG	SPACE: Restrooms
☐	AIM08660	104 Laundry	NOT BLDG	SPACE: Laundry/ Washing Area
☐	AIM09180	105 Hall	NOT BLDG	SPACE: Lounge/ Breakroom
☐	AIM10420	106 Living	NOT BLDG	SPACE: Lounge/ Breakroom
☐	AIM10990	201 Entry Hall	NOT BLDG	SPACE: Lounge/ Breakroom
☐	AIM11900	202 Bedroom	NOT BLDG	SPACE: Dormitory - Living quarters
☐	AIM12650	203 Bath	NOT BLDG	SPACE: Restrooms
☐	AIM13070	204 Bedroom	NOT BLDG	SPACE: Dormitory - Living quarters
☐	AIM13870	205 Bath	NOT BLDG	SPACE: Restrooms
☐	AIM14360	206 Master Bedroom	NOT BLDG	SPACE: Dormitory - Living quarters
☐	AIM15750	207 Master Bath	NOT BLDG	SPACE: Restrooms
☐	AIM17000	208 Linen	NOT BLDG	SPACE: Locker room

Figure 5.7 Space/Room group assignment

The fifth step is to select ASHRAE baseline constructions as shown in figure 5.8. The pre-defined construction materials will be imported into the construction database manager, with their default values correspond to the relevant ASHARE climate zone requirement.



Building type: Residential

Opaque

External walls: Steel-Framed
Roofs: Insulation Entirely above Deck
Doors: Swinging
Floors: Steel-Joist
Floors (slab-on-grade): Unheated

Fenestration

Vertical glazing: Metal framing, operable
Skylights: All types

Figure 5.8 Baseline construction type selection dialog box

The sixth step is to customize the construction materials for the proposed building model from ASHRAE assembly wizard as shown in figure 5.9. The user can choose to select or edit ASHRAE 90.1 baseline construction type for use in the building model.

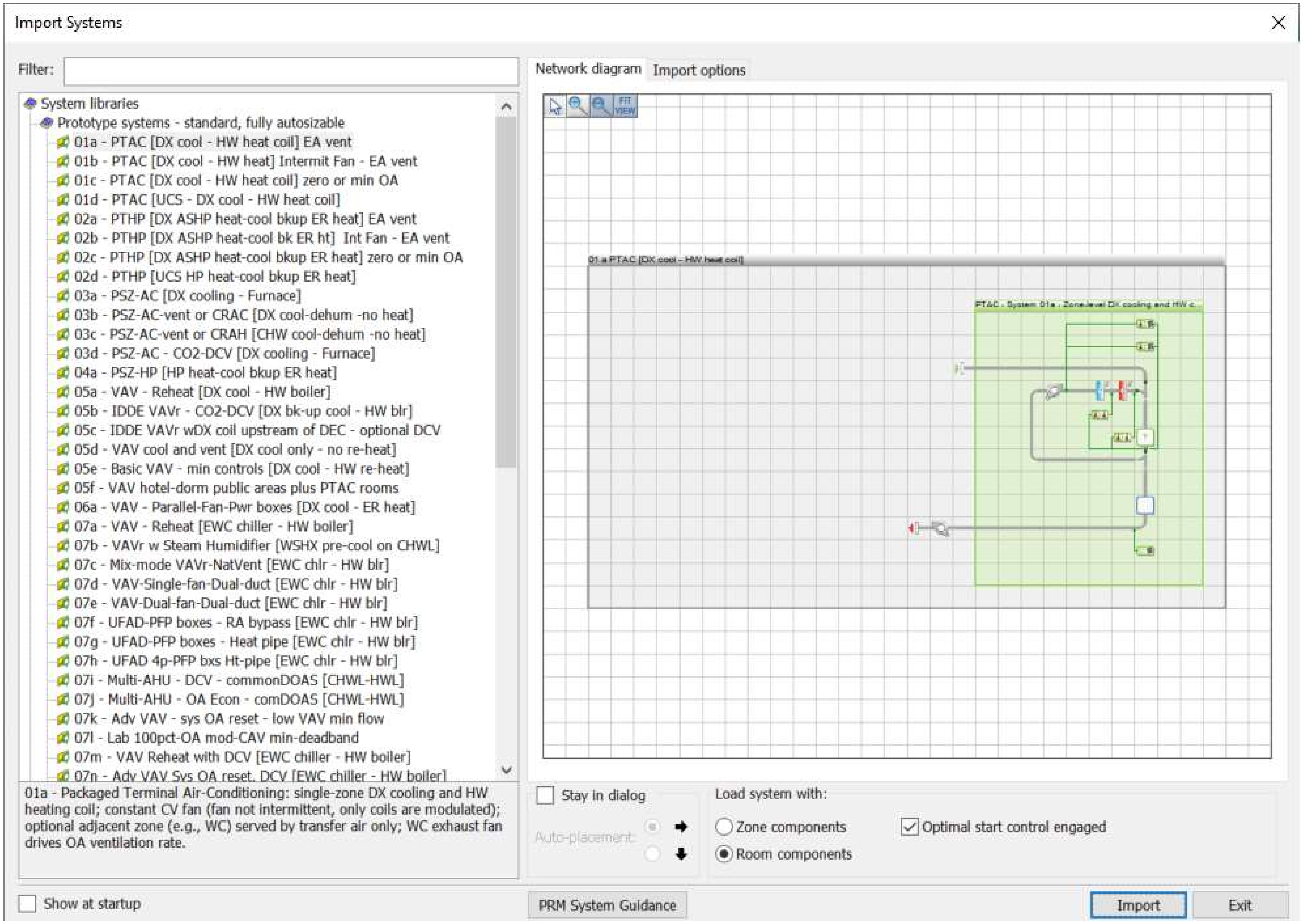
☐	ID	Category	Description	Data source	U value (W/m²·K)
☐	BSWAL30	External Wall	CZ5 Ext Wall (Res) - Steel Framed; R-13.0 + R-10.0 c.i; U=0....	ASHRAE 90.1	0.3105
☐	STD_CEIL	Internal Ceiling/Floor	2013 Internal Ceiling/Floor	Generic	1.0866
☐	STD_DOOR	Door	2013 Door	Generic	2.1997
☐	STD_EXTW	External Window	2013 External Window	Generic	1.6000
☐	STD_FLO1	Ground/Exposed Floor	2013 Exposed Floor	Generic	0.2200
☐	STD_PART	Internal Partition	2013 Internal Partition	Generic	1.7888
☐	STD_RFLT	Roof Light	2013 Rooflight	Generic	2.3000
☐	STD_ROOF	Roof	2013 Roof	Generic	0.1800
☐	STD_WAL1	External Wall	2013 External Wall	Generic	0.2599

Figure 5.9 Proposed model constructions assignment

The seventh step is space classification, which automatically assigns building thermal template information to the building model based on the selected thermal template scheme.

The eighth step is to generate the baseline model, which automatically generates the baseline models and assigns all relevant baseline information that are created in the previous steps.

The ninth step is to edit the proposed HVAC system. IES-VE library offer users with various HVAC systems to satisfy the different design conditions . For example, figure 5.10 illustrates the split system imported from the library.



System libraries
- Prototype systems - standard, fully autosizable
  - 01a - PTAC [DX cool - HW heat coil] EA vent
  - 01b - PTAC [DX cool - HW heat] Intermit Fan - EA vent
  - 01c - PTAC [DX cool - HW heat coil] zero or min OA
  - 01d - PTAC [UCS - DX cool - HW heat coil]
  - 02a - PTHP [DX ASHP heat-cool bkup ER heat] EA vent
  - 02b - PTHP [DX ASHP heat-cool bk ER ht] Int Fan - EA vent
  - 02c - PTHP [DX ASHP heat-cool bkup ER heat] zero or min OA
  - 02d - PTHP [UCS HP heat-cool bkup ER heat]
  - 03a - PSZ-AC [DX cooling - Furnace]
  - 03b - PSZ-AC-vent or CRAC [DX cool-dehum -no heat]
  - 03c - PSZ-AC-vent or CRAH [CHW cool-dehum -no heat]
  - 03d - PSZ-AC - CO2-DCV [DX cooling - Furnace]
  - 04a - PSZ-HP [HP heat-cool bkup ER heat]
  - 05a - VAV - Reheat [DX cool - HW boiler]
  - 05b - IDDE VAVr - CO2-DCV [DX bk-up cool - HW blr]
  - 05c - IDDE VAVr wDX coil upstream of DEC - optional DCV
  - 05d - VAV cool and vent [DX cool only - no re-heat]
  - 05e - Basic VAV - min controls [DX cool - HW re-heat]
  - 05f - VAV hotel-dorm public areas plus PTAC rooms
  - 06a - VAV - Parallel-Fan-Pwr boxes [DX cool - ER heat]
  - 07a - VAV - Reheat [EWC chiller - HW boiler]
  - 07b - VAVr w Steam Humidifier [WSHX pre-cool on CHWL]
  - 07c - Mix-mode VAVr-NatVent [EWC chlr - HW blr]
  - 07d - VAV-Single-fan-Dual-duct [EWC chlr - HW blr]
  - 07e - VAV-Dual-fan-Dual-duct [EWC chlr - HW blr]
  - 07f - UFAD-PFP boxes - RA bypass [EWC chlr - HW blr]
  - 07g - UFAD-PFP boxes - Heat pipe [EWC chlr - HW blr]
  - 07h - UFAD 4p-PFP bxs Ht-pipe [EWC chlr - HW blr]
  - 07i - Multi-AHU - DCV - commonDOAS [CHWL-HWL]
  - 07j - Multi-AHU - OA Econ - comDOAS [CHWL-HWL]
  - 07k - Adv VAV - sys OA reset - low VAV min flow
  - 07l - Lab 100pct-OA mod-CAV min-deadband
  - 07m - VAV Reheat with DCV [EWC chiller - HW boiler]
  - 07n - Adv VAV Sys OA reset, DCV [EWC chiller - HW boiler]

01a - Packaged Terminal Air-Conditioning: single-zone DX cooling and HW heating coil; constant CV fan (fan not intermittent, only coils are modulated); optional adjacent zone (e.g., WC) served by transfer air only; WC exhaust fan drives OA ventilation rate.

☐ Stay in dialog

Load system with:

○ Zone components

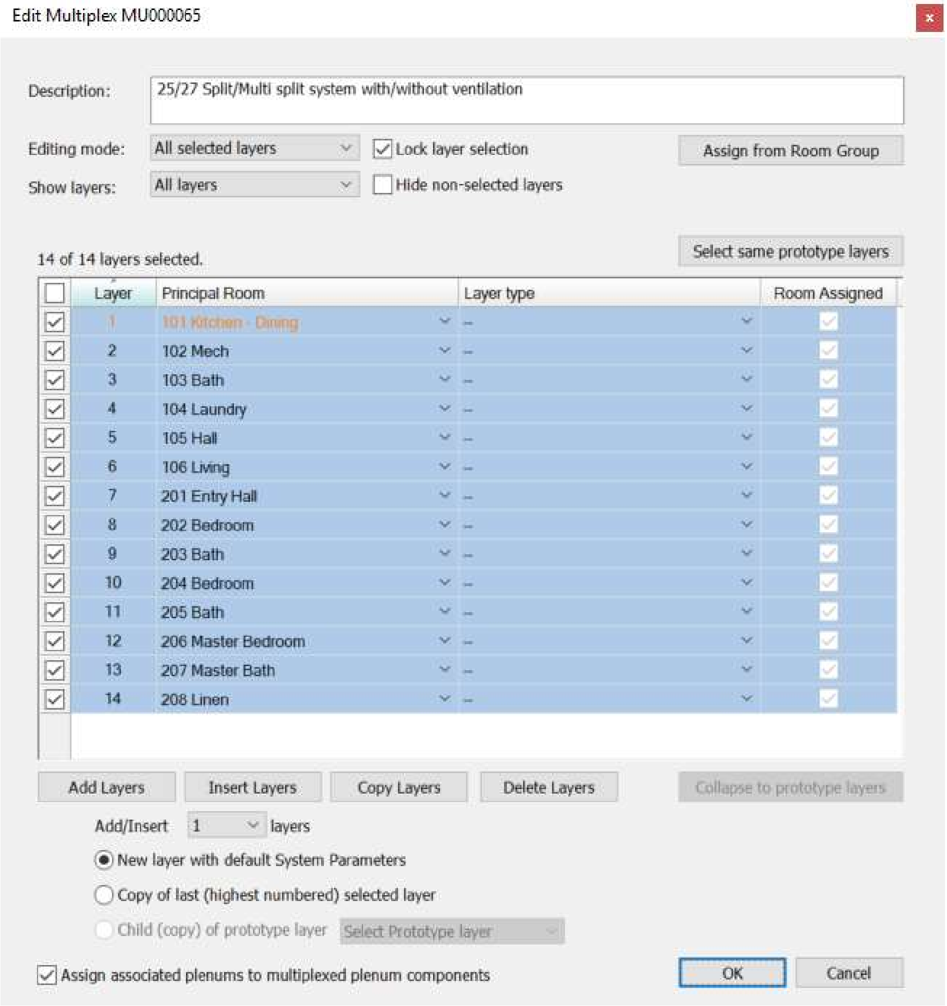
● Room components

☑ Optimal start control engaged

☐ Show at startup

Figure 5.10 Import of HVAC system

The tenth step is to multiplex HVAC system. As shown in figure 5.11, all rooms in the building are assigned to the HVAC system separately, this to satisfy the thermal and air requirement of each room.


Edit Multiplex MU000065

Description: 25/27 Split/Multi split system with/without ventilation

Editing mode: All selected layers ☑ Lock layer selection

Show layers: All layers ☐ Hide non-selected layers

14 of 14 layers selected.

☐	Layer	Principal Room	Layer type	Room Assigned
☑	1	101 Kitchen - Dining	--	✓
☑	2	102 Mech	--	✓
☑	3	103 Bath	--	✓
☑	4	104 Laundry	--	✓
☑	5	105 Hall	--	✓
☑	6	106 Living	--	✓
☑	7	201 Entry Hall	--	✓
☑	8	202 Bedroom	--	✓
☑	9	203 Bath	--	✓
☑	10	204 Bedroom	--	✓
☑	11	205 Bath	--	✓
☑	12	206 Master Bedroom	--	✓
☑	13	207 Master Bath	--	✓
☑	14	208 Linen	--	✓

Add/Insert 1 layers

● New layer with default System Parameters

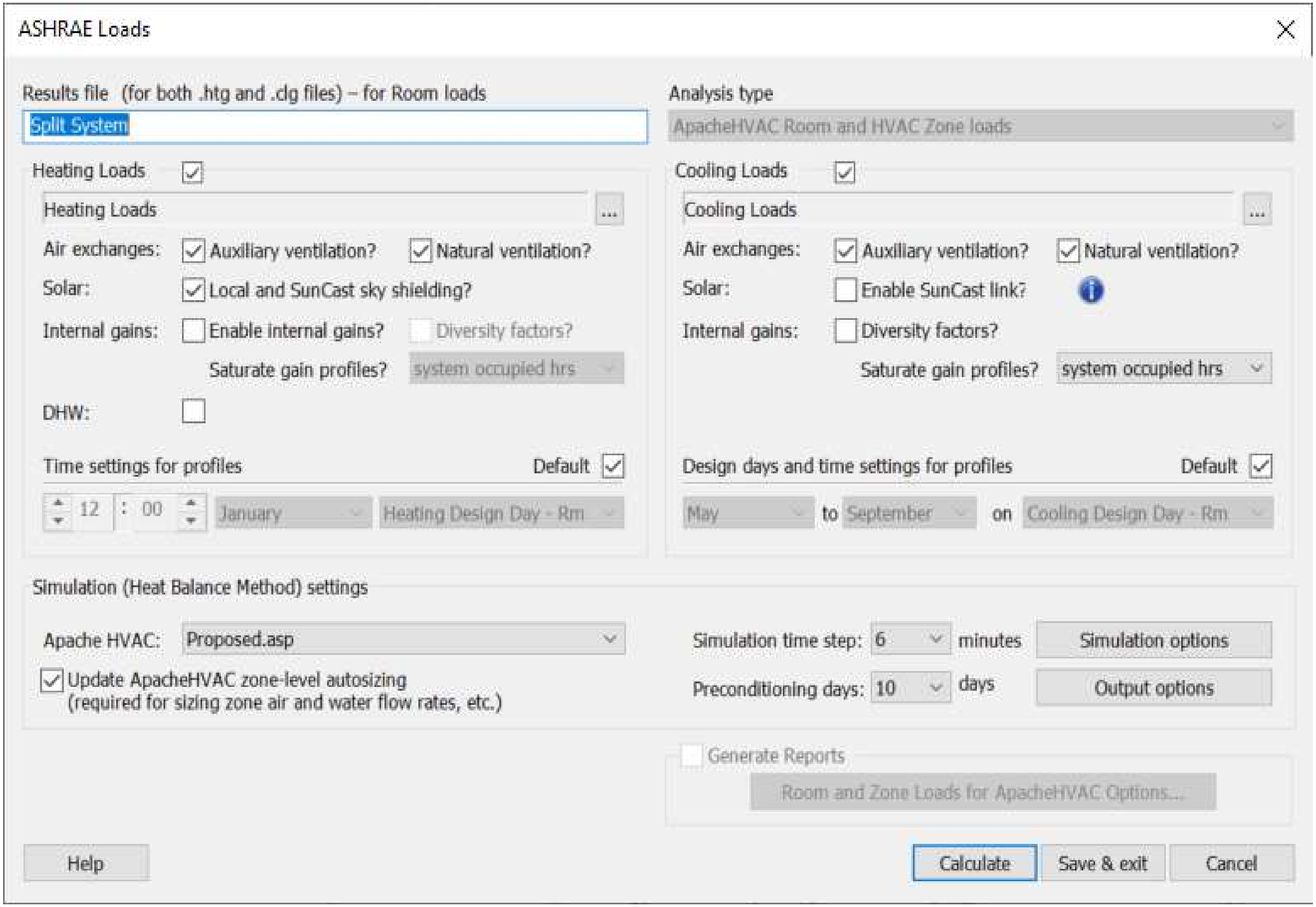
○ Copy of last (highest numbered) selected layer

○ Child (copy) of prototype layer Select Prototype layer

☑ Assign associated plenums to multiplexed plenum components

Figure 5.11 Multiplexing HVAC system

The eleventh step is room load calculation, which automatically opens the load dialog with the default information applied. The user can edit the information related to the building model as shown in figure 5.12.


ASHRAE Loads

Results file (for both .htg and .clg files) – for Room loads: Split System

Analysis type: ApacheHVAC Room and HVAC Zone loads

Heating Loads ☑

Heating Loads

Air exchanges: ☑ Auxiliary ventilation? ☑ Natural ventilation?

Solar: ☑ Local and SunCast sky shielding?

Internal gains: ☐ Enable internal gains? ☐ Diversity factors?

Saturate gain profiles? system occupied hrs

DHW: ☐

Time settings for profiles Default ☑

12 : 00 January Heating Design Day - Rm

Cooling Loads ☑

Cooling Loads

Air exchanges: ☑ Auxiliary ventilation? ☑ Natural ventilation?

Solar: ☐ Enable SunCast link?

Internal gains: ☐ Diversity factors?

Saturate gain profiles? system occupied hrs

Design days and time settings for profiles Default ☑

May to September on Cooling Design Day - Rm

Simulation (Heat Balance Method) settings

Apache HVAC: Proposed.asp

☑ Update ApacheHVAC zone-level autosizing (required for sizing zone air and water flow rates, etc.)

Simulation time step: 6 minutes

Preconditioning days: 10 days

☐ Generate Reports

Figure 5.12 Room load calculation

The twelfth step is system load calculation, which opens the load dialog again. However, this time a proposed HVAC system is assigned in order to enable a system sizing calculation.

The room load calculation report includes the peak cooling/heating load and required supply air flow of the building, and the system simulation report include the energy cost of the chosen HVAC system. The reports of room load and energy simulation of the building can be found in Appendix F and Appendix G. The thermal load and required air flow for the building are obtained as shown in Table 5-2. Meanwhile, the summary of annual energy consumption of the alternatives and baseline case are shown in figure 5.13.

Table 5-2 Design cooling and heating load

Cooling Load (Btuh)	Heating Load (Btuh)	Required Air Flow (cfm)
98,679	55,925	4,457

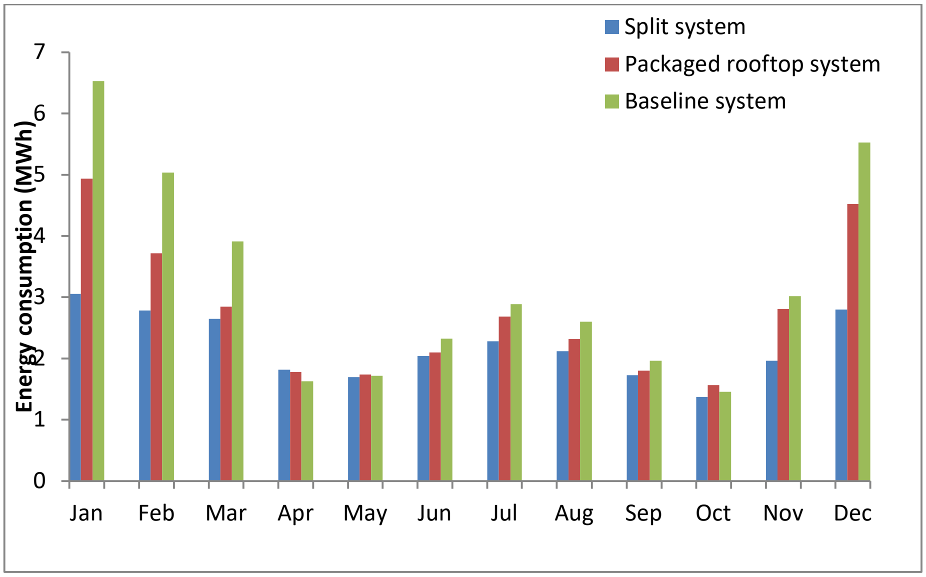


Figure 5.13 Monthly energy consumption of the alternatives

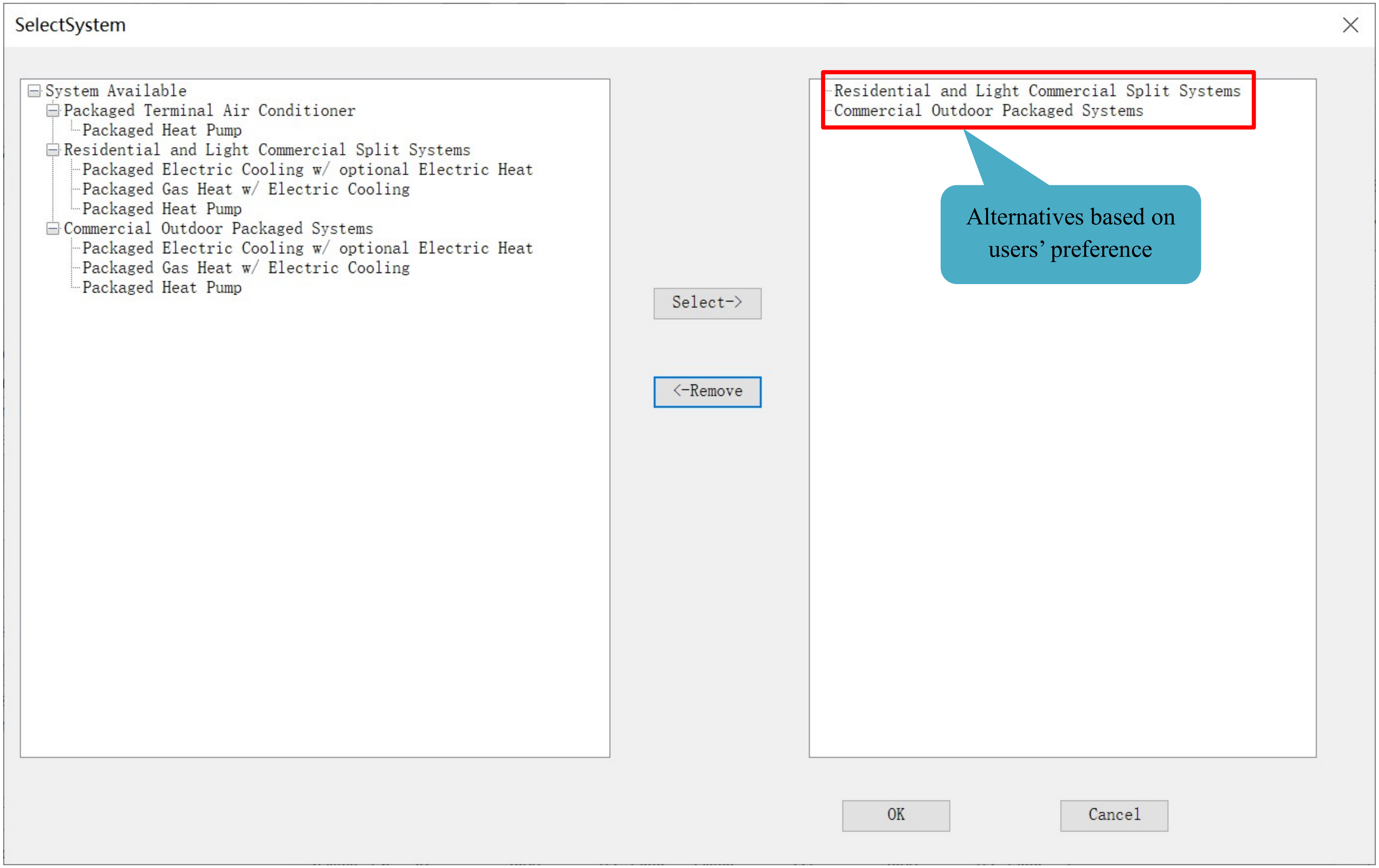
To earn the LEED points, the energy consumption saving of alternatives are compared with the baseline Case. The baseline case is selected to be the packaged terminal air conditioner (PTAC) with reheats according to ASHRAE 90.2-2016. The average electricity rate is 14.91¢/kWh in Boston. The annual energy consumption and cost of alternatives and baseline case are shown in Table 5-3. The Room load and the system simulation reports generated by IES-VE can be found in Appendix F.

Table 5-3 Energy consumption and cost of the alternatives

	Baseline Case	Split system	Packaged rooftop system
Energy consumption per year (MWh/yr)	38.58	26.29	32.82
Energy cost per year ($/yr)	5,752	3,920	4,813

5.4 HVAC Systems Selection

The third step is to select the type of HVAC systems based on users' preference. There are 2 HVAC alternatives chosen for the comparison in this case project. Alternative 1, is a split system for light commercial building, while alternative 2, is a packaged rooftop system for commercial building. Figure 5.14 illustrates the HVAC systems selection for this step.



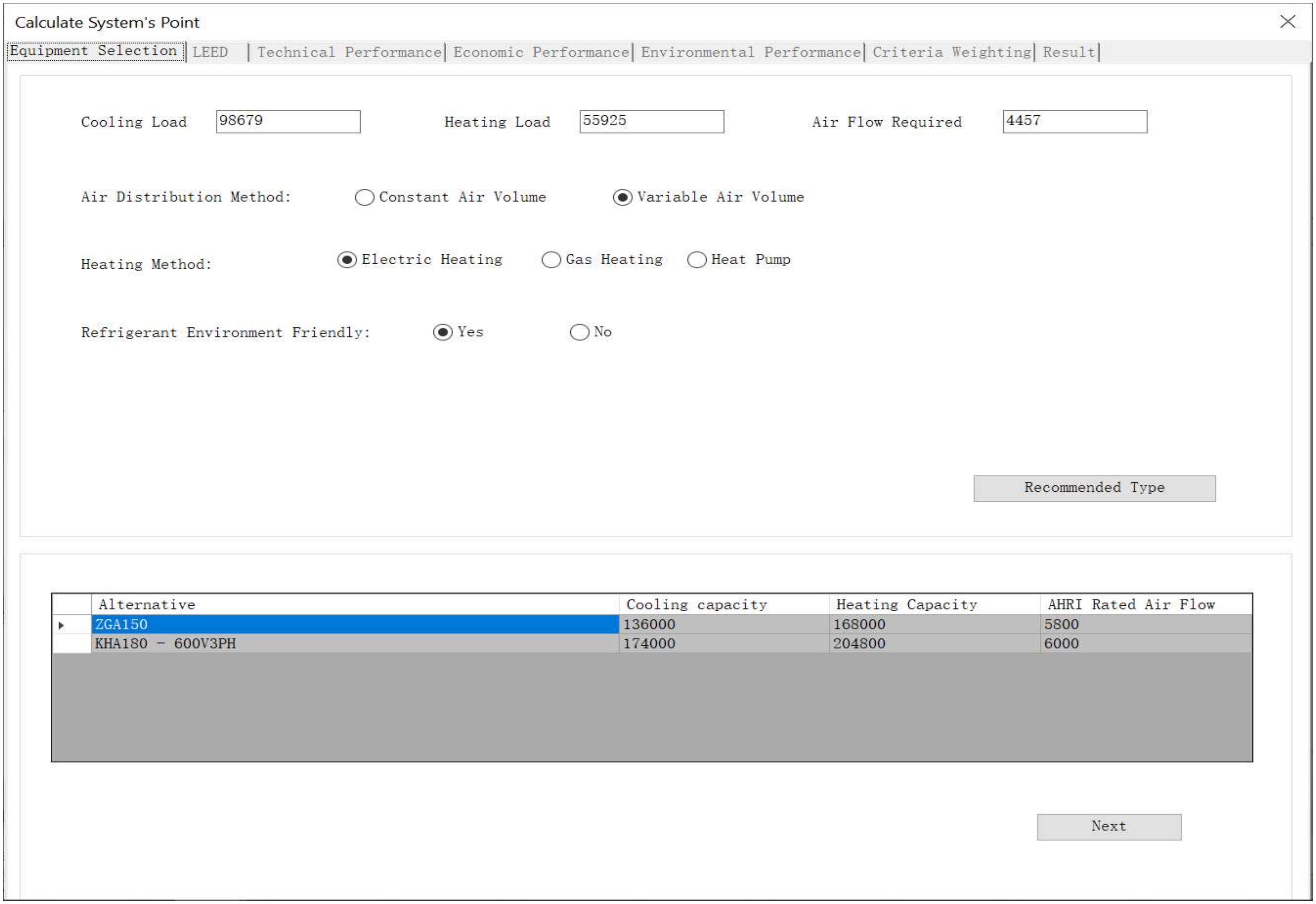
- System Available
  - Packaged Terminal Air Conditioner
    - Packaged Heat Pump
  - Residential and Light Commercial Split Systems
    - Packaged Electric Cooling w/ optional Electric Heat
    - Packaged Gas Heat w/ Electric Cooling
    - Packaged Heat Pump
  - Commercial Outdoor Packaged Systems
    - Packaged Electric Cooling w/ optional Electric Heat
    - Packaged Gas Heat w/ Electric Cooling
    - Packaged Heat Pump

- Residential and Light Commercial Split Systems
- Commercial Outdoor Packaged Systems

Figure 5.14 Selection of HVAC systems

5.5 HVAC Equipment Selection

The fourth step is the HVAC equipment selection. The principle of selecting HVAC equipment is to make the thermal capacity and fan capacity of the equipment match the threshold calculated by the energy analysis tool. According to the condition of energy cost, users can customize the heating method, including gas heating, electrical heating and heat pump. The air flow methods are divided into constant air volume (CAV) and variable air volume (VAV) to satisfy different running conditions of buildings. The model also inquires if users want the environmentally friendly refrigerant be applied. After collecting the data from the energy analysis and users' preference, the results will be used to retrieve the appropriate HVAC equipment from the general database. Figure 5.15 illustrates the HVAC equipment selection interface.



Cooling Load 98679

Heating Load 55925

Air Flow Required 4457

Air Distribution Method: ○ Constant Air Volume ● Variable Air Volume

Heating Method: ● Electric Heating ○ Gas Heating ○ Heat Pump

Refrigerant Environment Friendly: ● Yes ○ No

Alternative	Cooling capacity	Heating Capacity	AHRI Rated Air Flow
ZGA150	136000	168000	5800
KHA180 - 600V3PH	174000	204800	6000

Figure 5.15 Selection of HVAC equipment

5.6 LEED

The fifth step is to calculate the LEED performance value (PV_L) of alternatives. First, users need to enter the annual energy consumption of the alternatives, then choose if the project is an existing building or a new building. Based on the annual energy consumption of alternatives and baseline case, LEED EAc1 Optimize Energy Performance can be earned as illustrated in Table 5-4. Packaged rooftop system achieves 31.9% of energy cost savings compared to the Baseline Case, which corresponds to 3 points earned in EAc1. Alternative 2 achieves 14.9% of energy cost saving and earns 1 point in EAc1.

Table 5-4 EAc 1 earned for alternatives

	Split system	Packaged rooftop system
Percentage improvement compared to baseline case	31.9%	14.9%
Points earned	9	2

In order to earn LEED EAc4 Enhanced refrigerant management, the calculations should follow equations 3.4 through 3.8. Table 5-5 presents the global warming potential and ozone depletion potential of refrigerant. Table 5-6 shows the summary of points earned in LEED.

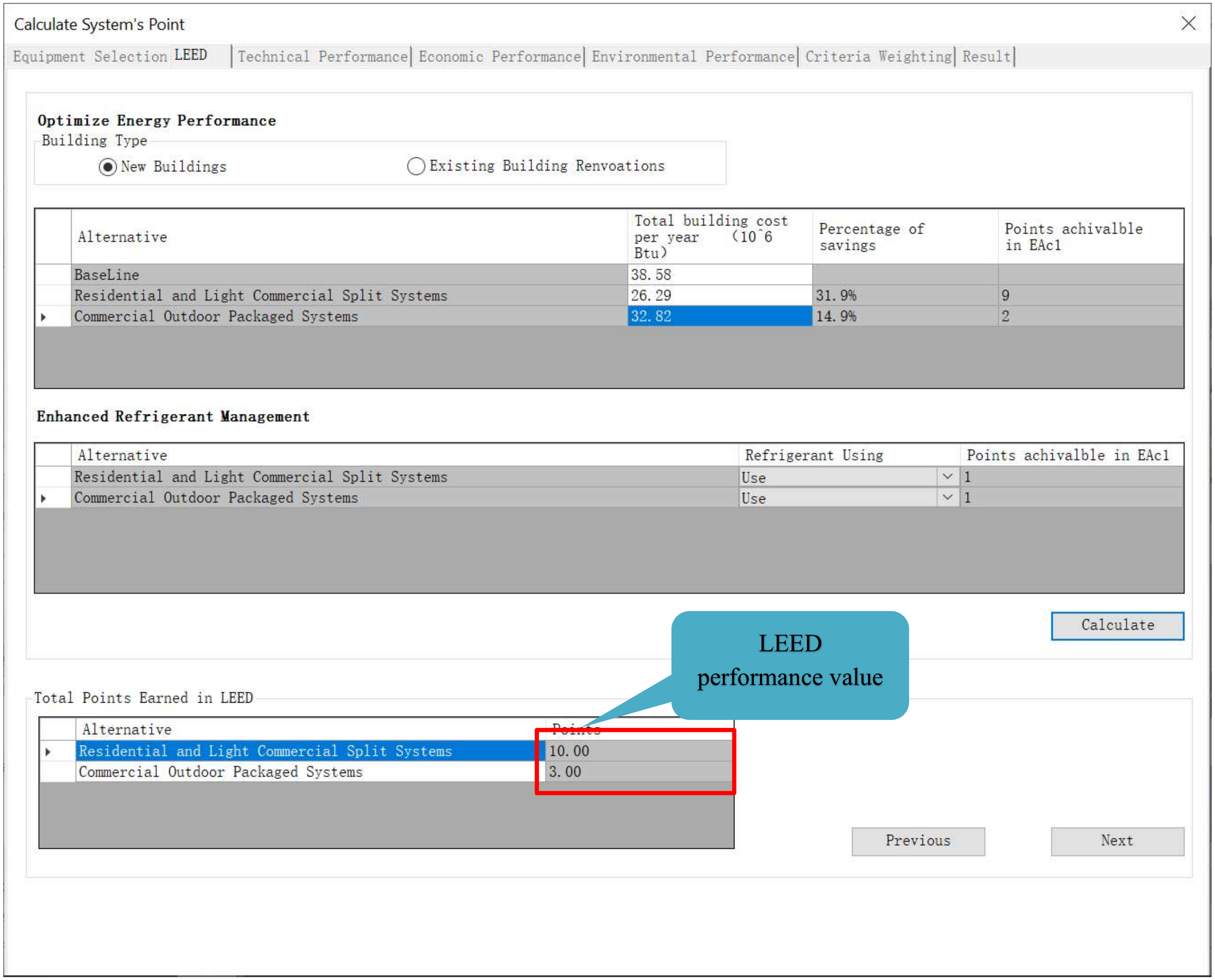
Table 5-5 EAc 4 earned for alternatives

	Alternative 1	Alternative 2
Refrigerant	R-401	R-401
GWPr (lbCO2/lbr)	1900	1900
ODPr (lbCFC11/lbr)	0	0
Rc (lb/ton)	0.5	0.5
Life (yrs)	20	20
Lr (%)	2%	2%
Mr (%)	10%	10%
Total Leakage	40%	40%
LCGWP	22.79	22.79
LCODP×1E5	51.20	51.20
Refrigerant Atmospheric Impact	73.99	73.99
Points	1	1

Table 5-6 The points earned in LEED for alternatives

	Alternative 1	Alternative 2
EAc1	9	2
EAc4	1	1
Total	10	3

Thus, the LEED performance value for the split system is 10, and for the packaged rooftop system is 3. Figure 5.16 illustrates the data entry of the LEED rating system.



Optimize Energy Performance

Building Type

● New Buildings ○ Existing Building Renvoations

	Alternative	Total building cost per year (10^6 Btu)	Percentage of savings	Points achivalble in EAc1
	BaseLine	38.58		
	Residential and Light Commercial Split Systems	26.29	31.9%	9
▸	Commercial Outdoor Packaged Systems	32.82	14.9%	2

Enhanced Refrigerant Management

	Alternative	Refrigerant Using	Points achivalble in EAc1
	Residential and Light Commercial Split Systems	Use	1
▸	Commercial Outdoor Packaged Systems	Use	1

Total Points Earned in LEED

	Alternative	Points
▸	Residential and Light Commercial Split Systems	10.00
	Commercial Outdoor Packaged Systems	3.00

LEED performance value

Figure 5.16 Entry of LEED performance for alternatives

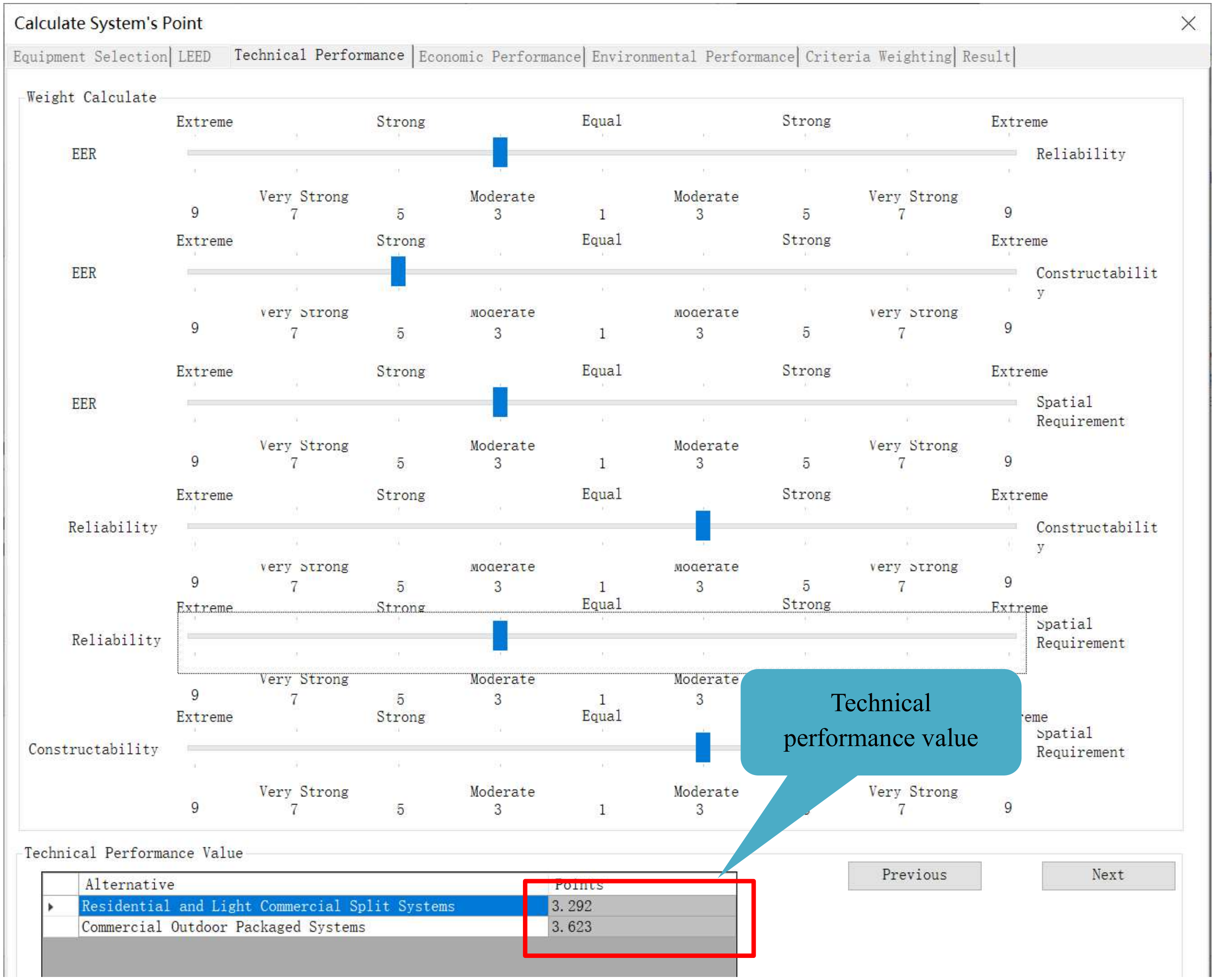
5.7 Technical Performance

The sixth step is to calculate the technical performance value (PV_T) of the alternatives. According to ASHRAE 2016 Handbook—HVAC Systems and Equipment, technical performance is indicated by the energy efficiency ratio, reliability, constructability and spatial requirement. Table 5-7 lists the technical performance for two alternatives in the scale of "poor, fair, good, and excellent", the performance value is set on a scale from 1 to 4.

Table 5-7 Technical performance for alternatives

	Packaged rooftop system	Split system
Energy efficiency	Good (3)	Good (3)
Reliability	Good (3)	Good (3)
Constructability	Excellent (4)	Good (3)
Spatial requirement	Excellent (4)	Excellent (4)

The pairwise comparisons are expressed in figure 5.17. There are 4 sub-criteria under technical performance, which includes EER; reliability; constructability; and spatial requirement. The scroll bars are constructed in a window form to make pairwise comparison between criteria. For example, the first scroll bar in the figure represents that based on user's preference, EER is moderately favored over reliability. Meanwhile, the interface displays the results of technical performance value after the pairwise comparison has been decided by users.



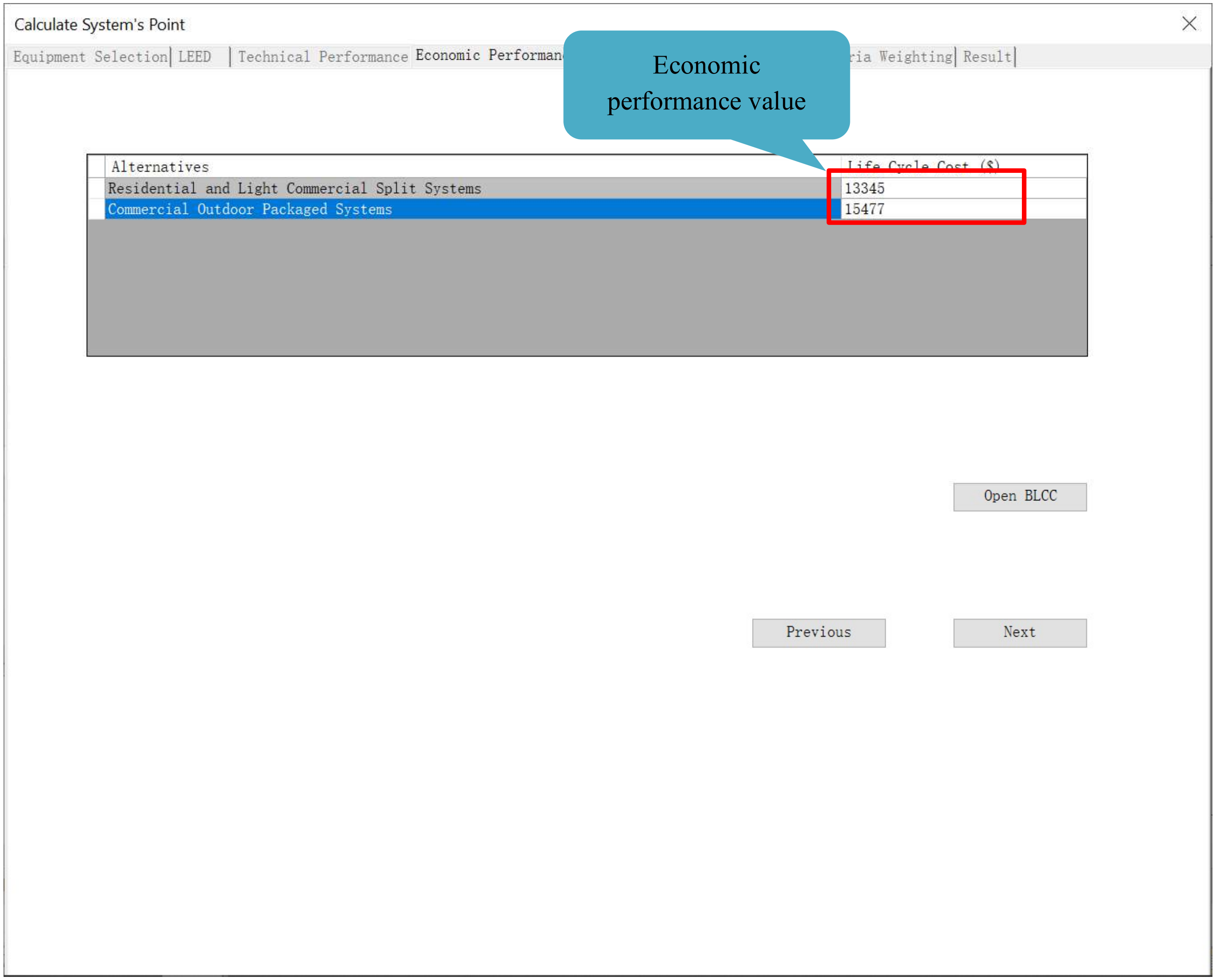
	Alternative	Points
▸	Residential and Light Commercial Split Systems	3.292
	Commercial Outdoor Packaged Systems	3.623

Technical performance value

Figure 5.17 Pairwise comparison of sub-criteria under technical performance

5.8 Economic Performance

The seventh step is to calculate the economic performance value (PV_C) of alternatives. Figure 5.18 illustrates the data entry of economic performance value for this step. Users need to enter the life cycle cost of alternatives into the interface. In this study, BLCC 5.3, the tool for calculating life cycle cost of project is applied. The Link at the bottom of the interface allows users to directly access BLCC.

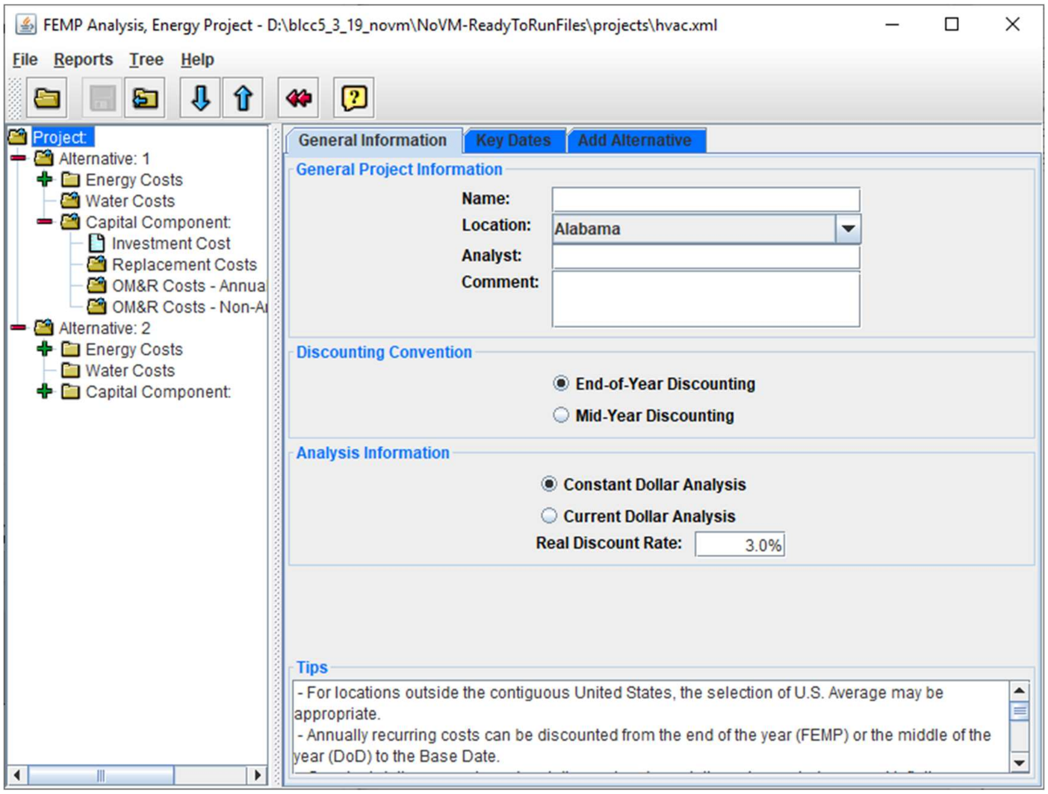


Economic performance value

Alternatives	Life Cycle Cost ($)
Residential and Light Commercial Split Systems	13345
Commercial Outdoor Packaged Systems	15477

Figure 5.18 Entry of LCC for alternatives

The process of calculating the life cycle cost of the HVAC systems within BLCC is shown in figures 5.19 through 5.23.



General Project Information

Name:

Location: Alabama

Analyst:

Comment:

Discounting Convention

● End-of-Year Discounting

○ Mid-Year Discounting

Analysis Information

● Constant Dollar Analysis

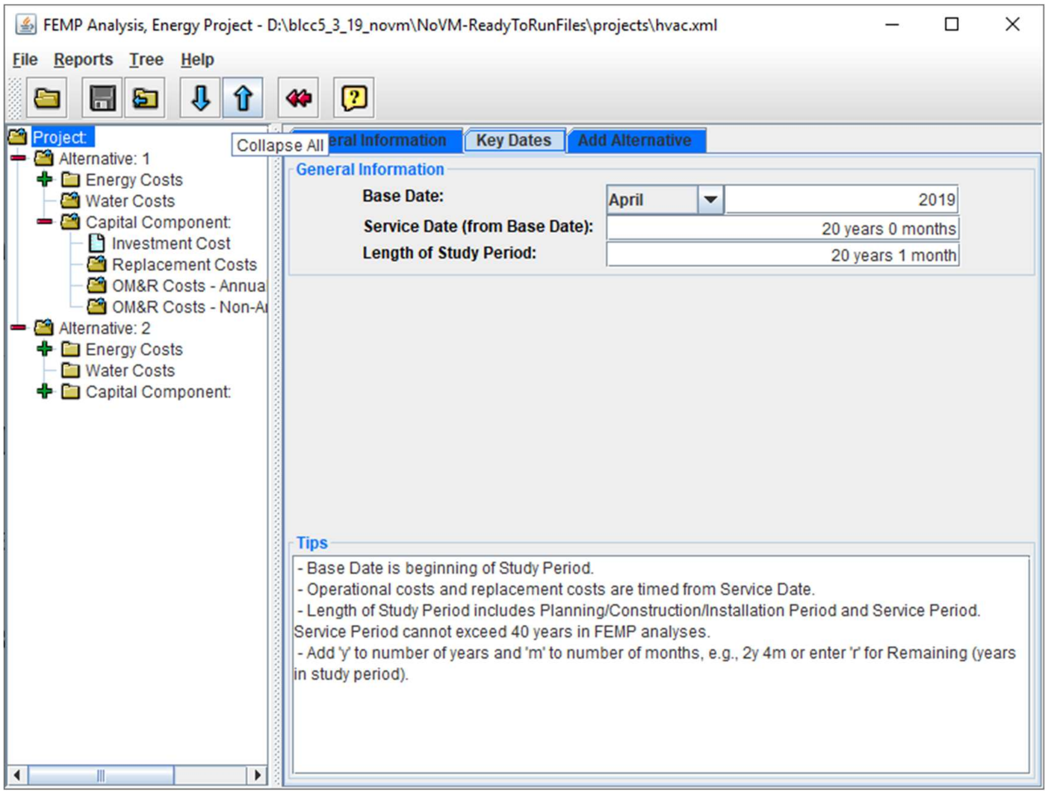
○ Current Dollar Analysis

Real Discount Rate: 3.0%

Tips

- For locations outside the contiguous United States, the selection of U.S. Average may be appropriate.
- Annually recurring costs can be discounted from the end of the year (FEMP) or the middle of the year (DoD) to the Base Date.

Figure 5.19 Process of calculating LCC of the project (a)



General Information

Base Date: April 2019

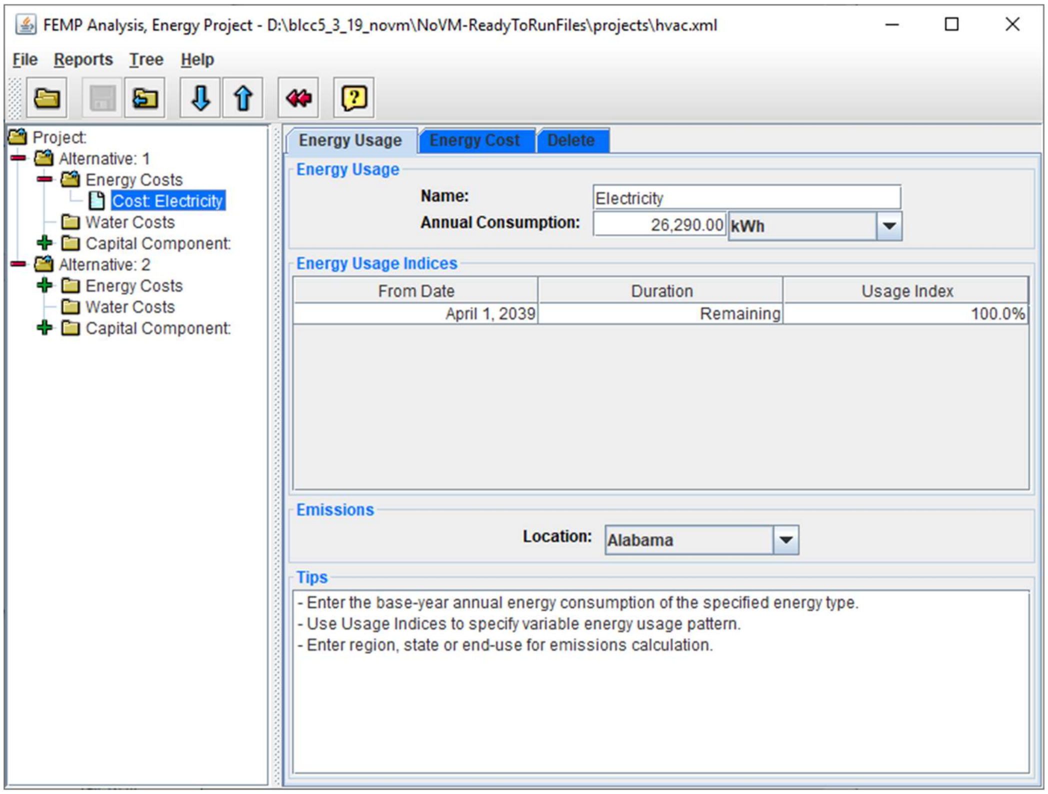
Service Date (from Base Date): 20 years 0 months

Length of Study Period: 20 years 1 month

Tips

- Base Date is beginning of Study Period.
- Operational costs and replacement costs are timed from Service Date.
- Length of Study Period includes Planning/Construction/Installation Period and Service Period. Service Period cannot exceed 40 years in FEMP analyses.
- Add 'y' to number of years and 'm' to number of months, e.g., 2y 4m or enter 'r' for Remaining (years in study period).

Figure 5.20 Process of calculating LCC of the project (b)



Energy Usage

Name: Electricity

Annual Consumption: 26,290.00 kWh

Energy Usage Indices

From Date	Duration	Usage Index
April 1, 2039	Remaining	100.0%

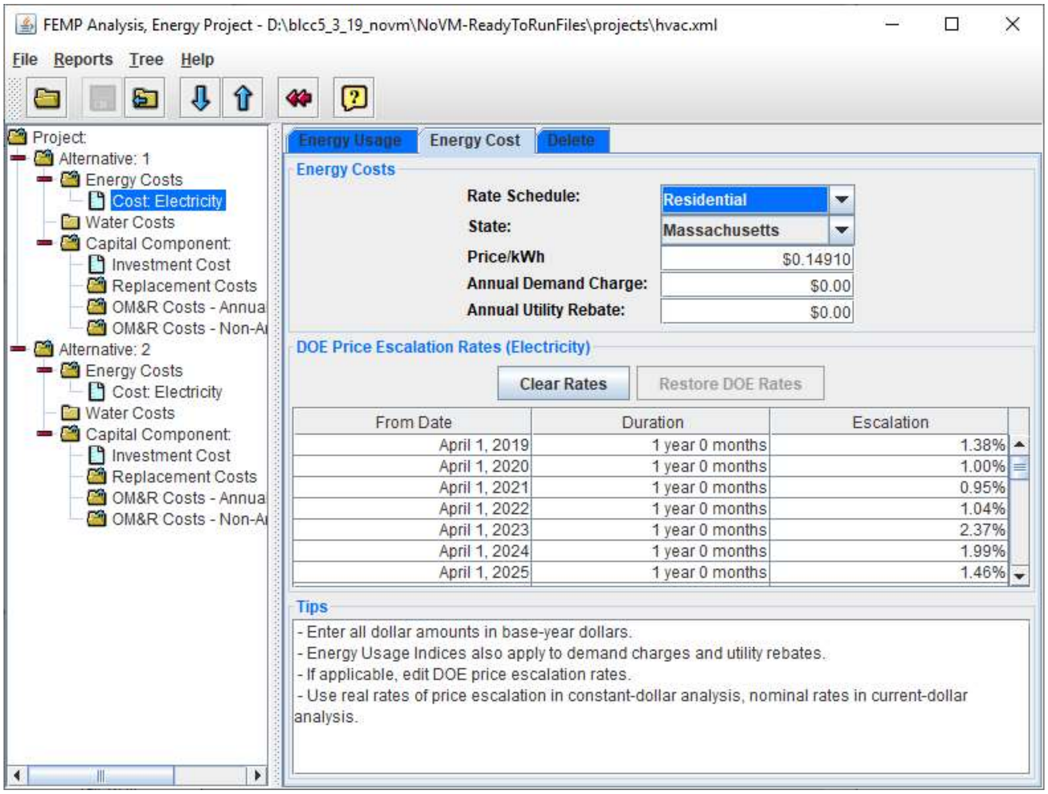
Emissions

Location: Alabama

Tips

- Enter the base-year annual energy consumption of the specified energy type.
- Use Usage Indices to specify variable energy usage pattern.
- Enter region, state or end-use for emissions calculation.

Figure 5.21 Process of calculating LCC of the project (c)



FEMP Analysis, Energy Project - D:\blcc5_3_19_novm\NoVM-ReadyToRunFiles\projects\hvac.xml

Energy Costs

Rate Schedule: Residential

State: Massachusetts

Price/kWh $0.14910

Annual Demand Charge: $0.00

Annual Utility Rebate: $0.00

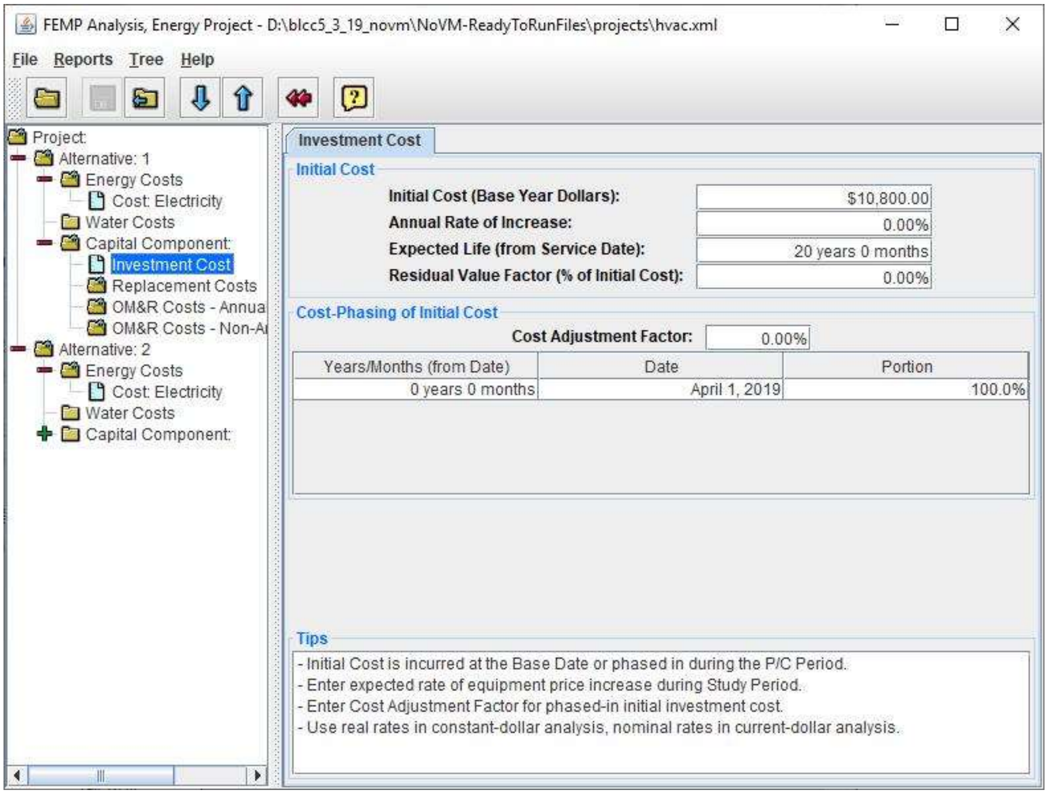
DOE Price Escalation Rates (Electricity)

From Date	Duration	Escalation
April 1, 2019	1 year 0 months	1.38%
April 1, 2020	1 year 0 months	1.00%
April 1, 2021	1 year 0 months	0.95%
April 1, 2022	1 year 0 months	1.04%
April 1, 2023	1 year 0 months	2.37%
April 1, 2024	1 year 0 months	1.99%
April 1, 2025	1 year 0 months	1.46%

Tips

- Enter all dollar amounts in base-year dollars.
- Energy Usage Indices also apply to demand charges and utility rebates.
- If applicable, edit DOE price escalation rates.
- Use real rates of price escalation in constant-dollar analysis, nominal rates in current-dollar analysis.

Figure 5.22 Process of calculating LCC of the project (d)



Initial Cost

Initial Cost (Base Year Dollars): $10,800.00
Annual Rate of Increase: 0.00%
Expected Life (from Service Date): 20 years 0 months
Residual Value Factor (% of Initial Cost): 0.00%

Cost-Phasing of Initial Cost

Cost Adjustment Factor: 0.00%

Years/Months (from Date)	Date	Portion
0 years 0 months	April 1, 2019	100.0%

Tips

- Initial Cost is incurred at the Base Date or phased in during the P/C Period.
- Enter expected rate of equipment price increase during Study Period.
- Enter Cost Adjustment Factor for phased-in initial investment cost.
- Use real rates in constant-dollar analysis, nominal rates in current-dollar analysis.

Figure 5.23 Process of calculating LCC of the project (e)

First, users need to enter the project information is required for the calculation, including general project information, discounting convention, analysis information and of the study period. The discount rate is set to be 3%. The study period for the alternatives is 20 years. Second, they should enter the annual energy consumption costs and capital component costs of the alternatives. The capital component of the systems, which only include the installation cost because of the shaded information from manufacturers, are collected from RS Means cost database, which can be found in Appendix A. It was found that the initial cost is $10,800 for alternative 1, and $12,300 for alternative 2.

Tables 5-8 and 5-9 show the results collected from BLCC 5.3. The life cycle cost for Alternative 1 is $13,345, which is the lower one. The life cycle cost for Alternative 2 is $15,477.

Table 5-8 Life cycle cost of split system

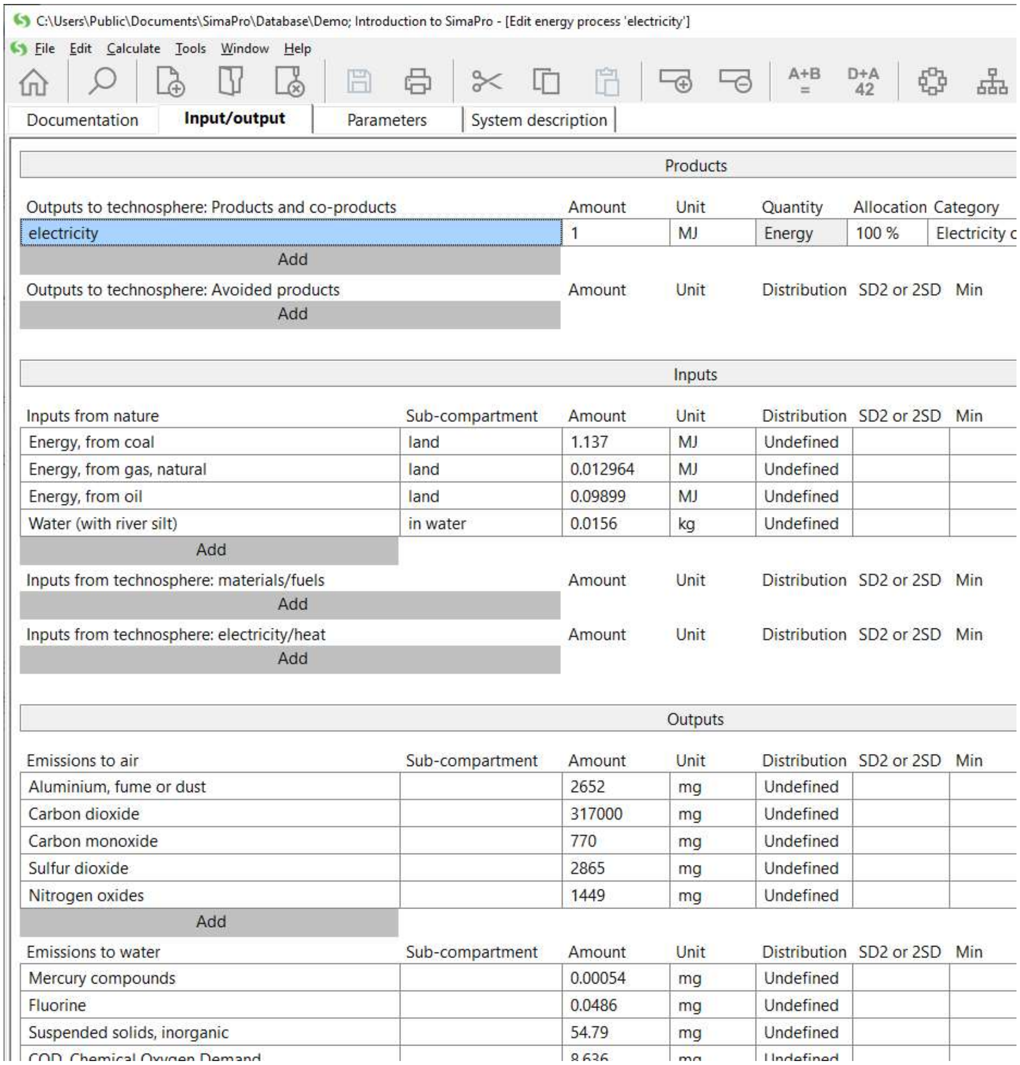
	Present value
Initial cost	$10,800
Energy consumption cost	$3,920
Annually Recurring OM&R costs	N/A
Non- Annually Recurring OM&R costs	N/A
Replacement costs	N/A
Less Remaining Value	N/A
Total Life-Cycle	$13,345

Table 5-9 Life cycle cost of packaged rooftop system

	Present value
Initial cost	$12,300
Energy consumption cost	$4,813
Annually Recurring OM&R costs	N/A
Non- Annually Recurring OM&R costs	N/A
Replacement costs	N/A
Less Remaining Value	N/A
Total Life-Cycle	$15,477

5.9 Environmental Performance

SimaPro 7 is the software used for evaluating the environmental performance of the HVAC systems alternatives, the process is instructed by SimaPro 7 Wizards. Because of the limited and shaded information from the manufacture on the composition of raw materials of the equipment, as well as the proof of low environmental contribution of equipment production phase over the whole life cycle based on the literature, the contribution of manufacture production and disposal phase of the HVAC systems is neglected. In this case project, the cooling and heating equipment of packaged rooftop system and split system are totally driven by electricity. First, users are required to create a new inventory data for the electricity usage. Figure 5.24 shows the inventory data of electricity usage based on the location’s conditions. Please refer to Appendix B for the detailed information of natural resource inputs and emissions for generating 1MJ electricity in Boston. The coal is the main source for the electricity production. Then, BEES+ is chosen to be the impact assessment method in the case project as shown in figure 5.25.



C:\Users\Public\Documents\SimaPro\Database\Demo; Introduction to SimaPro - [Edit energy process 'electricity']

Products

Outputs to technosphere: Products and co-products	Amount	Unit	Quantity	Allocation	Category
electricity	1	MJ	Energy	100 %	Electricity c

Outputs to technosphere: Avoided products	Amount	Unit	Distribution	SD2 or 2SD	Min

Inputs

Inputs from nature	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min
Energy, from coal	land	1.137	MJ	Undefined		
Energy, from gas, natural	land	0.012964	MJ	Undefined		
Energy, from oil	land	0.09899	MJ	Undefined		
Water (with river silt)	in water	0.0156	kg	Undefined		

Inputs from technosphere: materials/fuels	Amount	Unit	Distribution	SD2 or 2SD	Min

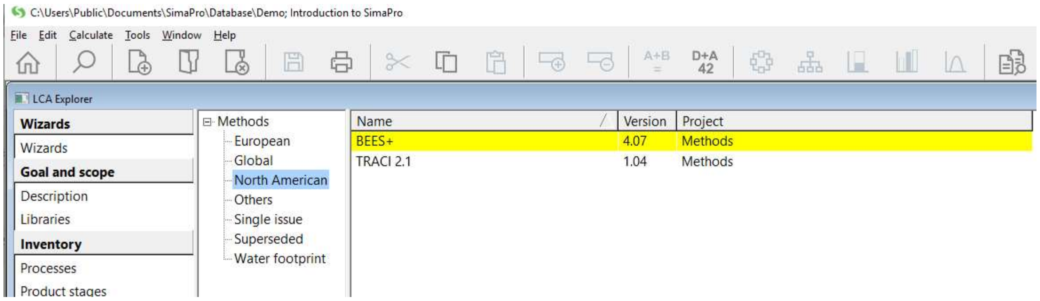
Inputs from technosphere: electricity/heat	Amount	Unit	Distribution	SD2 or 2SD	Min

Outputs

Emissions to air	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min
Aluminium, fume or dust		2652	mg	Undefined		
Carbon dioxide		317000	mg	Undefined		
Carbon monoxide		770	mg	Undefined		
Sulfur dioxide		2865	mg	Undefined		
Nitrogen oxides		1449	mg	Undefined		

Emissions to water	Sub-compartment	Amount	Unit	Distribution	SD2 or 2SD	Min
Mercury compounds		0.00054	mg	Undefined		
Fluorine		0.0486	mg	Undefined		
Suspended solids, inorganic		54.79	mg	Undefined		
COD, Chemical Oxygen Demand		8.636	mg	Undefined		

Figure 5.24 Entry of the inventory data of electricity usage



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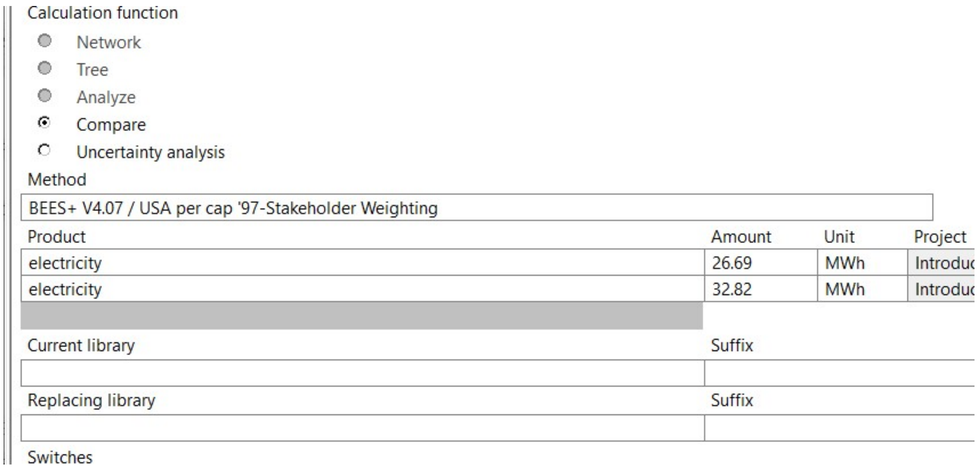
Name	Version	Project
BEES+	4.07	Methods
TRACI 2.1	1.04	Methods

Figure 5.25 Choosing impact assessment method

Finally, setup the calculations for electricity usage is shown in figure 5.26. The electricity usage, which is the annual energy consumption for alternative 1 is 26.69 MWh, and for alternative 2 is 32.82 MWh. Figure 5.27 illustrates the environmental impacts of the HVAC systems. The performance indicators of impact categories are also indicated in the Table 5-9.


Calculation function
- ○ Network
- ○ Tree
- ○ Analyze
- ● Compare
- ○ Uncertainty analysis

Method

BEES+ V4.07 / USA per cap '97-Stakeholder Weighting

Product	Amount	Unit	Project
electricity	26.69	MWh	Introduc
electricity	32.82	MWh	Introduc

Current library | Suffix

Replacing library | Suffix

Switches

Figure 5.26 Calculation setups for electricity usage

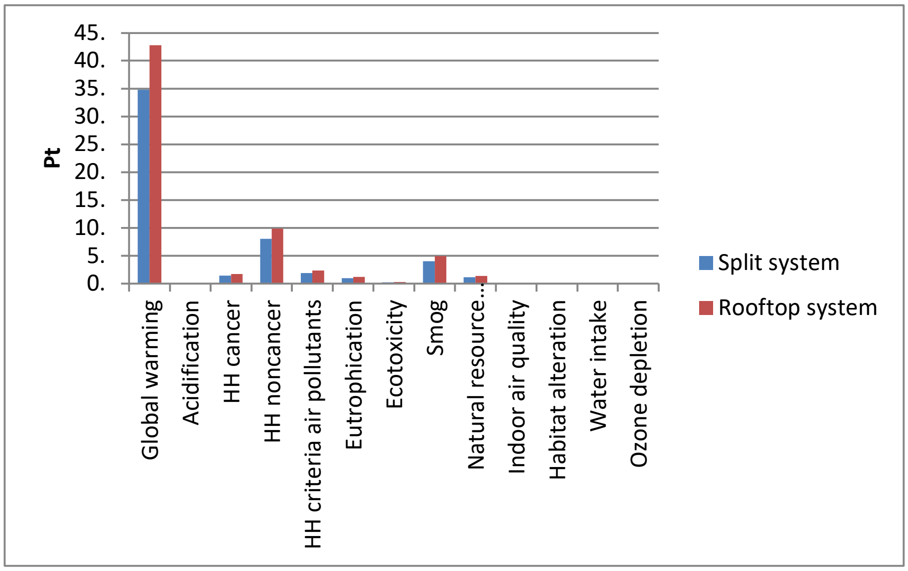
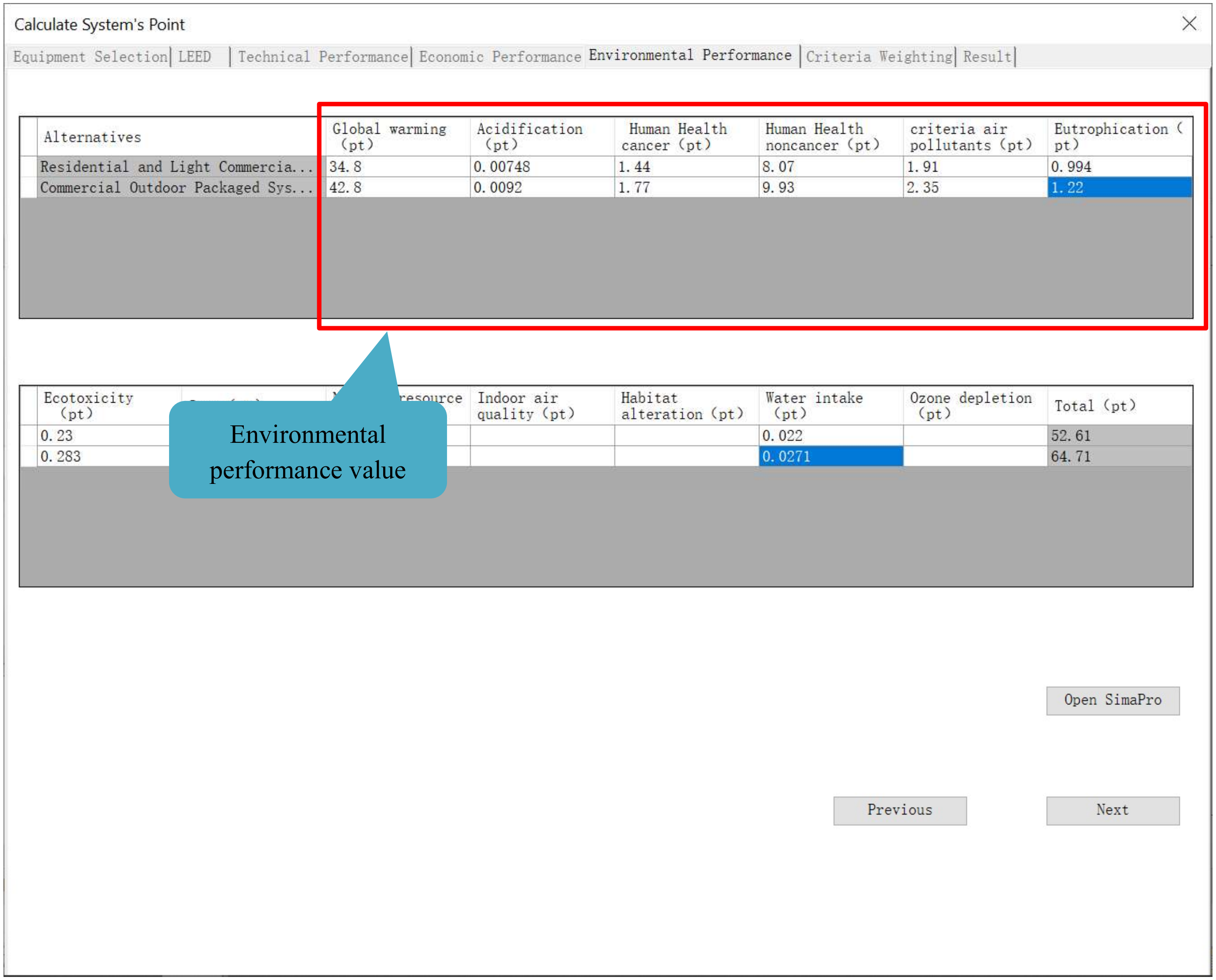


Figure 5.27 Environmental performance value for HVAC systems

Table 5-10 The performance indicator of impact categories for alternatives

	Alternative 1 (pt)	Alternative 2 (pt)
Global warming	68.4	70.3
Acidification	0.0147	0.0151
Human Health cancer	2.83	2.91
Human Health noncancer	15.9	16.3
criteria air pollutants	3.76	3.86
Eutrophication	1.95	2.01
Ecotoxicity	0.453	0.466
Smog	7.88	8.1
Natural resource depletion	2.24	2.31
Indoor air quality	0	0
Habitat alteration	0	0
Water intake	0.0433	0.0446
Ozone depletion	0	0
Total environmental impact	103	106

As shown in figure 5.28, users should input the results of environmental analysis, which is the performance value into the environmental performance interface.



Alternatives	Global warming (pt)	Acidification (pt)	Human Health cancer (pt)	Human Health noncancer (pt)	criteria air pollutants (pt)	Eutrophication (pt)
Residential and Light Commercia...	34. 8	0. 00748	1. 44	8. 07	1. 91	0. 994
Commercial Outdoor Packaged Sys...	42. 8	0. 0092	1. 77	9. 93	2. 35	1. 22

Ecotoxicity (pt)	[illegible]	resource	Indoor air quality (pt)	Habitat alteration (pt)	Water intake (pt)	Ozone depletion (pt)	Total (pt)
0. 23	[illegible]	[illegible]			0. 022		52. 61
0. 283	[illegible]	[illegible]			0. 0271		64. 71

Figure 5.28 Entry of LCA for alternatives

5.10 Decision-Making System

The criteria layer contains four criteria: Technical Requirement C1; Economic Performance C2; Environmental Performance C3; and Green building C4. The determination of the importance of each criterion is based on the preference of the decision maker. A 9-point importance scale is chosen for this case. Figure 5.29 indicates the subjective judgment based on the decision maker's preference when comparing each two of the criteria in pair wise. Users should give their preference on the importance of each criterion by the pairwise comparison. For example, the first scroll bar in the figure shows that the economic performance is strongly favored over the technical performance.

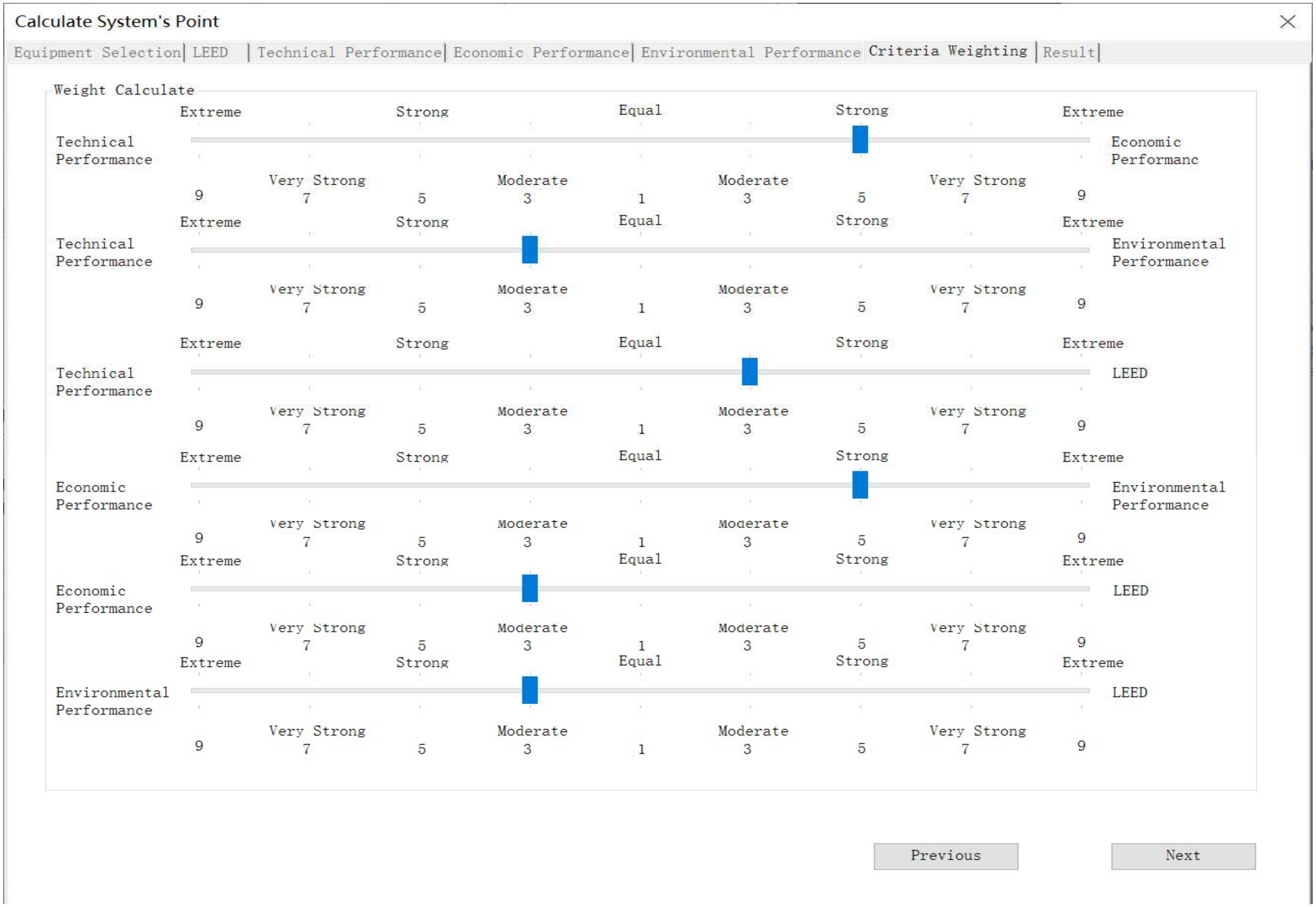


Figure 5.29 Pairwise comparison of performance criteria

Since the weights obtained by AHP method are based on users' preference, the entropy method is introduced to reduce the subjective influence on the results. Using equations 3.14 through 3.18, the decision matrix will be developed as shown in Table 5-10. Table 5-11 lists the weights as calculated by the AHP and Entropy method, as well as the combination results. All formulas are coded in the developed interface.

Table 5-11 Decision matrix for entropy analysis

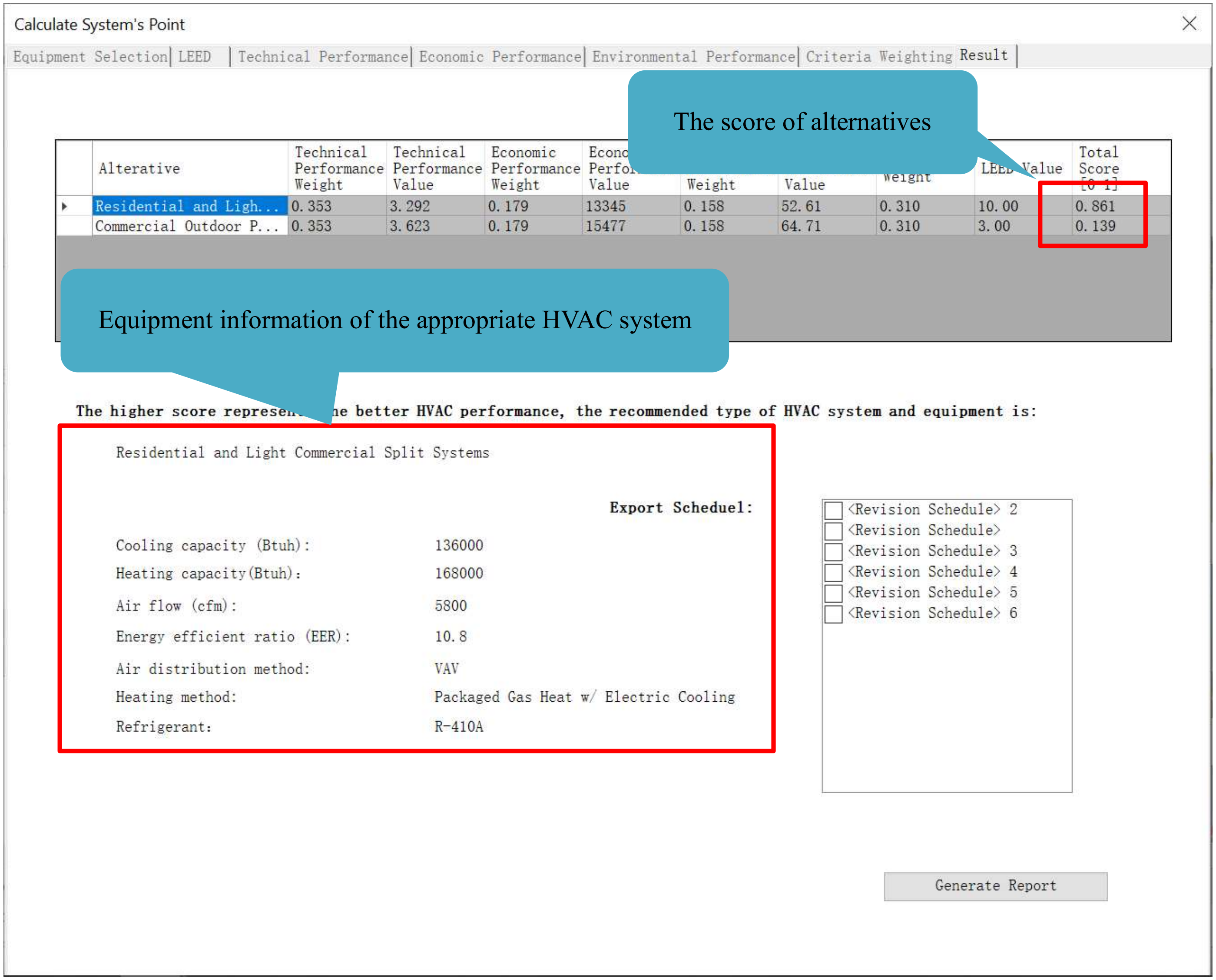
Alternatives	LEED	Technical performance	Economic performance	Environmental performance
Split system	4	3	$14,138	103 pt
Packaged rooftop system	2	4	$15,252	106 pt

Table 5-12 Weightings for HVAC performance

Criteria	AHP weights	Entropy weights	Combination weights
Technical performance	6.98%	25.08%	8.11%
Economic performance	12.1%	25.20%	13.93%
Environmental performance	40.46%	25.19%	46.60%
LEED	40.46%	24.53%	45.36%

5.11 Recommended HVAC Systems and Equipment

The final step is to recommend the HVAC product. The decision-making system will rank the score of each alternative in a range of 0 to 1. The greater score represents the highest matching degree based on users' preference and higher performance, which means the alternative with the highest scores will be recommended for design. Meanwhile, the equipment information will be presented, including the cooling and heating capacity, air flow, the applied refrigerant type and so on. Figure 5.30 shows the output of this module. By clicking the "Generate Report" button, all detailed information of recommended HVAC products and building schedules will be imported into spreadsheet, which can be found in Appendix E. The result of the model shows that alternative 1, the split system for light commercial building earn 0.861, while alternative 2, the packaged rooftop system for commercial building earn 0.139, which means that alternative 1 is the appropriate HVAC system based on the user's preference and building information.



	Alterative	Technical Performance Weight	Technical Performance Value	Economic Performance Weight	Econo Perfo Value	Weight	Value	Weight	LEED Value	Total Score [0-1]
▸	Residential and Ligh...	0.353	3.292	0.179	13345	0.158	52.61	0.310	10.00	0.861
	Commercial Outdoor P...	0.353	3.623	0.179	15477	0.158	64.71	0.310	3.00	0.139

The higher score represen... he better HVAC performance, the recommended type of HVAC system and equipment is:

Residential and Light Commercial Split Systems

Export Scheduel:

Cooling capacity (Btuh):	136000
Heating capacity(Btuh):	168000
Air flow (cfm):	5800
Energy efficient ratio (EER):	10.8
Air distribution method:	VAV
Heating method:	Packaged Gas Heat w/ Electric Cooling
Refrigerant:	R-410A

☐ <Revision Schedule> 2
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Figure 5.30 Output recommended HVAC products

5.12 Summary

This chapter provided the step taken to test the model. A 3D model of a hypothetical building is selected for HVAC design. The workability of each module of the integrated model is tested in terms of obtaining the logical flow of data its transmission and the desired results. The used project is located in Boston, USA. The technology, environmental impacts, economic cost and sustainability of each alternative are collected to describe the performance of HVAC. However, to integrate all these evaluations into one decision making system, users need to input their preference related to the kind of performance that is more important depending on the special condition of their projects. After ranking alternatives, the output of the developed model provided detailed information of the appropriate HVAC product that would satisfy the conceptual design requirement.

Chapter Six

Conclusion and Future Work

6.1 Conclusion

This thesis offers decision makers a comprehensive overview of the performance of HVAC systems and a way to combine their preference and real condition into the decision-making process. The interoperability of BIM developed in the HVAC field presents how the concept of BIM contributes to the HVAC design. In addition, the environmental performance of HVAC systems is usually overlooked in most studies listed in the literature. This thesis is inspired by the rising concern of environmental protection and the integration of life cycle assessment into the performance evaluation to help decision makers attain decisions that involve the environment. Furthermore, the developed decision-making system uses TOPSIS method to rank the alternatives for HVAC selection. Based on the preference of users, the weights of different performances are determined via AHP-Entropy method.

6.2 Research Contribution

The goal for this thesis is set to develop an integrated decision-making model for selecting appropriate HVAC products based on multiple performance criteria including the technical performance, economic performance, environmental performance and sustainability. As the most important module, HVAC performance module integrated these criterion into one decision support system, which bring forth a new idea how to solve HVAC problems for green buildings. HVAC designer can easily and quickly facilitate the conceptual designs and make decisions. The research contributions are as follows:

- The conventional HVAC design is combined with the concept of BIM by creating the connections among different analysis tools.
- A comprehensive evaluation and decision-making model for HVAC design was developed, which provides decision makers a user-friendly model that is simple and efficient and reliable.

6.3 Research Limitations

The developed model has the following limitations:

- The evaluation of the HVAC performance is limited to the primary equipment part, not including the design of air distribution system.
- The general database of HVAC products only collects data from major manufacturers, which may not satisfy some requirements for special design conditions.
- Due to the limited information provided by the manufacturers on the compositions of raw material of equipment and price, only the energy consumption caused by

the HVAC systems is accessible to evaluate the related environmental impacts and economic cost.

- The progress of developing model did not consider the projects for different climate and location.

6.4 Future Works

To enhance the capability of the developed model, a list of recommended improvement for the model is shown as follows:

- To include the evaluations of air distribution system to make the model more comprehensive and systematic for the HVAC design.
- Update the general database annually or regularly to obtain latest information about HVAC products from market.
- Make the evaluations of HVAC performance more accurate, the compositions of products and costs for equipment, transportation, maintenance, replacement and disposal are suggested to be included in the performance module.

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Appendix “A”

RSMeans Cost Data for the HVAC Installation (2019)

Capacity of Roof Top Air Conditioners	Bare Costs			
	Material	Labor	Total	Total Incl O&P
3 ton cooling, 60 MBH heating	3600	1125	4725	5600
4 ton cooling, 95 MBH heating	4250	1275	5525	6600
5 ton cooling, 112 MBH heating	4975	1400	6375	7550
6 ton cooling, 140 MBH heating	5825	1500	7325	8650
7.5 ton cooling, 170 MBH heating	7650	1575	9225	10800
10 ton cooling, 200 MBH heating	10600	1825	12425	14300
12.5 ton cooling, 230 MBH heating	13400	1925	15325	17600
17.5 ton cooling, 330 MBH heating	18800	2325	21125	24200
20 ton cooling, 360 MBH heating	21900	2474	24375	27800
25 ton cooling, 450 MBH heating	25000	2975	27975	31900
30 ton cooling, 540 MBH heating	25500	3525	29025	33400
40 ton cooling, 675 MBH heating	33400	4700	38100	43700

CapacityPackaged Terminal Air-Conditioners	Bare Costs			
	Material	Labor	Total	Total Incl O&P
6000 Btuh cooling, 8800 Btuh heating	715	130	845	980
9000 Btuh cooling, 8800 Btuh heating	810	156	966	1125
12000 Btuh cooling, 8800 Btuh heating	895	195	1090	1275
15000 Btuh cooling, 8800 Btuh heating	985	260	1245	1475

Appendix “B”

Natural Resource Inputs and Emissions for generating 1MJ electricity in Boston

Natural resource inputs	**Input quantity**
Coal	1.137 MJ
Natural Gas	0.012964 MJ
Oil	0.09899 MJ
Water	0.0156 kg

Emissions	**Emission quantity**
Dust	2652 mg
Carbon dioxide	317000 mg
Carbon monoxide	770 mg
Sulfur dioxide	2865 mg
Nitrogen oxides	1449 mg
Mercury compound	0.00054 mg
Fluorine	0.0486 mg
Suspend solid	54.79 mg
COD (chemical oxygen demand)	8.636 mg

Mineral oil	2.77 mg
Lead	0.0257 mg
Cadmium	0.000953 mg
Arsenic	0.022 mg
Solid waste	0.01272 kg

Appendix "C"

Sample of the Developed Code for Calculating Points Earned in LEED

```
private void button1_Click_1(object sender, EventArgs e)
        {
            bool isNewBuilding = false;
            if (radioButton2.Checked)
            {
                isNewBuilding = true;
            }
            double baseline = 0;
            bool b =
            double.TryParse(dataGridView5.Rows[0].Cells[1].Value.ToString(),
            out baseline);
            if (!b || Math.Abs(baseline) < 1e-6)
            {
                MessageBox.Show("Invalid value!Please input again!");
                return;
            }
            List<double> espis = new List<double>();
            for (int i = 1; i < dataGridView5.Rows.Count; i++)
            {
                double co = 0;
                bool bx =
                double.TryParse(dataGridView5.Rows[i].Cells[1].Value.ToString(
                ), out co);
                if (bx)
                {
                    double per = (baseline - co) / baseline;
                    string sss = (per * 100).ToString("f1") + "%";
                    int point = LEED_percentageTopoint(per, isNewBuilding);
                    dataGridView5.Rows[i].Cells[2].Value = sss;
                    dataGridView5.Rows[i].Cells[3].Value = point;
                    espis.Add(point);
                }
                else
                {
                    MessageBox.Show("Invalid value!Please input again!");
```

```
                    return;
                }
            }
            List<double> eac4 = new List<double>();
            for (int i = 0; i < dataGridView6.RowCount; i++)
            {
                string s = dataGridView6.Rows[i].Cells[1].Value.ToString();
                int point = 0;
                if (s == "No use")
                {
                    point = 1;
                }
                else
                {
                    double Life = 10;
                    double Rc = 0.5;
                    double Mr = 0.1;
                    double Lr = 0.02;
                    double GWPr = 1430;
                    double ODPr = 0;
                    double LCODP = (ODPr * (Lr * Life + Mr) * Rc) / Life;
                    double LCGWP = (GWPr * (Lr * Life + Mr) * Rc) / Life;
                    if (LCGWP + LCODP * 100000 <= 100)
                    {
                        point = 1;
                    }
                }
                dataGridView6.Rows[i].Cells[2].Value = point;
                eac4.Add(point);
            }
            for (int i = 0; i < systemDatas.Count; i++)
            {
                systemDatas[i].Leed = espis[i] + eac4[i];
                dataGridView8.Rows[i].Cells[0].Value =
systemDatas[i].SystemName;
                dataGridView8.Rows[i].Cells[1].Value =
                systemDatas[i].Leed.ToString("F2");
            }
        }
```

Appendix “D”

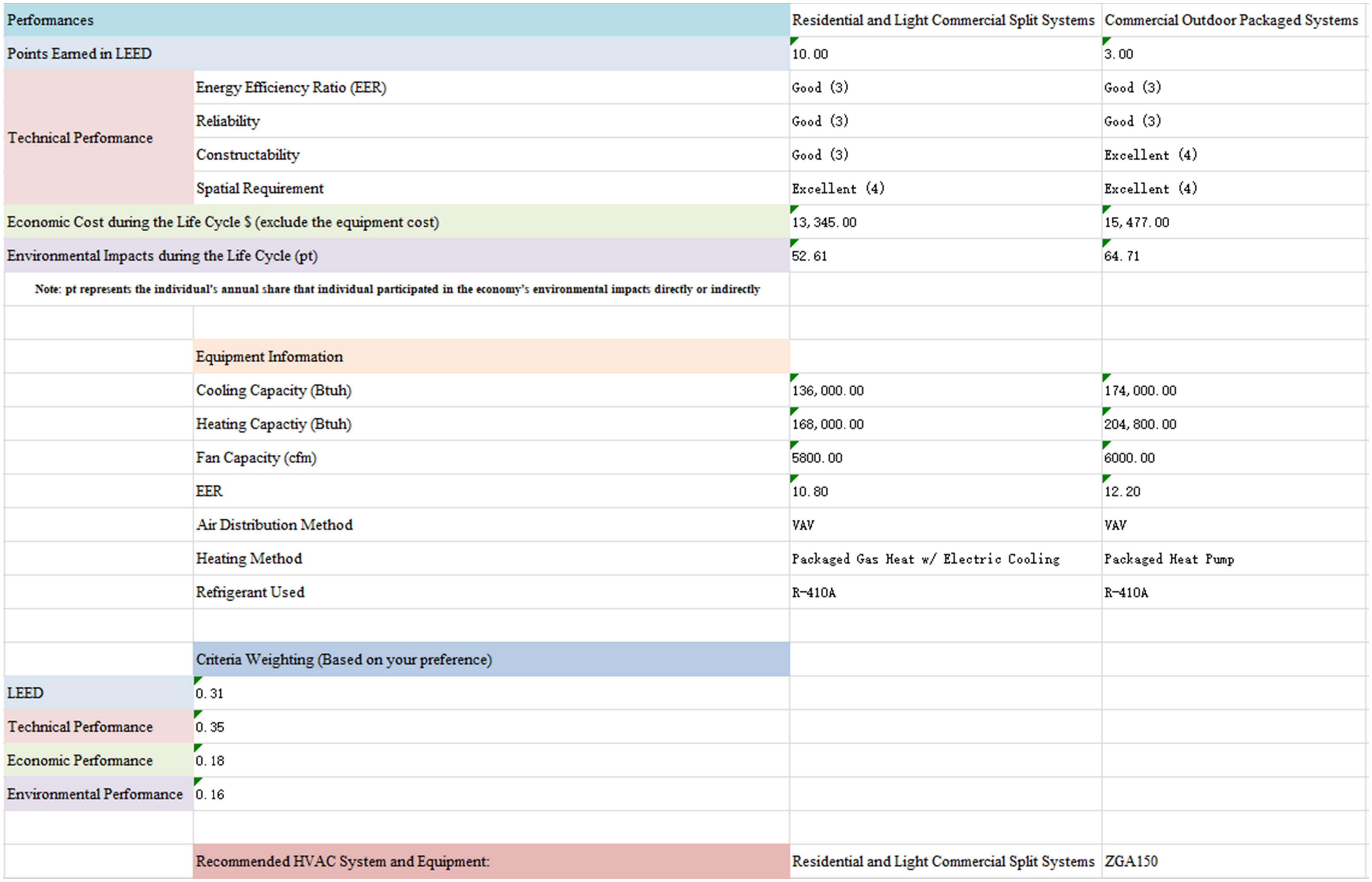
Sample of the Developed Code for Calculating Technical Performance Value

```
private double[] zhuanhuashu(string s)
        {
            double[] v=new double[2];
            Dictionary<string, double> keyValuePairs = new Dictionary<string,
double>();
            keyValuePairs.Add("0", 1.0 / 9.0);
            keyValuePairs.Add("1", 1.0 / 7.0);
            keyValuePairs.Add("2", 1.0 / 5.0);
            keyValuePairs.Add("3", 1.0 / 3.0);
            keyValuePairs.Add("4", 1);
            keyValuePairs.Add("5", 3);
            keyValuePairs.Add("6", 5);
            keyValuePairs.Add("7", 7);
            keyValuePairs.Add("8", 9);
            v[0] = keyValuePairs[s];
            v[1] = 1.0/v[0];
            return v;
        }
private void trackBar7_Scroll(object sender, EventArgs e)
        {
            double[,] first_mat = new double[4, 4];
            for (int i = 0; i < 4; i++)
            {
                first_mat[i, i] = 1;
            }
            first_mat[0, 1] = zhuanhuashu(trackBar7.Value.ToString())[0];
            first_mat[1, 0] = zhuanhuashu(trackBar7.Value.ToString())[1];
            first_mat[0, 2] = zhuanhuashu(trackBar8.Value.ToString())[0];
            first_mat[2, 0] = zhuanhuashu(trackBar8.Value.ToString())[1];
            first_mat[0, 3] = zhuanhuashu(trackBar9.Value.ToString())[0];
            first_mat[3, 0] = zhuanhuashu(trackBar9.Value.ToString())[1];
            first_mat[1, 2] = zhuanhuashu(trackBar10.Value.ToString())[0];
            first_mat[2, 1] = zhuanhuashu(trackBar10.Value.ToString())[1];
            first_mat[1, 3] = zhuanhuashu(trackBar11.Value.ToString())[0];
            first_mat[3, 1] = zhuanhuashu(trackBar11.Value.ToString())[1];
```

```
    first_mat[2, 3] = zhuanhuashu(trackBar12.Value.ToString())[0];
    first_mat[3, 2] = zhuanhuashu(trackBar12.Value.ToString())[1];
    double[] first_weight = new double[4];
    for (int i = 0; i < 4; i++)
    {
        double tem = 1;
        for (int j = 0; j < 4; j++)
        {
            tem = tem * first_mat[i, j];
        }
        tem = Math.Pow(tem, 1.0 / 4.0);
        first_weight[i] = tem;
    }
    double [] weight_t = new double[4];
    for(int i = 0; i < 4; i++)
    {
        weight_t[i] = first_weight[i] / first_weight.Sum();
    }
    first_weight = weight_t;
    for (int i = 0; i < systemDatas.Count; i++)
    {
        double sc = 0;
        for (int i1 = 0; i1 < first_weight.Length; i1++)
        {
            sc = sc + first_weight[i1] * systemDatas[i].Tec_v[i1];
        }
        systemDatas[i].Tech = sc;
        //int ix = dataGridView1.Rows.Add();
        dataGridView1.Rows[i].Cells[1].Value = sc.ToString("F3");
    }
}
```

Appendix “ E”

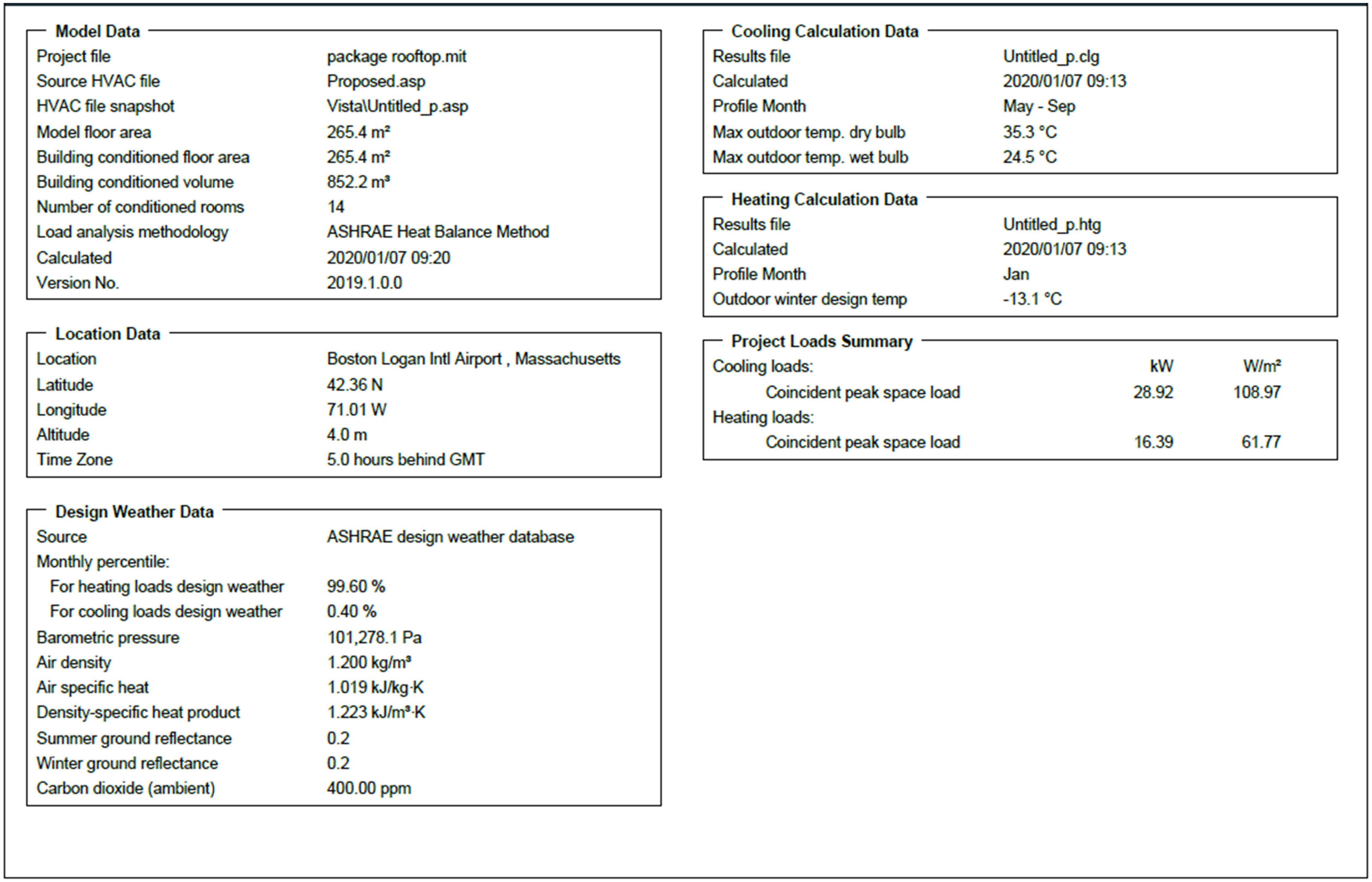
Information Report of Recommended HVAC Products and Building Schedule



Performances		Residential and Light Commercial Split Systems	Commercial Outdoor Packaged Systems
Points Earned in LEED		10.00	3.00
Technical Performance	Energy Efficiency Ratio (EER)	Good (3)	Good (3)
	Reliability	Good (3)	Good (3)
	Constructability	Good (3)	Excellent (4)
	Spatial Requirement	Excellent (4)	Excellent (4)
Economic Cost during the Life Cycle $ (exclude the equipment cost)		13,345.00	15,477.00
Environmental Impacts during the Life Cycle (pt)		52.61	64.71
Note: pt represents the individual's annual share that individual participated in the economy's environmental impacts directly or indirectly			
	Equipment Information		
	Cooling Capacity (Btuh)	136,000.00	174,000.00
	Heating Capactiy (Btuh)	168,000.00	204,800.00
	Fan Capacity (cfm)	5800.00	6000.00
	EER	10.80	12.20
	Air Distribution Method	VAV	VAV
	Heating Method	Packaged Gas Heat w/ Electric Cooling	Packaged Heat Pump
	Refrigerant Used	R-410A	R-410A
	Criteria Weighting (Based on your preference)		
LEED	0.31		
Technical Performance	0.35		
Economic Performance	0.18		
Environmental Performance	0.16		
	Recommended HVAC System and Equipment:	Residential and Light Commercial Split Systems	ZGA150

Appendix ؛ F؛

Room Load Report



Model Data

Project file	package rooftop.mit
Source HVAC file	Proposed.asp
HVAC file snapshot	Vista\Untitled_p.asp
Model floor area	265.4 m²
Building conditioned floor area	265.4 m²
Building conditioned volume	852.2 m³
Number of conditioned rooms	14
Load analysis methodology	ASHRAE Heat Balance Method
Calculated	2020/01/07 09:20
Version No.	2019.1.0.0

Location Data

Location	Boston Logan Intl Airport , Massachusetts
Latitude	42.36 N
Longitude	71.01 W
Altitude	4.0 m
Time Zone	5.0 hours behind GMT

Design Weather Data

Source	ASHRAE design weather database
Monthly percentile:	
For heating loads design weather	99.60 %
For cooling loads design weather	0.40 %
Barometric pressure	101,278.1 Pa
Air density	1.200 kg/m³
Air specific heat	1.019 kJ/kg·K
Density-specific heat product	1.223 kJ/m³·K
Summer ground reflectance	0.2
Winter ground reflectance	0.2
Carbon dioxide (ambient)	400.00 ppm

Cooling Calculation Data

Results file	Untitled_p.clg
Calculated	2020/01/07 09:13
Profile Month	May - Sep
Max outdoor temp. dry bulb	35.3 °C
Max outdoor temp. wet bulb	24.5 °C

Heating Calculation Data

Results file	Untitled_p.htg
Calculated	2020/01/07 09:13
Profile Month	Jan
Outdoor winter design temp	-13.1 °C

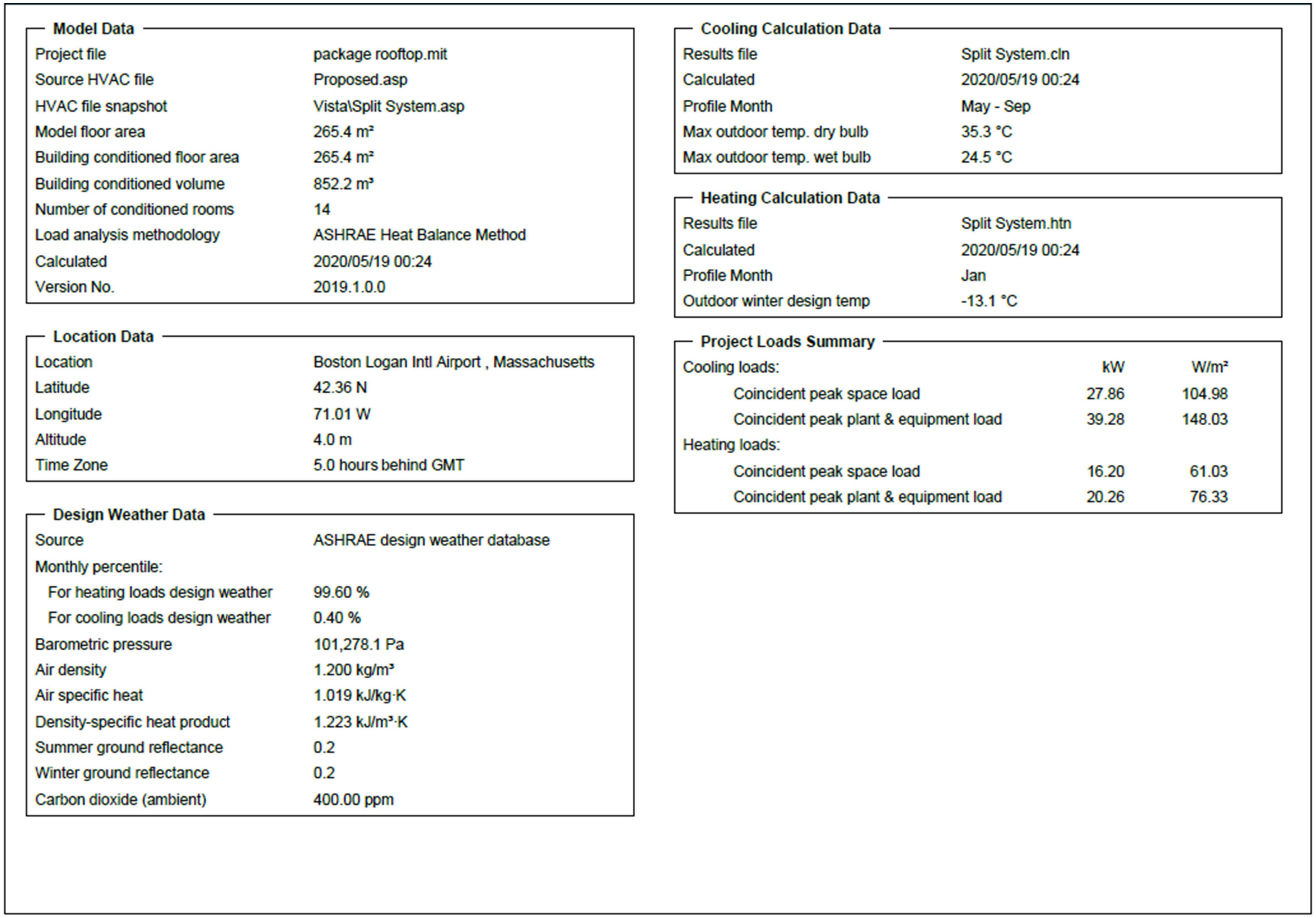
Project Loads Summary

	kW	W/m²
Cooling loads:		
Coincident peak space load	28.92	108.97
Heating loads:		
Coincident peak space load	16.39	61.77

Appendix “ G”

HVAC system simulation report

Alternative 1 Split system



Model Data

Project file	package rooftop.mit
Source HVAC file	Proposed.asp
HVAC file snapshot	Vista\Split System.asp
Model floor area	265.4 m²
Building conditioned floor area	265.4 m²
Building conditioned volume	852.2 m³
Number of conditioned rooms	14
Load analysis methodology	ASHRAE Heat Balance Method
Calculated	2020/05/19 00:24
Version No.	2019.1.0.0

Location Data

Location	Boston Logan Intl Airport , Massachusetts
Latitude	42.36 N
Longitude	71.01 W
Altitude	4.0 m
Time Zone	5.0 hours behind GMT

Design Weather Data

Source	ASHRAE design weather database
Monthly percentile:	
For heating loads design weather	99.60 %
For cooling loads design weather	0.40 %
Barometric pressure	101,278.1 Pa
Air density	1.200 kg/m³
Air specific heat	1.019 kJ/kg·K
Density-specific heat product	1.223 kJ/m³·K
Summer ground reflectance	0.2
Winter ground reflectance	0.2
Carbon dioxide (ambient)	400.00 ppm

Cooling Calculation Data

Results file	Split System.cln
Calculated	2020/05/19 00:24
Profile Month	May - Sep
Max outdoor temp. dry bulb	35.3 °C
Max outdoor temp. wet bulb	24.5 °C

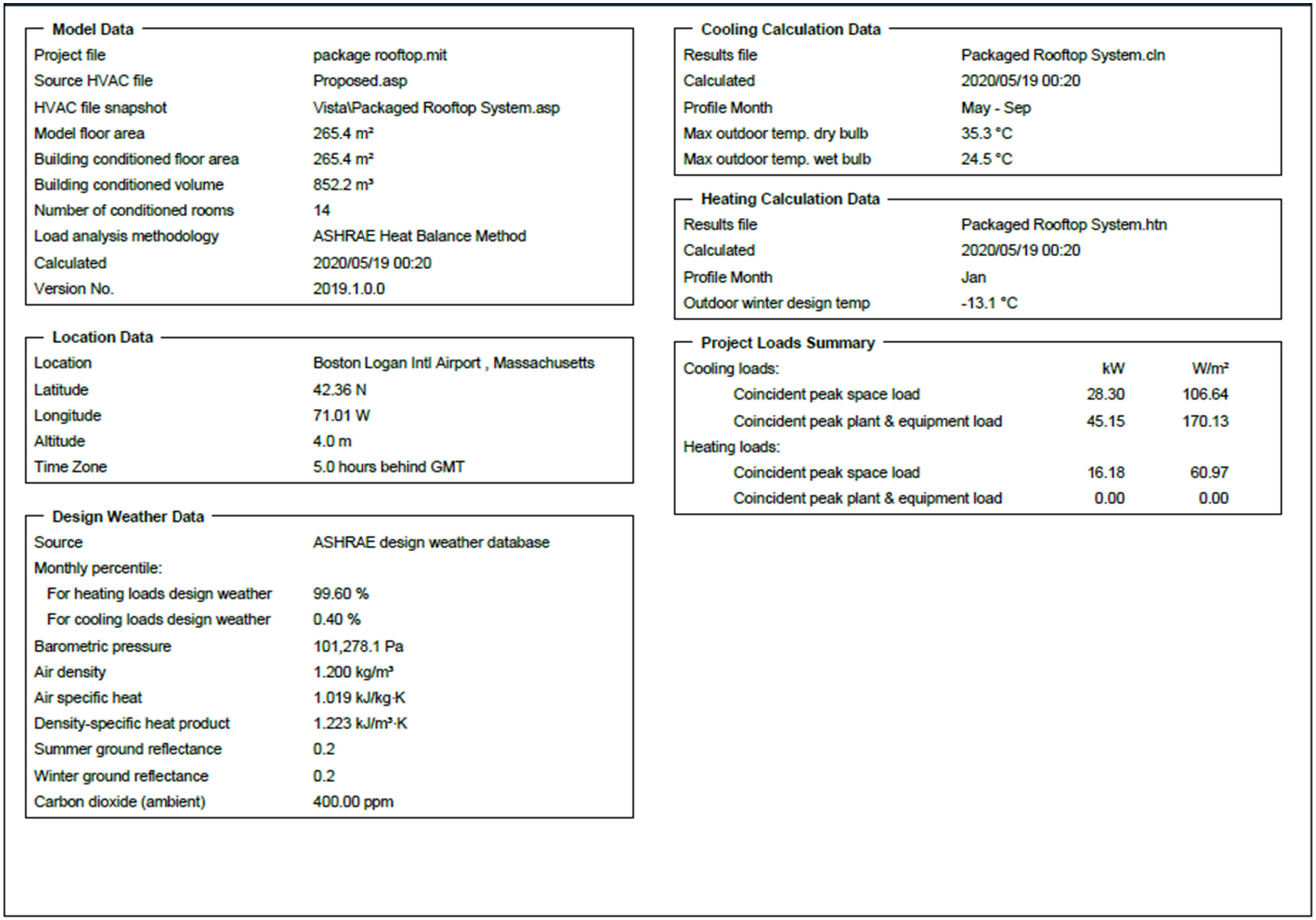
Heating Calculation Data

Results file	Split System.htn
Calculated	2020/05/19 00:24
Profile Month	Jan
Outdoor winter design temp	-13.1 °C

Project Loads Summary

	kW	W/m²
Cooling loads:		
Coincident peak space load	27.86	104.98
Coincident peak plant & equipment load	39.28	148.03
Heating loads:		
Coincident peak space load	16.20	61.03
Coincident peak plant & equipment load	20.26	76.33

Alternative 2 Packaged rooftop system



Model Data

Project file	package rooftop.mit
Source HVAC file	Proposed.asp
HVAC file snapshot	Vista\Packaged Rooftop System.asp
Model floor area	265.4 m²
Building conditioned floor area	265.4 m²
Building conditioned volume	852.2 m³
Number of conditioned rooms	14
Load analysis methodology	ASHRAE Heat Balance Method
Calculated	2020/05/19 00:20
Version No.	2019.1.0.0

Location Data

Location	Boston Logan Intl Airport , Massachusetts
Latitude	42.36 N
Longitude	71.01 W
Altitude	4.0 m
Time Zone	5.0 hours behind GMT

Design Weather Data

Source	ASHRAE design weather database
Monthly percentile:	
For heating loads design weather	99.60 %
For cooling loads design weather	0.40 %
Barometric pressure	101,278.1 Pa
Air density	1.200 kg/m³
Air specific heat	1.019 kJ/kg·K
Density-specific heat product	1.223 kJ/m³·K
Summer ground reflectance	0.2
Winter ground reflectance	0.2
Carbon dioxide (ambient)	400.00 ppm

Cooling Calculation Data

Results file	Packaged Rooftop System.cln
Calculated	2020/05/19 00:20
Profile Month	May - Sep
Max outdoor temp. dry bulb	35.3 °C
Max outdoor temp. wet bulb	24.5 °C

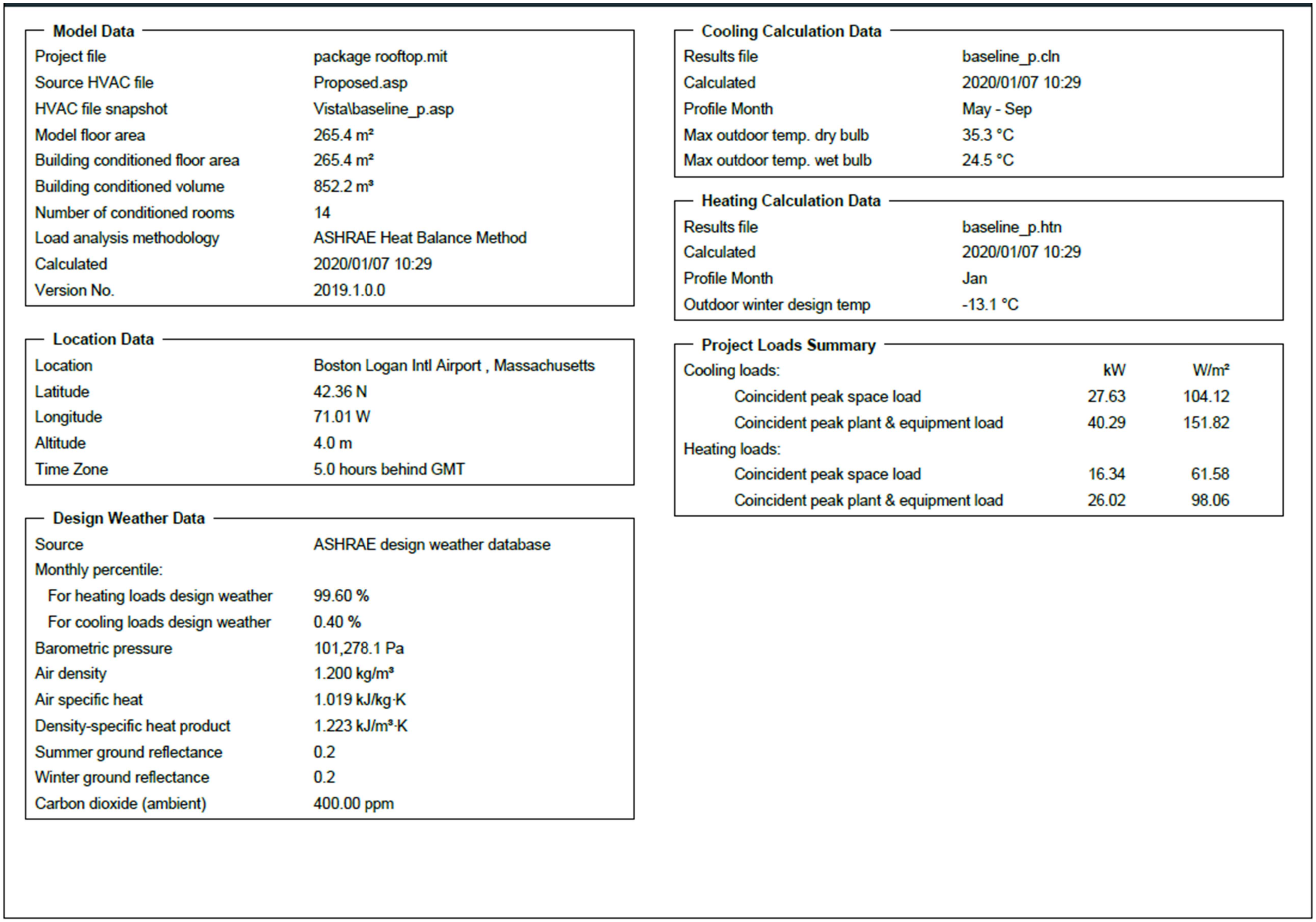
Heating Calculation Data

Results file	Packaged Rooftop System.htn
Calculated	2020/05/19 00:20
Profile Month	Jan
Outdoor winter design temp	-13.1 °C

Project Loads Summary

	kW	W/m²
Cooling loads:		
Coincident peak space load	28.30	106.64
Coincident peak plant & equipment load	45.15	170.13
Heating loads:		
Coincident peak space load	16.18	60.97
Coincident peak plant & equipment load	0.00	0.00

Baseline system （PTAC）



Model Data

Project file	package rooftop.mit
Source HVAC file	Proposed.asp
HVAC file snapshot	Vista\baseline_p.asp
Model floor area	265.4 m²
Building conditioned floor area	265.4 m²
Building conditioned volume	852.2 m³
Number of conditioned rooms	14
Load analysis methodology	ASHRAE Heat Balance Method
Calculated	2020/01/07 10:29
Version No.	2019.1.0.0

Location Data

Location	Boston Logan Intl Airport , Massachusetts
Latitude	42.36 N
Longitude	71.01 W
Altitude	4.0 m
Time Zone	5.0 hours behind GMT

Design Weather Data

Source	ASHRAE design weather database
Monthly percentile:	
For heating loads design weather	99.60 %
For cooling loads design weather	0.40 %
Barometric pressure	101,278.1 Pa
Air density	1.200 kg/m³
Air specific heat	1.019 kJ/kg·K
Density-specific heat product	1.223 kJ/m³·K
Summer ground reflectance	0.2
Winter ground reflectance	0.2
Carbon dioxide (ambient)	400.00 ppm

Cooling Calculation Data

Results file	baseline_p.cln
Calculated	2020/01/07 10:29
Profile Month	May - Sep
Max outdoor temp. dry bulb	35.3 °C
Max outdoor temp. wet bulb	24.5 °C

Heating Calculation Data

Results file	baseline_p.htn
Calculated	2020/01/07 10:29
Profile Month	Jan
Outdoor winter design temp	-13.1 °C

Project Loads Summary

Cooling loads:	kW	W/m²
Coincident peak space load	27.63	104.12
Coincident peak plant & equipment load	40.29	151.82
Heating loads:		
Coincident peak space load	16.34	61.58
Coincident peak plant & equipment load	26.02	98.06