AN INTEGRATED DECISION-MAKING MODEL FOR SELECTING HVAC SYSTEMS USING MULTIPLE PERFORMANCE CRITERIA

By

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To my parents, Yun Jia and Min Xu

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There is currently no comprehensive model which considers multiple performance criteria in choosing HVAC systems. This dissertation aims at developing an integrated decision-making model for selecting HVAC systems based on various performance criteria, including technical performance, environmental performance, economic performance and LEED performance. An analytical hierarchy process (AHP) method is used as the basis of the decision-making model to generate the optimal HVAC system. The preference weightings of performance criteria are assigned to the hierarchy structure based on the preference of the decision-makers. The weightings of the performance criteria are further integrated with the performance indicators of alternatives to calculate an overall score for each HVAC alternative of interest. With the decision-making model, the alternatives are ranked by the overall scores and the alternative with the highest score indicates the optimal HVAC system based on its comprehensive performance and preferences of the decision makers.

A case study is conducted to further test the validity of the methodology. Sensitivity analysis and consistency checks are conducted to track the sensibility and accuracy of the model. This dissertation also provides thoughts on the development of

software for the decision-making model for the purpose of facilitating the programming process and reducing the complexity of the model inputs and outputs.

CHAPTER 1
INTRODUCTION

Introduction

The building industry has a great impact on the environment and society. It is responsible for 40% of the energy use in the United States, 40% of green house gas emissions worldwide, 50% of natural resource consumption including 25% of the wood harvest worldwide and 1/6 of fresh water consumption according to the United Nations Environment Programme (UNEP). The demand for buildings and building renovation continues to increase worldwide. In 2002, there were more than 76 million residential buildings and more than 5 million commercial buildings in the United States and another 38 million are expected to be built by 2010, according to U.S. Department of Energy. Of particular interest to the author of this dissertation, in China, more than 50% of the urban residential and commercial building stock will have been constructed during the previous 15 years by 2015 estimated by the World Bank (UNEP, Sustainable building and construction: Facts and figures, April-September 2003). The energy consumption for buildings catches more attention than ever before because of its huge energy demand and its negative contribution to the environment. In developed countries, one-third of the energy end-use is consumed by heating, cooling, lighting, appliances and general services in non-industrial applications (i.e. residential, commercial and public) buildings, according to the International Energy Agency (IEA, 2009). In the United States, buildings account for 65% of electricity consumption. The negative environmental impact of buildings keeps rising with the increase demand in building and infrastructure as the population increases. With the severe environmental degradation and natural resource depletion occurring today, more and more emphasis is being paid to the use of environmental friendly products and processes. Since buildings have a great impact on the environment during their useful life time, it is urgent and vital to consider sustainability and “least-impact” principles during the design phase of the building system. Identifying and quantifying the environmental impact of HVAC products and systems is essential to the environmental performance of the building industry. Although there have been numerous environmental evaluations on building materials, very little research has been conducted on heating, ventilating and air conditioning systems. This is probably because of the complexity of their components and various arrangements. One of the focuses of this dissertation is to apply life-cycle assessment methodology in selecting HVAC products and systems.

Economic benefit is another important consideration for selecting a HVAC system. The initial investment, life-span energy consumption, the maintenance and replacement costs are critical factors for evaluating the economical performance of a certain system or equipment. Some of the systems may not save energy during their useful life, but the economic benefits may be significant. For many of the owners and developers, the “Cost and Benefit” is an essential consideration for choosing the system. So this dissertation also includes the economic performance for evaluating a HVAC systems combined with the other performances.

LEED (Leadership in Energy and Environmental Design) has gained popularity in recent years. Developed by USGBC (U.S. Green Building Council), it is a green building certification system recognized internationally. It provides strategies aimed at lessening the impact of the buildings on resources including saving energy, improving water efficiency, reducing CO_2 emissions, and improving indoor and outdoor environmental quality of buildings. More and more developers and building owners would like to get their buildings certified and show their commitment for sustainable and green environment. Choosing "green" HVAC systems is important to have a building certified with energy efficiency contributing the most credits in the rating system. Including LEED thinking into the HVAC system selections has almost became a necessity for new built HVAC design.

Other technical requirements may also be considered when choosing a system or equipment for a building. These requirements include full load effectiveness, part load effectiveness, reliability, maintainability and the spatial requirement.

It is more explicit to combine various performance criteria into a certain value to give a comprehensive result for decision making. For this purpose, the Analytical Hierarchy Process (AHP) method is introduced to assist the decision makers to find a solution that best suits their needs. It puts weighting on the performance criteria based on the preference of the decision makers and combines them with the performances of the alternatives to get the optimal HVAC system.

Purpose and Goal

Since there is currently no integrated model which considers comprehensive performances in choosing the optimal HVAC systems, this dissertation aims at developing an integrated decision-making model for selecting HVAC systems based on the preferences of decision makers as well as the performances of alternatives. The selection is based on multiple performance criteria including the technical performance, environmental performance, economic performance and LEED performance. These factors are combined into a single score and ranked for the easy interpretation and use by decision makers.

Scope of This Dissertation

The decision-making methodology can be applied to the selection of all kinds of HVAC systems, especially for large commercial building applications since the HVAC system scenario strategies are vital in the design phase and will have larger impact on the future operation. All of the HVAC systems in the scope of the decision-making model are assumed to meet the cooling and heating load of the building of interest and satisfy indoor thermal comfort requirements.

Methodology Overview

Performance assessment models are crated to evaluate the integrated performance of the HVAC system and equipment. The performance models include technical model, environmental model, economic model, and LEED model. The Analytical hierarchy process (AHP) method is used as the basis of the decision-making model to generate the optimal HVAC system. The outline and structure for choosing a HVAC system is shown in Figure 1-1. A hierarchy structure is set up and the preference weightings are assigned to performance models based on the preference of the decision-makers. The preference weightings of the performance criteria are further integrated with the performance indicators to calculate an overall score for each alternative. The alternative with the highest score indicates the best choice based on its comprehensive performance and the preference of the decision makers. During these processes, consistency checks and sensitivity analysis are performed to track the accuracy of the analysis. A case study is conducted to further explain and test the validity of the model. The decision-making model is also programmed with MATHCAD to facilitate the calculation.

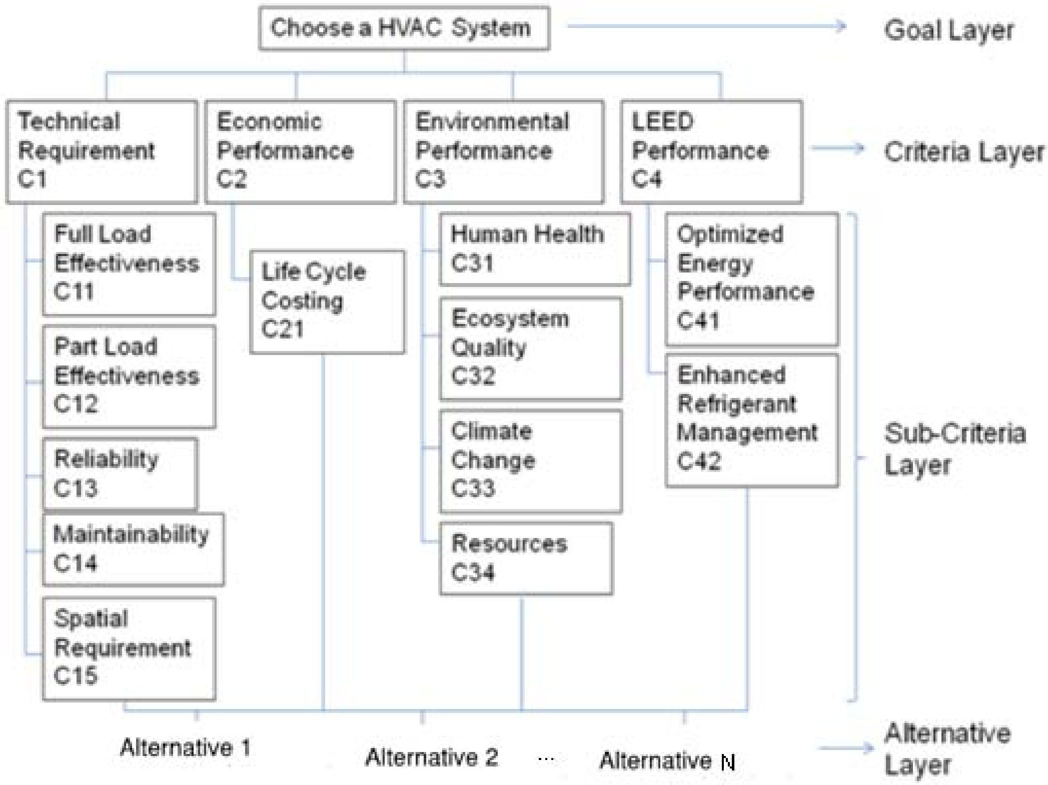


Figure 1-1. The decision-making model structure for choosing the optimal HVAC system

The dissertation also provides thoughts on software development for the decision-making model to facilitate the decision-making process and reduce the complexity of the model inputs and outputs. Figure 1-2 shows the 5 modules (sizing module, equipment and system module, energy simulation module, performance module and decision-making module) embedded in the overall model and the internal logical connection between modules.

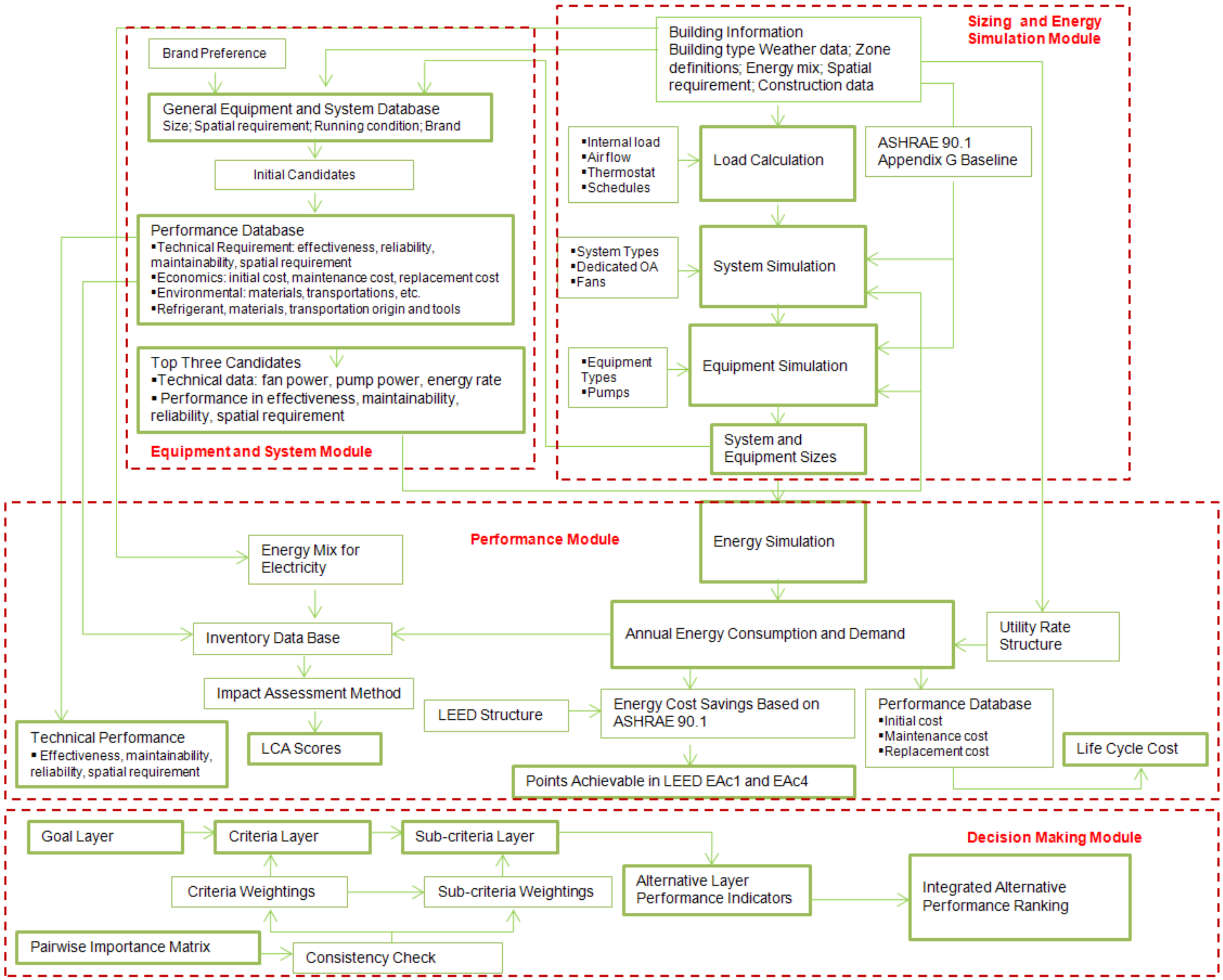


Fig 1-2. Overall diagram of the decision-making model structure for software development

CHAPTER 2
BACKGROUND AND LITERATURE REVIEW

Introduction

This chapter discusses typical HVAC systems applied in commercial buildings. Because of the large variety of HVAC systems, the reference sources of HVAC systems are listed for the further information on HVAC systems. This chapter also discusses different performance assessment methods for evaluating the technical, environmental and economic performances of HVAC systems. The technical performance includes effectiveness, reliability, maintainability and spatial requirement. Life cycle assessment (LCA) is used for evaluating the environmental performance of HVAC systems. Life cycle cost analysis (LCC) is the method for evaluating the economic performance of HVAC systems. In including, Analytical Hierarchy Process (AHP) is introduced as the basis for the decision-making model for selecting HVAC systems based on multiple performance criteria.

HVAC Systems

A typical HVAC system for commercial buildings contains a cooling plant, a heating plant and air-delivery system. For example, for chilled water and heating hot water system, chilled water or hot water is pumped from the chiller/boiler plant to the air handling unit(s) (AHU). At the air handling unit fresh air is introduced for ventilation purposes and often mixed with return air from the conditioned space, the mixed air is then heated and/or cooled and distributed to the conditioned space. The cooling water from the chiller's condenser is carried to the cooling tower to reject heat to the atmosphere. The building automation system (BAS) controls and manages the mechanical system.

ASHRAE (American Society of Refrigeration and Air-conditioning Engineers) is an international organization that establishes standards for the uniform testing and rating of heating, ventilation, air conditioning, and refrigeration equipment. Series of ASHRAE handbooks are the basis references for HVAC information and one of the handbooks is edited and published each year: ASHRAE Fundamentals (ASHRAE, ASHRAE Handbook - Fundamentals, 2005) discusses fundamental thermodynamics and heat transfer theory, load and energy calculation, duct and pipe design of HVAC systems; ASHRAE HVAC Systems and Equipment (ASHRAE, 2008) discusses all kinds of heating, cooling and air handling systems and equipment, and their components; ASHRAE HVAC Applications (ASHRAE, 2007) discusses HVAC systems in various applications including general application, comfort application, industrial application and energy-related application, as well as building operation and management; ASHRAE Refrigeration (ASHRAE, 2006) discusses refrigeration equipment and their application.

There are commonly accepted standards and guidelines for the use of architects and engineers. ASHRAE Standard 34 (ASHRAE, 2004) is the designation and Safety classification of refrigerants. ASHRAE Standard 55 (ASHRAE, 2004) is the thermal comfort standard for satisfactory indoor thermal environmental for human occupancy. ASHRAE Standard 62.1 (ASHRAE, 2007) is the ventilation standard for acceptable indoor air quality including the requirement and calculation of minimum ventilation rate. ASHRAE 90.1 (ASHRAE, 2007) is the energy standard for buildings except low-rise residential buildings. ASHRAE 135 (ASHRAE, 2004) is the data communication protocol for building automation and control networks.

For the purpose of LEED (Leadership in Energy and Environmental Design), ASHRAE 90.1 is the main reference standard to provide minimum energy efficiency design and build the baseline model for the energy simulation. It offers the minimum insulation factors for the building envelops in different climate zones, the minimum energy efficiency for heating and cooling equipment for different types of buildings, indoor and outdoor lighting allowances, etc. The Appendix G performance rating method in ASHRAE 90.1 is basis of LEED optimized energy performance for rating the energy efficiency of building designs that exceed the requirement of the standard. ASHRAE 62.1 is the reference guideline to meet the minimum ventilation requirement of the building for satisfactory indoor environmental quality in LEED. ASHRAE also provides green guide for the design, construction and operation of sustainable buildings to help designer with energy-saving and environmental-friendly strategies in designing mechanical systems.

Assessment Methods for HVAC Performance

Technical Performance

The design of heating, ventilating and air-conditioning system should consider meeting various requirements to provide comfortable, functional, and environmental-friendly indoor environment. These requirements include not only the energy effectiveness of the equipment, but also how reliable and maintainable it is. ASHRAE Handbook-Systems and Equipment lists several criteria when selecting an HVAC system considering thermal requirements as well as the economical requirement. The selection of sub-criteria for technical performance is based on ASHRAE System and Equipment Handbook.

Effectiveness

Coefficient of Performance (COP) and kW/ton. COP is used to describe the efficiency of chillers under full load. Another similar performance concept uses the electrical demand of the machine referenced to its capacity, i.e., kW/ton.

Integrated Part Load Value (IPLV). IPLV is applied to represent both the full and part-load performance of a chiller. The typical system load profile is defined by ARI. The efficiency of air conditioners is measured under a variety of conditions with 25%, 50%, 75% and 100% of capacity at different temperatures. IPLV is only applied for non-residential central air conditioner.

Seasonal Energy Efficiency Ratio (SEER). The efficiency of air conditioners and heat pumps less than 5 tons is often rated by the Seasonal Energy Efficiency Ratio (SEER). SEER is the ratio of cooling output (in Btu) during a typical cooling-season to the total electric energy input (in watt-hours) during the same period. The higher SEER rating, the better efficiency of the cooling unit is. In September 2006 DOE began enforcing a 13 SEER standard for all residential central air conditioners. ENERGY STAR-labeled central air conditioners have a minimum rating of SEER 12.

Energy Efficiency Ratio (EER). Similar to SEER, EER represents the efficiency of air conditioners and heat pumps greater than 5 tons. The efficiency is determined at a single rated condition specified by an appropriate equipment standard. It is defined as the ratio of the cooling capacity (in Btu/h) to the total input rate of electric power applied (in Watts). The units of *EER* are *Btu/Wh*.

Heating Seasonal Performance Factor (HSPF). The Heating Seasonal Performance Factor (HSPF) is used to measure the energy efficiency of a heat pump during the heating season. It represents the total heating output of a heat pump (including supplementary electric heat) during the normal heating season (in Btu) as compared to the total electricity consumed (in watt-hours) during the same period. All heat pumps should be rated at a minimum of 7.6 HSPF for energy efficient heat pumps.

Annual Fuel Utilization Efficiency (AFUE). The Annual Fuel Utilization Efficiency (AFUE) measures the amount of fuel converted to heat for combustion equipment (furnaces, boilers). ENERGY STAR labeled furnaces must meet a minimum AFUE of 90.

Reliability

Reliability defines the ability of a system or component to perform its required functions under stated conditions without failure. It is very important for a HVAC system to be reliable. A centralized system is reliable since it has longer estimated equipment service life. A decentralized system is generally reliable although with a shorter estimated equipment service life.

Maintainability

Maintainability is the ease, speed and cost for any maintenance activity to be carried out on an equipment or system. Both of the time needed and the convenience for maintenance are importance to HVAC system since it costs time and money as well as the satisfactory of tenants. A centralized system is typically located at an equipment room located in a basement, penthouse, and service area away from the occupancy space. Access to the occupancy space is not required thus eliminating the disruption to the tenants. A decentralized system may or may not need equipment rooms. The maintenance cost for a decentralized system is relatively low since it is conveniently located and equipment with associated components is standardized. Maintenance may be difficult during bad weather when the equipment is located outdoors.

Spatial requirements

The total mechanical and electrical space requirements range between 4 to 9% of the gross building area with most buildings falling within the 6 to 9% range according to ASHRAE. The heating and cooling system and associated distribution system often occupy a significant amount of space, so horizontal and vertical space requirements of the HVAC should be considered. A decentralized system may or may not require equipment rooms since the equipment may be located on the roof or ground adjacent to the building because of the space restriction. It also may not require duct and pipe shafts throughout the building. An equipment room is required by a centralized system which is normally located outside of the conditioned space: in a basement, service area adjacent to or remote from the building. Secondary equipment and system may be required for air or water distribution.

Technical performances of typical HVAC systems

Typical HVAC system applications in buildings are discussed in the following section in term of technical performance in energy and efficiency, reliability, maintainability and spatial requirement.

Packaged DX rooftop VAV system

System description. A rooftop VAV system uses a packaged rooftop VAV air conditioner to delivery conditioned air to VAV terminals which are located at the ceiling plenum above zones. An outdoor air ventilation duct is associated with the system to provide fresh air to the building. Since it is a VAV (Variable Air Volume) system, the quantity of supply air varies based on the cooling load of the building. The supply air flow is regulated by the thermostat in each zone. The rooftop VAV system can only provide cooling and the heating required in the perimeter zone is generally provided by the fan powered boxes with electric heat strip. The rooftop VAV system is also equipped with an air-cooled condenser.

Energy and efficiency. With the use of the VAV (Variable Air Volume) supply fan and multiple compressors, the rooftop VAV system can perform with great efficiency at the part load operation and save energy. The supply fan can be regulated with the variation of internal load. During the time with low internal load, e.g. after working hours or weekends, the supply air required is minimal thus saving fan motor energy.

Reliability/ maintenance. The rooftop VAV system is reliable related to repair and replacement since all the parts including compressor, evaporator, condenser, supply and return fan are equipped in one single unit. The single-unit configuration also results in fast easy and efficient maintenance since all the components are located on the roof and there is no need to interrupt the tenant for the availability of the space and time. However, if repair or replacement is required, the system must be totally shut down and all the tenants will be affected.

Spatial requirement. Since the rooftop VAV system is packaged and located on the roof, there is no need for the extra mechanical room inside of the building. The large duct size for delivery supply air and the associated return air duct may require more space on the ceiling than other systems.

Self-contained VAV system

System description. For a self-contained VAV system, or commonly called SWUD (Self-contained Water-cooled Unitary), all the components (including compressor, evaporator and condenser) are housed in a packaged unit. The packaged DX units are located indoors, typically in a small mechanical room on each floor of the building. The compressor is installed in the system to provide cooling. The cooling water from the condenser is piped to a cooling tower to reject heat to atmosphere. For multi-story office buildings or replacement, the self-contained VAV unit is installed on each floor.

Energy and efficiency. Since a water-cooled condenser is used for a self-contained VAV system, the efficiency is around 40% higher than the packaged rooftop units where an air-cooled condenser is used. A waterside economizer is also typically used to pre-cool air before it reaches the evaporator if the cooling water outside is cool enough. With the use of the VAV (Variable Air Volume) supply fan, fan power will be decreased with low internal load, e.g. after working hours or weekends.

Reliability/ maintenance. Since the complete SWUD system is distributed on separate floors, equipment on other floors will not be affected if one unit fails. Because the condenser piping is centralized into the cooling tower on the roof, the access to the roof is minimized. Since the cooling tower is used, chemical treatment must be provided to the cooling tower and the associated water loop to prevent corrosion. Failure in the cooling tower could result in total system failure.

Spatial requirement. The self-contained VAV system requires the space necessary for small mechanical rooms on each floor. The cooling tower is located on the roof.

Water source heat pump system

System description. In water source heat pump systems, all the heat pumps reject heat to a common water loop along with the cooling tower and hot water boiler. A dedicated outdoor system is used to condition all the ventilation air.

Energy and efficiency. Since the heat is rejected to or absorbed from the same water loop, heating and cooling load can be offset during the mild climate seasons when there is heating required in the perimeter zone while cooling requirement in the core zone. The energy efficiency of water source heat pumps is typically 30% higher than the packaged rooftop systems.

Reliability/ maintenance. Each heat pump has its own condenser and evaporator. If one heat pump fails, other heat pumps will not be affected. Similar to self-contained water-cooled unit, additional chemical treatment is required for the cooling tower and the water loop. The maintenance for the boiler and other associated pumps are minimal. Failure of the cooling tower can cause total system failure.

Spatial requirement. The water source heat pump system can be located in a mechanical room, on a roof or above the ceiling. A boiler room is required for the heating during the winter.

Chilled water VAV system

System description. For chilled water VAV system, chilled water and hot water are produced at the central location and pumped to the VAV air handlers. Each of the air handler unit deliveries a mixture of outdoor air and re-circulated air to VAV terminals throughout the building. A cooling tower is connected to the cooling water loop of the chilled water plant.

Energy and efficiency. The efficiency of the chiller plant is generally very good. With a water-cooled condenser, the system can run very efficiently. The minimum COP of the air cooled chiller is 2.80 and that of the water cooled centrifugal chiller is 4.90 defined by ASHRAE 90.1-2004.

Reliability/ maintenance. With the existence of the chillers and cooling tower, the maintenance cost is added.

Spatial requirement. Space is required for equipment room for the chilled water and hot water plant. A cooling tower is located on the roof.

Three HVAC systems talked about here are chosen for the case study conducted in the later chapter. They are self-contained VAV system, water source heat pump system, and chilled water VAV system since they are the most typical and popular systems used in the modern commercial buildings.

Environmental Performance

There are many tools developed for evaluating environmental impact including life cycle assessment (LCA), environmental impact assessment (EIA), ecological footprint (EF), emergy analysis, and risk assessment. Life cycle assessment is the most complete and detailed form of life cycle studies. Life cycle assessment (LCA) studies analyze the environmental aspects and potential impacts throughout a product's life cycle (e.g., cradle-to-grave or cradle-to-cradle) from raw material acquisition through production, use and disposal. LCA looks at a whole picture of the product system thus avoiding shifting environmental responsibility from one place to another. It has the obvious advantage of revealing potentially significant but “hidden” environmental impacts. It can provide decision-makers with the information needed for selecting the process or product which has the least environmental impact. It can be widely used in process analysis, material selection, product comparison and evaluation, measuring performance, marketing, policy-making and other decision making process. This dissertation uses Life Cycle Assessment (LCA) for evaluating environmental performance of HVAC systems (UNEP, 2003). Since LCA is a relatively new and complicate methodology, this dissertation will provide the reader with additional background information.

Brief history of LCA

Life cycle assessment has its beginning in the 1960s. Harold Smith published his calculation of accumulative energy for the production of chemical intermediates and products at the World Energy Conference in 1963. An internal study conducted by The Coca-Cola Company laid the foundation for the life cycle inventory analysis in the United State in 1969. To determine the least impact to the natural resources and the lowest release to the environment of different beverage containers, the study quantified the raw materials and energy consumption during the manufacturing processes for each container. In the 1970s, the methodology was refined by the U.S. Environmental Protection Agency and named the Resource and Environmental Profile Analysis (REPA) (Svoboda, 1995). In 1991, LCA standards for the International Standards Organization (ISO) 14000 series (1997 through 2002) were developed (American International Standard, 1998) (American International Standard, 2000) (American International Standard, 2000).

Definition of LCA

According to ISO 14040 (American International Standard, 1997), life cycle assessment is defined as a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle. It is a technique for assessing the environmental aspects and potential impacts by compiling an inventory of relevant inputs and outputs of a product system; evaluating the potential environmental impacts associated with those inputs and outputs; interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study. Figure 2-1 shows the elements and processes within LCA analysis based on (American International Standard, 1997). During the whole life cycle process from raw material acquisition until the end of the product's life, the potential environmental impacts of raw materials use, energy consumed and emissions & wastes are considered throughout the process (SAIC, 2006).

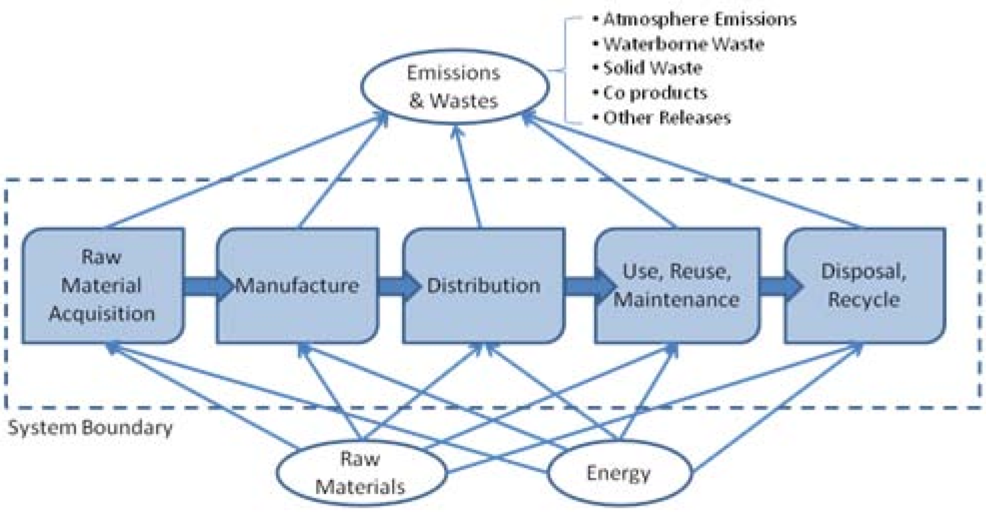


Figure 2-1. Life cycle processes

Phases of an LCA

Life cycle assessment methodology consists of four phases: definition of goal and scope, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and life cycle interpretation. These phases interact with each other. Figure 2-2 shows the relationship between these phases based on (American International Standard, 1997). Goal and scope definition gives guidance through the entire analysis; inventory analysis compiles and quantifies all the inputs and outputs through a product's life; impact assessment evaluates the significance of the potential environmental impacts of the inputs and outputs from inventory analysis; interpretation analysis identify the significant issues based on the results LCI and LCIA and draw conclusions and recommendations.

Goal and Scope Definition. This phase identifies the purpose and the goals for conducting this LCA study, the system/product/process to be studied, assumptions, types of impact and impact assessment method, allocation procedures, data quality requirement, and its limitations. And it also chooses a functional unit and the system boundaries for the product.

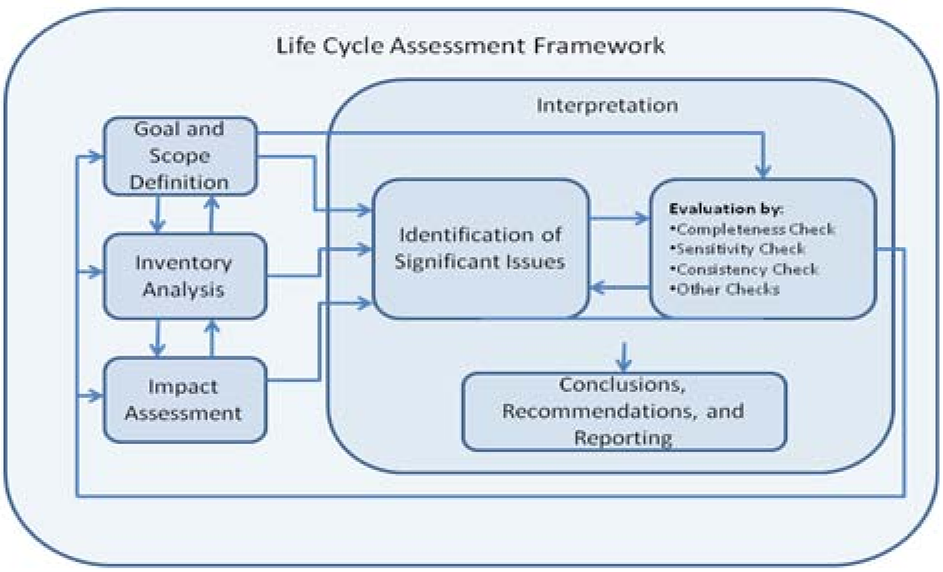


Figure 2-2. Relationship of interpretation steps with other phases of LCA

Inventory Analysis (LCI). Life cycle inventory analysis is the second phase of LCA. Inventory analysis compiles and quantifies all the inputs and outputs for a product system through its life time. Life cycle inventory (LCI) components of a product system can be derived to unit processes, elementary flows, product flows across the boundary, and intermediate product flows within the system. Some of the outputs are taken as a part of the inputs; some of the outputs are used as a component of the inputs; some ancillary inputs (e.g. catalyst) are used within the system boundary. All of these processes obey the mass and energy conservation law.

Depending on which database is used for the inventory inputs and outputs, the results of the environmental impact may vary based on the data source. SimaPro is one of the most popular and comprehensive LCA tools. SimaPro contains several library data bases for use. Some of the libraries deal with European data (e.g. Ecoinvent); some deal with data from the United States (e.g.Franklin US LCI 98), however, the US data base is limited. It is impossible to obtain all the necessary data from only a single data base. Thus the data source needed for this analysis is based on the available manufacture data, the Franklin US 98, as well as other European data bases available for use.

Impact Assessment (LCIA). Life Cycle Impact assessment (LCIA) evaluates the magnitude and significance of the potential environmental impacts of a product system. LCIA contains 6 steps (as shown in Figure2-3): Selection of impact categories, Classification, Characterization, Normalization, Grouping and Weighting. The first three steps are mandatory steps and the last three steps are optional steps according to (American International Standard, 2000).

Selection of the impact categories. There are several impact categories commonly being used: global warming, ozone depletion, acidification, eutrophication, photochemical smog, terrestrial toxicity, aquatic toxicity, human health, resource depletion, land use, and water use. These impact categories differ and change with different impact methods used. Impact categories are chosen based on the LCI results and the project interest.

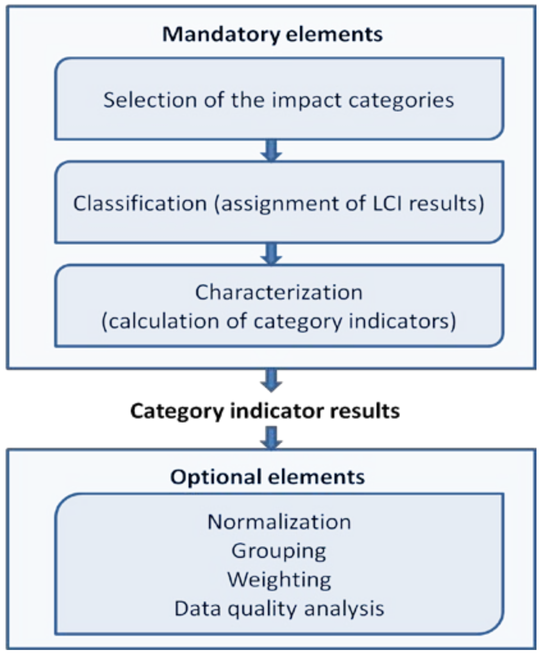


Figure 2-3. Elements of the LCIA phase

- **Global warming**. When solar radiation from the sun passes through the atmosphere, some of the solar radiation is absorbed by the surface of the earth and infrared radiation is emitted from the earth's surface. But green-house gases in the atmosphere acting as a thickening blanket, absorb and trapp this radiation and re-direct some portion back to the surface, warming up the planet; this is known as the greenhouse effect. Table 2-1 shows the main greenhouse gases and global warming contribution of these gases (David T. Allen, 2002). Water vapor, which is the major green house gas, is not included in the table because it is not mainly created by human activities. Emission rate, concentration, residence time and absorptivity rate are four factors for determining the contribution to global warming. The increase in carbon dioxide has the largest contribution to global warming (50%) due to fossil fuel combustion and deforestation. For building heating and cooling systems, huge amounts of electricity provided by the burning of fossil fuels are consumed, which cause high CO_2 emissions. From the table, it is shown that, except for CO_2, chlorofluorocarbon CFC-11 and CFC-12 also contribute greatly to the global warming (17-21%). Although CHC-11 and CHC 12 have low emission rates and concentrations, their long residence time and absorptivity capacity can lead to significant global warming. The type and amount of refrigerant use and the maintenance of air-conditioning equipment is significant in their contribution of global warming.

- **Ozone depletion potential**. The ozone layer in the stratosphere acts as a filter absorbing harmful short wave ultraviolet light while allowing longer wavelengths to pass through. The depletion of the ozone layer allows more harmful short wave radiation to reach the Earth's surface, causing changes to ecosystems. There may also be adverse effects on agricultural productivity. More harmful radiation can also cause higher skin cancer rates, eye cataracts and suppression of the immune system. CFC-11 is the reference substance for ozone depletion. For a vapor compression chiller, the use of its refrigerant has a key environmental impact on the global warming potential (ODP) and ozone depletion potential (ODP). Table 2-2 lists the contribution of commonly-used refrigerant to these two impacts (Calm, 2002).

Table 2-1. Global warming contribution of green house gases

Gas	Estimated Emission Rate (M tons/yr)	Approximate Current Concentration (ppm)	Estimated Residence Time (yrs)	Absorptivity capacity (CO2=1)	Estimated Contribution to Global Warming (%)
CO2	6,000	355	50-200	1	50
Methane (CH_4)	300-400	1.7	10	58	12-19
Nitrous Oxide (N_2O)	4-6	0.31	140-190	206	4-6
Chlorofluoro-carbons (CFC-11 & CFC-12)	1	0.0004-0.001	65-110	4860	17-21
Tropospheric Ozone (O_3)	not emitted directly	0.022	hrs-days	2000	8

Table 2-2. Global warming potential and ozone depletion potential of refrigerant

Refrigerant	Ozone Depletion Potential	Global Warming Potential
R-134a	0	1300
R-123	0.012	120
R-22	0.05	1700
R401a	0.027	970
R404a	0	3260
R407c	0	1525
R408a	0.016	3020
R409a	0.039	1290
R410a	0	1725
R502	0.18	5600
R717 (Ammonia)	0	0

- **Acidification potential**. Acidifying compounds can be dissolved in water or fixed on solid particles. They reach ecosystems through dissolution in rain or wet deposition and affect trees, soil, buildings, animals, and humans. The main two compounds of acidification are sulfur and nitrogen compounds. The general human source for acidification is fossil fuel and biomass combustion. Other compounds released such as hydrogen chloride and ammonia also contribute to acidification. The reference substance for acidification is the hydrogen ion. Other acidification compounds are converted to hydrogen ions in grams of hydrogen ions per functional unit with the same potential acidifying effect.

- **Eutrophication potential**. Eutrophication is the addition of mineral nutrients to the soil or water. Large quantities of mineral nutrients, such as nitrogen and phosphorous, can result in undesirable shifts in the number of species in ecosystems and a reduction in ecological diversity. Algae growth is increased in winter which can lead to lack of oxygen and therefore death of species like fish. Nitrogen is the reference substance. Other substances for eutrophication are converted to nitrogen in grams of nitrogen per functional unit with the same potential nitrifying effect.

- **Fossil fuel depletion**. This impact addresses only the depletion aspect of fossil fuel extraction, not the fact that the extraction itself may generate impacts. Extraction impacts, such as methane emissions from coal mining, are addressed in other impacts, such as global warming. The characterization factor of the fossil fuel depletion is in surplus mega joules (MJ) per functional unit of product.

- **Habitat alternation**. The land use by humans has potential impact on the habitat alternation which leads to the damage of Threatened and Endangered Species. For the life cycle of the buildings, the use and disposal/landfill stages contribute most on this impact.

- **Criteria air pollutants**. Criteria air pollutants are solid and liquid particles commonly found in the air. The coarse particles trigger and aggravate respiratory conditions such as asthma. The fine particles can lead to more serious respiratory symptoms and disease. Disability-adjusted life years, or DALYs, have been developed to measure health losses from outdoor air pollution.

- **Human health**. Many potential human health problems are caused by exposure to industrial and natural substances. Some substances have a wide range of different effects, and different individuals have widely varying tolerances to different substances.

- **Smog formation potential**. At certain climatic conditions, air emissions from industry and transportation can be trapped at ground level, where they react with sunlight to produce photochemical smog. One of the component s of smog is ozone, which is produced through the interactions of volatile organic compounds (VOC) and oxides of nitrogen (NO_X). Smog leads to harmful impacts on human health and vegetation. Nitrogen oxide is the reference substance used in smog formation potential.

- **Ecological toxicity**. The ecological toxicity impact measures the potential of a chemical released into the environment to harm terrestrial and aquatic ecosystems. The pollutant concentrations from industrial sources as well as the potential of these pollutants to harm ecosystems are measured. The reference substance is 2, 4-dichlorophenoxy-acetic acid (2, 4-D).

Classification. At this step, results from life cycle inventory (LCI) analysis are assigned to the specific impact categories. For example, CFC-11emission is classified into the ozone depletion impact and CO_2 is classified into the global warming impact. For LCI inputs and outputs which contribute to more than two categories, a representative portion of the LCI results are distributed to the impact categories they contribute.

Characterization. There are several chemicals from LCI results in each specific category. In order to put different kinds and quantities of chemicals on an equal scale to determine the impact of each one, the concept of category indicator is introduced. It allows inventory inputs and outputs to be calculated into the same characterization equivalents, so comparison and calculation can be made. All the inventory data in the impact category are converted into a single numerical category indicator result with a science-based conversion factor, called characterization factor. It is important to choose the appropriate characterization factor for the impact category. For example, all the green gas emissions are converted into the equivalent CO2 emission amount which is the category indicator of global warming potential. Thus the total contribution of this product on global warming can be calculated.

Normalization. After characterizing each impact category, the categories are measured in one commensurate unit, e.g. global warming is expressed in carbon dioxide equivalents and ozone depletion in CFC-11 equivalents. The purpose of the normalization is to get each indicator result on the same scale and prepare for additional procedures, such as grouping, weighting or life cycle interpretation. The normalized data can only be compared within a category. This procedure normalizes the category indicator by dividing it by a selected reference value. The reference value can be set as the total emissions or resource use for a given area, which may be global, regional, or local; or the total emissions or resource use for a given area on a per capita basis.

Grouping. Grouping assigns impact categories into sets of specific areas of concern as defined in the goal and scope definition. Sorting and/or ranking may be involved in the grouping stage. There are two ways for grouping LCIA data: Sort the indicators by characteristics, such as emissions, resources or locations; sort the indicators by ranking them in a given hierarchy, e.g. high, medium and low priority. Ranking is based on value choices.

Weighting. Although the weighting procedure is widely used in LCA, it is the most-disputed and challenged on choosing the weight factor for each impact category, because it is based on value-choices rather than based on natural science. But because it simplifies the LCA final results and reflects the stakeholder's choice value, it is also a popular step to be taken.

The weighting step assigns weights to the impact categories based on their perceived importance or relevance. Different individuals or organizations may have different preferences which result in different weighting factors and results.

Table 2-3 indicates a comparison between various impact assessment methods included in SimaPro (Mark Goedkoop, 2008). Impact 2002+ is the method used for assessing the environmental performance of HVAC alternative since it comes out with only four damage categories and a weighting scheme which can facilitate the result and represent the preference of decision-makers.

Table 2-3. Comparison of impact assessment methods in SimaPro

Name	Data source	Impact/damage categories	Characterization	Normalization	Normalization
Impact 2002+	Swiss	14 midpoint categories into 4 damage categories	Characterization factors are adapted from existing characterizing methods, i.e. Eco-indicator 99, CML 2001, impact 2002, etc.	Yes	Yes, self-determined weighting factor or a default weighting factor of one
TRACI 2	U.S. EPA	9 impact categories	Impact categories are characterized at the midpoint level	No	No
BEES 4.0	U.S., building materials	6 impact categories	SETAC method	No	No
CML 2001	European	9 impact categories	Baseline indicators	Yes	Yes
Eco-indicator 99	Swiss	3 damage categories	Resource analysis, land-use analysis, fate analysis and exposure effect analysis	Yes	Yes

Interpretation. Interpretation is the last phase of life cycle assessment. Life cycle interpretation step contains three key elements, as described in ISO 4042: identify the significant issues based on the results of the LCI and LCIA; evaluate the completeness, sensitivity, and consistency of the data; draw conclusions, recommendations and reporting

- **Completeness check**. The completeness check ensures all relevant information and data needed for interpretation are available and complete. A checklist should be formed to indicate each main area of the results and verify that data are consistent with the system boundaries and reflect the stated goal and scope of the LCA study.

- **Sensitivity check**. The sensitivity check assesses the reliability of the final results and conclusions by determining whether the significant issues are affected by the uncertainty in the data, allocation methods or calculation of category indicator results, etc. Sensitivity checks can be performed by conducting data quality analysis for the significant issues. Data quality analysis distinguishes the significance, difference and sensitivity of the indicator results. It comprises three evaluation techniques.

- **Gravity analysis**. Gravity analysis identifies data which has the greatest contribution to the indicator results. These items may then be investigated with increased priority.

- **Uncertainty analysis**. Uncertainty analysis describes the statistically variability in order to determine if indicator results from the same impact category are significantly different from each other.

- **Consistency check**. Consistency check determines whether the assumptions, methods and data are consistent with the goal and scope. A checklist should be developed to indicate the inconsistency of the study. Some inconsistency may be acceptable depending on the goal and scope of the LCA.

Recent research of applying LCA to HVAC systems

There are several papers of apply life cycle assessment into HVAC related systems (Prek, 2004) (Avat Osman, 2007) . Shah, Debella and Ries conducted a life cycle assessment on three types of heating and cooling systems (warm-air furnace with air conditioning, hot water boiler with air conditioning, and an air-air heat pump) over a 35-year study period in four regions (Minnesota, Oregon, Pennsylvania and Texas) (Shah V.P., 2008). The LCA software SimaPro 7 was used to analyze the systems in this study. In SimaPro, the Franklin USA 98 and ETH-ESU 96 databases are introduced for life cycle inventory (LCI). The Impact 2002+ method is applied to the life cycle impact assessment. It links the results of the inventory to four damage categories: human health, climate change, ecosystem quality and resources, via 14 impact categories. The scores calculated in the damage categories are further normalized based on the overall impacts to one person in 1 year in Western Europe and thus make these damage categories comparable to each other. Results are divided into two categories: the impacts due to the system infrastructure and the impacts for the energy use during the operation time. The boiler and air conditioning system had the highest impact on all four damage categories due to the large use of metals, which includes the use of copper pipes and steel radiators for the boiler system and steel duct for the AC system. The heat pump has the least impact on the environment because it is a single appliance used for both heating and cooling. For analyzing life cycle impacts of operational energy use, four energy midpoint categories in Impact 2002+ are picked, including respiratory inorganics (SO_x and NO_x from natural gas for the furnace and boiler systems or coal-generated electricity for the heat pump), aquatic ecotoxicity (oil emissions during natural gas manufacturing and dispersion of metallic ions during the manufacturing of equipment), global warming (fossil fuels extraction and combustion), and non-renewable energy (fossil fuels extraction and combustion). Thus boiler and furnace systems have higher impacts. In this study, it also shows that the energy mix and the climate of different states play a significant role in determining the environmental performance of these three systems. Oregon has the least environmental impact because its large percentage of hydropower and other renewable sources for electricity production (67%) and the least annual heating and cooling load. The heat pump has the highest impacts in the regions where fossil fuel provides the large percentage of the energy mix for electricity. In these states, the furnace and air conditioning is the best system to use. However, the heat pump shows least environmental impact in Oregon, where a large share of electricity is generated from hydropower and other renewable sources. So the fuel energy mix for electricity and the region's climate are two important factors which play significant impact on the environment.

Mikko and Carey compared the LCA performance of two different ventilation units with air-to-air energy exchangers and electrical resistance heating in a cold climate in Finland (Mikko Nyman, 2005). Both of the systems provide the same outdoor ventilation airflow at 50 l/s, but are different in sizes, energy effectiveness for the energy exchanger and frost control strategies, etc. The functional unit included in the study was only to provide outdoor air, not to condition the air. Unit 1 had two plate energy exchangers in series with an effectiveness of 69%, and unit 2 had only one exchanger and an effectiveness of 58%. Unit 1 consumed 3W/l/s electricity while unit 2 consumed 2W/l/s.

The article did not consider much on the allocation methods in the production phases because the differences in allocation methods had a marginal effect on the study since the environmental impacts associated with the use of the ventilation units are at least an order of magnitude greater than those associated with production. Analysis showed that non-renewable energy represented the main portion of energy for production. The steel and aluminum in the system required the most energy since steel contributes 61%-66% of the material and 26%-27% of energy use and aluminum requires 9%-13% of the material and 20%-27% of the energy use.

Since an air conditioning function is not considered but only the ventilation function is considered in this study, energy consumption by the fan was the only source for consumption. Results showed that the annual energy consumed in the operation period is four times higher than the energy consumed during the production phase. The emissions during the 50 year operation period are 100-200 times greater than the results from production and transportation. Energy savings by the energy exchanger is five times as much as the energy consumed by the fan. Although there are two plate exchangers in series and higher electricity consumption of the fan for unit 1, the analysis shows greater reduction in emissions due to higher heat energy recovery effectiveness. Thus the energy recovery effectiveness has a larger impact on the environmental performance of the unit compared with the material amount for the unit.

Katarina evaluated the environmental performance of two air-conditioning systems for a office building in Sweden using a weighting method for LCA study which leads to a single score of the selected phase (production, use, and disposal) (K. H. , 2004). The two AC systems include System A: an all-air air handling unit (AHU) with a cooling coil and a vapor compression chiller; System B: an all-air desiccant cooling air handling unit. The functional unit of this study is an air handling unit which generates a constant air volume (CAV) at 4.8 m^3/s 24 h/day for 15 years. The filter is changed once every year, and the annual leakage of the refrigerant is 2% of the refrigerant charge.

EPS Design System 4.0 was applied for the inventory data base for the systems. The paper did not state which impact assessment method was used; however, the weighting method used in this paper is the EPS 2000 default method, which was developed in Sweden.

Results show that System B with the desiccant cooling AHU had a greater environmental impact than System A with the chilled water AHU through the entire life of the system because of the large amount quantity of copper in the system (highest ELU/kg). The consumption of other materials and sources in the production phase was negligible compared with copper and steel. The usage phase of the life cycle of both units still played a significant critical part of the overall impact compared with the production and disposal phase of the systems. The reason why system B has the greater impact is because of its higher pressure loss caused by extra components (desiccant rotor, evaporative coolers, and regeneration heating coil); higher energy consumption during the use phase due to its higher SFP (specific fan power, kW/(m^3/s)). The end phase of both systems has positive effects on the environment since 90% of the metals were recycled. The impact of the filter materials (mostly sheet steel and rock wool) was negligible.

Katarina also evaluated the environmental performance of a bore-hole based, ground loop heat pump system for cooling compared with a traditional air-conditioning cooling system with a chiller (K. H. , 2008). The functional unit is the air conditioning system which conditions and distributes a variable air flow volume (VAV) of a maximum 5m^3/s.

Results show that the bole-hole heat pump had better environmental performance in three of four impact categories: global warming, acidification, and eutrophication. This is mainly due to the fewer materials used in its production and less operating energy use for the bore-hole heat pump system. In the category of photochemical ozone creation potential (POCP), the bole-hole heat pump system performed 4 times worse than the traditional air-conditioning system. This is primarily because the use of the polyethylene for the bole-hole pipes. However, the overall environmental impact of the bore-hole based system is 10% better than the tradition system. Since the electricity use in the building is pretty low (6.28 kW/m^2) due to the VAV system control and low supply temperature (15°C), the production phase contributed to the most (70%) to the overall impact. The impact related to energy use is around 20% less for bore-hole based system than for the traditional air-conditioning system. Since 95% of metals are recycled, the environmental impact of the end of life phase was positive.

For further discussion about the influence of weighting methods on the results, different weighting methods are compared in this study for evaluating the same inventory data. LCI data were weighted with five methods: EPS, Ecoscarcity-Ch, Ecoscarcity-S, Effect category and the Tellus method. Results are normalized with respect to the environmental impact of the traditional system, which is equal to 1. The results shows that bore-hole based system has 30% lower environmental impact. Although the weighting methods are based on different value principles, the results are very similar.

Economic Performance

Besides environmental impact of building products, economic benefits are also important factors for consumers and manufactures in making a decision. A poll conducted by the American Institute of Architects in 2006 showed that 90 % of U.S. consumers would be willing to pay more to reduce their home's environmental impact, but they would pay only \$4000 to \$5000, or about 2 %, more (Barbara C. Lippiatt, 2008). Even the most environmentally conscious building product manufacturer or designer will ultimately weigh environmental benefits against economic costs.

The most popular method for analyzing the economic performance is life cycle cost analysis. Life cycle cost is an economic evaluation of the total cost of purchasing, operating, maintaining, and disposing/recycling of a system during a period of time. Whether a HVAC system is cost-effective through its useful life time depends on equipment price and installation cost (first cost), operating cost and maintenance cost.

Life Cycle Cost (LCC) analysis utilizes initial cost, operating cost, maintenance cost, replacement cost, disposal cost, salvage, other periodic costs and take into account the time value of money (C.Lippiatt, 2007).

Initial Cost

The initial cost of HVAC systems includes 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.

Operating Costs

The electricity and other fuel energy usage costs are the main costs during the operation period. Most of the electricity and fuel energy cost are from HVAC equipment. The energy consumption is calculated by conducting an annual energy use calculation of the HVAC system.

The electrical energy cost is a combination of several costs: energy consumption charges, fuel adjustment charges, demand charges, special allowances or other adjustments. In order to reduce peak time electricity usage, some utilities may provide different rates (on-peak and off-peak) for electricity consumption according to the time of use and season. Fuel adjustment cost may be charged by electricity companies due to the variations in fuel prices. Although the fuel adjustment charge varies, there will be an average annual or seasonal estimate calculated by the utility. Special allowances may be applicable for customers who can receive power at higher voltages or those who can use renewable energy for electricity production. Demand charge is based on the customer's peak kW demand usage. The demand charge is considered important when load shifting or shedding devices are considered.

Natural gas cost is calculated either by volume or by energy content (therm). The cost per therm/volume is a combination of the utility rate for gas consumption and the PGA (purchased gas adjustment), plus taxes and other adjustments.

Maintenance and Repair Costs

Maintenance and repair cost include the cost for materials and labors. The maintenance cost may be required on a 6-month basis or a yearly basis. The repair cost varies with the situation.

Study Period

The study period may greatly affect the results of LCC analysis. The length of the study period depends on the specific goal of the analysis. In general, the study period can be defined as the length of the ownership.

Interest and Discount Rate

The discount factors used in this dissertation are based on FEMP (Federal Energy Management Program). All of the updated discount factors for calculation can be found in the supplemental of LCC handbook 135 developed by DOE (Building and Fire Research Laboratory, Office of applied Economics, 2009).

Other Periodic Costs

Periodic costs include insurance, property taxes, income taxes, refurbishment, or disposal fee (refrigerant recycling cost) and decommissioning expenses.

Building Life Cycle-Cost (BLCC) Software

Developed by National Institute of Standard and Technology (NIST), Building Life Cycle-Cost (BLCC) software is a tool to evaluate the economic performance of building systems. It contains the latest energy escalating rate updated every year. This dissertation will use BLCC 5.3 to facilitate the economic analysis (Federal Energy Management Program, 2009).

Green Building Rating System: LEED

LEED (Leadership in Energy & Environmental Design) is a foremost and internationally recognized green building rating system developed by USGBC (U.S. Green Building Council) LEED promotes design, construction and operation practices that economically and sustainably lessen the negative impacts of building on their occupants and on the environment. USGBC is a non-profit organization founded in 1993. It is a collection of architects, public policy makers, and designers who provide third-party verification that a building was designed and built in order to save energy and materials, reduce water use and CO_2 emissions and improve indoor environmental quality. The growth of USGBC membership is very fast. It now has 78 local affiliates, more than 20,000 member companies and more than 10,000 LEED Accredited Professionals (U.S. Green Building Council) in 41 countries. Architects, engineers, realtors, designers, construction managers, lenders, and government officials all consider LEED as a tool to make building sustainability. It's now becoming a more important and popular criterion for building industry to consider.

USGBC has four levels of LEED: Certified, Silver, Gold and Platinum. The level of LEED you can reach depends on the total points achieved for each category of LEED. LEED has rating systems for both commercial and residential buildings including: New Construction, Existing Buildings, Homes, Schools, Healthcare, Retail, Commercial Interior, and Core& Shell. But most of the buildings fall under the umbrella of LEED-NC (New Construction). The latest version of LEED called LEED v3 was launched on April 27, 2009. This study will use the criteria in LEED-NC v3 as the criteria for evaluating the performance of HVAC systems (U.S. Green Building Council, 2009).

LEED-NC v3 has 7 categories: Sustainable Sites, Water Efficiency, Energy & Atmosphere, Material & Resources, Indoor Environmental Quality, Innovation in Design and Regional Priority. It has 100 base points in total. There also have 6 possible points in Innovation in Design and 4 points in Regional Priority. The categories that relate the most to the HVAC systems is the Energy and Atmosphere category.

Energy and Atmosphere (EA). Energy and Atmosphere yield the most possible points among these categories (35 /100 points).

EA Prerequisite 2: Minimum Energy Performance. One of the EA prerequisites is to perform a whole building energy simulation. It requires demonstrating a 10% improvement in the proposed building performance rating for new buildings and 5% improvement for major renovations to existing buildings compared with the baseline. The baseline building performance rating is calculated according to the building performance rating method in Appendix G of ASHRAE/ESNA Standard 90.1-2007 using a computer simulation model for the whole building project.

EA Prerequisite 3: Fundamental Refrigerant Management. It is a mandatory prerequisite by LEED that there should be no CFC refrigerants used in new construction or a phase-out plan for renovation of existing buildings with CFC refrigerants.

EA Credit 1: Optimize Energy Performance. A percentage improvement is demonstrated in the proposed building performance rating compared with the baseline building performance rating calculated according to Appendix G of ASHRAE/IESNA standard 90.1-2007 using a computer simulation model for the whole building project. The energy cost savings percentage threshold is shown in Table 2-4 (U.S. Green Building Council, 2009).

Table 2-4. LEED 2009 energy performance score card

New Buildings	Existing Building Renovations	Points
12%	8%	1
14%	10%	2
16%	12%	3
20%	16%	5
24%	20%	7
28%	24%	9
32%	28%	11
36%	32%	13
40%	36%	15
44%	40%	17
48%	44%	19

EA Credit 4: Enhanced Refrigerant Management. Refrigerant in chillers may have environmental issues on ozone depletion potential (ODP) and global warming potential (GWP). EA credit 4 can be earned by any of the two options: Option1 do not use ANY refrigerants or Option 2 use refrigerants and HVAC that minimizes or eliminates emission of compounds that cause ozone depletion & global warming.

CHAPTER 3
PERFORMANCE ASSESSMENT MODELS

Technical Model

Effectiveness

kW/ton Rating. One of the most common efficiency factors to evaluate the effectiveness of the cooling equipment (mostly chillers) is kW/ton. It is expressed as the power input to compressor motor divided by tons of cooling produced. The lower kW/ton indicates the higher efficiency of the equipment.

Coefficient of Performance (COP)

$$COP = \frac{Cooling\ or\ Heating\ Output\ Q\ (uniform\ Unit)}{Electric\ Energy\ Input\ W\ (uniform\ Unit)} \tag{3-1}$$

Integrated Part Load Value (IPLV). It measures the efficiency of equipment (in kW/ton) under full load and part load conditions -- that is, when the unit is operating at 25%, 50%, 75% and 100% of capacity and at different temperatures.

Energy Efficiency Ratio (EER)

$$EER = \frac{Capacity\ (BTUH)}{Power\ Input\ (Watts)} \tag{3-2}$$

$$EER = COP \times 3.412 \tag{3-3}$$

Heating Seasonal Performance Factor (HSPF):

$$HSPF = \frac{Heating\ Output\ of\ a\ Heat\ Pump\ Q\ (Btu)}{Total\ Electricity\ Consumed\ W\ (Watt{-}hours)} \tag{3-4}$$

Maintainability

Maintainability is the ease, accuracy, safety, and economy of maintenance. Since the cost of maintenance is considered in the economic performance section, maintainability only refers to the ease in which maintenance actions can be performed.

According to 1999 ASHRAE Application Handbook: HVAC Applications (ASHRAE, 1999), the value of maintainability is calculated as following:

$$M = 1 - (B/Y) \tag{3-5}$$

B: the time that the system is being repaired in regular occupancy

Y: the time that the system is operated in one year

Reliability

Reliability is the probability that a system will perform its function without failure for a specific period of time when used under specific conditions. For multiple integrated systems, the combined reliability can be calculated as following:

If the systems are arranged in series, the combined reliability is

$$R = R_1 \cdot R_2 \cdots R_n \tag{3-6}$$

If the systems are arranged in parallel, the combined reliability is

$$R = 1 - (1 - R_1)(1 - R_2) \cdots (1 - R_n) \tag{3-7}$$

Spatial Requirement

For a central system, the equipment room is normally needed which is located outside of the conditioned area. The additional cost should be considered to install secondary equipment for the air/water distribution. The performance of the spatial requirement of equipment depends on the real area it takes. The smaller area of the equipment room is, the better the spatial requirement will be.

Environmental Model: Life Cycle Assessment

Goal and Scope

Generally speaking, the functional unit of analysis is the HVAC system which can satisfy the cooling or heating load of the building and sustain comfort indoor environment.

Inventory Analysis

There are several data base embedded in SimaPro. Most of the data base is European, only a few are based on data from the United States (e.g. Franklin USA 98). The order from choosing these data input is: USA data has the priority compared with the European data and newer data has the priority compared with the older data.

Impact Assessment

The impact 2002+ is the life cycle impact assessment method for this study. It links the life cycle inventory results via 14 midpoint categories to four damage categories. All midpoint scores are expressed in units of a reference substance and related to four damage categories human health, ecosystem quality, climate change and resources. Normalization was performed at damage level rather than midpoint level (Oele, 2006).

Characterization. Table 3-1 lists the number of LCI results covered, damage categories, and reference substances used in the Impact 2002+ (O.Jolliet, 2003).

Damage Categories. Damage characterization factors of any substance can be obtained by multiplying the midpoint characterization potentials with the damage characterization factors of the reference substances shown in Table 3-2.

Normalization. In order to facilitate interpretation, the normalization of the damage categories was performed. The normalization factor was determined by the ratio of the impact per unit of emission divided by the total impact of all substances of the specific category for which characterization factors exist, per person per year. Table 3-3 shows the normalization factors for the four damage categories for western Europe (Jolliet et al).

Table 3-1. Characterization and grouping into damage category in Impact 2002+

Midpoint categories	Damage category	Midpoint reference substance
Carcinogens	Human health	kg_{eq} chloroethylene into air
Non-carcinogens	Human health	kg_{eq} chloroethylene into air
Respiratory inorganics	Human health	kg_{eq} PM2.5 into air
Ozone layer	Human health	kg_{eq} CFC-11into air
Radiation	Human health	Bq_{eq} carbon-14 into air
Respiratory organics	Human health, Ecosystem quality	kg_{eq} ethylene into air
Aquatic ecotoxicity	Ecosystem quality	PDF·m^2·yr/kg·triethylene glycol
Terrestrial ecotoxicity	Ecosystem quality	PDF·m^2·yr/kg·triethylene glycol
Terrestrial acidification/nutr.	Ecosystem quality	PDF·m^2·yr/kg SO_2
Land occupation	Ecosystem quality	$m^2{}_{eq}$ organic arable land·year
Global Warming	Climate change	kg_{eq} CO_2 into air
Mineral extraction	Resources	MJ additional energy or kg_{eq} iron (in core)
Non-renewable energy	Resources	MJ total primary non-renewable or kg_{eq} crude oil

Table 3-2. Characterization damage factors of various reference substances

Midpoint categories	Damage factors	Units
Carcinogens	1.45E-6	DALY/kg chloroethylene
Non-carcinogens	1.45E-6	DALY/kg chloroethylene
Respiratory inorganics	7.00E-4	DALY/kg PM2.5
Ozone layer	1 .05E-3	DALY/kg CFC-11
Radiation	2.10E-10	DALY/Bq carbon-14
Respiratory organics	2.13E-6	DALY/kg ethylene
Aquatic ecotoxicity	8.86E-5	PDF·m^2·yr/kg·triethylene glycol
Terrestrial ecotoxicity	8.86E-5	PDF·m^2·yr/kg·triethylene glycol
Terrestrial acidification/nutr.	1.04	PDF·m^2·yr/kg SO_2
Land occupation	1.09	PDF·m^2·yr/ m^2·organic arable land·year
Global Warming	1	kg CO_2/kg CO_2
Mineral extraction	5.10E-02	MJ/kg iron
Non-renewable energy	45.6	MJ/kg crude oil

Table 3-3. Normalization factors for the four damage categories for Western Europe

Damage categories	Normalization factors	Units
Human health	0.0077	Daily/person/yr
Ecosystem quality	4650	PDF·m^2·yr/person/yr
Climate change	9950	kg CO_2/person/yr
Resources	152000	MJ/person/yr

Interpretation

Sensitivity analysis. Sensitivity analysis estimates the effects on the outcome of a study of a chosen method and data. Sensitivity analysis is typically conducted in the goal and scope or data collection phase.

Uncertainty analysis. Some data required in the life cycle inventory analysis were unavailable and they are assumed based on engineering judgment. Uncertainty analysis is introduced to make sure and quantify the accumulative impact of the uncertainty and data variability.

Economic Model: Life Cycle Cost

There are generally two categories of economic analysis methods: present value method and payback method. Payback method measures the time required to get initial investment recovered. Simple payback method is the most popular method in this category. The most comprehensive present value method is the life cycle cost analysis (LCCA). There are also some supplementary measures using the present value method including Net Savings (NS), the Savings-to-Investment Ratio (SIR), Adjusted Internal Rate of Return (AIRR). The SIR and AIRR are usually applied for ranking independent projects when faced with a budget issue, and they are not suitable to identify the most cost effective alternative. And Net Savings method is based on the same theory with LCCA. After considering the scope and application of this study, only LCCA performance with be considered to evaluate the economic performance of HVAC systems.

Simple Payback Method

Simple payback method measures the time required to recover initial investment costs. It is a simple technique which does not consider the time value of money, inflation, and interest.

$$Simple\ Payback\ year = \frac{First\ Cost\ (\$)}{Savings\ per\ year\ (\$)} \tag{3-8}$$

Present Value Method

Present value method takes into consideration the time value of money, which returns all future costs into today's dollar. The methodology is based on FEMP LCC handbook 135.

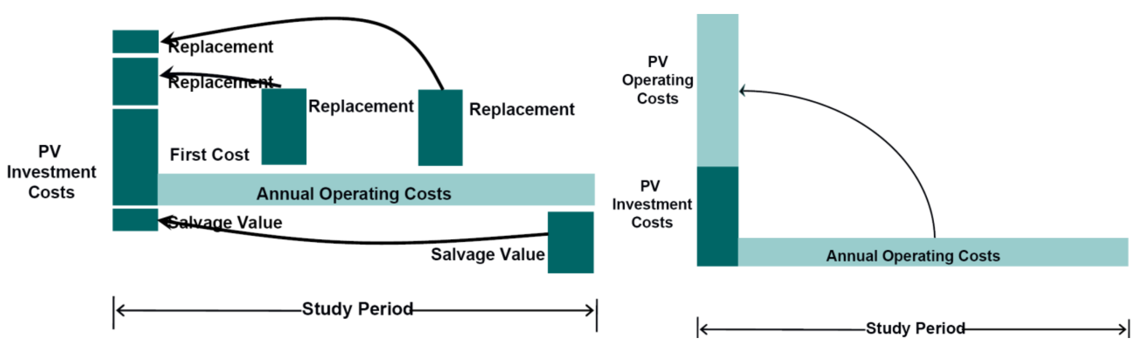


Figure 3-1. Present value method

$$PV = \frac{F_t}{(1+d)^t} \tag{3-9}$$

$$\mathrm{LCC} = \sum_{t=0}^{n} \frac{F_t}{(1+d)^t} \tag{3-10}$$

Where, PV = present value, Ct = future value, t=time of period, d=discount rate or interest rate, n= length of study period.

Discount factors. The method and discount factor used in this dissertation were based on FEMP (Federal Energy Management Program). All of the updated discount factors for calculation can be found in the supplemental of LCC handbook 135 developed by Department of Energy.

- **Single Present Value Factor (SPV)** – Used in Replacement/Repair cost or Salvage**.** Single Present Value factor (SPV) is used for single one-time costs. This factor can be used for estimating the present worth of replacement/repair cost or salvage assuming that the future cost for replacement is constant.

$$PV = F_t \times SPV_{(n,d)} \tag{3-11}$$

$$SPV = \frac{1}{(1+d)^n} \tag{3-12}$$

  Where, Ft = Future Value

- **Uniform Present Value Factor (UPV)** – Used in Maintenance Cost. Uniform Present Value Factor (UPV) is used for uniform annual recurring amount. In this dissertation, present value of maintenance cost is assumed to be constant and is calculated based on uniform annual payment.

$$PV = A'_0 \times UPV_{(n,d)} \tag{3-13}$$

$$UPV = \frac{(1+d)^n - 1}{d(1+d)^n} \tag{3-14}$$

  Where, A'0 = Annual cost of maintenance,

- **Modified Uniform Present Value Factor (UPV*)** – Used in Energy Cost. Modified Uniform Present Value Factor (UPV^*) is used for annually recurring non-uniform escalating amount. It is used in calculating the present value of annually recurring energy cost over years based on DOE projections.

$$PV = A_0 \times UPV^*{}_{(n,d,e)} \tag{3-15}$$

$$UPV^* = \left(\frac{1+e}{d-e}\right)\left[1-\left(\frac{1+e}{1+d}\right)^n\right] \tag{3-16}$$

Where, A_0 = Annual cost of energy, e=escalation rate, n= length of study period, d=discount rate

The DOE escalation rates vary according to year, region, fuel type (electricity, natural gas, Liquefied petroleum gas (LPG), distillate and residual fuel oils, and coal) and rate type (residential, commercial and industrial). Energy Escalation Rate Calculator (EERC) is used for calculating an average annual escalation rate for fuel price based on annually-updated EIA energy price forecasts (U.S. Department of Commerce, 2009).

If inflation is considered in calculating the PV (current dollars), the price of the equipment is based on a nominal discount rate and the price of energy is based on a nominal escalation rate; if inflation is not considered in the study (constant dollars), they are all based on a real discount and escalation rate. Both of the approaches will yield the same present value results. For simplicity, constant dollars (excludes inflation) is considered in this study. The relationship between a real interest rate, d, and a nominal discount rate, D, is expressed as follows,

$$d = \frac{1+D}{1+I} - 1 \tag{3-17}$$

Where, I is the inflation rate.

The discount and inflation rates for 2009 by DOE are:

Real rate (excluding price inflation): 3.0%

Nominal rate (including price inflation): 4.2%

Table 3-4. Life cycle cost calculation

	Initial Investment	Energy	Maintenance	Repair	Replacement	Salvage
Year of Occurrence	0	Annually	Annually	At certain year	End of service life	End of service life
Discount Factor	1	$UPV^*_{(n,d,e)}$	$UPV_{(n,d)}$	$SPV_{(n,d)}$	$SPV_{(n,d)}$	$SPV_{(n,d)}$
Present Value	PV_i= initial cost	$PV_e=A_0\times UPV^*_{(n,d,e)}$	$PV_m=A'_0\times UPV_{(n,d,e)}$	$PV_r=F_r\times SPV_{(n,d)}$	$PV_{rt}=F_{rt}\times SPV_{(n,d)}$	$PV_s=F_s\times SPV_{(n,d)}$
Life Cycle Cost	$LCC= PV_i + PV_e + PV_m + PV_r + PV_{rt} - PV_s$					

LEED Green Building Rating System

In order to earn points in Energy and Atmosphere in LEED, two prerequisites associated with HVAC systems which define the minimum energy performance and fundamental refrigerant management are required. After meeting the prerequisites, more points may be earned through the following credits:

Optimize Energy Performance

Refer to Table 2-7 for LEED 2009 –NC energy performance score card.

Enhanced Refrigerant Management

There are 2 points available for obtaining this credit. 2 options can be chose (U.S. Green Building Council, 2009):

OPTION 1: do not use ANY refrigerants

OPTION 2: use refrigerants and HVAC that minimizes or eliminates emission of compounds that cause ozone depletion & global warming

For Option 2, the refrigerants should meet the following calculation,

$$LCGWP + LCODP \times 10^5 \leq 100 \tag{3-18}$$

Where,

$$LCODP = [ODPr \times (Lr \times Life + Mr) \times Rc]/Life \tag{3-19}$$

$$LCGDP = [GWPr \times (Lr \times Life + Mr) \times Rc]/Life \quad (3\text{-}20)$$

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

LCGWP = Lifecycle Direct Global Warming Potential (lbCO2/Ton-Year)

ODPr = Ozone Depletion Potential of Refrigerant (0 to 0.2 lbCFC11/lbr)

GWPr = Global Warming Potential of Refrigerant (0 to 12,000 lbCO2/lbr)

Lr = Refrigerant Leakage Rate (0.5% to 2.0%; default of 2% unless otherwise demonstrated)

Mr = End-of-life Refrigerant Loss (2% to 10%; default of 10% unless other wised demonstrated)

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

Life = Equipment Life (10 years; default based on equipment type, unless otherwise demonstrated)

CHAPTER 4
AHP DECISION MAKING MODEL DEVELOPMENT

AHP (Analytic Hierarchy Process) is a structured and logical technique for dealing with complicated decision making problems, which helps decision makers find a solution that best suits their needs and preferences. It was developed by Thomas L. Saaty in 1977 and has been refined and widely used in many areas of the society including business, government, defense, industry, education, etc. It is a comprehensive methodology to build a logical framework for quantifying and evaluating alternative solutions based on various criteria (Satty, 1982). This dissertation utilizes AHP structure for selecting the optimal HVAC system based on the performance of alternatives as well as the preferences of the decision makers.

The Structure of AHP Model

The AHP model contains several layers: a goal layer, criteria layers, and an alternative layer. The criteria layer can be can be further developed into sub-criteria, sub-sub-criteria and so on, in as many levels as needed. Each box in the model is called a node. The boxes descending from any node are called its children. The node from which child nods descend is called their parent.

The first step is to form the AHP hierarchy structure including the decision goal, the criteria for evaluating the alternatives, the alternatives chosen to be evaluated. Then the importance of each criterion is established by making a series of judgments based on pairwise comparisons among criteria. If there is a sub-criteria layer, the importance of each sub-criterion is also determined by the pairwise comparison. The final weighting of the sub-criterion is the product of the weighting of the sub-criterion among the sub-criteria under the same criterion and the weighting of the criteria. The third step is to evaluate each alternative with respect to each sub-criterion and then multiply that evaluation by the importance of the sub-criterion. This product is summed over all the sub-criteria for the specific alternative to generate the overall score of the alternative. The alternative with the highest overall score is the best choice based on the performance of alternatives as well as the preference of the decision makers on the importance of the criteria. Equation 4-1 shows it mathematically,

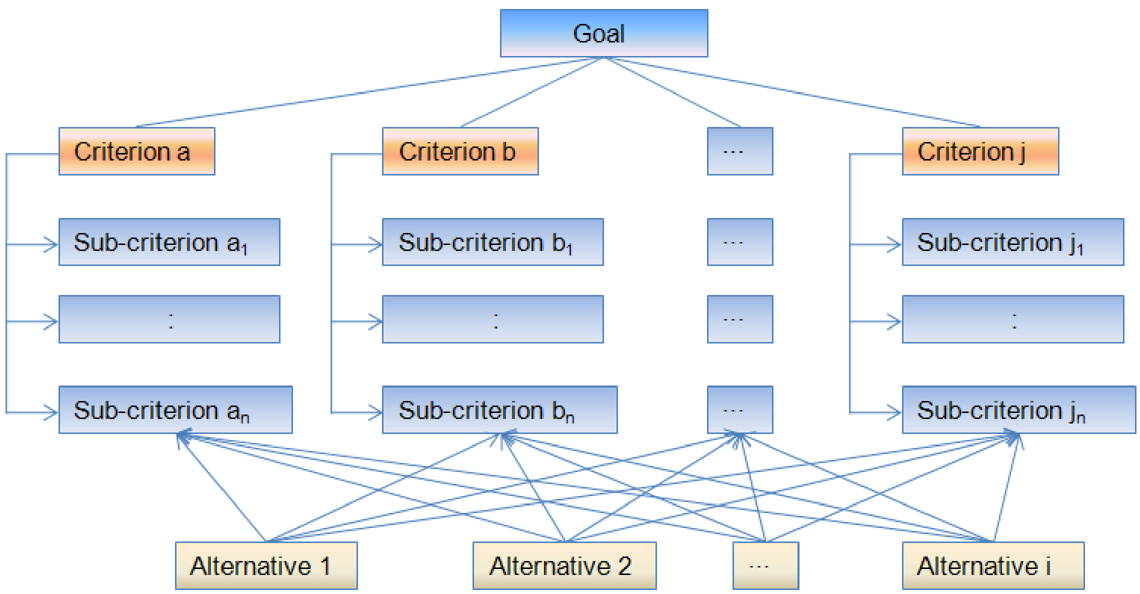


Figure 4-1. The structure of analytic hierarchy process

$$OS_i = \sum_{j=1}^{n} PI_{ij} w_j \qquad (4\text{-}1)$$

Where, OS_i is the overall score of the *i* th alternative,

PI_{ij} is the performance indicator of the *i* th alternative under *j* th sub-criteria

w_j is the weighting or the importance of the *j*th sub-criterion

Figure 4-2 shows the hierarchy structure established for choosing the optimal HVAC system. The goal layer is to choose a HVAC system which is the purpose for establishing the decision-making model. The criteria layer contains the four performance factors for evaluating the HVAC systems: technical requirement, economic performance, environmental performance and LEED performance. These criteria are further expended into their own sub-criteria in the sub-criteria layer.

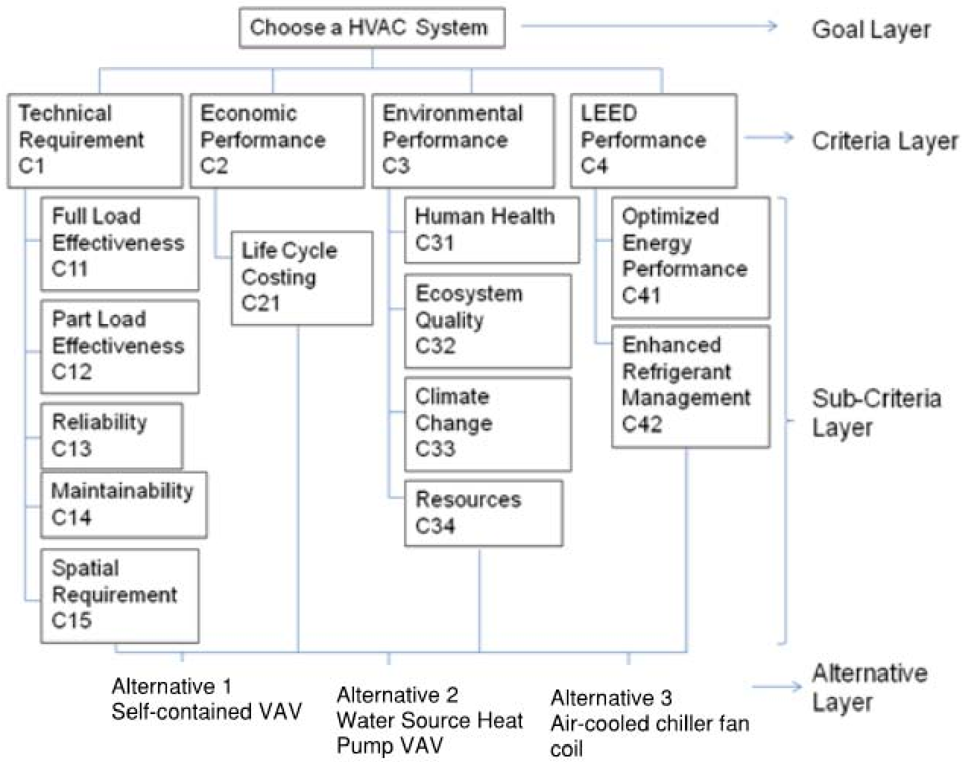


Figure 4-2. Hierarchy structure for choosing the optimal HVAC system

The technical requirement criterion contains four sub-criteria: full load effectiveness, part load effectiveness, reliability, maintainability and spatial requirement; the economic performance criterion contains only 1 sub-criterion, which is life cycle costing; the environmental performance contains four sub-criteria: human health, ecosystem, climate change and resources; the LEED performance criterion contains 2 sub-criteria: optimized energy performance and enhanced refrigerant management. The alternative layer contains several HVAC alternatives considered for comparison.

Goal Layer

The goal for this analysis is to find a HVAC system which has the optimal combined performance and also best suits the preference of decision makers.

Criteria Layer

The criteria layer contains the four performance factors for evaluating the HVAC systems: technical requirement, economic performance, environmental performance and LEED performance. Pairwise comparisons are conducted between each two criteria in order to get the weighting of each criterion.

Pairwise comparison

Each two criteria are compared in pair. The pairwise comparison is based on the preference of the decision maker on the criteria. In order to quantize the importance of one criterion over another, the importance intensity is introduced as shown in Table 4-1. A 9-point importance scale is used to indicate the importance comparison between criteria in terms of equally importance, moderately favored, strongly favored, very strongly favored, and extremely favored. If two criteria are equally important, the importance for both of the criteria is set to be 1. If criterion A is extremely favored over criterion B, the importance of criterion A is 7 compared with criterion B and the importance of criterion B is 1/7 compared with criterion A. The number of the pairwise comparison is based on the number of criteria to be compared,

$$N = \frac{n\,(n-1)}{2} \tag{4-2}$$

Where, N is the number of pairwise comparison; and n is the number of criteria to be compared.

Table 4-1. Importance scale for pairwise comparison

Importance Scale	Details
1	Two criteria are equally important to the preference
3	One criteria is moderately favored over the other
5	One criteria is strongly favored over the other
7	One criteria is very strongly favored over the other
9	One criteria is extremely favored over the other
2,4,6,8	Intermediate values between two adjacent importance judgment

Figure 4-3 is an example of the subjective importance judgment for comparing the criteria in pair based on the decision maker's preference.

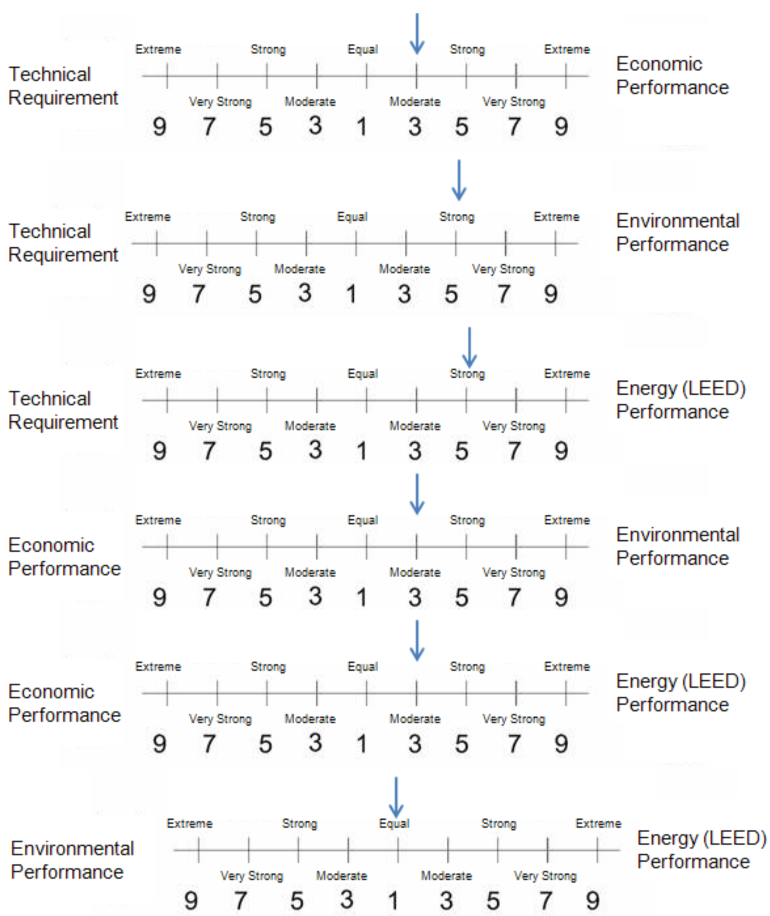


Figure 4-3. Pairwise comparison of performance criteria

The importance judgment matrix

With the pairwise comparison for each two of the criteria, weightings of the criteria are calculated by the importance judgment matrix. The size of the matrix is 4 since there are four criteria in the criteria layer. Table 4-2 shows the importance judgment matrix in criteria layer. The element W_{ij} represents the importance comparison between the vertical criteria i and the horizontal criteria j. If W_{ij} equals to 5, that means the vertical criteria i is very strongly important over the horizontal criteria j. If W_{ij} equals to 1/5, that means the horizontal criteria j is very strongly important over the vertical criteria i. The elements along the diagonal equal to 1 (equally important) since the criterion is compared to itself. Notice that the matrix is reciprocal. The values in the lower triangular matrix are filled by using the reciprocal values of the upper triangular matrix.

Table 4-2. Importance judgment matrix in criteria layer

Criteria	Technical C1	Economic C2	Environmental C3	LEED C4
Technical C1	1	w_{12}	w_{13}	w_{14}
Economic C2	w_{21}	1	w_{23}	w_{24}
Environmental C3	w_{31}	w_{32}	1	w_{34}
LEED C4	w_{41}	w_{42}	w_{43}	1

The weighting w_i for the performance criteria i is calculated from equation 4-3 and 4-4. The sum of the weightings in each layer equals to 1. The sum of the weightings for the sub-criteria under the same criteria is equal to the weighting for the criteria.

$$W_{Ci} = \sqrt[n]{(1 \times w_{i2} \times \cdots \times w_{in})} = (\prod_{j=1}^{n} w_{ij})^{1/n} \tag{4-3}$$

The weighting of criteria $\overline{w}_{Ci}$ is

$$\overline{w}_{Ci} = \frac{w_i}{\sum_{i=1}^{n} w_i} = \frac{(\prod_{j=1}^{n} w_{ij})^{1/n}}{\sum_{i=0}^{n}(\prod_{j=1}^{n} w_{ij})^{1/n}} \tag{4-4}$$

Consistency check

Consistency check is important to check cardinal transitivity of preferences of decision-makers. In order to check the consistency of the subjective judgment and make sure the comparison is transitive, the consistency ratio (CR) is used. The consistency ratio is the ratio of the consistency index (CI) over the random consistency index (RI), shown in equation 4-5. The consistency index CI is calculated by equation 4-6. λmax is the maximum Eigen value of the matrix, n is the size of the matrix. Random Consistency Index (RI) is randomly generated from of a sample size 500 matrices. It is decided by the size of the matrix, which is shown in Table 4-3. The judgment matrix is considered consistent if CR≤0.1. If CR is greater than 0.1, the subjective judgment is needed to be revised.

$$CR = \frac{CI}{RI} \quad (\leq 0.1\ if\ consistent) \tag{4-5}$$

$$CI = \frac{\lambda max - n}{n-1} \tag{4-6}$$

Table 4-3. Random consistency index

n	1	2	3	4	5
RI	0	0	0.58	0.9	1.12

Sub-criteria Layer

Similar to the weighting calculation for the criteria layer, the weighting for the sub-criteria under Technical requirement is also based on the pairwise importance matrix generated by the decision-makers. Since life cycle costing is the only criteria in the Environmental performance criterion, the weighting is set to 1. For the weightings of sub-criteria under environmental performance criteria, a recommended weighting structure for the damage categories is used based on Impact 2002+ in SimaPro. Table

4-4 shows the recommended weightings for the four impact categories. For LEED criteria, the weightings between Optimized Energy Performance and Enhanced Refrigerant Management are calculated based on the points available in each credit. Note that the total weighting factors for sub-criteria in the sub-criteria layer should be multiplied by the weighting of the criteria under which the sub-criteria locate. The sum of the total weightings for all sub-criteria is 1.

Table 4-4. Weightings of damage categories in Impact 2002+

Environmental factors	Human health	Climate change	Resources	Ecosystem quality
Weighting	30.1%	35.2%	32.6%	2.1%

Alternative Layer

To avoid the addition of performance values in different units, the performance Indicator (PI) is introduced to evaluate the performance of alternatives. The performance indicator (PI) is a unitless number, in a range from1 to 9, indicating how good the performance of an alternative is among general candidates in the same performance category. The higher performance indicator means a better performance.

For LEED criteria, the maximum and minimum performance values are known and listed in Table 4-5. PI correlated to the maximum value is equal to 9 and PI correlated to the minimum value is equal to 1. All the other values between the maximum and minimum values can be interpolated into a certain PI by using equation 4-12. PV_{max} means the maximum performance value. PI_{min} means the minimum performance indicator.

Similar to the situation for LEED criteria, the conversion of performance values corresponded with the performance indicators for sub-criteria under technical criteria is also listed in Table 4-6. The maximum performance value is 4 which is corresponded to PI=9. The minimum performance value is 1 and it is corresponded to PI=1. The values in between is calculated based on equation 4-12.

Table 4-5. Conversions of performance values into PIs for LEED performance

Sub-criteria	PV_{max}	PI_{max}	PV_{min}	PI_{min}
Optimized energy performance	19	9	0	1
Enhanced refrigeration management	1	9	0	1

Table 4-6. Conversions of performance values into PIs for technical performance

Technical performance	poor	fair	good	excellent
Performance values	1	2	3	4
Performance indicators	1	3.67	6.33	9

For environmental and economical criteria, the maximum value and minimum value are unknown. The major categories of HVAC systems in these two criteria are distributed in certain range. The probability of HVAC systems with extremely good or extremely bad economical performance and environmental performance are very small. This kind of data distribution follows the pattern of normal distribution. Since there is no enough resources and time to collect a data base big enough, it is assumed that the economical performance and environmental performance results fall into the normal distribution.

The confidence interval is used to define the boundary values of the general performance. μ is expectation and it is shown in equation 4-7. σ is the standard deviation and it is calculated by equation 4-8. For normal distribution, 68.2% of the set falls into the area with less than one standard deviation from the expectation (μ ± σ); 95.4% of the data set falls into the interval with two standard deviations from the expectation (μ ± 2σ); 99.73% of the data sets is within three standard deviations from the expectation (μ ± 3σ). The confidence interval with 99.73% data covered is used to set the performance boundary limit and it can be calculated by equation 4-9.

$$\mu = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{4-7}$$

Where, μ - The arithmetic mean of the performance values of alternatives in interest

x_i- The performance value for an alternative under a sub-criterion

n - The number of the alternatives in interest

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \mu)^2} \tag{4-8}$$

Where, σ - standard deviation

$$CI = \mu \pm 3\sigma \tag{4-9}$$

Where, CI - Confidence interval

Figure 4-4 shows the correlation between the PI values and standard normal distribution. For standard normal distribution, μ=0, σ=1. The first row in the table is the z value of the standard normal distribution. The second row is the PI corresponding to the z value. The third row is the probability between two PI values.

Standard normal	-3	-2.25	-1.50	-0.75	0	0.75	1.5	2.25	3
PI	1	2	3	4	5	6	7	8	9
					54.7%				
					86.6%				
					97.6%				
					99.7%				

Figure 4-4. Correlation between PI and standard normal distribution

Because of the small sample size, it is hard to calculate the expectation and deviation size of population. Thus the mean value of the observations and standard deviation of sample is used as the estimate value of μ and σ. So μ is the mean value of the performance values of alternatives in interest under a specific sub-criterion. The upper limit of the confidence interval corresponds to indicator 9 which indicates the best performance and the lower limit of the confidence interval is corresponded to 1 which defines the worst performance. And the boundary conversion to PI can be found in equation 4-10 and 4-11. Other values between the maximum and minimum CI values can be interpolated into a certain PI by using equation 4-12. For software development in the future, with a comprehensive larger database, a fully developed system would have the ability to calculate the PI values of candidate systems.

$$CImax = \mu + 3\sigma \ \rightarrow PI = 9 \tag{4-10}$$

$$CImax = \mu - 3\sigma \ \rightarrow PI = 1 \tag{4-11}$$

$$CI = x \ \rightarrow PI = 9 - (9 - 1)\frac{(CImax - x)}{(CImax - CImin)} \tag{4-12}$$

CHAPTER 5
CASE STUDY

Background

Building and Location Description

The building is a 6 story office building located in Atlanta, Georgia. The gross area of the building is 145,583 square feet. Table 5-1 shows the weather data in Atlanta and building information as the basis for building energy simulation. The purpose is to choose the optimum cooling system which has the best integrated performance in technical, economic, environmental and LEED aspect, as well as the preference of the owners or decision-makers. The heating systems are identical in all alternative cases. There are 3 Proposed Cases or alternative systems/plants chosen for the case study. The baseline case is used as basis to calculate the energy cost savings of alternatives for LEED Energy and Atmosphere Credit. The Baseline Case is designed to meet the requirement of ASHRAE 90.1-2004. The Proposed Cases improve the building envelope and have CO_2 sensors in each room. The building information and schedules for all three alternatives are identical.

Table 5-2 shows the energy mix of electricity in Georgia for calculating the environmental contribution of the electricity consumption for both Baseline Case and the Proposed Cases. Table 5-3 shows the rate structure for electricity consumption, electricity demand and water charge.

Alternative Systems Description

There are 3 alternatives chosen for the building in the case study. Alternative 1 is a self-contained parallel fan powered VAV (PFP) system with dedicated outdoor air system located on each floor. Alternative 2 is a water source heat pump with series fan-powered VAV system with dedicated outdoor air system. Alternative 3 is an air-cooled chiller with constant volume fan coil units system. The system in the Baseline Case is a water-cooled chiller VAV system designed based on ASHRAE 90.1-2004 Appendix G. Table 5-4 shows the performance parameter for each alternatives and baseline case.

Table 5-1. Weather and building information

Weather Data		
Summer design dry bulb (°F)	96	
Summer design wet bulb (°F)	73	
Winter design dry bulb (°F)	22	
Building Information		
Floor Area (Gross Area =145,583 sf)	1st Floor (sf)	23883
	2nd-6th Floor (sf/floor)	24162
	Elevator machine room (sf)	900
	Baseline ASHRAE 90.1-2004 Case	Proposed Cases
Building Envelope		
Wall U-value (Btu/hr-sq ft °F)	0.124	0.065
Roof U-value (Btu/hr-sq ft °F)	0.063	0.0425
Slab U-value (Btu/hr-sq ft °F)	0.052	0.213
Window U-value (Btu/hr-sq ft °F)	0.57	0.27
Window shading coefficient	0.291	0.29
Internal load (people, equipment, lighting)	Identical	
Thermostat (dry bulb, relative humidity, driftpoint, CO_2 sensors)	Same except CO_2 sensors. No CO_2 sensors in the Baseline case	
Airflow (supply, ventilation, infiltration, exhaust, VAV minimum)	Identical, ventilation rate is designed based on ASHRAE 62.1-2004/2007	

Table 5-2. The energy mixes of electricity generation in Georgia

	Coal	Nuclear	Natural gas	Oil	Hydro	Non-Hydro renewables and others
Percentage	62.5%	23.1%	9.3%	0.6%	1.9%	2.6%

Table 5-3. Rate structure and water charge

Electricity Demand Charge		
For the first 30kW of billing demand per month		No Charge
For all over 30kW of billing demand per month		$3.19 per kW
Energy Charge		
For the first 125 kWh per kW billing demand per month	For the first 3000 kWh per month	9.78 cents per kWh
	For the next 87000 kWh per month	5.43 cents per kWh
	For all over 90000 kWh per month	4.14 cents per kWh
For the next 275 kWh per kW billing demand per month	For the first 6000 kWh per month	5.55 cents per kWh
	For the next 134000 kWh per month	5.44 cents per kWh
	For all over 140000 kWh per month	5.07 cents per kWh
For all over 400 kWh per kW billing demand per month	For all kWh per month	4.84 cents per kWh
Water Charge	$6.61765 per 1000 gallons	

Performance Results

LEED Performance

Energy simulation results

To evaluate the performance of alternatives in Energy and Atmosphere Credit of LEED, the energy cost savings for each alternative based on the Baseline Case is calculated using Trace 700 (TRANE, 2005). The whole energy simulation report is available in Appendix of the dissertation. Figure 5-1 shows monthly HVAC energy consumption of alternatives. To notice that Alternative 2 is set to be the Baseline Case in Trace and Alternative 3 and Alternative 4 are water-source VAV and air-cooled chiller fan coil unit accordingly. The HVAC energy consumption of the Baseline Case dominates during the heating season since the large amount of heating energy consumption. This is mainly because of the high U-value of the building envelope. The self-contained parallel fan powered VAV system has the lowest energy consumption during the cooling season.

Table 5-4. Performance parameters for alternative and baseline systems

	System and plant type	Plant energy rate (kW/ton)	System fan full load energy rate (kW/cfm)	
			Primary	Secondary
Alternative 1	Self-contained unit + parallel fan powered VAV + dedicated OA	0.77	0.000668	0.00032
Alternative 2	Water source heat pump + series fan powered VAV + dedicated OA	0.86	0.000668	0.000332
Alternative 3	Air-cooled chiller + constant volume fan coil units	1.00	0.000668	0.000332
Baseline ASHRAE 90.1 -2004	Water-cooled chiller + VAV with reheat	0.72	0.001025	0.00035

Figure 5-2 shows the energy consumption summary for the Proposed Cases and the Baseline Case. The Baseline Case has the highest electricity consumption due to its high primary heating and auxiliary (supply fans and pumps) energy consumption. Alternative 1 has the lowest energy consumption. Alternative 3 has the highest energy consumption among all three alternatives mostly because of its highest supply fans and pumps energy consumption due to the use of constant volume fan coil unit.

To calculate the energy cost of the ASHRAE 90.1-2004 baseline case, LEED and table G3.1 No.5(a) of ASHRAE Standard 90.1-2004 require the baseline building performance generated by averaging the simulating results of the building with its actual orientation and again after rotating the entire building 90, 180, 270 degrees. Table 5-5 shows the energy cost performance ratings for the Baseline Case by rotating the building into four directions. The average energy cost for the Baseline ASHRAE90.1-2004 is $183,445.

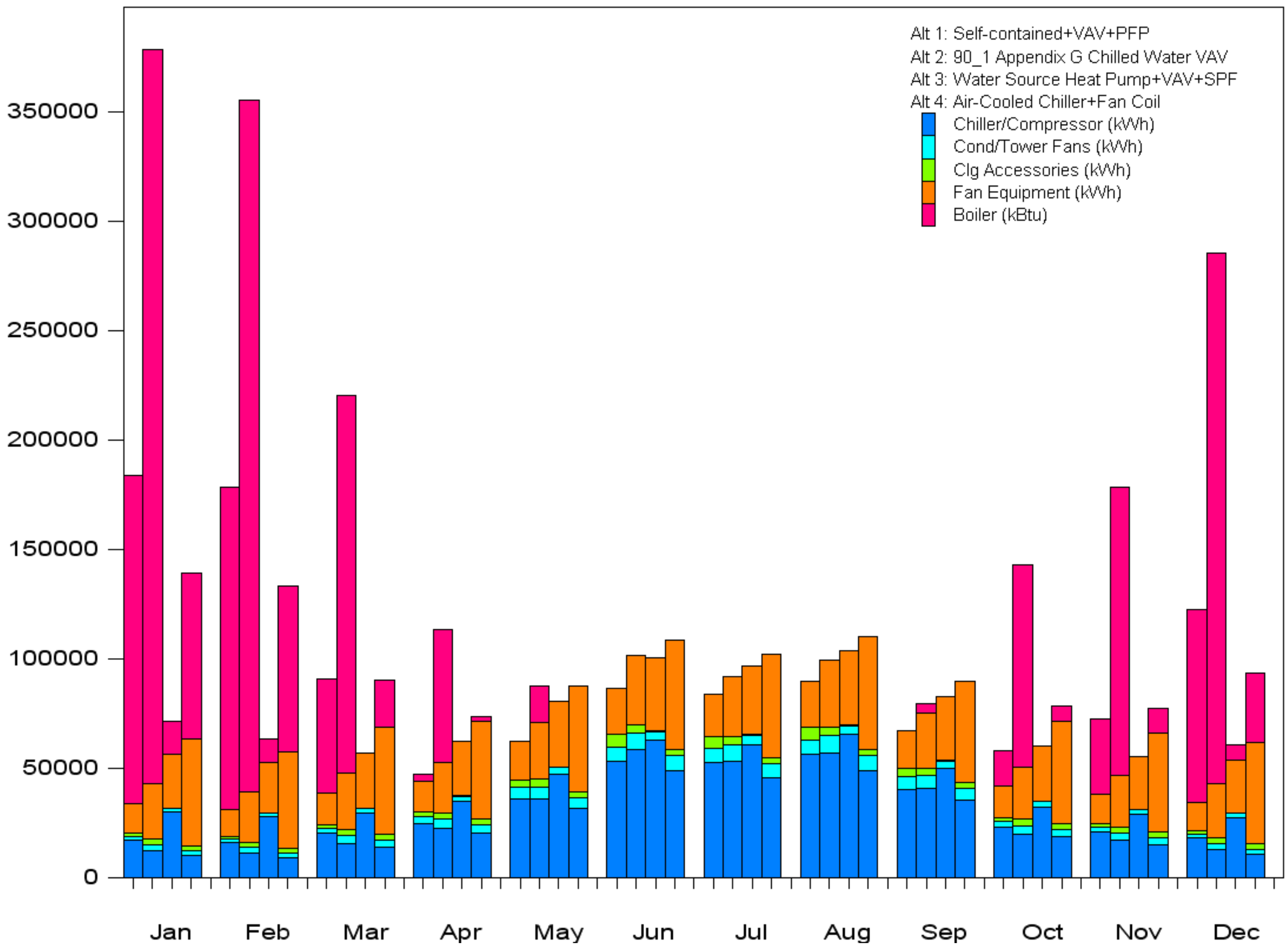


Figure 5-1. Monthly HVAC energy consumption of alternatives

Figure 5-3 shows the energy cost savings of alternatives compared to the Baseline Case ASHRAE 90.1. Table 5-6 shows the points earned in EAc1Enhanced Energy Performance of LEED-NC for each alternative based on the energy cost savings. Alternative 1 achieves 16.1% of energy cost savings compared to the Baseline Case, which corresponds to 3 points earned in EAc1. Alternative 2 achieves 13.6% of energy

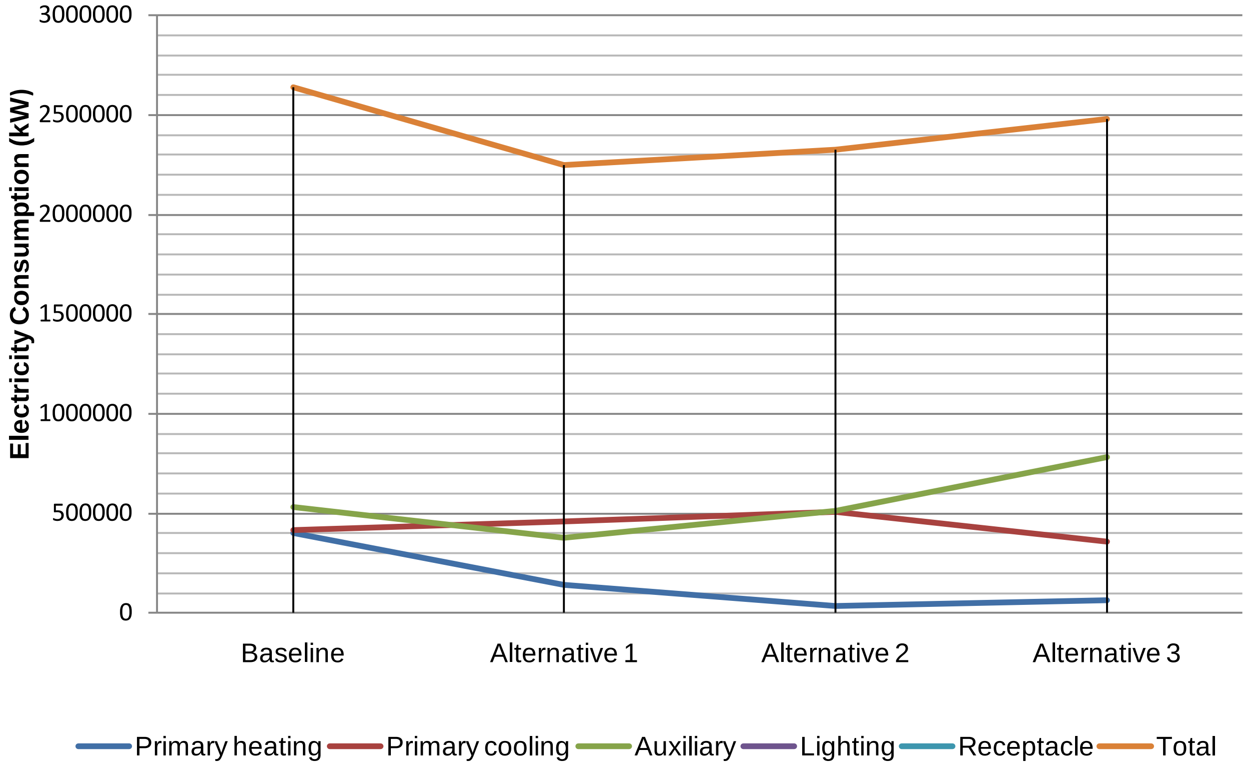


Figure 5-2. Annual energy consumption for alternatives and baseline

Table 5-5. Performance energy cost rating for baseline case: ASHRAE 90.1-2004

	Space Heating		Space Cooling		Total Building Cost ($/yr)
	Energy (10^6 Btu/yr)	Peak (kBtuh)	Energy (10^6 Btu/yr)	Peak (kBtuh)	
0° Rotation	1,372.3	1,522	1,221.2	852	178,190
90° Rotation	1345.61	1497.7	1246.65	695.07	184,993
180° Rotation	1,372.2	1,520	1,257.4	685	185,581
270° Rotation	1346.36	1496.28	1246.64	695.48	185,017
Average	1,359.1	1,509	1,243.0	732	183,445

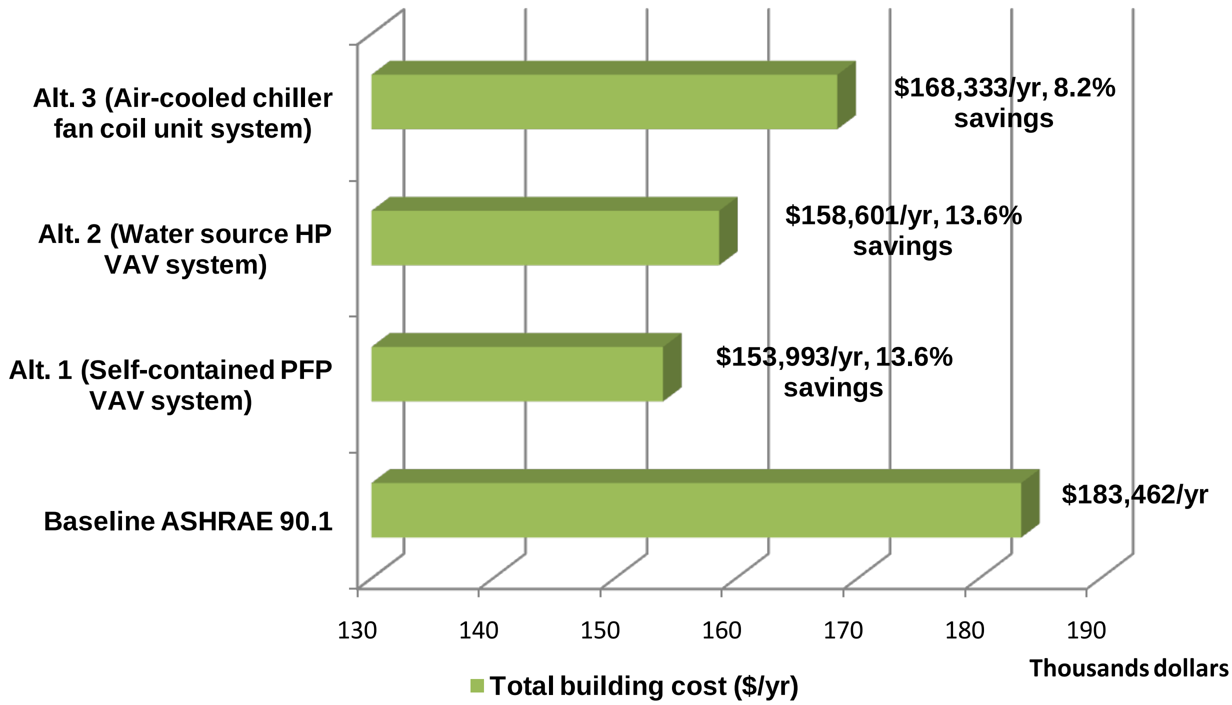


Figure 5-3. Energy cost savings of alternatives compared with baseline 90.1

Table 5-6. Energy cost savings and earned points in EAc1, LEED-NC

	Baseline Case (Water-cooled chiller VAV System)	Alternative 1 (Self-contained PFP VAV system)	Alternative 2 (Water source HP VAV system)	Alternative 3 (Air-cooled chiller fan coil unit system)
Total building consumption (10^6 Btu/yr))	9320	7677	7931.4	8456.4
Total building cost per year ($/year)	183,462	153,993	158,601	168,333
Percentage of savings compared to the Baseline Case	-	16.1%	13.6%	8.2%
Points achievable in EAc1, LEED-NC	-	3	1	0

cost saving and earns 1 point in EAc1. Alternative 3 achieves 8.2% of energy cost saving but since it has not exceed the minimum of energy cost savings (12%) required by LEED, no points is earned to Alternative 3.

EAc4 Enhanced refrigerant management

Table 5-7 shows the global warming potential and ozone depletion potential of refrigerants for three alternatives. In order to earn this refrigerant credit in LEED, the GWP and ODP contributions of alternatives should meet the following threshold required by LEED,

$$\mathrm{LCGWP} + \mathrm{LCODP} \times 10^5 \leq 100$$

Where

$$LCODP = [ODPr \times (Lr \times Life + Mr) \times Rc]/Life$$
$$LCGDP = [GWPr \times (Lr \times Life + Mr) \times Rc]/Life$$

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

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

ODPr = Ozone Depletion Potential of Refrigerant (lbCFC11/lbr)

GWPr = Global Warming Potential of Refrigerant (lbCO_2/lbr)

Lr = Refrigerant Leakage Rate=2%

Mr = End-of-life Refrigerant Loss =10%

Rc = Refrigerant Charge (lbs/ ton of cooling capacity)

Life = Equipment Life

Alternative 1 and 2 meet the requirement and can earn 1 point in LEED. Since Alternative 3 excess the maximum threshold required by LEED, no point is earned.

Table 5-8 summarizes the LEED performance for three alternatives. Alternative 1 Self-contained unit + parallel fan powered VAV + dedicated OA can earn 4 points in total since its good energy cost savings by using more efficient pumps and fans. Alternative 2 Water source heat pump + series fan powered VAV + dedicated OA can earn 2 points. There is no point earned in Alternative 3 Air-cooled chiller + VAV with reheat since it does not meet the minimum requirements in EAc4.

Table 5-7. Refrigerant contributions for alternatives

	Alternative 1 Self-contained unit + parallel fan powered VAV + dedicated OA	Alternative 2 Water source heat pump + series fan powered VAV + dedicated OA	Alternative 3 Air-cooled chiller + Fan coil units
Inputs			
Refrigerant	R-22	R-22	R-134a
GWPr ($lbCO_2$/lbr)	1780	1780	1320
ODPr (lbCFC11/lbr)	0.04	0.04	0
Rc (lb/ton)	0.5	0.5	2.66
Life (yrs)	20	20	20
Lr (%)	2%	2%	2%
Mr (%)	10%	10%	10%
Calculations			
Tr Total Leakage (Lr×Life + Mr)	40%	40%	50%
LCGWP (GWPr×Tr ×Rc)/Life	22.79	22.79	102.3
LCODP×1E5 (GWPr×Tr ×Rc)/Life	51.20	51.20	0
Refrigerant Atmospheric Impact=LCGWP + LCODP×1E5	73.99	73.99	102.3
Points achievable in EAc4, LEED-NC	1	1	0

Table 5-8. Summary of LEED performance of alternatives

	Alternative 1 Self-contained unit + parallel fan powered VAV + dedicated OA	Alternative 2 Water source heat pump + series fan powered VAV + dedicated OA	Alternative 3 Air-cooled chiller + Fan coil units
Total points earned in LEED	4	2	0

Economic Performance

Capital components

The initial costs and yearly maintenance costs of the systems are based on the catalog of Trane Company. The initial costs are \$8.75/sf for Alternative 1 self-contained VAV system, \$8.15/sf for Alternative 2 water source heat pump system, and \$9/sf for air-cooled chiller system. The yearly maintenance costs are \$72.81/ton for Alternative 1, \$81.72/ton for Alternative 2, and \$70.15/ton for Alternative 3. Table 5-9 summarizes the initial and maintenance cost of alternatives.

Table 5-9. Summary of initial and maintenance cost of alternatives

Alt #	First Cost ($/ton)	First Cost ($/sf)	Total First Cost ($)	Maint. Cost($/ton)	Maint. Cost($/ft^2)	Total Maint. Cost ($)	Total Alt. Cost ($)
Alt 1	4,688.32	8.75	1,273,939	72.81	0.14	19,784	1,293,723
Alt 2	4,366.84	8.15	1,186,583	81.72	0.15	22,205	1,208,788
Alt 3	4,822.27	9.00	1,310,337	70.15	0.13	19,062	1,329,399

Utility cost

Water cost. Figure 5-4 shows annual water cost of three alternatives. The annual water cost is \$6,399 for Alternative 1 self-contained VAV system since the condenser is cooled by water from the cooling tower. The annual water cost for Alternative 2 water cooled heat pump is \$13,276 for the large amount use of water in the cooling tower. And that for Alternative 3 air-cooled chiller fan coil system is \$43 since it uses outdoor air to cool the condenser.

Electricity cost. Figure 5-5 and Figure 5-6 shows the monthly utility cost and annual operating costs of the three alternatives along with the baseline ASHRAE 90.1 Appendix G chilled water VAV system (indicated as Alternative 2 in Figure 5-6).

Alternative 1 self-contained VAV system has the lowest yearly total operating cost ($180,177) including utility cost and maintenance cost. Alternative 2 has the highest yearly operating cost (indicated as Alternative 3 in Figure 5-6, $194,083) among three alternatives. That for Alternative 3 (indicated as Alternative 4 in Figure 5-6) is $187,438. The annual savings of Alternative 1 compared with Alternative 2 (indicated as Alternative 3 in Figure 5-6) is $13,906.

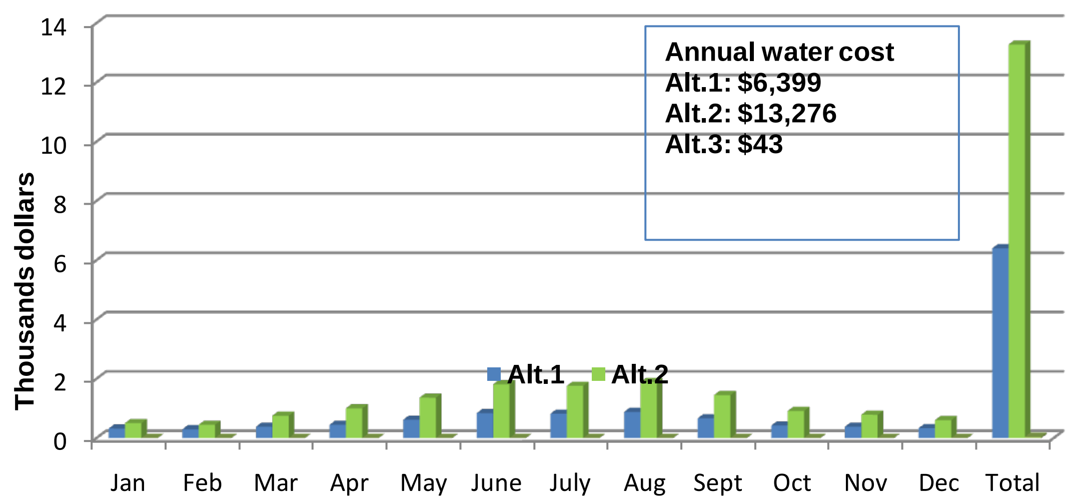


Figure 5-4. Annual water cost of alternatives

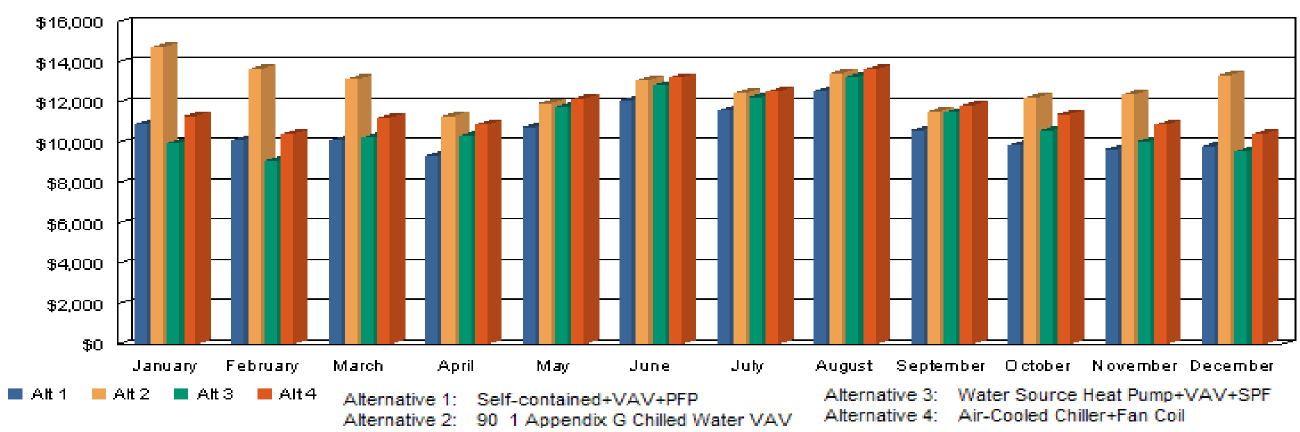
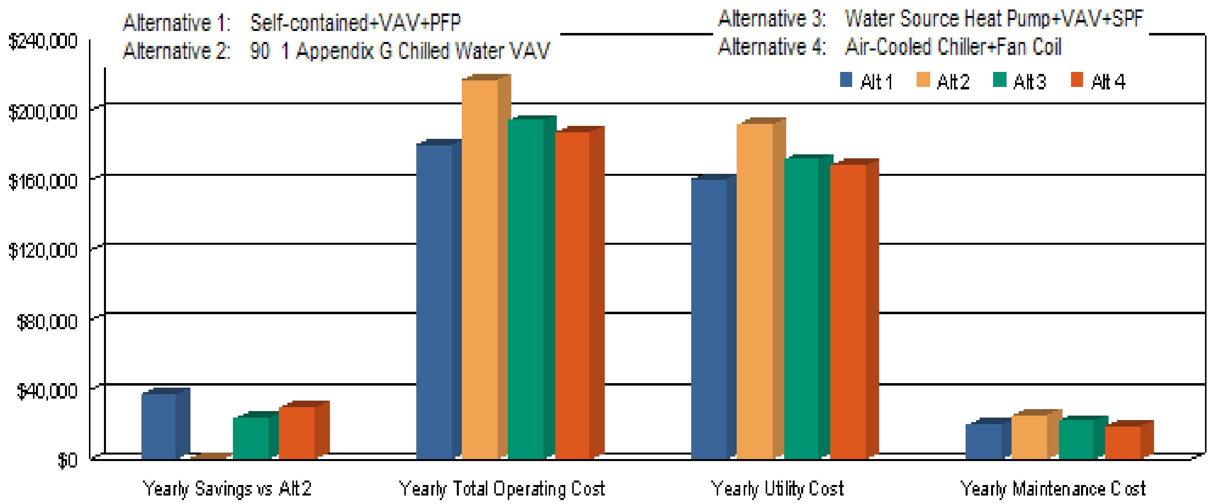


Figure 5-5. Monthly utility cost of alternatives



	Yearly Savings vs Alt 2	Yearly Total Operating Cost	Yearly Utility Cost ($)	Yearly Maintenance Cost ($)
Alt 1	37,333	180,177	160,393	19,784
Alt 2	0	217,510	191,877	25,632
Alt 3	23,427	194,083	171,877	22,205
Alt 4	30,072	187,438	168,376	19,062

Figure 5-6. Annual Operating Cost of alternatives

Life cycle cost

Life cycle cost performance for each alternative is calculated by BLCC 5.3 developed by National Institute of Standard Technology (NIST). Energy escalating rate is embedded in the program and updated annually. Since BLCC 5.3 does not consider complicated rate structure but one index Price/kWh, the total annual electricity consumption (dollars) is used while set the annual kWh consumption as1. Since the water rate is not considered as summer and winter rates separately, the total water consumption is assigned to either summer or winter. The discount rate is set to 3%. Inflation for maintenance expense is 2%. The study periods for all the alternatives are 20 years.

Table 5-10, 11, 12 show the results calculated from BLCC 5.3. The life cycle cost for Alternative 1 self-contained VAV system is $4,251,937, which is the lowest among the three. The life cycle cost for Alternative 2 is $4,386,235. Alternative 3 has the highest life cycle cost which is $4,415,848. To note that the initial cost for Alternative 2 is not the lowest one, but since the operational energy consumption for the system is lower than the other two alternatives, it compensates the loss for initial cost and also contributes to the lowest life cycle cost among the three alternatives.

Table 5-10. Life cycle cost of alternative 1

	Present Value	Annual Value
Initial Cost	$1,273,939	$85,637
Energy Consumption costs	$2,525,062	$169,741
Energy Demand Costs	$0	$0
Energy Utility Rebates	$0	$0
Water Usage Costs	$95,208	$6,400
Water Disposal Costs	$0	$0
Annually Recurring OM&R costs	$357,728	$24,047
Non- Annually Recurring OM&R costs	$0	$0
Replacement costs	$0	$0
Less Remaining Value	$0	$0
Total Life-Cycle	$4,251,937	$285,825

Table 5-11. Life cycle cost of alternative 2

	Present Value	Annual Value
Initial Cost	$1,186,583	$79,765
Energy Consumption costs	$2,600,621	$174,820
Energy Demand Costs	$0	$0
Energy Utility Rebates	$0	$0
Water Usage Costs	$197.528	$13,278
Water Disposal Costs	$0	$0
Annually Recurring OM&R costs	$401,504	$26,990
Non- Annually Recurring OM&R costs	$0	$0
Replacement costs	$0	$0
Less Remaining Value	$0	$0
Total Life-Cycle	$4,386,235	$294,853

Table 5-12. Life cycle cost of alternative 3

	Present Value	Annual Value
Initial Cost	$1,310,337	$88,084
Energy Consumption costs	$2,760,119	$185,547
Energy Demand Costs	$0	$0
Energy Utility Rebates	$0	$0
Water Usage Costs	$640	$43
Water Disposal Costs	$0	$0
Annually Recurring OM&R costs	$344,673	$23,170
Non- Annually Recurring OM&R costs	$0	$0
Replacement costs	$0	$0
Less Remaining Value	$0	$0
Total Life-Cycle	$4,415,848	$296,844

Environmental Performance

SimaPro 7 is the software used for evaluating the life cycle environmental performance of the three alternative HVAC systems. Impact 2002+ is the impact assessment method used in the case study. The environmental performance is mainly based on the particular energy mix in the region. Table 5-13 shows the energy mix for electricity in Atlanta, GA. The coal is the main source for electricity production in Atlanta. Because of the limited and shaded information from the manufacture on the composition of raw materials of the equipment, also with 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.

Table 5-13. Energy mix for electricity in Atlanta, GA

Coal (%)	Nuclear (%)	Natural Gas (%)	Oil (%)	Hydro and Non-hydro renewable and others* (%)
62.5%	23.1%	9.3%	0.6%	4.7%

Figure 5-7 shows the environmental performance of the three alternatives. Alternative 2 water source heat pump dominates in all impact categories. Alternative 1 self-contained VAV has the lowest impact among all the impact categories. Figure 5-8 shows the environmental performance of alternatives in four impact categories. The weightings of impact categories are also indicated in the figure by comparing the pts among impact categories for a specific alternative. Similarly, alternative 1 self-contained VAV system has the best environmental performance among all the impact categories. Figure 5-9 shows the single score for each alternative. The contribution of ecosystem quality of the overall environmental performance is negligible. Alternative 1 has the best environmental performance in total and Alternative 2 has the worst environmental performance among the three.

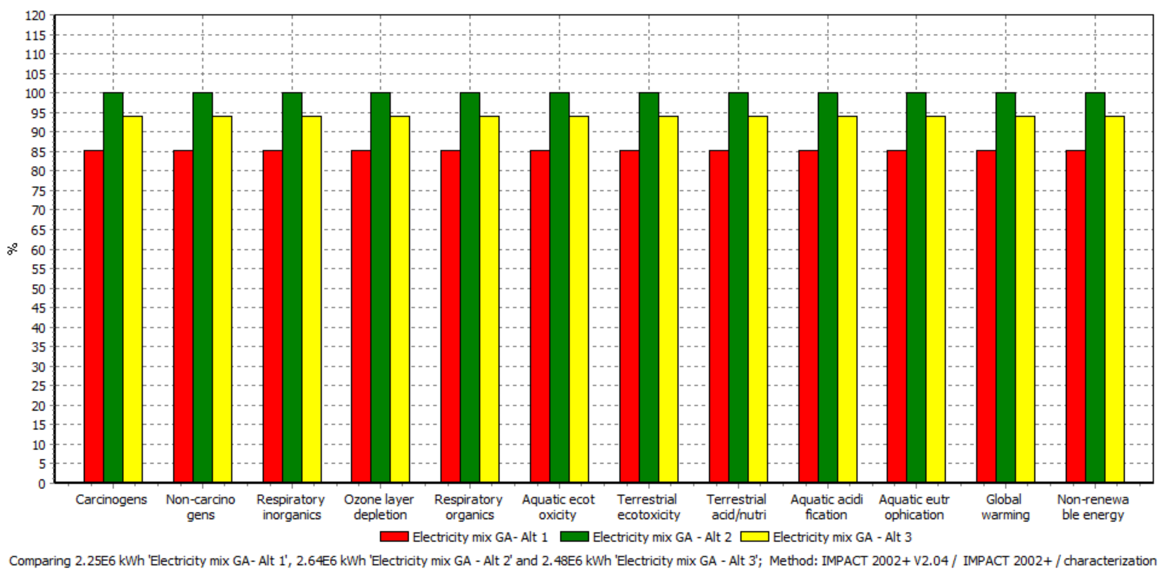


Figure 5-7. Characterization of environmental performance in fourteen midpoint categories

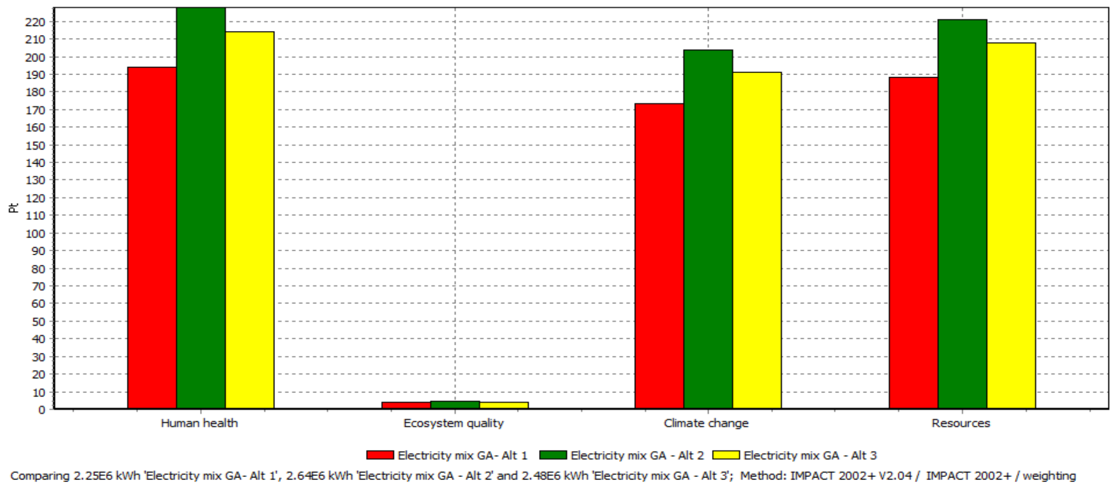


Figure 5-8. Weighting of environmental performance in four impact categories

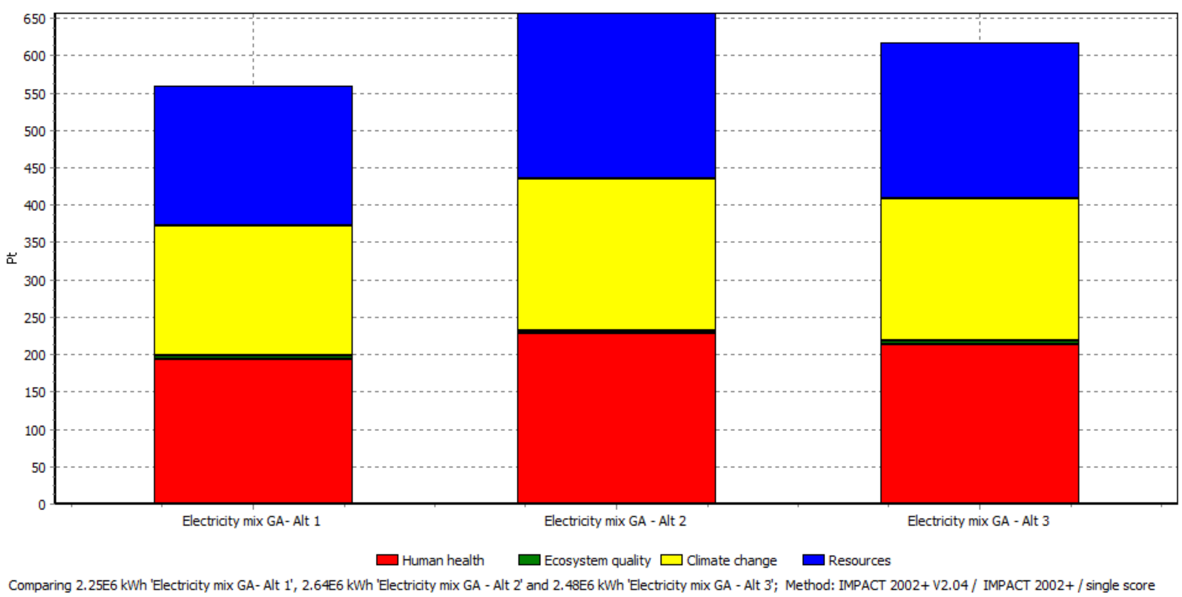


Figure 5-9. Single score of environmental performance for three alternatives

Technical Performance

Technical performance is indicated by the full load efficiency, part load efficiency, reliability, maintainability and spatial requirement. Table 5-14 lists the technical performance for three alternatives in the scale of “poor, fair, good, and excellent”.

Table 5-14. Technical performance of alternatives

	Alternative 1 Self-contained unit + parallel fan powered VAV + dedicated OA	Alternative 2 Water source heat pump + series fan powered VAV + dedicated OA	Alternative 3 Air-cooled chiller + fan coil unit
Full load effectiveness	good	good	good
Part load effectiveness	excellent	good	poor
Reliability	excellent	excellent	fair
Maintainability	fair	poor	good
Spatial Requirement	fair	fair	good

The application of Variable Air Volume (VAV) system in Alternative 1 and Alternative 2 greatly reduces the fan power usage during the part load condition. Constant volume fan coil unit is used in Alternative 3, so the power consumption for the fans is significant. Since Alternative 1 self-contained water-cooled unit complete is equipped on separate floors, equipment on other floors will not be affected if one unit fails. Similar to self-contained water-cooled unit, for Alternative 2 water source heat pump system, each heat pump has its own condenser and evaporator. If one heat pump fails, other heat pumps will not be affected. Additional chemical treatment for the cooling towers is required for the cooling tower to prevent corrosion and the water loop in Alternative 1 and 2, thus the maintenance effort in these alternatives is increased. Since Alternative 3 air-cooled chilled water fan coil unit system does not include a cooling tower, the maintenance effort is reduced. Alternative 1 self-contained VAV system requires the space for small mechanical rooms on each floor. Cooling tower is located on the roof. Alternative 2 water source heat pump system can be located in a mechanical room, on a roof or above the ceiling. Space is required for the air-cooled chiller for Alternative 3; however, it does not require the space for the cooling tower system.

AHP Module Application

Established Hierarchy Structure

Figure 5-10 shows the established hierarchy structure for choosing the optimal HVAC system. There are three alternatives in the alternative layer: Alternative 1self-contained unit + parallel fan powered VAV + dedicated OA, Alternative 2 water source heat pump + series fan powered VAV + dedicated OA, and Alternative 3 air-cooled chiller + fan coil unit system.

The criteria layer contains four criteria: Technical Requirement C1, Economic Performance C2, Environmental Performance C3 and LEED Performance C4. The weightings for the four criteria are calculated by the pairwise importance matrix based on the preference of the owners or decision-makers. Each criterion has its own sub-criteria.

Similar to the weighting calculation for the criteria layer, the weighting for the sub-criteria under Technical requirement is also based on the pairwise importance matrix originally from the decision-makers. Since life cycle costing is the only criteria in the Environmental performance criterion, the weighting is set to 1. For the weightings of sub-criteria under Environmental Performance, a recommended weighting structure for Impact 2002+ in SimaPro is used. The weightings between Optimized Energy Performance and Enhanced Refrigerant Management are calculated based on the points available in each credit.

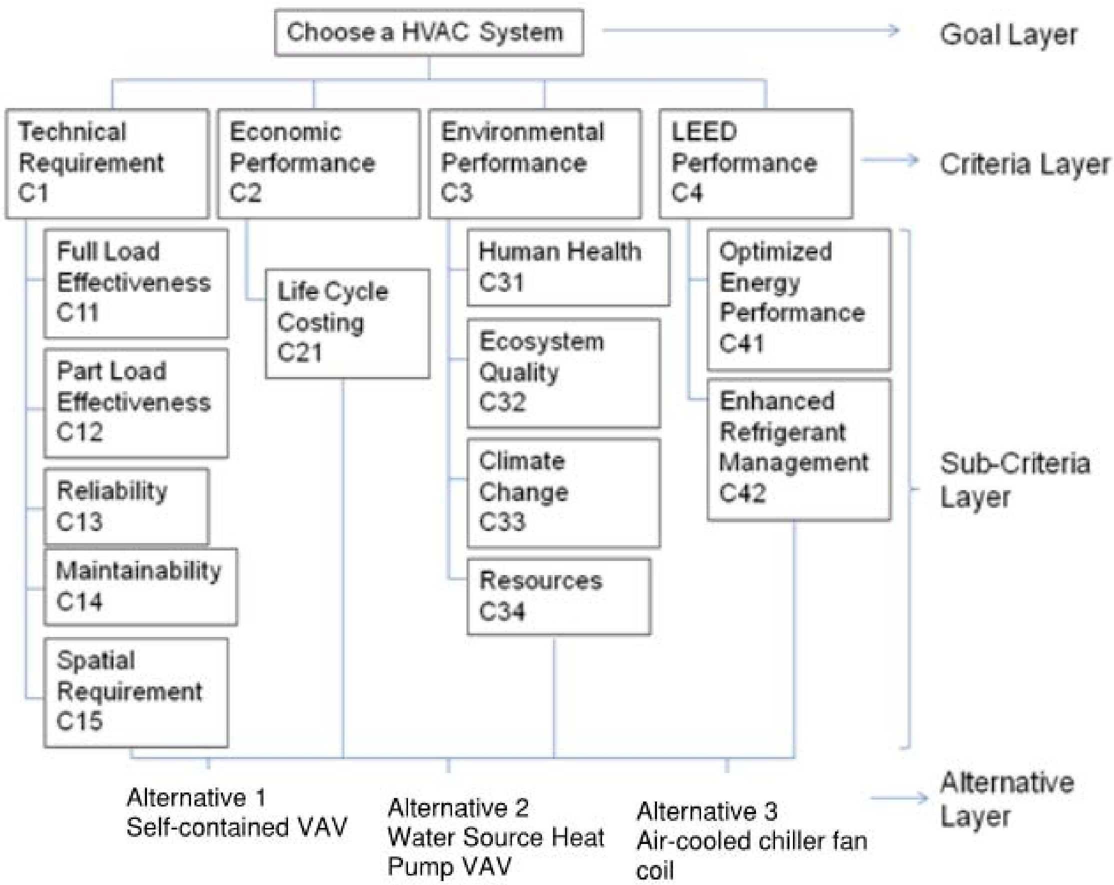


Figure 5-10. The decision-making hierarchy structure

Goal Layer

The goal for this analysis is to find a HVAC system which has the optimal combined performance and also best suits the preference of decision makers for a 6-story office building located in Atlanta, GA. In this case study, the decision makers would like to choose an environmental-friendly HVAC system. And since the project is trying to earn LEED credits, sound performance in LEED Energy and Atmosphere category is also preferable. The economic performance is also an important factor to consider, but not as important as the other two factors mentioned above. The technical requirement is the least important factor to consider.

Criteria Layer

Pairwise comparison

The way for setting the importance intensity when comparing two performance criteria is based on the preference of the decision maker. Table 4-1 in Chapter 4 defines the intensity of importance when comparing two criteria. A 9-point importance scale is chosen for this case. Figure 5-11 indicates the subjective judgment based on the decision maker's preference when comparing each two of the criteria in pair wise.

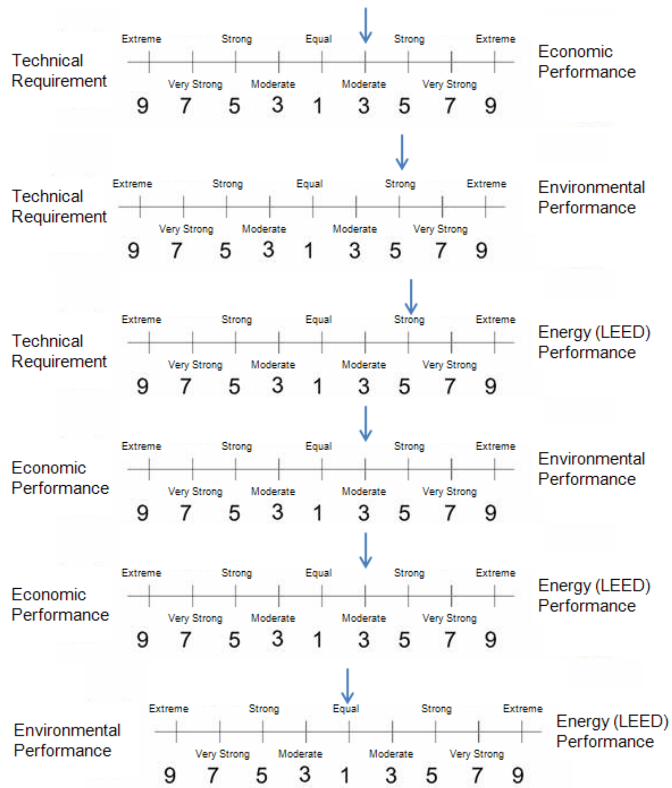


Figure 5-11. Pairwise comparison of performance criteria

Table 5-15 shows a 4 by 4 reciprocal comparison matrix in the criteria layer based on pairwise comparison discussed above. Numbers on the diagonal are all 1. The values in the lower triangular matrix are filled by using the reciprocal values of the upper triangular matrix.

Table 5-15. Comparison matrix for criteria layer

	Technical	Economic	Environmental	LEED Energy
Technical	1	$\frac{1}{3}$	$\frac{1}{5}$	$\frac{1}{5}$
Economic	3	1	$\frac{1}{3}$	$\frac{1}{3}$
Environmental	5	3	1	1
LEED Energy	5	3	1	1

Calculating weightings of performance criteria

The weighting of each performance criteria in the criteria layers then calculated as following,

$$Technical\ Performance\ C1 = \sqrt[4]{c11 \times c12 \times c13 \times c14}$$
$$= \sqrt[4]{(1 \times \tfrac{1}{3} \times \tfrac{1}{5} \times \tfrac{1}{5})} = 0.3398$$
$$Economic\ Performance\ C2 = \sqrt[4]{c21 \times c22 \times c23 \times c24}$$
$$= \sqrt[4]{(3 \times 1 \times \tfrac{1}{5} \times \tfrac{1}{5})} = 0.5886$$
$$Environmental\ Performance\ C3 = \sqrt[4]{c31 \times c32 \times c33 \times c34}$$
$$= \sqrt[4]{(5 \times 3 \times 1 \times 1)} = 1.968$$
$$LEED\ Energy\ Performance\ C4 = \sqrt[4]{c41 \times c42 \times c43 \times c44}$$
$$= \sqrt[4]{(5 \times 3 \times 1 \times 1)} = 1.968$$

The weighting of criteria Wn is,

$$Technical\ Performance\ W1 = \frac{C1}{\sum_{n=1}^{4} Cn} \times 100\% = 6.98\%$$
$$Economic\ Performance\ W2 = \frac{C2}{\sum_{n=1}^{4} Cn} \times 100\% = 12.1\%$$
$$Environmental\ Performance\ W3 = \frac{C3}{\sum_{n=1}^{4} Cn} \times 100\% = 40.46\%$$
$$LEED\ Energy\ Performance\ W4 = \frac{C4}{\sum_{n=1}^{4} Cn} \times 100\% = 40.46\%$$

Consistency check

The maximum Eigen value of the matrix λ_{max} is 3.9145 and the consistency index is $CI = \frac{\lambda max - N}{N-1}$ (N=4), which is 0.0285. The random consistency index (RI) is 0.9 for a 4 by 4 matrix. Then the consistency ratio (CR) is calculated,

$$CR = \frac{CI}{RI} = \frac{0.0285}{0.9} = 0.0317$$

Since CR< 0.1, the matrix is considered consistent.

Sub-criteria Layer

Technical criteria

Pairwise comparison. There are five factors representing the technical performance of a HVAC system. The comparison between these factors is similar with what is done for the performance criteria in the criteria layer as discussed above. A 5 by 5 pairwise comparison matrix is established according to the preference of the decision maker. The pairwise comparison matrix can be expressed in Table 5-16.

Table 5-16. Comparison matrix in technical requirement criteria

$$\begin{array}{l} \\ \text{Full load effectiveness} \\ \text{Part load effectiveness} \\ \text{Reliability} \\ \text{Maintainability} \\ \text{Spatial requirement} \end{array} \begin{array}{c} \text{Full load effectiveness} \quad \text{Part load effectiveness} \quad \text{Reliability} \quad \text{Maintainability} \quad \text{Spatial requirement} \\ \begin{bmatrix} 1 & 1 & 5 & 5 & 7 \\ 1 & 1 & 5 & 5 & 7 \\ \frac{1}{5} & \frac{1}{5} & 1 & 1 & 3 \\ \frac{1}{5} & \frac{1}{5} & 1 & 1 & 3 \\ \frac{1}{7} & \frac{1}{7} & \frac{1}{3} & \frac{1}{3} & 1 \end{bmatrix} \end{array}$$

Weighting calculation. Similar for the weighting calculation for the performance criteria, the weighting of technical factors is calculated,

$$Full\ load\ effectiveness\ W_{T1} = \frac{C1}{\sum_{n=1}^{5} Cn} \times 100\% = 38.89\ \%$$

$$Part\ load\ effectiveness\ W_{T2} = \frac{C2}{\sum_{n=1}^{5} Cn} \times 100\% = \ 38.89\%$$

$$Reliability\ W_{T3} = \frac{C3}{\sum_{n=1}^{5} Cn} \times 100\% = \ 9.06\%$$

$$Maintainability\ W_{T4} = \frac{C4}{\sum_{n=1}^{5} Cn} \times 100\% = 9.06\%$$

$$Spatial\ requirement\ W_{T5} = \frac{C5}{\sum_{n=1}^{5} Cn} \times 100\% = 4.1\%$$

Consistency check. The maximum Eigen value λ_{max} for this matrix is 5.0736, and the consistency index is $CI = \frac{\lambda max - N}{N-1}$ (N=5), which is 0.0184. The random consistency index (RI) is 1.12 for a 5 by 5 matrix. Then the consistency ratio (CR) is calculated,

$$CR = \frac{CI}{RI} = \frac{0.0285}{0.9} = 0.0317$$

Since CR< 0.1, the matrix is considered consistent.

Economic criteria

Weighting. Life cycle costing is the only sub-criteria indicating the economic performance of a HVAC system. So the weighting factor for life cycle cost is 1.

Environmental criteria

Weighting. Life cycle assessment is used to evaluate environmental performance of HVAC systems. The impact method used in LCA analysis is Impact 2002+. It contains four damage categories: human health, climate change, resources, and

Table 5-17. Weighting sets in impact 2002+

Environmental factors	Human health	Climate change	Resources	Ecosystem quality
Weighting	30.1%	35.2%	32.6%	2.1%

ecosystem quality. In this case study, recommended weightings for these categories by the Impact 2002+ method in SimaPro program is used and listed in Table 5-17.

LEED criteria

Weighting. The relative importance or weightings between EAc1 Optimized Energy Performance and EAc4 Enhanced Refrigerant Management depend on the points available in each credit. There are 19 points available for Optimized Energy Performance credit under LEED 2009-NC. And 2 points are obtainable if the refrigerant used in the cooling plant satisfies the requirement in Enhanced Refrigerant Management credit. Thus the weighting between these two factors can be evaluated in specific.

$$Optimized\ Energy\ Performance\ W_{L1} = \frac{19}{19+2} \times 100\% = 90.48\%$$

$$Enhanced\ Refrigerant\ Management\ W_{L2} = \frac{2}{19+2} \times 100\% = 9.52\%$$

Summary of weightings for criteria and sub-criteria

Table 5-15 shows the weighting factors calculated in criteria layer and sub-critieria layer. The summation of the weighting factors in the criteria layer is 1. Similarly, the sum for the sub-criteria under the same criteria is also 1. So the total weighting factors for sub-criteria in the sub-criteria layer should be multiplied by the weighting of the criteria under which the sub-criteria locate. The sum of the total weightings for all sub-criteria is 1. Table 5-15 shows complete weighting results for criteria and sub-criteria. LEED and environmental criteria have the highest weighting among the criteria which are 40.46%. Technical criterion has the lowest weighting (6.98%) based on the preference of the decision makers.

Table 5-18. Weightings for criteria and sub-criteria

Criteria level		Sub-criteria level		Total weighting
Technical	6.98%	Full load effectiveness	38.89%	2.71%
		Part load effectiveness	38.89%	2.71%
		Reliability	9.06%	0.63%
		Maintainability	9.06%	0.63%
		Spatial requirement	4.1%	0.29%
Environmental	40.46%	Ecosystem quality	2.1%	0.85%
		Human health	30.1%	12.18%
		Climate change	35.2%	14.24%
		Resources	32.6%	13.19%
Economical	12.1%	Life cycle cost	100%	12.11%
LEED	40.46%	Optimized energy performance	90.48%	36.61%
		Enhanced refrigerant management	9.52%	3.85%

Alternative Layer

Table 5-18 to Table 5-29 list the performance indicators for three alternatives under the performance sub-criteria.

Economic performance criteria

For economic performance, the performance indicators (PI) are calculated based on equation 4-12. The maximum and minimum PI values are calculated by the performance values and the mean of performance values for all alternatives based on equation 4-7, 4-8, 4-9 mentioned in Chapter 4. The calculated mean value and the standard deviation for performance values are also listed in the table. To note that since the best economic performance is corresponded to the lowest life cycle cost, the reciprocals of the life cycle cost of three alternatives are made before calculating the mean value of alternatives and its standard deviation. Similar situation is also applicable for environmental performance criteria. The lower point means the better environmental performance under that environmental performance category.

Table 5-19. Performance indicators in life cycle cost (μ=2.30E-7, 3σ=1.40E-8)

Alternatives	Life Cycle Cost ($)	Preference Indicator (PI)
Self-contained unit + parallel fan powered VAV + dedicated OA	4,251,937	5.427
Water source heat pump + series fan powered VAV + dedicated OA	4,386,235	4.105
Air-cooled chiller + fan coil units	4,415,848	2.658

Environmental performance

The way for calculating the performance indicators for environmental performance is the same as that for economical performance.

Table 5-20. Performance indicators for human health (μ=0.025, 3σ=3.762E-3)

Alternatives	Result in Human Health (pt)	Preference Indicator (PI)
Self-contained unit + parallel fan powered VAV + dedicated OA	84	6.372
Water source heat pump + series fan powered VAV + dedicated OA	73	3.709
Air-cooled chiller + fan coil units	78	4.919

Table 5-21. Performance indicators for ecosystem quality (μ=1.45, 3σ=0.213)

Alternatives	Result in Ecosystem Quality (pt)	Preference Indicator (PI)
Self-contained unit + parallel fan powered VAV + dedicated OA	5	4.23
Water source heat pump + series fan powered VAV + dedicated OA	5	4.23
Air-cooled chiller + fan coil units	7.5	6.54

Table 5-22. Performance indicators for climate change (μ=0.035, 3σ=4.98E-3)

Alternatives	Result in Climate Change (pt)	Preference Indicator (PI)
Self-contained unit + parallel fan powered VAV + dedicated OA	72	6.17
Water source heat pump + series fan powered VAV + dedicated OA	61.5	5.282
Air-cooled chiller + fan coil units	41	3.548

Table 5-23. Performance indicators for resources (μ=0.022, 3σ=3.237E-3)

Alternatives	Result in Resources (pt)	Preference Indicator (PI)
Self-contained unit + parallel fan powered VAV + dedicated OA	78	6.223
Water source heat pump + series fan powered VAV + dedicated OA	66	5.199
Air-cooled chiller + fan coil units	47	3.578

LEED performance

For LEED and technical performance, the maximum and minimum performance values in each sub-criterion are defined in Chapter 4. Equation 4-12 is used for converting the performance values into the performance indicators for LEED and technical performance criteria.

Table 5-24. Performance indicators for optimized energy performance

Alternatives	Points achievable in Optimized Energy Performance	Preference Indicator (PI)
Self-contained unit + parallel fan powered VAV + dedicated OA	4	3.4
Water source heat pump + series fan powered VAV + dedicated OA	2	1.8
Air-cooled chiller + fan coil units	0	1

Table 5-25. Performance indicators for enhanced refrigerant management

Alternatives	Points achievable in Enhanced Refrigerant Management	Preference Indicator (PI)
Self-contained unit + parallel fan powered VAV + dedicated OA	1	9
Water source heat pump + series fan powered VAV + dedicated OA	1	9
Air-cooled chiller + fan coil units	0	1

Technical performance criteria

Table 5-26. Performance indicators for full load effectiveness

Alternatives	Full load effectiveness	Preference Indicator (PI)
Self-contained unit + parallel fan powered VAV + dedicated OA	3	6.333
Water source heat pump + series fan powered VAV + dedicated OA	3	6.333
Air-cooled chiller + fan coil units	3	6.333

Table 5-27. Performance indicators for part load effectiveness

Alternatives	Part load effectiveness	Preference Indicator (PI)
Self-contained unit + parallel fan powered VAV + dedicated OA	4	9
Water source heat pump + series fan powered VAV + dedicated OA	3	6.333
Air-cooled chiller + fan coil units	1	1

Table 5-28. Performance indicators for reliability

Alternatives	Reliability	Preference Indicator (PI)
Self-contained unit + parallel fan powered VAV + dedicated OA	4	9
Water source heat pump + series fan powered VAV + dedicated OA	4	9
Air-cooled chiller + fan coil units	2	3.667

Table 5-29. Performance indicators for maintainability

Alternatives	Maintainability	Preference Indicator (PI)
Self-contained unit + parallel fan powered VAV + dedicated OA	2	3.667
Water source heat pump + series fan powered VAV + dedicated OA	1	1
Air-cooled chiller + fan coil units	3	6.333

Results

The integrated score for an alternative is the sum of the product of the weighting for the sub-criterion and the performance indicator under this sub-criterion. There are 12 sub-criteria. The alternative with the highest integrated score is the optimal system based both on the system performance and the preference of the decision makers.

$$Integrated\ Score = \sum_{i=1}^{12} W_i \times PI_i$$

Table 5-30. Performance indicators for spatial requirement

Alternatives	Spatial Requirement	Preference Indicator (PI)
Self-contained unit + parallel fan powered VAV + dedicated OA	2	3.667
Water source heat pump + series fan powered VAV + dedicated OA	2	3.667
Air-cooled chiller + fan coil units	3	6.333

Where, W_i is the weighting of the sub-criterion

PI_i is the performance indicator under that sub-criteria for an alternative

The integrated scores for three alternatives interested are shown in Table 5-28. Alternative 1 Self-contained unit + parallel fan powered VAV + dedicated OA has the highest score with 5.034, thus it is the best choice among all the alternatives.

Table 5-31. Integrated score for three alternatives

Alternatives	Integrated Score
Self-contained unit + parallel fan powered VAV + dedicated OA	5.034
Water source heat pump + series fan powered VAV + dedicated OA	3.943
Air-cooled chiller + fan coil units	3.213

Sensitivity Analysis

Fuel Mix of Electricity

The emissions from burning fossil fuel for electricity and natural gas for the HVAC system during its operation are the main sources for environmental concerns. The major emissions include CO2, SO2, NOx, CO, and particles. These emissions contribute to various environmental issues: global warming, ozone depletion, acidification, eutrophication, land use, human toxicity, fossil fuel depletion, etc. The energy mix for electricity in different states varies and the differences may results in different interpretation for the environmental performance of alternatives.

The cleanness of the sources for electricity plays an important role in evaluating the environmental performance of the system. The energy mix of electricity typically constitutes of coal, natural gas, nuclear, oil and hydropower. The more fossil fuel (coal, oil and natural gas) involved in the production of the electricity, the worse environmental problems it may cause. The burning of coal at the power plant may cause problems in global warming, ecotoxicity, resources depletion, land use and respiratory/carcinogen problems for human health. The burning of natural gas for electricity mainly causes human health problems, climate change and resources depletion. The use of nuclear for electricity contributes most environmental effects in ionizing radiation, ozone layer depletion and resources depletion. And burning of oil mostly contributes to the ozone depletion. There is no significant environmental problem by utilizing hydropower for electricity production. Because of the various fuel mixes for electricity in different states, the environmental contribution for the same system with the identical electricity consumption may very differently.

SimaPro7 is the software to model the life cycle impacts of the system. Franklin USA 98 database which reflects the average data in the USA is used for energy inputs and outputs. The Impact 2002+ is the life cycle impact assessment method.

Table 5-32 shows the fuel mix for electricity in five regions in the United States from Energy Information Administration (EIA) (Energy Information Administration, 2007) (Edision Electric Institute, 2010). 97.7% of the electricity is produced from coal in West Virginia. South Carolina has 51.1% of electricity produced from nuclear. The electricity production in Washington is most clean, which 78.1% is produced from hydropower and other non-hydro renewable.

Table 5-32. Fuel mix for electricity in five regions of the United States

	Coal (%)	Nuclear (%)	Natural Gas (%)	Oil (%)	Hydro and Non-hydro renewable and others* (%)
Washington	6	8.6	7.3	0	78.1
West Virginia	97.7	0	0.4	0.2	1.7
South Carolina	39.8	51.1	6.1	0.3	2.8
Wisconsin	64.9	19.9	9.1	1.4	4.8
Florida	29.1	14	43	10.2	3.6

*"Non-Hydro Renewables and Other" includes generation from solar, wind, geothermal, biomass (agricultural waste, municipal solid waste, landfill gas recovery, wood, pitch), hydrogen, batteries, chemicals, non-wood waste, purchased steam, sulfur, and miscellaneous technologies.

Figure 5-12 and 5-13 shows the midpoint environmental impact and the damage assessment for producing 1kWh electricity in five states of the United States. Electricity in Florida causes the highest impact in human health because of the high composition of natural gas (43%) in electricity production. Because of the large percentage use of coal, electricity production for West Virginia keeps high in all the impact categories. Environmental performances in the four damage categories are further normalize and weighted to a single score in Figure 5-14. The lower score indicates better environmental performance. Electricity production in Washington has the lowest environmental impact among the five regions as a result of the high level use of hydropower.

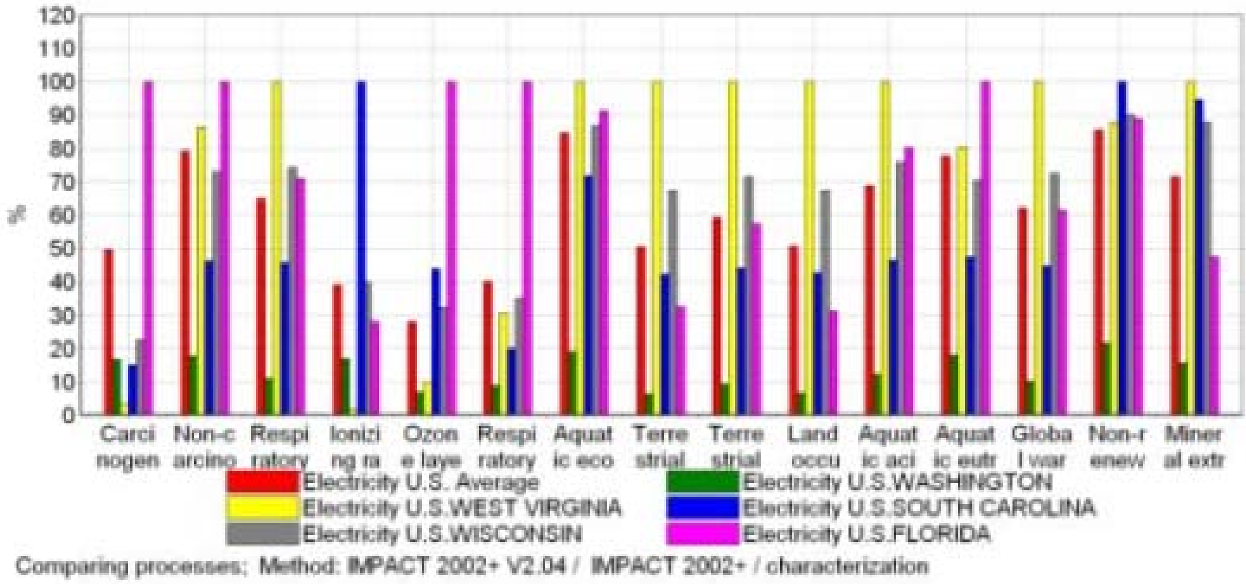


Figure 5-12. Midpoint impact of fuel mix for 1kWh electricity in five states of the United States

To evaluate the sensitivity of the model on the energy mix in a different region, another set of calculation is conducted assuming the 6-story office building by using the energy mix of electricity in Washington State since it has the maximum percentage use of hydro power and other renewable sources. Because only energy mix effect is considered in the sensitivity analysis, changes in weather and utility cost for a different region is excluded.

To evaluate the sensitivity of energy mix to the decision making model, energy mix scenario in Washington is chosen since it has the lowest composition in coal and oil and highest composition in hydropower for electricity production. If the result shows the model is not sensitive on the Washington energy mix scenario, it has little chance to be sensitive on the energy mix scenario for the states in the United States. Figure 5-15 shows the four damage impacts of three alternatives with the energy mix in Washington State. And Figure 5-16 shows the overall score of environmental impacts among three alternatives. Alternative 3 Chilled Water VAV System has the highest environmental impact in the four categories compared with alternative 2 which has the highest impact with Atlanta energy mix scenario. Alternative 1 still has the lowest environmental impact among all three alternatives.

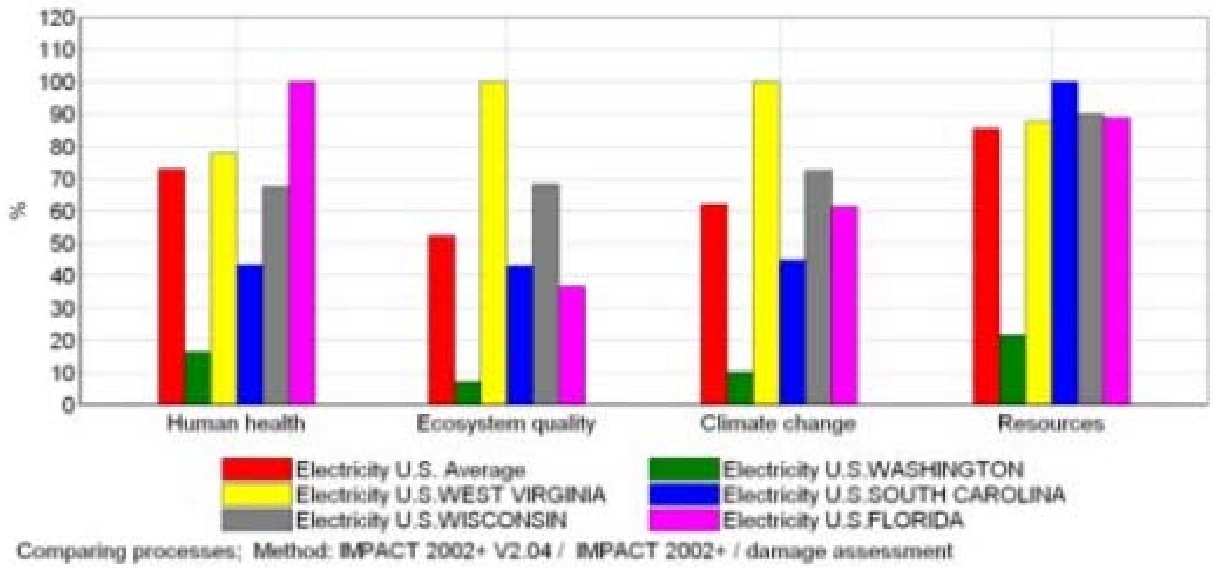


Figure 5-13. Damage assessment of electricity mix for 1kWh electricity in five states of the United States.

Table 5-30 shows the overall score with Washington energy mix scenario. Although the order of environmental performances changes between Alternative 2 and Alternative 3, the ranking order for the overall performance for three alternatives does not change compared with the Atlanta energy mix scenario in the case study. The result indicates that energy mixes in different regions are not sensitive for the case study even with the most possible mix difference between the two states.

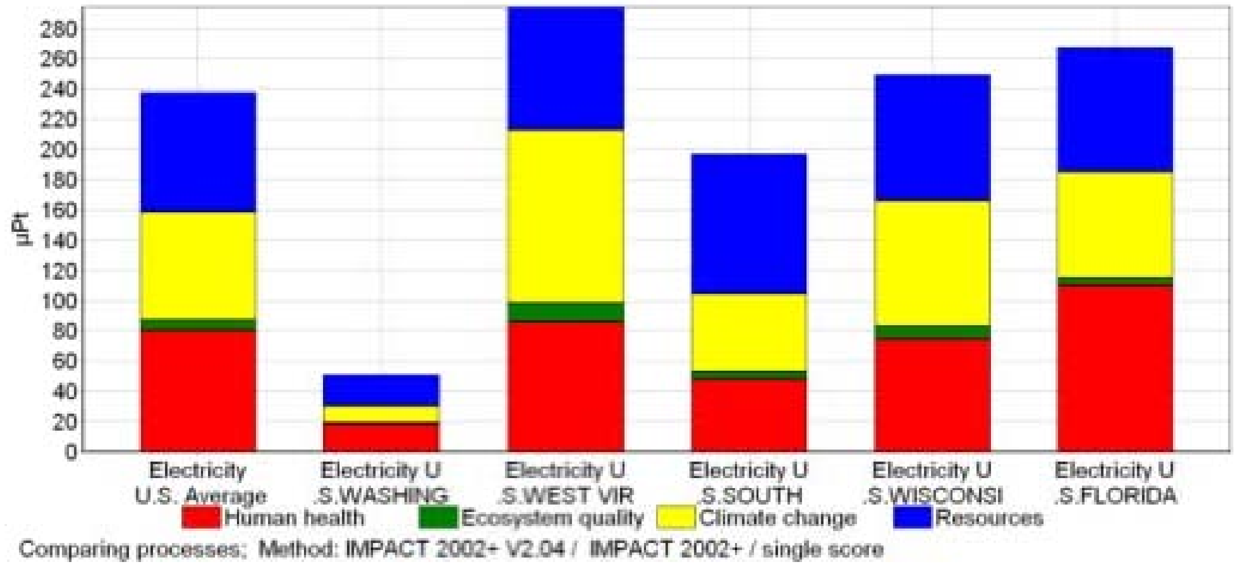


Figure 5-14. Single score for the environmental impact of electricity mix for 1kWh electricity in five states of the United States

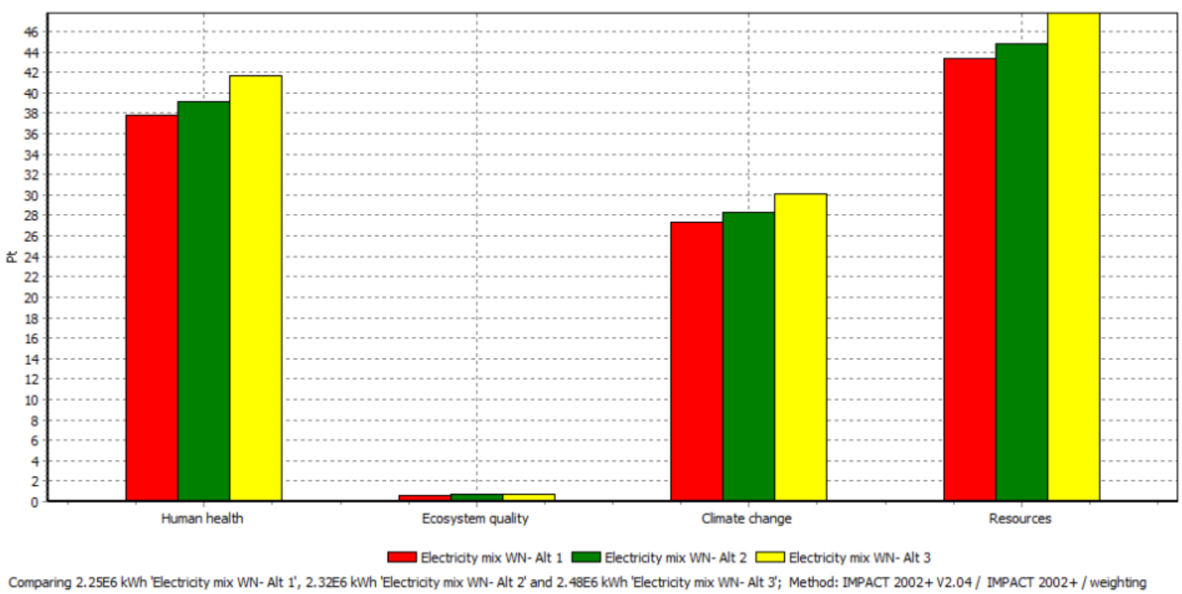


Figure 5-15. Damage impacts for alternatives with energy mix in Washington

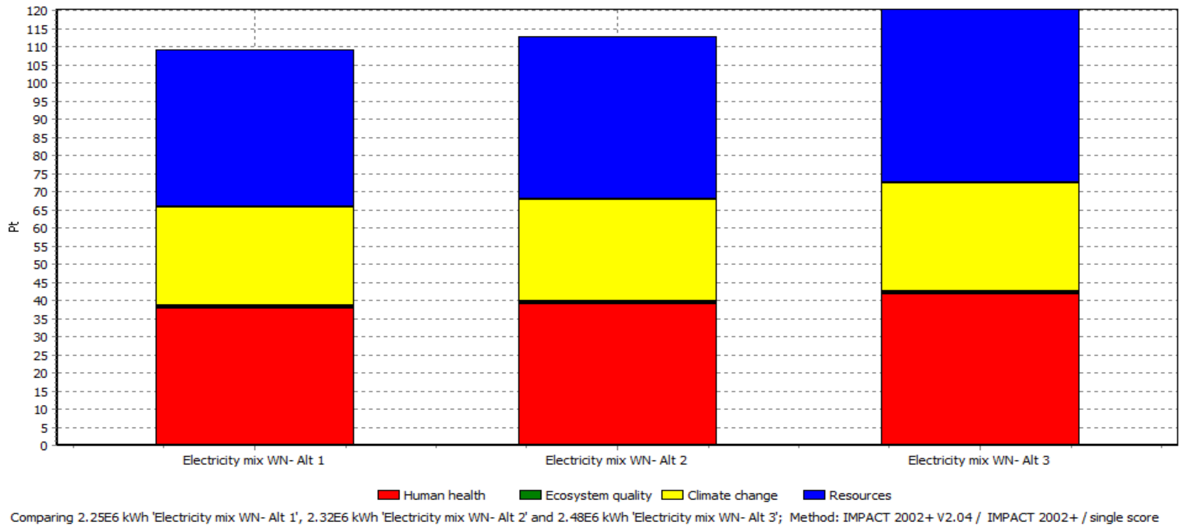


Figure 5-16. Overall scores for alternatives with energy mix in Washington

Table 5-30. Integrated score with Washington energy mix scenario

Alternatives	Integrated Score	Original Score
Self-contained unit + parallel fan powered VAV + dedicated OA	5.375	5.034
Water source heat pump + series fan powered VAV + dedicated OA	4.228	3.943
Air-cooled chiller + fan coil units	2.587	3.213

Weighting Effect

The preferences of the decision-makers have impact on the results since the preference weightings which are decided by the pairwise matrix developed by the preference of the decision-makers are part of overall performance score calculations.

In order to identify the weighting effect in the criteria layer, assume the weighting for one of the four criteria equal to x. And the total weightings of the other three are all equal to 1-x. The ratio among the other three criteria is kept the same. The relationships between the weighting of each criterion and the overall score of each criterion are shown form Figure 5-17 to Figure 5-20. OS means the overall score for an alternative.

Figure 5-17 shows that overall scores for all three alternatives are increased with the weighting of the technical requirement, and the ranking order for overall scores does not change with the increased weighting of technical requirement. And the overall score also increases with the increase of the weighting of the technical requirement for all three alternatives. The slopes of three alternatives are almost the same.

Figure 5-18 shows that the ranking order for overall scores does not change with the increased weighting of economical performance. And the overall score also increases with the increase of the weighting of the technical requirement for all three alternatives.

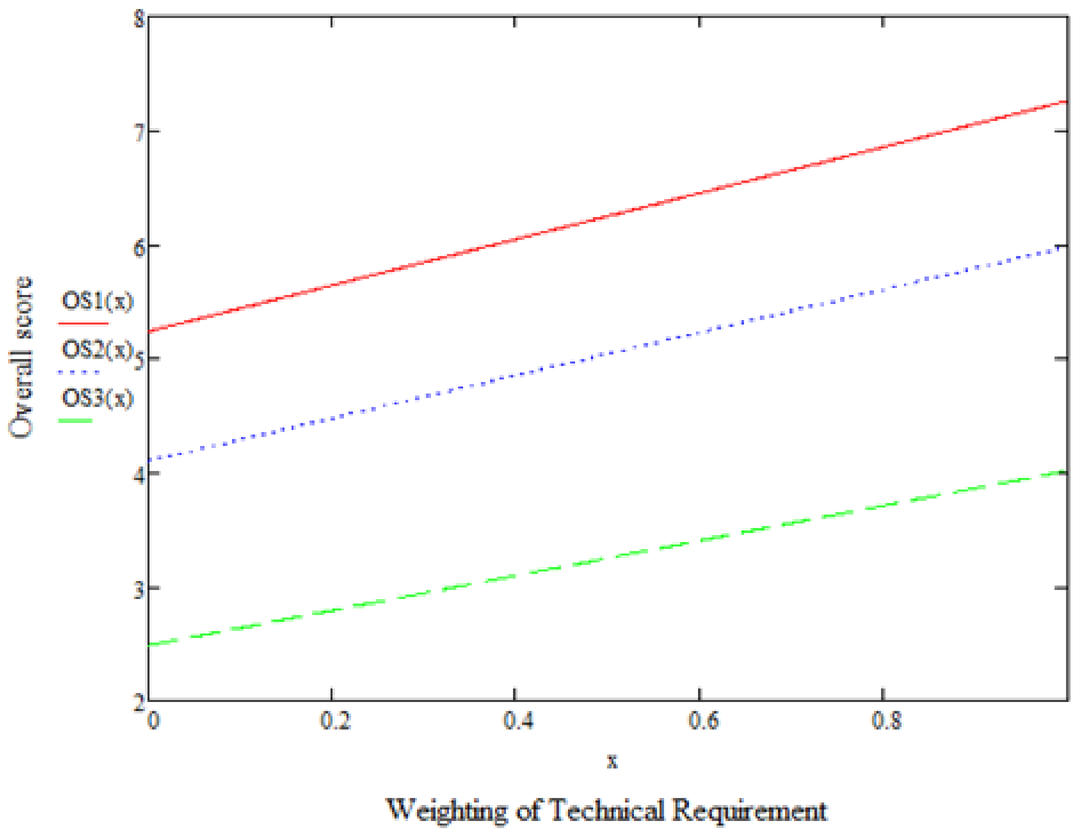


Figure 5-17. Sensitivity analysis for the weighting of technical requirement

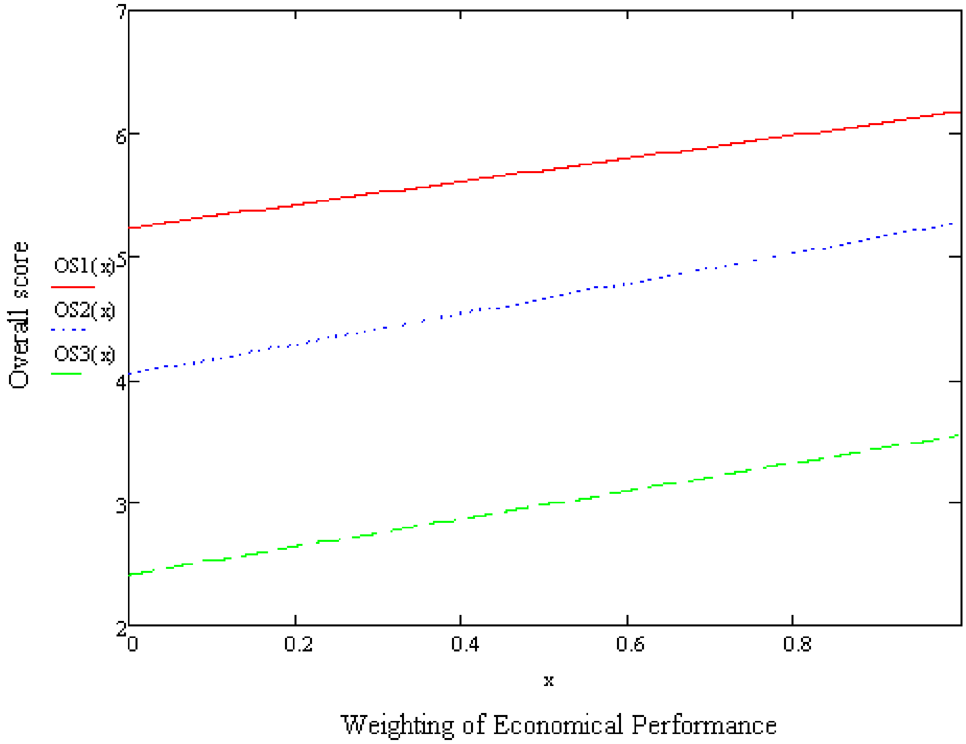


Figure 5-18. Sensitivity analysis for the weighting of economical performance

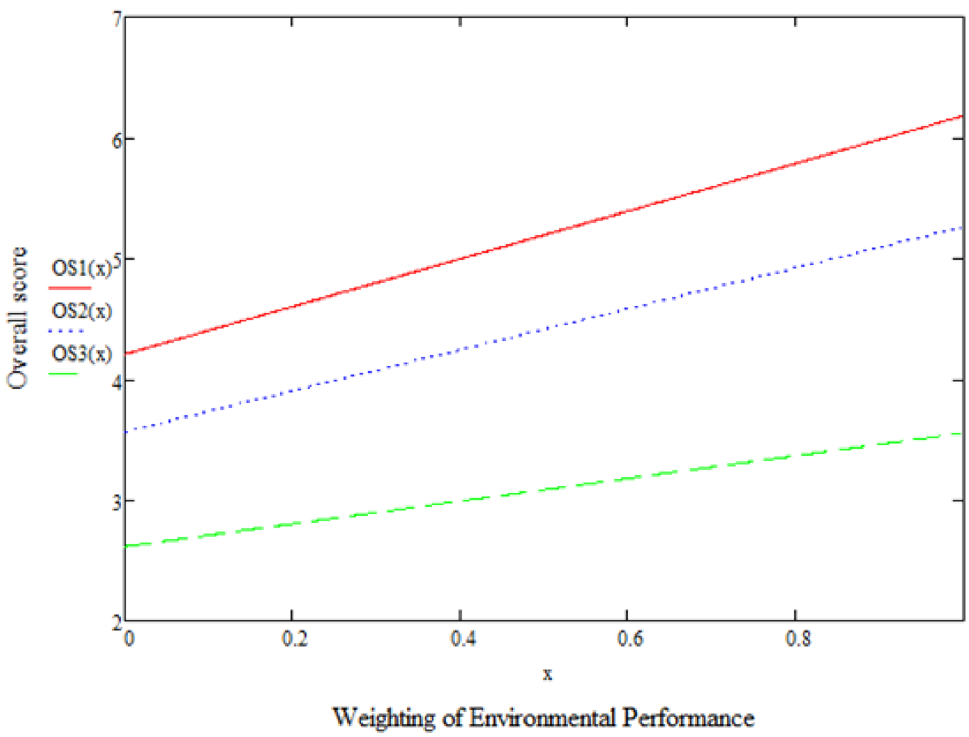


Figure 5-19. Sensitivity analysis for the weighting of environmental performance

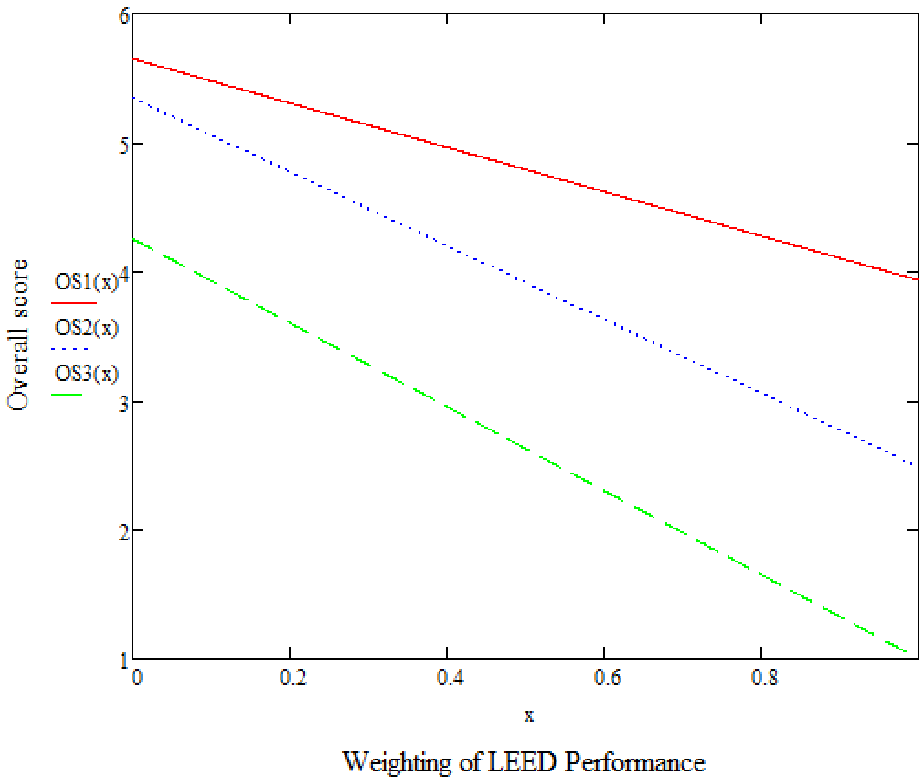


Figure 5-20. Sensitivity analysis for the weighting of LEED performance

The overall scores of all three alternatives are increased with the increase of the weighting of the environmental performance as shown in Figure 5-19. The ranking order of the overall scores does not change with the increase of the weighting of the environmental performance. The magnitude of the slope is decided by the difference in value between the environmental performance and the other three performance criteria. The larger difference is, the steeper slope of the weightings will be.

The overall scores of all three alternatives are decreased with the weighting of LEED performance as shown in Figure 5-20. And the ranking order of overall scores does not change with the increase of the weighting of LEED performance.

CHAPTER 6
THOUGHTS ON SOFTWARE DEVELOPMENT

The integrated decision-making model provides a comprehensive and systemic way to evaluate HVAC systems. It combines the performance data of alternatives and quantized preferences of the decision maker to find the optimal HVAC system. However, the calculation of the performance indicators and the AHP decision-making model is complicated and heavy. In addition, in the real world, there might have more than 3 alternatives exist to choose from. Sometimes the decision makers even don't have a detailed preference on the system other than some general ideas about the system or performance preferred.

To facilitate the decision-making process and reduce the complexity of model inputs to make it easier to use, 5 modules are created for software development: sizing module, equipment and system module, energy simulation module, performance module and decision-making module. The inputs of modules include the information of the building, general preferences on performance criteria and HVAC systems from the decision makers, and design data from the consultant engineers. The calculation of these modules can also be integrated with some of popular building calculation software in industry, for example, the load calculation software, Auto CAD, energy simulation software, and economic life cycle cost software. Table 6-1 summarizes software used in the case study and their alternatives. Other possible software or database needed for building up the entire decision-making module in the future is also listed. Software which can meet the requirement of analysis is not limited to what are listed in the Table. The structures and inputs/outputs of five module blocks are also discuss in details in the following sections.

Table 6-1. Summarization of software used or needed for the decision-making modules and their alternatives

Modules	Software used in the dissertation	Alternatives	Other possible software for modules
Sizing module	Trace Load 700	CHVAC 6, HAP 4.40.0.61, eQUEST3.63 Energy Plus 5.0.0 DOE-2.2 Energy Pro 4.4	Auto CAD, Revit
Equipment and system module	N/A	N/A	Performance data base is needed to be developed
Energy simulation module	Trace 700	DOE-2.2, eQUEST3.63, Energy Plus 5.0.0 Energy-10 HAP 4.40.0.61,	None
Performance module	SimaPro 7 BLCC 5	GaBi 4.3	None
Decision-making module	Self-coded	Expert Choice 11.5	None

Sizing Module

The sizing module is the first module in the model and the basis for generating the appropriate HVAC system alternatives. It calculates the size of air systems and heating and cooling equipment which can serve the building heating and cooling demand appropriately. In order to size the air system and the heating and cooling equipment, load calculation is conducted firstly. Figure 6-1 shows the structure of the sizing module. The inputs for load calculation include the building information (location, type, weather data, zone definition and construction data of the building) and design requirement for comfortable indoor environment (internal load, air flow requirement, thermostat, and schedules). Design cooling load and design heating load can be calculated from the load calculation and they are combined with the air system type, dedicated outdoor air system (if applicable), general fan size to get the air volume required for supply air, outdoor air, return air and exhaust air. The equipment is sized based on the air volume required for the air system and the input for equipment type and general pump sizes.

Equipment and System Module

Equipment and system module selects the top three system and equipment candidates as the alternatives for further performance evaluation. This step greatly minimizes the calculation load and improves the efficiency of the software. Figure 6-2 shows the structure of the equipment and system module. A large general database about information of heating and cooling equipment and air systems for major manufacture brands in the industry are embedded in the module. The general database contains sizes, spatial requirement, running conditions of various air systems and equipment from major HVAC manufacture brands.

With the inputs of air system and equipment sizes, brand preference and the spatial requirement of the building, some initial candidates are selected to enter the performance database which contains more detailed information about the performance data for the systems and equipment. These performance data include the technical performance (full load effectiveness, part load effectiveness, maintainability, reliability, and spatial requirement), economic cost (initial cost, maintenance cost, replacement cost), environmental data (material, transportation), refrigerant management and brands. After the internal initial comparison based on the performance data, Top three candidates are selected with the best performances in technical, environmental, economical aspects. The three alternatives are further evaluated in the following energy simulation module, performance module and decision-making module to conclude the optimal HVAC system for the building. And technical performance data of three alternatives from the performance database can be used for the evaluation under technical requirement criteria of the decision-making model.

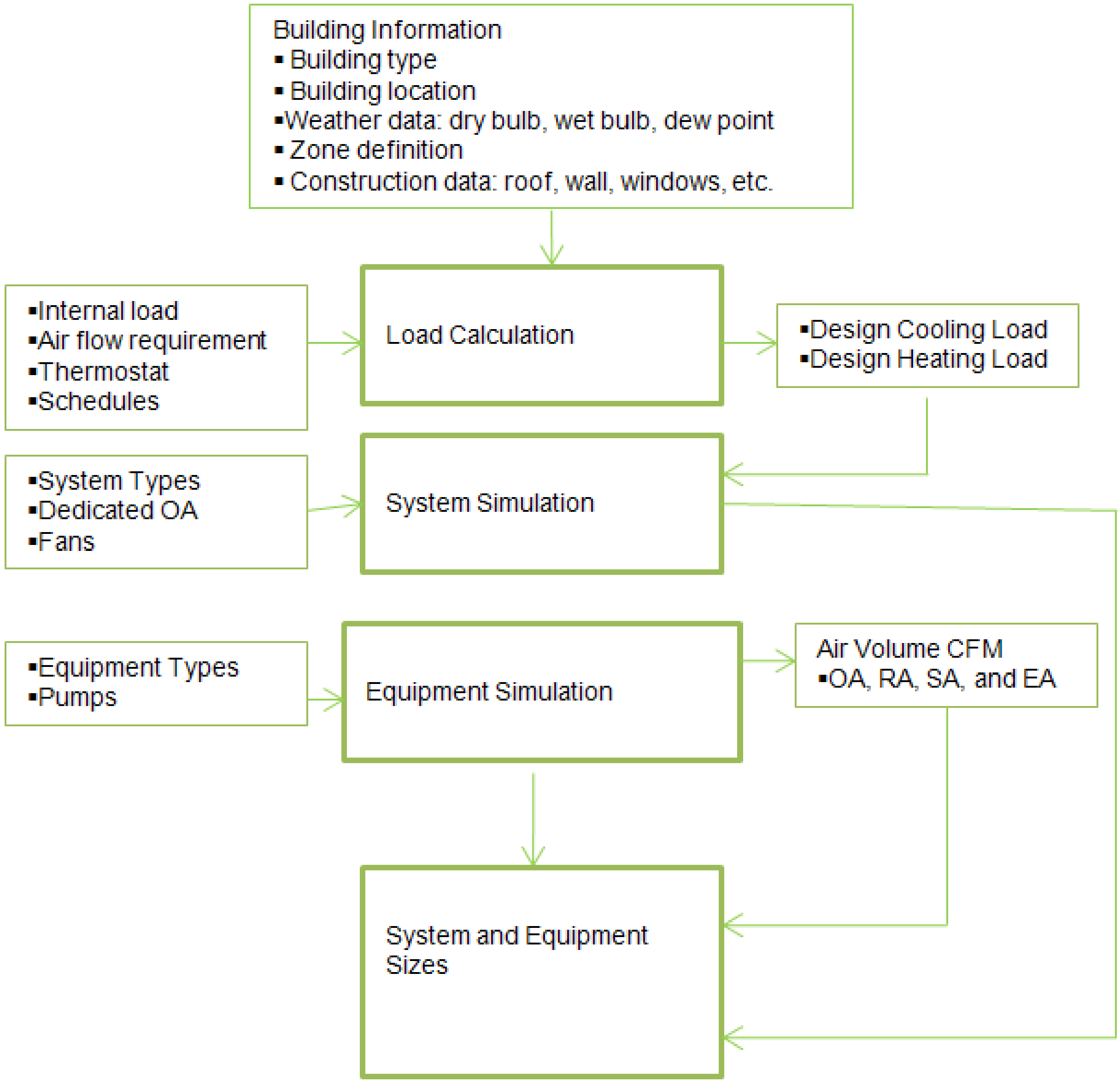


Figure 6-1. Structure of the sizing module

Notice that since the systems and cooling and heating equipment data in the general and performance database are from major HVAC manufactures, the annual or regular update of the system and equipment database is recommended.

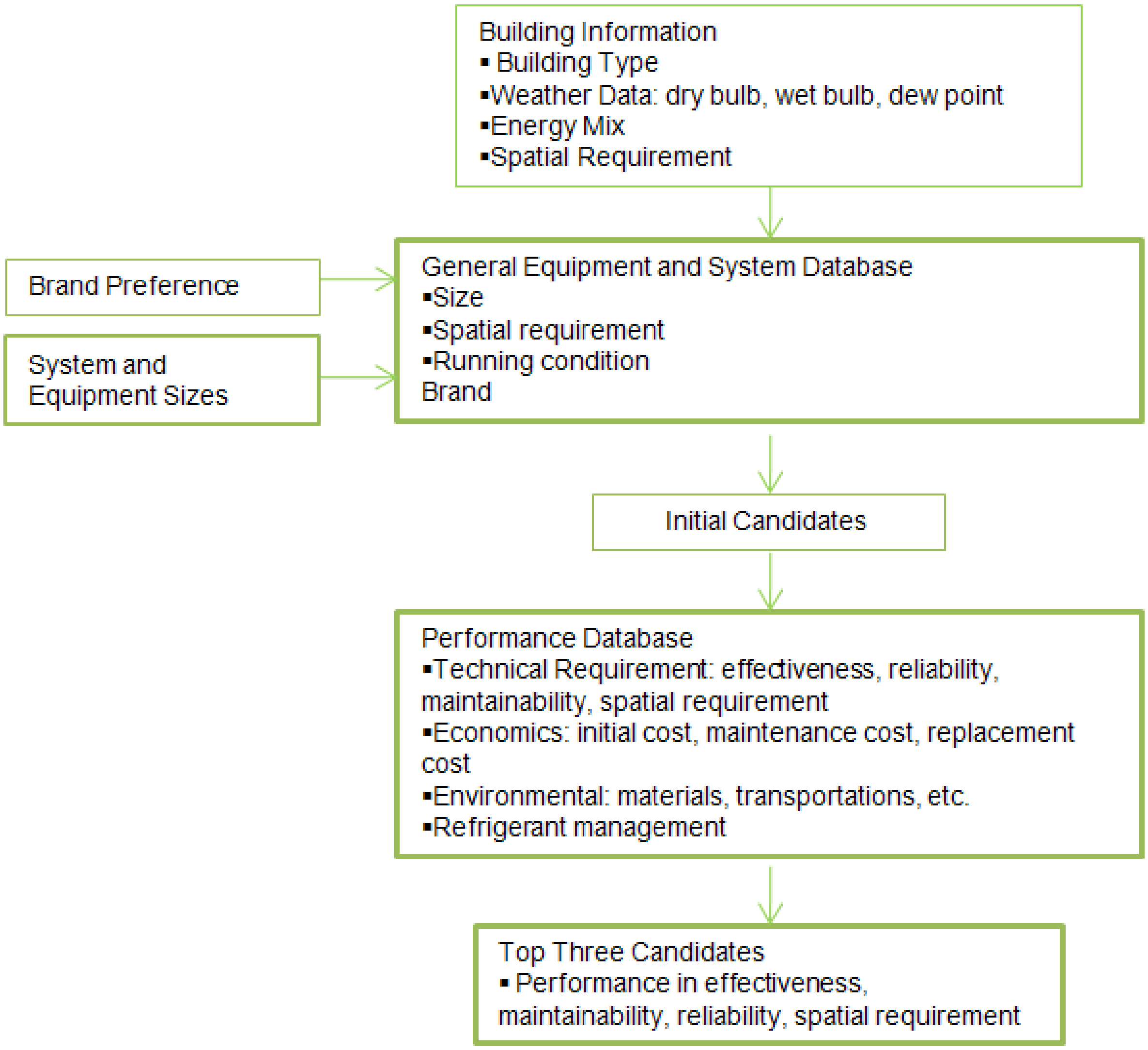


Figure 6-2. Equipment and system module

Energy Simulation Module

Energy simulation module is the key for evaluating the environmental performance, economic performance and LEED performance in the criteria and sub-criteria layer of AHP decision-making model. Figure 6-3 shows the structure of energy simulation module. The annual energy consumption of the system and equipment which meet the requirement of ASHRAE 90.1 Appendix G baseline case are also simulated. It will be compared with annual energy consumption of the other three alternatives in order to find energy cost savings of alternatives for the achievable points in LEED EAc1 Optimized Energy Performance.

The inputs of the energy simulation module include the system and equipment information (energy rate of pumps, fans, and equipment) of the three alternatives and ASHRAE 90.1 Appendix G Baseline Case. The outputs for the energy and consumption module are the annual energy consumption and energy demand of the ASHRAE Baseline Case and three alternatives.

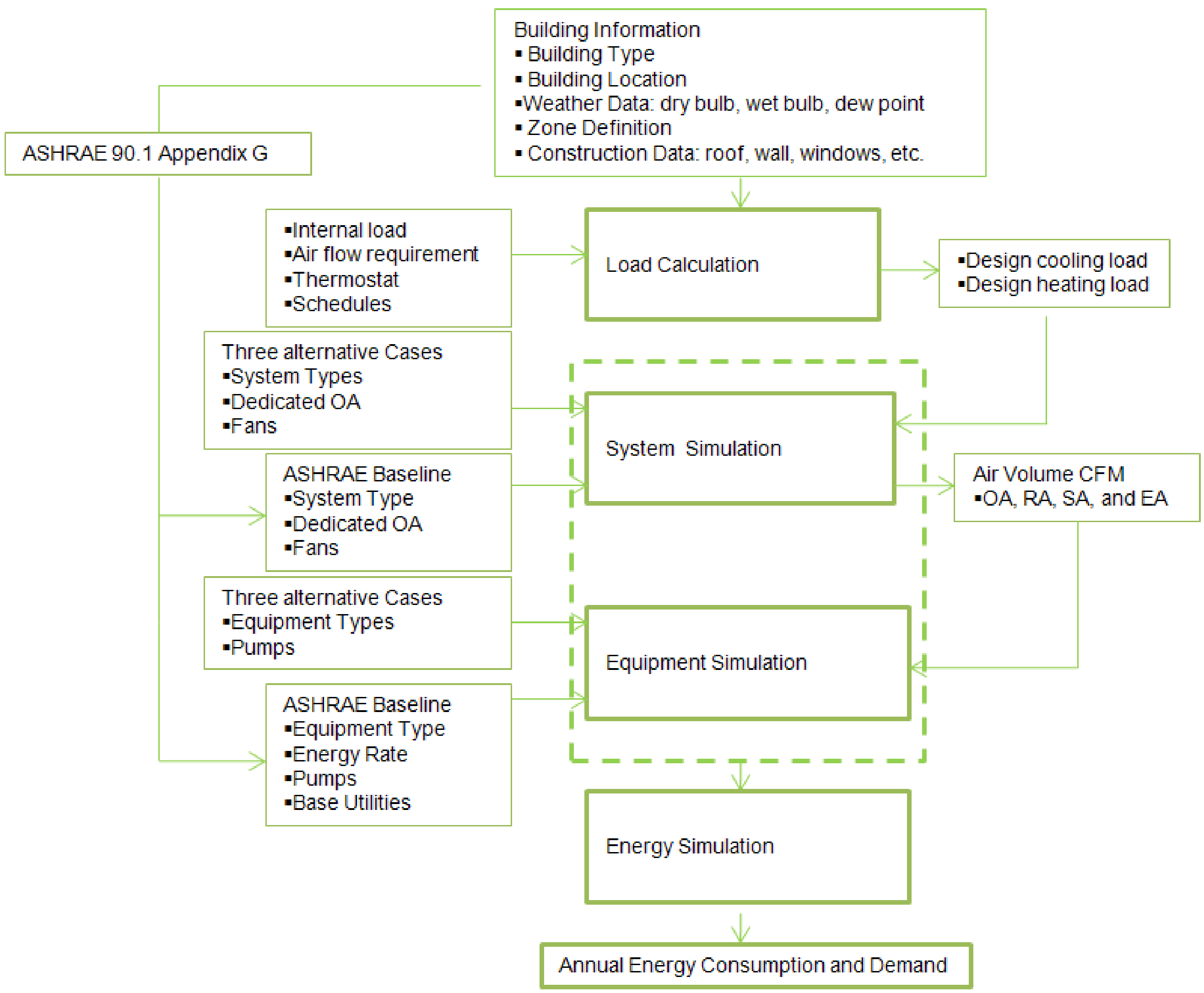


Figure 6-3. Structure of energy simulation model

Performance Module

Figure 6-4 shows the structure of the performance module. As discussed above, the annual energy consumption and demand from the energy simulation module serve several performance criteria in the performance module. The utility rate structure for electricity consumption, electricity demand, water charge and other charges from the utility companies at the building location are imported into the module for calculating the annual energy cost for alternatives and ASHRAE Baseline Case.

The results combine with the economic performance data (initial cost, maintenance cost and replacement cost) from the performance database and the annual energy cost of alternatives to get the life cycle cost of alternatives. The annual energy costs of alternatives are compared with the ASHRAE Baseline Case to get energy cost savings for the achievable points in LEED EAc1 Optimized Energy Performance point structure.

Annual energy consumption data are also imported into Inventory Database with the electricity fuel mix of the region where the building is located and the performance database (materials, refrigerant, and transportation from the origin) to calculate the emissions of alternatives during life cycle period. The emissions are further evaluated by the impact assessment method chosen to get final results in Human Health, Global Warming, Energy Resources, and Ecosystem Quality of Life Cycle Assessment categories.

Technical Performance of alternatives and the points achievable in LEED EAcr4 Advanced Refrigerant Management credit are available from the performance database in the system and equipment module.

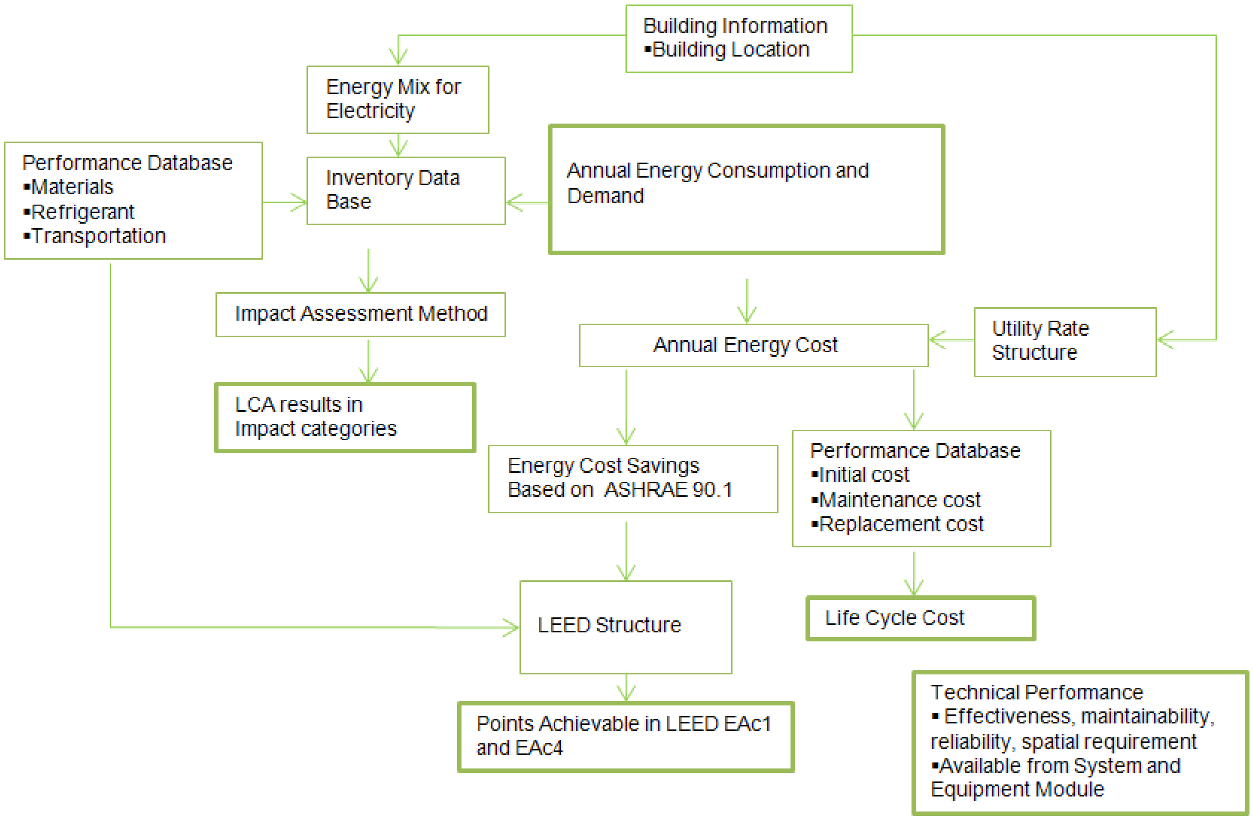


Figure 6-4. Structure of performance model

Decision Making Module

There are five steps include in the decision-making module. The goal layer defines the goal and scope of the module. Figure 6-5 shows the structure of the performance module. Pairwise comparisons in criteria or sub-criteria are made based on the preference feedback from the decision makers and the according pairwise importance matrix for each criterion is formed. With the satisfactory results from consistency check, the weightings for criteria and sub-criteria are calculated and applied to the criteria layer and sub-criteria layer as inputs for the alternative layer.

Performance results from the performance module (including LCA results in impact categories, points achievable in LEED EAc1 and EAc4, life cycle cost, and technical performance) are the inputs for calculating the performance indicators in the alternative layer. Then the performance indicators are combined with the weighting for each performance sub-criteria to finally calculate the integrated performance ranking of alternatives. The alternative with the highest integrated score is ranked top which indicates that HVAC system is the optimal system based on the performance results and the preference of the decision makers.

Figure 6-6 shows the whole picture of the entire model structures and the connections between modules.

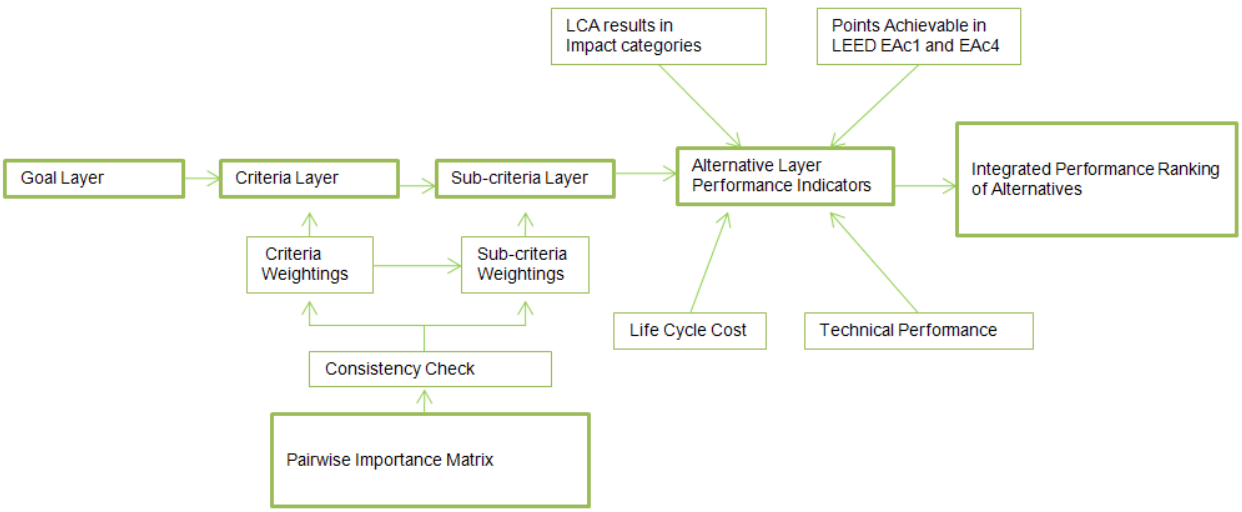


Figure 6-5. Structure of decision-making model

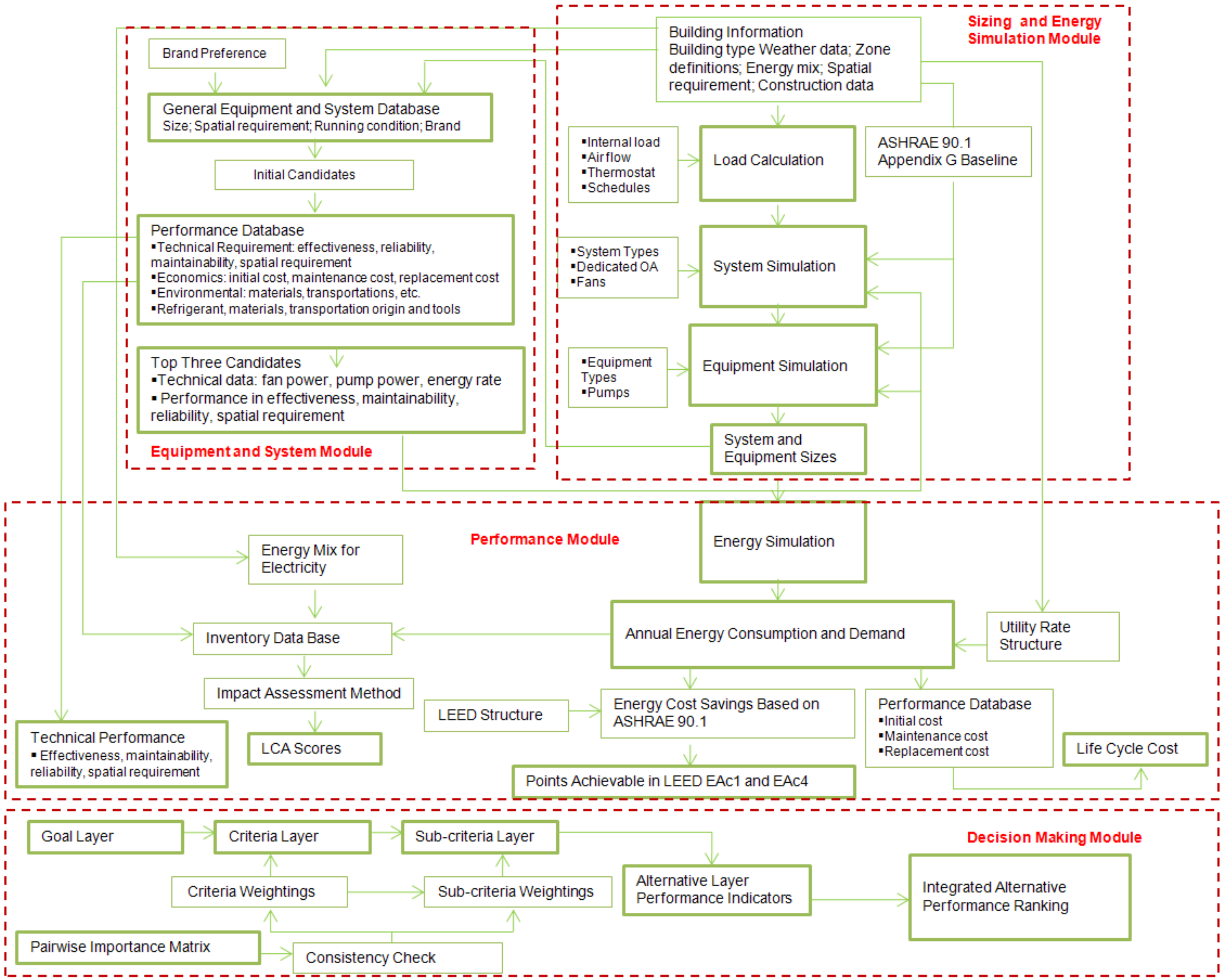


Figure 6-6. Overall diagram of the entire decision-making model structure

CHAPTER 7
CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The goal for this dissertation is to develop an integrated decision making model for selecting HVAC system based on multiple performance criteria including the technical performance, economic performance, environmental performance, LEED performance as well as the preferences of decision makers. There is no research conducted before which systematically integrates the overall objective performance of HVAC systems with people's subjective preference together when make a selection. This dissertation offers the decision makers a comprehensive view of the performance of HVAC systems and also a way to put their preferences and realistic condition into the decision-making process.

In addition, the environmental performance of HVAC systems is used to be overlooked through the industrial practice and there is very little research on that. This dissertation is inspired by the rising concern of environmental protection and the introduction of life cycle assessment thinking into the performance evaluation helps decision makers to make a decision which is responsible to the environment.

The introduction of the Performance Indicator (PI) provides an innovative way to measure the performance of alternatives among general candidates with a unitless number which avoids the addition of performance values in different units from the original AHP model.

The case study conducted in Chapter 5 for a 6-story office building located in Atlanta, GA indicates the self-contained variable air volume system is the optimal system among all the three alternatives based on its multiple performances as well as the preference of the decision-makers on performance criteria.

The energy mix in different states does not have significant effect on the final ranking order of overall performance in this case study. However, the regional effects including weather condition, utility cost should still be considered. With the certain performance values of all alternatives, the preference weightings put on performance criteria are important to the final results. With different weightings assigned to the performance criteria, the ranking for alternatives may vary. The overall score of an alternative may increase or decrease with the weighting increase of a performance criterion, depending on the performance values under that performance criterion compared with the values of other criteria. When the ranking order of alternatives for a specific performance criterion is not consistent with the ranking order of the overall performance, the ranking order of overall performance may be changed with the increased weighting of that specific criterion.

Recommendations for Future Work

This dissertation does not address the interaction between the performance criteria. Some of the performance criteria use the same performance value as part of their inputs and it may contribute to the double counting on the final performance results. One suggestion is to put all the performance criteria, which partially sharing the same performance value under the same umbrella of a parent node in the AHP decision making structure and let them share the total weighting of that parent they are subject to.

Another suggestion for selecting the appropriate system alternatives is to cooperate with the manufactures, ASHARE or the related and available resources to build a powerful and comprehensive performance database for HVAC systems for the easy access to the performance data especially on the material composition of equipment. As long as the performance database is big enough, appropriate candidates can be generated as the alternatives for the decision making process. For calculating the Performance Indicators (PI) by using normal distribution, a fully developed decision making system would also have the ability to calculate the PI values of candidate systems with a comprehensive larger database.

To facilitate the decision-making process and reduce the complexity of model inputs to make it easier to use, 5 modules are created for software development in Chapter 6 Thoughts for Software Development. The modules include sizing module, equipment and system module, energy simulation module, performance module and decision-making module. The inputs of modules include the information of the building, general preferences on performance criteria and HVAC systems from the decision makers, and design data from the consultant engineers. Software developers can use these five modules to develop comprehensive HVAC system selection software for public use. And the program for the AHP HVAC decision-making model has been also coded and attached in the appendix for the ease of programming and use.

APPENDIX A
ENERGY SIMULATION RESULTS

PROJECT INFORMATION

Location	Atlanta, GA
Building owner	
Program user	
Company	
Comments	

TRACE® 700 version	6.2.4	
Location	Atlanta, GA	
Latitude	33.0	deg
Longitude	84.0	deg
Time Zone	6	
Elevation	1,005	ft
Barometric pressure	28.8	in. Hg
Air density	0.0731	lb/cu ft
Air specific heat	0.2444	Btu/lb·°F
Density-specific heat product	1.0727	Btu/h·cfm·°F
Latent heat factor	4,721.8	Btu·min/h·cu ft
Enthalpy factor	4.3883	lb·min/hr·cu ft
Summer design dry bulb	96	°F
Summer design wet bulb	73	°F
Winter design dry bulb	22	°F
Summer clearness number	0.90	
Winter clearness number	0.90	
Summer ground reflectance	0.20	
Winter ground reflectance	0.20	
Carbon Dioxide Level	400	ppm
Design simulation period	January - December	
Cooling load methodology	RTS (Heat Balance)	
Heating load methodology	UATD	

TRANE

TRACE 700 comprehensive building analysis software from Trane

System Checksums

1st fl

Parallel Fan-Powered VAV

COOLING COIL PEAK / CLG SPACE PEAK

Cooling Coil Peak — Peaked at Time: Mo/Hr: 8 / 16; Outside Air: OADB/WB/HR: 92 / 73 / 99

Clg Space Peak — Mo/Hr: 6 / 16; OADB: 96

	Space Sens. + Lat. Btu/h	Plenum Sens. + Lat Btu/h	Net Total Btu/h	Percent Of Total (%)	Space Sensible Btu/h	Percent Of Total (%)
Envelope Loads						
Skylite Solar	0	0	0	0	0	0
Skylite Cond	0	0	0	0	0	0
Roof Cond	0	0	0	0	0	0
Glass Solar	63,925	0	63,925	13	65,027	20
Glass/Door Cond	25,634	0	25,634	5	29,128	9
Wall Cond	6,567	6,454	13,020	3	7,004	2
Partition/Door	0		0	0	0	0
Floor	0		0	0	0	0
Adjacent Floor	0	0	0	0	0	0
Infiltration	0		0	0	0	0
Sub Total ==>	96,125	6,454	102,579	20	101,159	31
Internal Loads						
Lights	74,569	18,642	93,211	19	74,569	23
People	65,061	0	65,061	13	36,145	11
Misc	104,293	0	104,293	21	104,293	32
Sub Total ==>	243,923	18,642	262,566	52	215,007	66
Ceiling Load	8,332	-8,332	0	0	8,385	3
Ventilation Load	0	0	113,213	22	0	0
Adj Air Trans Heat	0		0	0	0	0
Dehumid. Ov Sizing			0	0		
Ov/Undr Sizing	0		0	0	0	0
Exhaust Heat		-2,900	-2,900	-1		
Sup. Fan Heat			27,943	6		
Ret. Fan Heat		0	0	0		
Duct Heat Pkup		0	0	0		
Underflr Sup Ht Pkup			0	0		
Supply Air Leakage		0	0	0		
Grand Total ==>	348,380	13,864	503,400	100.00	324,551	100.00

HEATING COIL PEAK

Mo/Hr: Heating Design; OADB: 22

	Space Peak Space Sens Btu/h	Coil Peak Tot Sens Btu/h	Percent Of Total (%)
Envelope Loads			
Skylite Solar	0	0	0.00
Skylite Cond	0	0	0.00
Roof Cond	0	0	0.00
Glass Solar	0	0	0.00
Glass/Door Cond	-43,757	-43,757	15.33
Wall Cond	-9,863	-19,800	6.94
Partition/Door	0	0	0.00
Floor	-19,342	-19,342	6.78
Adjacent Floor	0	0	0
Infiltration	0	0	0.00
Sub Total ==>	-72,962	-82,899	29.05
Internal Loads			
Lights	0	0	0.00
People	0	0	0.00
Misc	0	0	0.00
Sub Total ==>	0	0	0.00
Ceiling Load	-3,176	0	0.00
Ventilation Load	0	-40,392	14.15
Adj Air Trans Heat	0	0	0
Ov/Undr Sizing	0	0	0.00
Exhaust Heat		1,082	-0.38
OA Preheat Diff.		-88,863	31.14
RA Preheat Diff.		-74,333	26.04
Additional Reheat		0	0.00
Underflr Sup Ht Pkup		0	0.00
Supply Air Leakage		0	0.00
Grand Total ==>	-76,138	-285,406	100.00

TEMPERATURES

	Cooling	Heating
SADB	55.0	74.7
Ra Plenum	76.1	69.6
Return	76.1	69.6
Ret/OA	78.8	64.2
Fn MtrTD	0.1	0.0
Fn BldTD	0.4	0.0
Fn Frict	1.1	0.1

AIRFLOWS

	Cooling	Heating
Diffuser	18,067	15,020
Terminal	18,067	15,020
Main Fan	15,128	6,808
Sec Fan	18,067	11,973
Nom Vent	2,510	2,510
AHU Vent	2,510	2,510
Infil	0	0
MinStop/Rh	6,808	6,808
Return	15,073	6,702
Exhaust	2,455	2,404
Rm Exh	55	106
Auxiliary	0	0
Leakage Dwn	0	0
Leakage Ups	0	0

ENGINEERING CKS

	Cooling	Heating
% OA	16.6	13.9
cfm/ft²	0.63	0.76
cfm/ton	363.00	
ft²/ton	573.08	
Btu/hr-ft²	20.94	-12.12
No. People	145	

COOLING COIL SELECTION

	Total Capacity ton	Total Capacity MBh	Sens Cap. MBh	Coil Airflow cfm	Enter DB °F	Enter WB °F	Enter HR gr/lb	Leave DB °F	Leave WB °F	Leave HR gr/lb
Main Clg	41.7	500.1	403.2	14,891	78.8	63.2	65.3	53.5	51.5	55.8
Aux Clg	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Opt Vent	0.0	0.0	0.0	2,510	90.9	70.7	84.7	90.9	70.7	84.7
Total	41.7	500.1								

AREAS

	Gross Total	Glass ft²	Glass (%)
Floor	23,883		
Part	0		
Int Door	0		
ExFlr	552		
Roof	0	0	0
Wall	9,688	3,300	34
Ext Door	0	0	0

HEATING COIL SELECTION

	Capacity MBh	Coil Airflow cfm	Ent °F	Lvg °F
Main Htg	-200.7	15,020	62.3	74.7
Aux Htg	0.0	0	0.0	0.0
Preheat	0.0	0	0.0	0.0
Humidif	0.0	0	0.0	0.0
Opt Vent	-88.9	2,510	22.0	55.0
Total	-289.5			

System Checksums

elevator machine room

Packaged Terminal Air Conditioner

COOLING COIL PEAK / CLG SPACE PEAK

Cooling Coil Peak — Peaked at Time: Mo/Hr: 6 / 18; Outside Air: OADB/WB/HR: 92 / 70 / 77

Clg Space Peak — Mo/Hr: Sum of; OADB: Peaks

	Space Sens. + Lat. Btu/h	Plenum Sens. + Lat Btu/h	Net Total Btu/h	Percent Of Total (%)	Space Sensible Btu/h	Percent Of Total (%)
Envelope Loads						
Skylite Solar	0	0	0	0	0	0
Skylite Cond	0	0	0	0	0	0
Roof Cond	0	1,709	1,709	5	0	0
Glass Solar	0	0	0	0	0	0
Glass/Door Cond	0	0	0	0	0	0
Wall Cond	1,868	712	2,580	8	1,868	6
Partition/Door	0		0	0	0	0
Floor	0		0	0	0	0
Adjacent Floor	0	0	0	0	0	0
Infiltration	732		732	2	292	1
Sub Total ==>	2,601	2,421	5,022	15	2,160	7
Internal Loads						
Lights	0	0	0	0	0	0
People	0	0	0	0	0	0
Misc	27,435	0	27,435	84	27,435	91
Sub Total ==>	27,435	0	27,435	84	27,435	91
Ceiling Load	457	-457	0	0	457	2
Ventilation Load	0	0	0	0	0	0
Adj Air Trans Heat	0		0	0	0	0
Dehumid. Ov Sizing			0	0		
Ov/Undr Sizing	0		0	0	0	0
Exhaust Heat		-39	-39	0		
Sup. Fan Heat			181	1		
Ret. Fan Heat		0	0	0		
Duct Heat Pkup		0	0	0		
Underflr Sup Ht Pkup			0	0		
Supply Air Leakage		0	0	0		
Grand Total ==>	30,492	1,926	32,599	100.00	30,052	100.00

HEATING COIL PEAK

Mo/Hr: Heating Design; OADB: 22

	Space Peak Space Sens Btu/h	Coil Peak Tot Sens Btu/h	Percent Of Total (%)
Envelope Loads			
Skylite Solar	0	0	0.00
Skylite Cond	0	0	0.00
Roof Cond	0	-1,214	26.85
Glass Solar	0	0	0.00
Glass/Door Cond	0	0	0.00
Wall Cond	-1,835	-2,540	56.20
Partition/Door	0	0	0.00
Floor	0	0	0.00
Adjacent Floor	0	0	0
Infiltration	-796	-796	17.62
Sub Total ==>	-2,631	-4,550	100.68
Internal Loads			
Lights	0	0	0.00
People	0	0	0.00
Misc	0	0	0.00
Sub Total ==>	0	0	0.00
Ceiling Load	-362	0	0.00
Ventilation Load	0	0	0.00
Adj Air Trans Heat	0	0	0
Ov/Undr Sizing	0	0	0.00
Exhaust Heat		31	-0.68
OA Preheat Diff.		0	0.00
RA Preheat Diff.		0	0.00
Additional Reheat		0	0.00
Underflr Sup Ht Pkup		0	0.00
Supply Air Leakage		0	0.00
Grand Total ==>	-2,993	-4,520	100.00

TEMPERATURES

	Cooling	Heating
SADB	55.0	57.5
Ra Plenum	81.6	53.7
Return	81.6	53.7
Ret/OA	81.6	53.7
Fn MtrTD	0.0	0.0
Fn BldTD	0.0	0.0
Fn Frict	0.1	0.0

AIRFLOWS

	Cooling	Heating
Diffuser	1,121	1,121
Terminal	1,121	1,121
Main Fan	1,121	1,121
Sec Fan	0	0
Nom Vent	0	0
AHU Vent	0	0
Infil	23	23
MinStop/Rh	0	0
Return	1,143	1,143
Exhaust	23	23
Rm Exh	0	0
Auxiliary	0	0
Leakage Dwn	0	0
Leakage Ups	0	0

ENGINEERING CKS

	Cooling	Heating
% OA	0.0	0.0
cfm/ft²	1.25	1.25
cfm/ton	412.51	
ft²/ton	331.30	
Btu/hr-ft²	36.22	-5.02
No. People	0	

COOLING COIL SELECTION

	Total Capacity ton	Total Capacity MBh	Sens Cap. MBh	Coil Airflow cfm	Enter DB °F	Enter WB °F	Enter HR gr/lb	Leave DB °F	Leave WB °F	Leave HR gr/lb
Main Clg	2.7	32.6	32.2	1,121	81.8	60.5	48.0	55.0	49.9	47.2
Aux Clg	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Opt Vent	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Total	2.7	32.6								

AREAS

	Gross Total	Glass ft²	Glass (%)
Floor	900		
Part	0		
Int Door	0		
ExFlr	0		
Roof	900	0	0
Wall	1,200	0	0
Ext Door	0	0	0

HEATING COIL SELECTION

	Capacity MBh	Coil Airflow cfm	Ent °F	Lvg °F
Main Htg	-4.5	1,121	53.7	57.5
Aux Htg	0.0	0	0.0	0.0
Preheat	-1.4	1,121	53.7	54.9
Humidif	0.0	0	0.0	0.0
Opt Vent	0.0	0	0.0	0.0
Total	-4.5			

Dataset Name: CASE STUDY.TRC

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System Checksums

top floor

Parallel Fan-Powered VAV

COOLING COIL PEAK / CLG SPACE PEAK

	Cooling Coil Peak				CLG Space Peak	
Peaked at Time:	Mo/Hr: 7 / 15				Mo/Hr: 6 / 16	
Outside Air:	OADB/WB/HR: 92 / 74 / 102				OADB: 96	
	Space Sens. + Lat. Btu/h	Plenum Sens. + Lat Btu/h	Net Total Btu/h	Percent Of Total (%)	Space Sensible Btu/h	Percent Of Total (%)
Envelope Loads						
Skylite Solar	0	0	0	0	0	0
Skylite Cond	0	0	0	0	0	0
Roof Cond	0	67,423	67,423	11	0	0
Glass Solar	57,404	0	57,404	10	65,452	18
Glass/Door Cond	25,757	0	25,757	4	29,135	8
Wall Cond	6,217	4,424	10,641	2	7,189	2
Partition/Door	0		0	0	0	0
Floor	0		0	0	0	0
Adjacent Floor	0	0	0	0	0	0
Infiltration	0		0	0	0	0
Sub Total ==>	89,378	71,847	161,225	27	101,776	29
Internal Loads						
Lights	74,542	18,635	93,177	16	74,542	21
People	69,017	0	69,017	12	38,343	11
Misc	110,604	0	110,604	19	111,302	31
Sub Total ==>	254,163	18,635	272,798	46	224,186	63
Ceiling Load	28,864	-28,864	0	0	28,060	8
Ventilation Load	0	0	141,506	24	0	0
Adj Air Trans Heat	0		0	0	0	0
Dehumid. Ov Sizing			0	0		
Ov/Undr Sizing	0		0	0	0	0
Exhaust Heat		-11,620	-11,620	-2		
Sup. Fan Heat			29,251	5		
Ret. Fan Heat		0	0	0		
Duct Heat Pkup		0	0	0		
Underflr Sup Ht Pkup			0	0		
Supply Air Leakage		0	0	0		
Grand Total ==>	372,404	49,998	593,160	100.00	354,022	100.00

HEATING COIL PEAK

	Space Peak Space Sens Btu/h	Coil Peak Tot Sens Btu/h	Percent Of Total (%)
Mo/Hr: Heating Design			
OADB: 22			
Envelope Loads			
Skylite Solar	0	0	0.00
Skylite Cond	0	0	0.00
Roof Cond	0	-46,861	17.99
Glass Solar	0	0	0.00
Glass/Door Cond	-43,757	-43,757	16.80
Wall Cond	-10,025	-17,744	6.81
Partition/Door	0	0	0.00
Floor	0	0	0.00
Adjacent Floor	0	0	0
Infiltration	0	0	0.00
Sub Total ==>	-53,782	-108,362	41.59
Internal Loads			
Lights	0	0	0.00
People	0	0	0.00
Misc	0	0	0.00
Sub Total ==>	0	0	0.00
Ceiling Load	-18,113	0	0.00
Ventilation Load	0	-47,553	18.25
Adj Air Trans Heat	0	0	0
Ov/Undr Sizing	0	0	0.00
Exhaust Heat		0	0.00
OA Preheat Diff.		-104,618	40.16
RA Preheat Diff.		0	0.00
Additional Reheat		0	0.00
Underflr Sup Ht Pkup		0	0.00
Supply Air Leakage		0	0.00
Grand Total ==>	-71,895	-260,533	100.00

TEMPERATURES

	Cooling	Heating
SADB	55.0	77.4
Ra Plenum	78.8	67.6
Return	78.8	67.6
Ret/OA	81.2	62.4
Fn MtrTD	0.1	0.0
Fn BldTD	0.4	0.0
Fn Frict	1.2	0.1

AIRFLOWS

	Cooling	Heating
Diffuser	16,502	11,144
Terminal	16,502	11,144
Main Fan	16,502	7,185
Sec Fan	0	3,959
Nom Vent	2,955	2,955
AHU Vent	2,955	2,955
Infil	0	0
MinStop/Rh	7,185	7,185
Return	16,420	6,968
Exhaust	2,873	688
Rm Exh	82	217
Auxiliary	0	0
Leakage Dwn	0	0
Leakage Ups	0	0

ENGINEERING CKS

	Cooling	Heating
% OA	17.9	23.9
cfm/ft²	0.68	0.21
cfm/ton	333.84	
ft²/ton	488.81	
Btu/hr-ft²	24.55	-14.27
No. People	153	

COOLING COIL SELECTION

	Total Capacity ton	Total Capacity MBh	Sens Cap. MBh	Coil Airflow cfm	Enter DB/WB/HR °F	Enter DB/WB/HR °F	Enter DB/WB/HR gr/lb	Leave DB/WB/HR °F	Leave DB/WB/HR °F	Leave DB/WB/HR gr/lb
Main Clg	49.4	593.2	474.9	15,929	81.2	64.2	66.4	53.3	51.4	55.7
Aux Clg	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Opt Vent	0.0	0.0	0.0	2,955	90.9	70.7	84.7	90.9	70.7	84.7
Total	49.4	593.2								

AREAS

	Gross Total	Glass ft²	Glass (%)
Floor	24,162		
Part	0		
Int Door	0		
ExFlr	0		
Roof	24,162	0	0
Wall	9,128	3,300	36
Ext Door	0	0	0

HEATING COIL SELECTION

	Capacity MBh	Coil Airflow cfm	Ent °F	Lvg °F
Main Htg	-240.1	12,346	59.3	77.4
Aux Htg	0.0	0	0.0	0.0
Preheat	0.0	0	0.0	0.0
Reheat	-128.8	7,185	53.3	70.0
Humidif	0.0	0	0.0	0.0
Opt Vent	-104.6	2,955	22.0	55.0
Total	-344.7			

Dataset Name: CASE STUDY.TRC

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System Checksums

TYP FLOOR 2_3_4_5

Parallel Fan-Powered VAV

COOLING COIL PEAK / CLG SPACE PEAK

Cooling Coil Peak — Peaked at Time: Mo/Hr: 8 / 16; Outside Air: OADB/WB/HR: 92 / 73 / 99

Clg Space Peak — Mo/Hr: 6 / 16; OADB: 96

	Space Sens. + Lat. Btu/h	Plenum Sens. + Lat Btu/h	Net Total Btu/h	Percent Of Total (%)	Space Sensible Btu/h	Percent Of Total (%)
Envelope Loads						
Skylite Solar	0	0	0	0	0	0
Skylite Cond	0	0	0	0	0	0
Roof Cond	0	0	0	0	0	0
Glass Solar	264,136	0	264,136	12	267,042	20
Glass/Door Cond	102,987	0	102,987	5	116,541	9
Wall Cond	27,300	21,434	48,734	2	29,018	2
Partition/Door	0		0	0	0	0
Floor	0		0	0	0	0
Adjacent Floor	0	0	0	0	0	0
Infiltration	0		0	0	0	0
Sub Total ==>	394,423	21,434	415,856	19	412,601	31
Internal Loads						
Lights	298,168	74,542	372,709	17	298,168	22
People	276,067	0	276,067	13	153,371	11
Misc	443,041	0	443,041	21	443,041	33
Sub Total ==>	1,017,276	74,542	1,091,818	51	894,580	67
Ceiling Load	31,382	-31,382	0	0	31,528	2
Ventilation Load	0	0	532,067	25	0	0
Adj Air Trans Heat	0		0	0	0	0
Dehumid. Ov Sizing			0	0		
Ov/Undr Sizing	0		0	0	0	0
Exhaust Heat		-12,679	-12,679	-1		
Sup. Fan Heat			107,788	5		
Ret. Fan Heat		0	0	0		
Duct Heat Pkup		0	0	0		
Underflr Sup Ht Pkup			0	0		
Supply Air Leakage		0	0	0		
Grand Total ==>	1,443,080	51,915	2,134,850	100.00	1,338,709	100.00

HEATING COIL PEAK

Mo/Hr: Heating Design; OADB: 22

	Space Peak Space Sens Btu/h	Coil Peak Tot Sens Btu/h	Percent Of Total (%)
Envelope Loads			
Skylite Solar	0	0	0.00
Skylite Cond	0	0	0.00
Roof Cond	0	0	0.00
Glass Solar	0	0	0.00
Glass/Door Cond	-175,029	-175,029	20.45
Wall Cond	-40,099	-72,340	8.45
Partition/Door	0	0	0.00
Floor	0	0	0.00
Adjacent Floor	0	0	0
Infiltration	0	0	0.00
Sub Total ==>	-215,128	-247,369	28.90
Internal Loads			
Lights	0	0	0.00
People	0	0	0.00
Misc	0	0	0.00
Sub Total ==>	0	0	0.00
Ceiling Load	-10,747	0	0.00
Ventilation Load	0	-190,214	22.22
Adj Air Trans Heat	0	0	0
Ov/Undr Sizing	0	0	0.00
Exhaust Heat		0	0.00
OA Preheat Diff.		-418,470	48.88
RA Preheat Diff.		0	0.00
Additional Reheat		0	0.00
Underflr Sup Ht Pkup		0	0.00
Supply Air Leakage		0	0.00
Grand Total ==>	-225,875	-856,053	100.00

TEMPERATURES

	Cooling	Heating
SADB	55.0	76.8
Ra Plenum	76.0	69.7
Return	76.0	69.7
Ret/OA	79.1	63.6
Fn MtrTD	0.1	0.0
Fn BldTD	0.4	0.0
Fn Frict	1.2	0.1

AIRFLOWS

	Cooling	Heating
Diffuser	62,400	44,195
Terminal	62,400	44,195
Main Fan	62,400	28,550
Sec Fan	0	15,646
Nom Vent	11,822	11,822
AHU Vent	11,822	11,822
Infil	0	0
MinStop/Rh	28,550	28,550
Return	62,113	27,562
Exhaust	11,535	277
Rm Exh	287	987
Auxiliary	0	0
Leakage Dwn	0	0
Leakage Ups	0	0

ENGINEERING CKS

	Cooling	Heating
% OA	18.9	26.5
cfm/ft²	0.65	0.17
cfm/ton	350.75	
ft²/ton	543.26	
Btu/hr-ft²	22.09	-13.00
No. People	613	

COOLING COIL SELECTION

	Total Capacity ton	Total Capacity MBh	Sens Cap. MBh	Coil Airflow cfm	Enter DB °F	Enter WB °F	Enter HR gr/lb	Leave DB °F	Leave WB °F	Leave HR gr/lb
Main Clg	177.9	2,134.9	1,693.1	61,546	79.1	63.5	66.4	53.4	51.5	55.9
Aux Clg	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Opt Vent	0.0	0.0	0.0	11,822	90.9	70.7	84.7	90.9	70.7	84.7
Total	177.9	2,134.9								

AREAS

	Gross Total	Glass ft²	Glass (%)
Floor	96,648		
Part	0		
Int Door	0		
ExFlr	0		
Roof	0	0	0
Wall	36,512	13,200	36
Ext Door	0	0	0

HEATING COIL SELECTION

	Capacity MBh	Coil Airflow cfm	Ent °F	Lvg °F
Main Htg	-838.0	44,571	59.2	76.8
Aux Htg	0.0	0	0.0	0.0
Preheat	0.0	0	0.0	0.0
Reheat	-509.4	28,550	53.4	70.0
Humidif	0.0	0	0.0	0.0
Opt Vent	-418.5	11,822	22.0	55.0
Total	-1,256.5			

Dataset Name: CASE STUDY.TRC

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System Checksums

1st fl

Parallel Fan-Powered VAV

COOLING COIL PEAK / CLG SPACE PEAK

Cooling Coil Peak — Peaked at Time: Mo/Hr: 8 / 16; Outside Air: OADB/WB/HR: 92 / 73 / 99

Clg Space Peak — Mo/Hr: 6 / 16; OADB: 96

	Space Sens. + Lat. Btu/h	Plenum Sens. + Lat Btu/h	Net Total Btu/h	Percent Of Total (%)	Space Sensible Btu/h	Percent Of Total (%)
Envelope Loads						
Skylite Solar	0	0	0	0	0	0
Skylite Cond	0	0	0	0	0	0
Roof Cond	0	0	0	0	0	0
Glass Solar	82,686	0	82,686	14	83,848	23
Glass/Door Cond	29,253	0	29,253	5	36,444	10
Wall Cond	16,479	17,152	33,631	6	18,035	5
Partition/Door	0		0	0	0	0
Floor	0		0	0	0	0
Adjacent Floor	0	0	0	0	0	0
Infiltration	0		0	0	0	0
Sub Total ==>	128,417	17,152	145,569	25	138,328	37
Internal Loads						
Lights	78,692	19,673	98,365	17	78,692	21
People	65,061	0	65,061	11	36,145	10
Misc	105,608	0	105,608	18	105,608	29
Sub Total ==>	249,361	19,673	269,034	47	220,445	60
Ceiling Load	10,140	-10,140	0	0	10,373	3
Ventilation Load	0	0	131,900	23	0	0
Adj Air Trans Heat	0		0	0	0	0
Dehumid. Ov Sizing			0	0		
Ov/Undr Sizing	0		0	0	0	0
Exhaust Heat		-4,030	-4,030	-1		
Sup. Fan Heat			32,682	6		
Ret. Fan Heat		0	0	0		
Duct Heat Pkup		0	0	0		
Underflr Sup Ht Pkup			0	0		
Supply Air Leakage		0	0	0		
Grand Total ==>	387,918	22,655	575,155	100.00	369,146	100.00

HEATING COIL PEAK

Mo/Hr: Heating Design; OADB: 22

	Space Peak Space Sens Btu/h	Coil Peak Tot Sens Btu/h	Percent Of Total (%)
Envelope Loads			
Skylite Solar	0	0	0.00
Skylite Cond	0	0	0.00
Roof Cond	0	0	0.00
Glass Solar	0	0	0.00
Glass/Door Cond	-98,901	-98,901	35.30
Wall Cond	-17,903	-36,765	13.12
Partition/Door	0	0	0.00
Floor	-19,342	-19,342	6.90
Adjacent Floor	0	0	0
Infiltration	0	0	0.00
Sub Total ==>	-136,146	-155,008	55.33
Internal Loads			
Lights	0	0	0.00
People	0	0	0.00
Misc	0	0	0.00
Sub Total ==>	0	0	0.00
Ceiling Load	-5,755	0	0.00
Ventilation Load	0	-46,251	16.51
Adj Air Trans Heat	0	0	0
Ov/Undr Sizing	22,847	22,847	-8.15
Exhaust Heat		0	0.00
OA Preheat Diff.		-101,753	36.32
RA Preheat Diff.		0	0.00
Additional Reheat		0	0.00
Underflr Sup Ht Pkup		0	0.00
Supply Air Leakage		0	0.00
Grand Total ==>	-119,054	-280,166	100.00

TEMPERATURES

	Cooling	Heating
SADB	55.0	83.6
Ra Plenum	76.3	69.2
Return	76.3	69.2
Ret/OA	78.7	64.2
Fn MtrTD	0.1	0.0
Fn BldTD	0.4	0.0
Fn Frict	1.1	0.1

AIRFLOWS

	Cooling	Heating
Diffuser	19,788	13,022
Terminal	19,788	13,022
Main Fan	19,788	8,034
Sec Fan	0	4,987
Nom Vent	2,875	2,875
AHU Vent	2,875	2,875
Infil	0	0
MinStop/Rh	8,034	8,034
Return	19,717	7,876
Exhaust	2,804	132
Rm Exh	71	158
Auxiliary	0	0
Leakage Dwn	0	0
Leakage Ups	0	0

ENGINEERING CKS

	Cooling	Heating
% OA	14.5	21.7
cfm/ft^2	0.83	0.22
cfm/ton	359.00	
ft^2/ton	433.30	
Btu/hr-ft^2	27.69	-18.53
No. People	145	

COOLING COIL SELECTION

	Total Capacity ton	Total Capacity MBh	Sens Cap. MBh	Coil Airflow cfm	Enter DB °F	Enter WB °F	Enter HR gr/lb	Leave DB °F	Leave WB °F	Leave HR gr/lb
Main Clg	55.1	661.4	536.1	19,244	78.7	62.8	63.6	53.4	50.7	52.8
Aux Clg	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Opt Vent	0.0	0.0	0.0	2,875	90.9	70.7	84.7	90.9	70.7	84.7
Total	55.1	661.4								

AREAS

	Gross Total	Glass ft^2	Glass (%)
Floor	23,883		
Part	0		
Int Door	0		
ExFlr	552		
Roof	0	0	0
Wall	9,688	3,460	36
Ext Door	0	0	0

HEATING COIL SELECTION

	Capacity MBh	Coil Airflow cfm	Ent °F	Lvg °F
Main Htg	-340.9	13,262	59.7	83.6
Aux Htg	0.0	0	0.0	0.0
Preheat	0.0	0	0.0	0.0
Reheat	-142.9	8,034	53.4	70.0
Humidif	0.0	0	0.0	0.0
Opt Vent	-101.8	2,875	22.0	55.0
Total	-442.6			

System Checksums

elevator machine room

Incremental Heat Pump

COOLING COIL PEAK / CLG SPACE PEAK

Cooling coil peak — Peaked at Time: Mo/Hr: 6 / 18; Outside Air: OADB/WB/HR: 92 / 70 / 77

Clg space peak — Mo/Hr: Sum of; OADB: Peaks

	Space Sens. + Lat. Btu/h	Plenum Sens. + Lat Btu/h	Net Total Btu/h	Percent Of Total (%)	Space Sensible Btu/h	Percent Of Total (%)
Envelope Loads						
Skylite Solar	0	0	0	0	0	0
Skylite Cond	0	0	0	0	0	0
Roof Cond	0	2,062	2,062	6	0	0
Glass Solar	0	0	0	0	0	0
Glass/Door Cond	0	0	0	0	0	0
Wall Cond	3,888	2,025	5,913	16	3,888	12
Partition/Door	0		0	0	0	0
Floor	0		0	0	0	0
Adjacent Floor	0	0	0	0	0	0
Infiltration	667		667	2	263	1
Sub Total ==>	4,555	4,087	8,641	24	4,150	13
Internal Loads						
Lights	0	0	0	0	0	0
People	0	0	0	0	0	0
Misc	27,850	0	27,850	76	27,850	85
Sub Total ==>	27,850	0	27,850	76	27,850	85
Ceiling Load	721	-721	0	0	721	2
Ventilation Load	0	0	0	0	0	0
Adj Air Trans Heat	0		0	0	0	0
Dehumid. Ov Sizing			0	0		
Ov/Undr Sizing	0		0	0	0	0
Exhaust Heat		-55	-55	0		
Sup. Fan Heat			197	1		
Ret. Fan Heat		0	0	0		
Duct Heat Pkup		0	0	0		
Underflr Sup Ht Pkup			0	0		
Supply Air Leakage		0	0	0		
Grand Total ==>	33,126	3,311	36,634	100.00	32,722	100.00

HEATING COIL PEAK

Mo/Hr: Heating Design; OADB: 22

	Space Peak Space Sens Btu/h	Coil Peak Tot Sens Btu/h	Percent Of Total (%)
Envelope Loads			
Skylite Solar	0	0	0.00
Skylite Cond	0	0	0.00
Roof Cond	0	-1,752	24.26
Glass Solar	0	0	0.00
Glass/Door Cond	0	0	0.00
Wall Cond	-3,157	-4,799	66.45
Partition/Door	0	0	0.00
Floor	0	0	0.00
Adjacent Floor	0	0	0
Infiltration	-717	-717	9.93
Sub Total ==>	-3,874	-7,268	100.63
Internal Loads			
Lights	0	0	0.00
People	0	0	0.00
Misc	0	0	0.00
Sub Total ==>	0	0	0.00
Ceiling Load	-599	0	0.00
Ventilation Load	0	0	0.00
Adj Air Trans Heat	0	0	0
Ov/Undr Sizing	0	0	0.00
Exhaust Heat		46	-0.63
OA Preheat Diff.		0	0.00
RA Preheat Diff.		0	0.00
Additional Reheat		0	0.00
Underflr Sup Ht Pkup		0	0.00
Supply Air Leakage		0	0.00
Grand Total ==>	-4,473	-7,222	100.00

TEMPERATURES

	Cooling	Heating
SADB	55.0	58.4
Ra Plenum	82.5	52.9
Return	82.5	52.9
Ret/OA	82.5	52.9
Fn MtrTD	0.0	0.0
Fn BldTD	0.0	0.0
Fn Frict	0.1	0.0

AIRFLOWS

	Cooling	Heating
Diffuser	1,220	1,220
Terminal	1,220	1,220
Main Fan	1,220	1,220
Sec Fan	0	0
Nom Vent	0	0
AHU Vent	0	0
Infil	20	20
MinStop/Rh	0	0
Return	1,240	1,240
Exhaust	20	20
Rm Exh	0	0
Auxiliary	0	0
Leakage Dwn	0	0
Leakage Ups	0	0

ENGINEERING CKS

	Cooling	Heating
% OA	0.0	0.0
cfm/ft²	1.36	1.36
cfm/ton	399.69	
ft²/ton	294.81	
Btu/hr-ft²	40.70	-8.02
No. People	0	

COOLING COIL SELECTION

	Total Capacity ton	Total Capacity MBh	Sens Cap. MBh	Coil Airflow cfm	Enter DB °F	Enter WB °F	Enter HR gr/lb	Leave DB °F	Leave WB °F	Leave HR gr/lb
Main Clg	3.1	36.6	36.2	1,220	82.7	60.7	47.4	55.0	49.7	46.7
Aux Clg	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Opt Vent	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Total	3.1	36.6								

AREAS

	Gross Total	Glass ft²	Glass (%)
Floor	900		
Part	0		
Int Door	0		
ExFlr	0		
Roof	900	0	0
Wall	1,200	0	0
Ext Door	0	0	0

HEATING COIL SELECTION

	Capacity MBh	Coil Airflow cfm	Ent °F	Lvg °F
Main Htg	-7.2	1,220	52.9	58.4
Aux Htg	0.0	0	0.0	0.0
Preheat	-2.6	1,220	52.9	54.9
Humidif	0.0	0	0.0	0.0
Opt Vent	0.0	0	0.0	0.0
Total	-7.2			

System Checksums

top floor

Parallel Fan-Powered VAV

COOLING COIL PEAK / CLG SPACE PEAK

	Cooling Coil Peak				Clg Space Peak	
Peaked at Time:	Mo/Hr: 6 / 15				Mo/Hr: 6 / 16	
Outside Air:	OADB/WB/HR: 96 / 73 / 89				OADB: 96	
	Space Sens. + Lat. Btu/h	Plenum Sens. + Lat Btu/h	Net Total Btu/h	Percent Of Total (%)	Space Sensible Btu/h	Percent Of Total (%)
Envelope Loads						
Skylite Solar	0	0	0	0	0	0
Skylite Cond	0	0	0	0	0	0
Roof Cond	0	102,726	102,726	15	0	0
Glass Solar	71,084	0	71,084	11	77,687	20
Glass/Door Cond	35,546	0	35,546	5	34,407	9
Wall Cond	14,101	15,788	29,889	4	15,392	4
Partition/Door	0		0	0	0	0
Floor	0		0	0	0	0
Adjacent Floor	0	0	0	0	0	0
Infiltration	0		0	0	0	0
Sub Total ==>	120,731	118,514	239,245	36	127,485	33
Internal Loads						
Lights	76,977	19,244	96,222	14	76,977	20
People	69,017	0	69,017	10	38,343	10
Misc	110,658	0	110,658	17	111,398	29
Sub Total ==>	256,652	19,244	275,897	41	226,718	58
Ceiling Load	36,436	-36,436	0	0	33,720	9
Ventilation Load	0	0	130,536	19	0	0
Adj Air Trans Heat	0		0	0	0	0
Dehumid. Ov Sizing			0	0		
Ov/Undr Sizing	0		0	0	0	0
Exhaust Heat		-14,586	-14,586	-2		
Sup. Fan Heat			38,409	6		
Ret. Fan Heat		0	0	0		
Duct Heat Pkup		0	0	0		
Underflr Sup Ht Pkup			0	0		
Supply Air Leakage		0	0	0		
Grand Total ==>	413,820	86,736	669,501	100.00	387,922	100.00

HEATING COIL PEAK

Mo/Hr: Heating Design
OADB: 22

	Space Peak Space Sens Btu/h	Coil Peak Tot Sens Btu/h	Percent Of Total (%)
Envelope Loads			
Skylite Solar	0	0	0.00
Skylite Cond	0	0	0.00
Roof Cond	0	-67,798	20.24
Glass Solar	0	0	0.00
Glass/Door Cond	-93,371	-93,371	27.87
Wall Cond	-15,484	-33,488	10.00
Partition/Door	0	0	0.00
Floor	0	0	0.00
Adjacent Floor	0	0	0
Infiltration	0	0	0.00
Sub Total ==>	-108,854	-194,657	58.10
Internal Loads			
Lights	0	0	0.00
People	0	0	0.00
Misc	0	0	0.00
Sub Total ==>	0	0	0.00
Ceiling Load	-26,493	0	0.00
Ventilation Load	0	-47,553	14.19
Adj Air Trans Heat	0	0	0
Ov/Undr Sizing	11,800	11,800	-3.52
Exhaust Heat		0	0.00
OA Preheat Diff.		-104,618	31.23
RA Preheat Diff.		0	0.00
Additional Reheat		0	0.00
Underflr Sup Ht Pkup		0	0.00
Supply Air Leakage		0	0.00
Grand Total ==>	-123,548	-335,028	100.00

TEMPERATURES

	Cooling	Heating
SADB	55.0	83.3
Ra Plenum	79.8	66.5
Return	79.8	66.5
Ret/OA	82.1	62.3
Fn MtrTD	0.1	0.0
Fn BldTD	0.4	0.0
Fn Frict	1.2	0.1

AIRFLOWS

	Cooling	Heating
Diffuser	20,794	12,752
Terminal	20,794	12,752
Main Fan	20,794	7,989
Sec Fan	0	4,763
Nom Vent	2,955	2,955
AHU Vent	2,955	2,955
Infil	0	0
MinStop/Rh	7,989	7,989
Return	20,696	7,826
Exhaust	2,857	630
Rm Exh	98	163
Auxiliary	0	0
Leakage Dwn	0	0
Leakage Ups	0	0

ENGINEERING CKS

	Cooling	Heating
% OA	14.2	21.0
cfm/ft²	0.86	0.25
cfm/ton	324.10	
ft²/ton	376.59	
Btu/hr-ft²	31.87	-19.51
No. People	153	

COOLING COIL SELECTION

	Total Capacity ton	Total Capacity MBh	Sens Cap. MBh	Coil Airflow cfm	Enter DB °F	Enter WB °F	Enter HR gr/lb	Leave DB °F	Leave WB °F	Leave HR gr/lb
Main Clg	64.2	769.9	661.8	20,538	82.1	63.6	61.7	53.3	50.4	52.0
Aux Clg	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Opt Vent	0.0	0.0	0.0	2,955	90.9	70.7	84.7	90.9	70.7	84.7
Total	64.2	769.9								

AREAS

	Gross Total	Glass ft²	Glass (%)
Floor	24,162		
Part	0		
Int Door	0		
ExFlr	0		
Roof	24,162	0	0
Wall	9,128	3,267	36
Ext Door	0	0	0

HEATING COIL SELECTION

	Capacity MBh	Coil Airflow cfm	Ent °F	Lvg °F
Main Htg	-366.7	14,042	59.0	83.3
Aux Htg	0.0	0	0.0	0.0
Preheat	0.0	0	0.0	0.0
Reheat	-143.5	7,989	53.3	70.0
Humidif	0.0	0	0.0	0.0
Opt Vent	-104.6	2,955	22.0	55.0
Total	-471.3			

System Checksums

TYP FLOOR 2_3_4_5

Parallel Fan-Powered VAV

COOLING COIL PEAK / CLG SPACE PEAK

Cooling Coil Peak — Peaked at Time: Mo/Hr: 8 / 15; Outside Air: OADB/WB/HR: 92 / 74 / 101

Clg Space Peak — Mo/Hr: 6 / 16; OADB: 96

	Space Sens. + Lat. Btu/h	Plenum Sens. + Lat Btu/h	Net Total Btu/h	Percent Of Total (%)	Space Sensible Btu/h	Percent Of Total (%)
Envelope Loads						
Skylite Solar	0	0	0	0	0	0
Skylite Cond	0	0	0	0	0	0
Roof Cond	0	0	0	0	0	0
Glass Solar	295,250	0	295,250	13	316,764	22
Glass/Door Cond	114,222	0	114,222	5	137,626	9
Wall Cond	53,432	64,958	118,390	5	63,547	4
Partition/Door	0		0	0	0	0
Floor	0		0	0	0	0
Adjacent Floor	0	0	0	0	0	0
Infiltration	0		0	0	0	0
Sub Total ==>	462,904	64,958	527,862	23	517,936	35
Internal Loads						
Lights	307,910	76,977	384,887	17	307,910	21
People	276,067	0	276,067	12	153,371	10
Misc	447,701	0	447,701	19	447,701	30
Sub Total ==>	1,031,678	76,977	1,108,655	48	908,981	62
Ceiling Load	39,920	-39,920	0	0	42,178	3
Ventilation Load	0	0	570,268	25	0	0
Adj Air Trans Heat	0		0	0	0	0
Dehumid. Ov Sizing			0	0		
Ov/Undr Sizing	0		0	0	0	0
Exhaust Heat		-16,053	-16,053	-1		
Sup. Fan Heat			134,977	6		
Ret. Fan Heat		0	0	0		
Duct Heat Pkup		0	0	0		
Underflr Sup Ht Pkup			0	0		
Supply Air Leakage		0	0	0		
Grand Total ==>	1,534,501	85,963	2,325,709	100.00	1,469,096	100.00

HEATING COIL PEAK

Mo/Hr: Heating Design; OADB: 22

	Space Peak Space Sens Btu/h	Coil Peak Tot Sens Btu/h	Percent Of Total (%)
Envelope Loads			
Skylite Solar	0	0	0.00
Skylite Cond	0	0	0.00
Roof Cond	0	0	0.00
Glass Solar	0	0	0.00
Glass/Door Cond	-373,484	-373,484	34.42
Wall Cond	-61,934	-138,310	12.75
Partition/Door	0	0	0.00
Floor	0	0	0.00
Adjacent Floor	0	0	0
Infiltration	0	0	0.00
Sub Total ==>	-435,418	-511,793	47.17
Internal Loads			
Lights	0	0	0.00
People	0	0	0.00
Misc	0	0	0.00
Sub Total ==>	0	0	0.00
Ceiling Load	-23,451	0	0.00
Ventilation Load	0	-190,213	17.53
Adj Air Trans Heat	0	0	0
Ov/Undr Sizing	35,432	35,432	-3.27
Exhaust Heat		0	0.00
OA Preheat Diff.		-418,470	38.57
RA Preheat Diff.		0	0.00
Additional Reheat		0	0.00
Underflr Sup Ht Pkup		0	0.00
Supply Air Leakage		0	0.00
Grand Total ==>	-423,437	-1,085,045	100.00

TEMPERATURES

	Cooling	Heating
SADB	55.0	82.5
Ra Plenum	76.3	69.2
Return	76.3	69.2
Ret/OA	78.8	64.0
Fn MtrTD	0.1	0.0
Fn BldTD	0.4	0.0
Fn Frict	1.2	0.1

AIRFLOWS

	Cooling	Heating
Diffuser	78,750	51,524
Terminal	78,750	51,524
Main Fan	78,750	32,214
Sec Fan	0	19,310
Nom Vent	11,822	11,822
AHU Vent	11,822	11,822
Infil	0	0
MinStop/Rh	32,214	32,214
Return	78,408	31,436
Exhaust	11,480	596
Rm Exh	341	778
Auxiliary	0	0
Leakage Dwn	0	0
Leakage Ups	0	0

ENGINEERING CKS

	Cooling	Heating
% OA	15.0	22.5
cfm/ft²	0.81	0.21
cfm/ton	353.33	
ft²/ton	433.63	
Btu/hr-ft²	27.67	-17.76
No. People	613	

COOLING COIL SELECTION

	Total Capacity ton	Total Capacity MBh	Sens Cap. MBh	Coil Airflow cfm	Enter DB/WB/HR °F	Enter °F	Enter gr/lb	Leave DB/WB/HR °F	Leave °F	Leave gr/lb
Main Clg	222.9	2,674.6	2,129.9	75,678	78.8	63.0	64.4	53.3	50.6	52.5
Aux Clg	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Opt Vent	0.0	0.0	0.0	11,822	90.9	70.7	84.7	90.9	70.7	84.7
Total	222.9	2,674.6								

AREAS

	Gross Total	Glass ft²	Glass (%)
Floor	96,648		
Part	0		
Int Door	0		
ExFlr	0		
Roof	0	0	0
Wall	36,512	13,066	36
Ext Door	0	0	0

HEATING COIL SELECTION

	Capacity MBh	Coil Airflow cfm	Ent °F	Lvg °F
Main Htg	-1,297.7	52,549	59.5	82.5
Aux Htg	0.0	0	0.0	0.0
Preheat	0.0	0	0.0	0.0
Reheat	-575.8	32,214	53.3	70.0
Humidif	0.0	0	0.0	0.0
Opt Vent	-418.5	11,822	22.0	55.0
Total	-1,716.2			

Dataset Name: CASE STUDY.TRC

Alternative - 2 System Checksums Report Page 8 of 16

System Checksums

1st fl

Series Fan-Powered VAV

COOLING COIL PEAK / CLG SPACE PEAK

Peaked at Time: Mo/Hr: 8 / 16 — Outside Air: OADB/WB/HR: 92 / 73 / 99 (Cooling Coil Peak)

Mo/Hr: 6 / 16 — OADB: 96 (Clg Space Peak)

	Space Sens. + Lat. Btu/h	Plenum Sens. + Lat Btu/h	Net Total Btu/h	Percent Of Total (%)	Space Sensible Btu/h	Percent Of Total (%)
Envelope Loads						
Skylite Solar	0	0	0	0	0	0
Skylite Cond	0	0	0	0	0	0
Roof Cond	0	0	0	0	0	0
Glass Solar	63,925	0	63,925	13	65,027	20
Glass/Door Cond	25,634	0	25,634	5	29,128	9
Wall Cond	6,567	6,454	13,020	3	7,004	2
Partition/Door	0		0	0	0	0
Floor	0		0	0	0	0
Adjacent Floor	0	0	0	0	0	0
Infiltration	0		0	0	0	0
Sub Total ==>	96,125	6,454	102,579	20	101,159	31
Internal Loads						
Lights	74,569	18,642	93,211	19	74,569	23
People	65,061	0	65,061	13	36,145	11
Misc	104,293	0	104,293	21	104,293	32
Sub Total ==>	243,923	18,642	262,566	52	215,007	66
Ceiling Load	8,332	-8,332	0	0	8,385	3
Ventilation Load	0	0	113,213	22	0	0
Adj Air Trans Heat	0		0	0	0	0
Dehumid. Ov Sizing			0	0		
Ov/Undr Sizing	0		0	0	0	0
Exhaust Heat		-2,900	-2,900	-1		
Sup. Fan Heat			27,943	6		
Ret. Fan Heat		0	0	0		
Duct Heat Pkup		0	0	0		
Underflr Sup Ht Pkup			0	0		
Supply Air Leakage		0	0	0		
Grand Total ==>	348,380	13,864	503,400	100.00	324,551	100.00

HEATING COIL PEAK

Mo/Hr: Heating Design — OADB: 22

	Space Peak Space Sens Btu/h	Coil Peak Tot Sens Btu/h	Percent Of Total (%)
Envelope Loads			
Skylite Solar	0	0	0.00
Skylite Cond	0	0	0.00
Roof Cond	0	0	0.00
Glass Solar	0	0	0.00
Glass/Door Cond	-43,757	-43,757	15.33
Wall Cond	-9,863	-19,800	6.94
Partition/Door	0	0	0.00
Floor	-19,342	-19,342	6.78
Adjacent Floor	0	0	0
Infiltration	0	0	0.00
Sub Total ==>	-72,962	-82,899	29.05
Internal Loads			
Lights	0	0	0.00
People	0	0	0.00
Misc	0	0	0.00
Sub Total ==>	0	0	0.00
Ceiling Load	-3,176	0	0.00
Ventilation Load	0	-40,392	14.15
Adj Air Trans Heat	0	0	0
Ov/Undr Sizing	0	0	0.00
Exhaust Heat		1,082	-0.38
OA Preheat Diff.		-88,863	31.14
RA Preheat Diff.		-74,333	26.04
Additional Reheat		0	0.00
Underflr Sup Ht Pkup		0	0.00
Supply Air Leakage		0	0.00
Grand Total ==>	-76,138	-285,406	100.00

TEMPERATURES

	Cooling	Heating
SADB	55.0	74.7
Ra Plenum	76.1	69.6
Return	76.1	69.6
Ret/OA	78.8	64.2
Fn MtrTD	0.1	0.0
Fn BldTD	0.4	0.0
Fn Frict	1.1	0.1

AIRFLOWS

	Cooling	Heating
Diffuser	18,067	15,020
Terminal	18,067	15,020
Main Fan	15,128	6,808
Sec Fan	18,067	11,973
Nom Vent	2,510	2,510
AHU Vent	2,510	2,510
Infil	0	0
MinStop/Rh	6,808	6,808
Return	15,073	6,702
Exhaust	2,455	2,404
Rm Exh	55	106
Auxiliary	0	0
Leakage Dwn	0	0
Leakage Ups	0	0

ENGINEERING CKS

	Cooling	Heating
% OA	16.6	13.9
cfm/ft²	0.63	0.76
cfm/ton	363.00	
ft²/ton	573.08	
Btu/hr-ft²	20.94	-12.12
No. People	145	

COOLING COIL SELECTION

	Total Capacity ton	Total Capacity MBh	Sens Cap. MBh	Coil Airflow cfm	Enter DB °F	Enter WB °F	Enter HR gr/lb	Leave DB °F	Leave WB °F	Leave HR gr/lb
Main Clg	41.7	500.1	403.2	14,891	78.8	63.2	65.3	53.5	51.5	55.8
Aux Clg	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Opt Vent	0.0	0.0	0.0	2,510	90.9	70.7	84.7	90.9	70.7	84.7
Total	41.7	500.1								

AREAS

	Gross Total	Glass ft²	Glass (%)
Floor	23,883		
Part	0		
Int Door	0		
ExFlr	552		
Roof	0	0	0
Wall	9,688	3,300	34
Ext Door	0	0	0

HEATING COIL SELECTION

	Capacity MBh	Coil Airflow cfm	Ent °F	Lvg °F
Main Htg	-200.7	15,020	62.3	74.7
Aux Htg	0.0	0	0.0	0.0
Preheat	0.0	0	0.0	0.0
Humidif	0.0	0	0.0	0.0
Opt Vent	-88.9	2,510	22.0	55.0
Total	-289.5			

System Checksums

elevator machine room

Packaged Terminal Air Conditioner

COOLING COIL PEAK / CLG SPACE PEAK

Cooling Coil Peak — Peaked at Time: Mo/Hr: 6 / 18; Outside Air: OADB/WB/HR: 92 / 70 / 77

Clg Space Peak — Mo/Hr: Sum of; OADB: Peaks

	Space Sens. + Lat. Btu/h	Plenum Sens. + Lat Btu/h	Net Total Btu/h	Percent Of Total (%)	Space Sensible Btu/h	Percent Of Total (%)
Envelope Loads						
Skylite Solar	0	0	0	0	0	0
Skylite Cond	0	0	0	0	0	0
Roof Cond	0	1,709	1,709	5	0	0
Glass Solar	0	0	0	0	0	0
Glass/Door Cond	0	0	0	0	0	0
Wall Cond	1,868	712	2,580	8	1,868	6
Partition/Door	0		0	0	0	0
Floor	0		0	0	0	0
Adjacent Floor	0	0	0	0	0	0
Infiltration	732		732	2	292	1
Sub Total ==>	2,601	2,421	5,022	15	2,160	7
Internal Loads						
Lights	0	0	0	0	0	0
People	0	0	0	0	0	0
Misc	27,435	0	27,435	84	27,435	91
Sub Total ==>	27,435	0	27,435	84	27,435	91
Ceiling Load	457	-457	0	0	457	2
Ventilation Load	0	0	0	0	0	0
Adj Air Trans Heat	0		0	0	0	0
Dehumid. Ov Sizing			0	0		
Ov/Undr Sizing	0		0	0	0	0
Exhaust Heat		-39	-39	0		
Sup. Fan Heat			181	1		
Ret. Fan Heat		0	0	0		
Duct Heat Pkup		0	0	0		
Underflr Sup Ht Pkup			0	0		
Supply Air Leakage		0	0	0		
Grand Total ==>	30,492	1,926	32,599	100.00	30,052	100.00

HEATING COIL PEAK

Mo/Hr: Heating Design; OADB: 22

	Space Peak Space Sens Btu/h	Coil Peak Tot Sens Btu/h	Percent Of Total (%)
Envelope Loads			
Skylite Solar	0	0	0.00
Skylite Cond	0	0	0.00
Roof Cond	0	-1,214	26.85
Glass Solar	0	0	0.00
Glass/Door Cond	0	0	0.00
Wall Cond	-1,835	-2,540	56.20
Partition/Door	0	0	0.00
Floor	0	0	0.00
Adjacent Floor	0	0	0
Infiltration	-796	-796	17.62
Sub Total ==>	-2,631	-4,550	100.68
Internal Loads			
Lights	0	0	0.00
People	0	0	0.00
Misc	0	0	0.00
Sub Total ==>	0	0	0.00
Ceiling Load	-362	0	0.00
Ventilation Load	0	0	0.00
Adj Air Trans Heat	0	0	0
Ov/Undr Sizing	0	0	0.00
Exhaust Heat		31	-0.68
OA Preheat Diff.		0	0.00
RA Preheat Diff.		0	0.00
Additional Reheat		0	0.00
Underflr Sup Ht Pkup		0	0.00
Supply Air Leakage		0	0.00
Grand Total ==>	-2,993	-4,520	100.00

TEMPERATURES

	Cooling	Heating
SADB	55.0	57.5
Ra Plenum	81.6	53.7
Return	81.6	53.7
Ret/OA	81.6	53.7
Fn MtrTD	0.0	0.0
Fn BldTD	0.0	0.0
Fn Frict	0.1	0.0

AIRFLOWS

	Cooling	Heating
Diffuser	1,121	1,121
Terminal	1,121	1,121
Main Fan	1,121	1,121
Sec Fan	0	0
Nom Vent	0	0
AHU Vent	0	0
Infil	23	23
MinStop/Rh	0	0
Return	1,143	1,143
Exhaust	23	23
Rm Exh	0	0
Auxiliary	0	0
Leakage Dwn	0	0
Leakage Ups	0	0

ENGINEERING CKS

	Cooling	Heating
% OA	0.0	0.0
cfm/ft²	1.25	1.25
cfm/ton	412.51	
ft²/ton	331.30	
Btu/hr·ft²	36.22	-5.02
No. People	0	

COOLING COIL SELECTION

	Total Capacity ton	Total Capacity MBh	Sens Cap. MBh	Coil Airflow cfm	Enter DB °F	Enter WB °F	Enter HR gr/lb	Leave DB °F	Leave WB °F	Leave HR gr/lb
Main Clg	2.7	32.6	32.2	1,121	81.8	60.5	48.0	55.0	49.9	47.2
Aux Clg	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Opt Vent	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Total	2.7	32.6								

AREAS

	Gross Total	Glass ft²	Glass (%)
Floor	900		
Part	0		
Int Door	0		
ExFlr	0		
Roof	900	0	0
Wall	1,200	0	0
Ext Door	0	0	

HEATING COIL SELECTION

	Capacity MBh	Coil Airflow cfm	Ent °F	Lvg °F
Main Htg	-4.5	1,121	53.7	57.5
Aux Htg	0.0	0	0.0	0.0
Preheat	-1.4	1,121	53.7	54.9
Humidif	0.0	0	0.0	0.0
Opt Vent	0.0	0	0.0	0.0
Total	-4.5			

System Checksums

top floor

Series Fan-Powered VAV

COOLING COIL PEAK / CLG SPACE PEAK

Peaked at Time: Mo/Hr: 7 / 15 | CLG Space Peak Mo/Hr: 6 / 15

Outside Air: OADB/WB/HR: 92 / 74 / 102 | OADB: 96

	Space Sens. + Lat. Btu/h	Plenum Sens. + Lat Btu/h	Net Total Btu/h	Percent Of Total (%)	Space Sensible Btu/h	Percent Of Total (%)
Envelope Loads						
Skylite Solar	0	0	0	0	0	0
Skylite Cond	0	0	0	0	0	0
Roof Cond	0	67,423	67,423	12	0	0
Glass Solar	57,404	0	57,404	10	65,452	18
Glass/Door Cond	25,757	0	25,757	4	29,135	8
Wall Cond	6,217	4,424	10,641	2	7,189	2
Partition/Door	0		0	0	0	0
Floor	0		0	0	0	0
Adjacent Floor	0	0	0	0	0	0
Infiltration	0		0	0	0	0
Sub Total ==>	89,378	71,847	161,225	28	101,776	29
Internal Loads						
Lights	74,542	18,635	93,177	16	74,542	21
People	69,017	0	69,017	12	38,343	11
Misc	110,604	0	110,604	19	111,302	31
Sub Total ==>	254,163	18,635	272,798	47	224,186	63
Ceiling Load	28,864	-28,864	0	0	28,060	8
Ventilation Load	0	0	118,018	21	0	0
Adj Air Trans Heat	0		0	0	0	0
Dehumid. Ov Sizing			0	0		
Ov/Undr Sizing	0		0	0	0	0
Exhaust Heat		-9,653	-9,653	-2		
Sup. Fan Heat			32,699	6		
Ret. Fan Heat		0	0	0		
Duct Heat Pkup		0	0	0		
Underflr Sup Ht Pkup			0	0		
Supply Air Leakage		0	0	0		
Grand Total ==>	372,404	51,966	575,088	100.00	354,022	100.00

HEATING COIL PEAK

Mo/Hr: Heating Design

OADB: 22

	Space Peak Space Sens Btu/h	Coil Peak Tot Sens Btu/h	Percent Of Total (%)
Envelope Loads			
Skylite Solar	0	0	0.00
Skylite Cond	0	0	0.00
Roof Cond	0	-46,996	15.52
Glass Solar	0	0	0.00
Glass/Door Cond	-43,757	-43,757	14.45
Wall Cond	-10,025	-17,766	5.87
Partition/Door	0	0	0.00
Floor	0	0	0.00
Adjacent Floor	0	0	0
Infiltration	0	0	0.00
Sub Total ==>	-53,782	-108,520	35.84
Internal Loads			
Lights	0	0	0.00
People	0	0	0.00
Misc	0	0	0.00
Sub Total ==>	0	0	0.00
Ceiling Load	-17,107	0	0.00
Ventilation Load	0	-39,501	13.05
Adj Air Trans Heat	0	0	0
Ov/Undr Sizing	0	0	0.00
Exhaust Heat		5,574	-1.84
OA Preheat Diff.		-86,903	28.70
RA Preheat Diff.		-73,453	24.26
Additional Reheat		0	0.00
Underflr Sup Ht Pkup		0	0.00
Supply Air Leakage		0	0.00
Grand Total ==>	-70,889	-302,803	100.00

TEMPERATURES

	Cooling	Heating
SADB	55.0	74.2
Ra Plenum	78.8	67.8
Return	78.8	67.8
Ret/OA	80.8	63.4
Fn MtrTD	0.1	0.0
Fn BldTD	0.4	0.0
Fn Frict	1.2	0.1

AIRFLOWS

	Cooling	Heating
Diffuser	19,488	15,700
Terminal	19,488	15,700
Main Fan	16,502	7,185
Sec Fan	19,488	12,474
Nom Vent	2,455	2,455
AHU Vent	2,455	2,455
Infil	0	0
MinStop/Rh	7,185	7,185
Return	16,434	7,055
Exhaust	2,387	2,325
Rm Exh	68	130
Auxiliary	0	0
Leakage Dwn	0	0
Leakage Ups	0	0

ENGINEERING CKS

	Cooling	Heating
% OA	14.9	12.6
cfm/ft²	0.68	0.81
cfm/ton	346.41	
ft²/ton	507.21	
Btu/hr·ft²	23.66	-12.71
No. People	153	

COOLING COIL SELECTION

	Total Capacity ton	Total Capacity MBh	Sens Cap. MBh	Coil Airflow cfm	Enter DB °F	Enter WB °F	Enter HR gr/lb	Leave DB °F	Leave WB °F	Leave HR gr/lb
Main Clg	47.6	571.6	467.7	15,929	80.8	63.8	64.8	53.3	51.3	55.4
Aux Clg	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Opt Vent	0.0	0.0	0.0	2,455	90.9	70.7	84.7	90.9	70.7	84.7
Total	47.6	571.6								

AREAS

	Gross Total	Glass ft²	Glass (%)
Floor	24,162		
Part	0		
Int Door	0		
ExFlr	0		
Roof	24,162	0	0
Wall	9,128	3,300	36
Ext Door	0	0	0

HEATING COIL SELECTION

	Capacity MBh	Coil Airflow cfm	Ent °F	Lvg °F
Main Htg	-220.1	15,700	61.1	74.2
Aux Htg	0.0	0	0.0	0.0
Preheat	0.0	0	0.0	0.0
Humidif	0.0	0	0.0	0.0
Opt Vent	-86.9	2,455	22.0	55.0
Total	-307.0			

Dataset Name: CASE STUDY.TRC

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System Checksums

TYP FLOOR 2_3_4_5

Series Fan-Powered VAV

COOLING COIL PEAK / CLG SPACE PEAK

Peaked at Time: Mo/Hr: 8 / 16 — CLG Space Peak Mo/Hr: 6 / 16

Outside Air: OADB/WB/HR: 92 / 73 / 99 — CLG Space Peak OADB: 96

	Space Sens. + Lat. Btu/h	Plenum Sens. + Lat Btu/h	Net Total Btu/h	Percent Of Total (%)	Space Sensible Btu/h	Percent Of Total (%)
Envelope Loads						
Skylite Solar	0	0	0	0	0	0
Skylite Cond	0	0	0	0	0	0
Roof Cond	0	0	0	0	0	0
Glass Solar	264,136	0	264,136	13	267,042	20
Glass/Door Cond	102,987	0	102,987	5	116,541	9
Wall Cond	27,300	21,434	48,734	2	29,018	2
Partition/Door	0		0	0	0	0
Floor	0		0	0	0	0
Adjacent Floor	0	0	0	0	0	0
Infiltration	0		0	0	0	0
Sub Total ==>	394,423	21,434	415,856	20	412,601	31
Internal Loads						
Lights	298,168	74,542	372,709	18	298,168	22
People	276,067	0	276,067	13	153,371	11
Misc	443,041	0	443,041	21	443,041	33
Sub Total ==>	1,017,276	74,542	1,091,818	52	894,580	67
Ceiling Load	31,382	-31,382	0	0	31,528	2
Ventilation Load	0	0	466,643	22	0	0
Adj Air Trans Heat	0		0	0	0	0
Dehumid. Ov Sizing			0	0		
Ov/Undr Sizing	0		0	0	0	0
Exhaust Heat		-11,094	-11,094	-1		
Sup. Fan Heat			121,497	6		
Ret. Fan Heat		0	0	0		
Duct Heat Pkup		0	0	0		
Underflr Sup Ht Pkup			0	0		
Supply Air Leakage		0	0	0		
Grand Total ==>	1,443,080	53,500	2,084,721	100.00	1,338,709	100.00

HEATING COIL PEAK

Mo/Hr: Heating Design

OADB: 22

	Space Peak Space Sens Btu/h	Coil Peak Tot Sens Btu/h	Percent Of Total (%)
Envelope Loads			
Skylite Solar	0	0	0.00
Skylite Cond	0	0	0.00
Roof Cond	0	0	0.00
Glass Solar	0	0	0.00
Glass/Door Cond	-175,029	-175,029	15.99
Wall Cond	-40,099	-72,354	6.61
Partition/Door	0	0	0.00
Floor	0	0	0.00
Adjacent Floor	0	0	0
Infiltration	0	0	0.00
Sub Total ==>	-215,128	-247,382	22.60
Internal Loads			
Lights	0	0	0.00
People	0	0	0.00
Misc	0	0	0.00
Sub Total ==>	0	0	0.00
Ceiling Load	-10,122	0	0.00
Ventilation Load	0	-166,434	15.20
Adj Air Trans Heat	0	0	0
Ov/Undr Sizing	0	0	0.00
Exhaust Heat		3,496	-0.32
OA Preheat Diff.		-366,156	33.44
RA Preheat Diff.		-318,364	29.08
Additional Reheat		0	0.00
Underflr Sup Ht Pkup		0	0.00
Supply Air Leakage		0	0.00
Grand Total ==>	-225,250	-1,094,841	100.00

TEMPERATURES

	Cooling	Heating
SADB	55.0	73.4
Ra Plenum	76.0	69.7
Return	76.0	69.7
Ret/OA	78.7	64.4
Fn MtrTD	0.1	0.0
Fn BldTD	0.4	0.0
Fn Frict	1.2	0.1

AIRFLOWS

	Cooling	Heating
Diffuser	75,270	62,424
Terminal	75,270	62,424
Main Fan	62,400	28,550
Sec Fan	75,270	49,520
Nom Vent	10,344	10,344
AHU Vent	10,344	10,344
Infil	0	0
MinStop/Rh	28,550	28,550
Return	62,149	28,065
Exhaust	10,093	9,859
Rm Exh	251	485
Auxiliary	0	0
Leakage Dwn	0	0
Leakage Ups	0	0

ENGINEERING CKS

	Cooling	Heating
% OA	16.6	13.7
cfm/ft²	0.65	0.78
cfm/ton	361.56	
ft²/ton	560.00	
Btu/hr-ft²	21.43	-11.51
No. People	613	

COOLING COIL SELECTION

	Total Capacity ton	Total Capacity MBh	Sens Cap. MBh	Coil Airflow cfm	Enter DB °F	Enter WB °F	Enter HR gr/lb	Leave DB °F	Leave WB °F	Leave HR gr/lb
Main Clg	172.6	2,071.0	1,668.1	61,546	78.7	63.2	65.3	53.4	51.4	55.7
Aux Clg	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Opt Vent	0.0	0.0	0.0	10,344	90.9	70.7	84.7	90.9	70.7	84.7
Total	172.6	2,071.0								

AREAS

	Gross Total	Glass ft²	Glass (%)
Floor	96,648		
Part	0		
Int Door	0		
ExFlr	0		
Roof	0	0	0
Wall	36,512	13,200	36
Ext Door	0	0	0

HEATING COIL SELECTION

	Capacity MBh	Coil Airflow cfm	Ent °F	Lvg °F
Main Htg	-746.6	62,424	62.2	73.4
Aux Htg	0.0	0	0.0	0.0
Preheat	0.0	0	0.0	0.0
Humidif	0.0	0	0.0	0.0
Opt Vent	-366.2	10,344	22.0	55.0
Total	-1,112.8			

Dataset Name: CASE STUDY.TRC

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System Checksums

1st fl | Fan Coil

COOLING COIL PEAK / CLG SPACE PEAK

Cooling Coil Peak — Peaked at Time: Mo/Hr: 8 / 16; Outside Air: OADB/WB/HR: 92 / 73 / 99

Clg Space Peak — Mo/Hr: Sum of; OADB: Peaks

	Space Sens. + Lat. Btu/h	Plenum Sens. + Lat Btu/h	Net Total Btu/h	Percent Of Total (%)	Space Sensible Btu/h	Percent Of Total (%)
Envelope Loads						
Skylite Solar	0	0	0	0	0	0
Skylite Cond	0	0	0	0	0	0
Roof Cond	0	0	0	0	0	0
Glass Solar	63,925	0	63,925	13	131,565	34
Glass/Door Cond	25,634	0	25,634	5	29,782	8
Wall Cond	6,567	6,482	13,048	3	4,069	1
Partition/Door	0		0	0	0	0
Floor	0		0	0	0	0
Adjacent Floor	0	0	0	0	0	0
Infiltration	0		0	0	0	0
Sub Total ==>	96,125	6,482	102,607	21	165,416	43
Internal Loads						
Lights	74,569	18,642	93,211	19	74,569	19
People	65,061	0	65,061	13	36,145	9
Misc	104,293	0	104,293	21	102,862	27
Sub Total ==>	243,923	18,642	262,566	54	213,577	55
Ceiling Load	7,277	-7,277	0	0	7,144	2
Ventilation Load	0	0	94,194	19	0	0
Adj Air Trans Heat	0		0	0	0	0
Dehumid. Ov Sizing			0	0		
Ov/Undr Sizing	0		0	0	0	0
Exhaust Heat		-2,105	-2,105	0		
Sup. Fan Heat			29,788	6		
Ret. Fan Heat		0	0	0		
Duct Heat Pkup		0	0	0		
Underflr Sup Ht Pkup			0	0		
Supply Air Leakage		0	0	0		
Grand Total ==>	347,325	15,742	487,049	100.00	386,136	100.00

HEATING COIL PEAK

Mo/Hr: Heating Design; OADB: 22

	Space Peak Space Sens Btu/h	Coil Peak Tot Sens Btu/h	Percent Of Total (%)
Envelope Loads			
Skylite Solar	0	0	0.00
Skylite Cond	0	0	0.00
Roof Cond	0	0	0.00
Glass Solar	0	0	0.00
Glass/Door Cond	-43,757	-43,757	22.66
Wall Cond	-9,863	-19,810	10.26
Partition/Door	0	0	0.00
Floor	-19,342	-19,342	10.02
Adjacent Floor	0	0	0
Infiltration	0	0	0.00
Sub Total ==>	-72,962	-82,909	42.94
Internal Loads			
Lights	0	0	0.00
People	0	0	0.00
Misc	0	0	0.00
Sub Total ==>	0	0	0.00
Ceiling Load	-2,814	0	0.00
Ventilation Load	0	-34,689	17.96
Adj Air Trans Heat	0	0	0
Ov/Undr Sizing	0	0	0.00
Exhaust Heat		814	-0.42
OA Preheat Diff.		-76,315	39.52
RA Preheat Diff.		0	0.00
Additional Reheat		0	0.00
Underflr Sup Ht Pkup		0	0.00
Supply Air Leakage		0	0.00
Grand Total ==>	-75,776	-193,099	100.00

TEMPERATURES

	Cooling	Heating
SADB	55.0	73.9
Ra Plenum	76.0	69.6
Return	76.0	69.6
Ret/OA	77.9	67.9
Fn MtrTD	0.1	0.0
Fn BldTD	0.4	0.0
Fn Frict	1.1	0.0

AIRFLOWS

	Cooling	Heating
Diffuser	17,999	17,999
Terminal	17,999	17,999
Main Fan	17,999	17,999
Sec Fan	0	0
Nom Vent	2,156	2,156
AHU Vent	2,156	2,156
Infil	0	0
MinStop/Rh	0	0
Return	17,883	17,883
Exhaust	2,041	2,041
Rm Exh	115	115
Auxiliary	0	0
Leakage Dwn	0	0
Leakage Ups	0	0

ENGINEERING CKS

	Cooling	Heating
% OA	12.0	12.0
cfm/ft²	0.75	0.75
cfm/ton	443.45	
ft²/ton	588.43	
Btu/hr-ft²	20.39	-8.09
No. People	145	

COOLING COIL SELECTION

	Total Capacity ton	Total Capacity MBh	Sens Cap. MBh	Coil Airflow cfm	Enter DB °F	Enter WB °F	Enter HR gr/lb	Leave DB °F	Leave WB °F	Leave HR gr/lb
Main Clg	40.6	487.1	402.8	17,999	79.4	63.4	65.0	55.0	54.1	63.7
Aux Clg	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Opt Vent	0.0	0.0	0.0	2,156	90.9	70.7	84.7	90.9	70.7	84.7
Total	40.6	487.1								

AREAS

	Gross Total	Glass ft²	Glass (%)
Floor	23,883		
Part	0		
Int Door	0		
ExFlr	552		
Roof	0	0	0
Wall	9,688	3,300	34
Ext Door	0	0	0

HEATING COIL SELECTION

	Capacity MBh	Coil Airflow cfm	Ent °F	Lvg °F
Main Htg	-116.8	17,999	67.9	73.9
Aux Htg	0.0	0	0.0	0.0
Preheat	0.0	0	0.0	0.0
Humidif	0.0	0	0.0	0.0
Opt Vent	-76.3	2,156	22.0	55.0
Total	-193.1			

System Checksums

elevator machine room

Fan Coil

COOLING COIL PEAK / CLG SPACE PEAK

Cooling Coil Peak — Peaked at Time: Mo/Hr: 6 / 18; Outside Air: OADB/WB/HR: 92 / 70 / 77

Clg Space Peak — Mo/Hr: Sum of; OADB: Peaks

	Space Sens. + Lat. Btu/h	Plenum Sens. + Lat Btu/h	Net Total Btu/h	Percent Of Total (%)	Space Sensible Btu/h	Percent Of Total (%)
Envelope Loads						
Skylite Solar	0	0	0	0	0	0
Skylite Cond	0	0	0	0	0	0
Roof Cond	0	1,709	1,709	5	0	0
Glass Solar	0	0	0	0	0	0
Glass/Door Cond	0	0	0	0	0	0
Wall Cond	1,868	712	2,580	8	1,868	6
Partition/Door	0		0	0	0	0
Floor	0		0	0	0	0
Adjacent Floor	0	0	0	0	0	0
Infiltration	732		732	2	292	1
Sub Total ==>	2,601	2,421	5,022	15	2,160	7
Internal Loads						
Lights	0	0	0	0	0	0
People	0	0	0	0	0	0
Misc	27,435	0	27,435	84	27,435	91
Sub Total ==>	27,435	0	27,435	84	27,435	91
Ceiling Load	457	-457	0	0	457	2
Ventilation Load	0	0	0	0	0	0
Adj Air Trans Heat	0		0	0	0	0
Dehumid. Ov Sizing			0	0		
Ov/Undr Sizing	0		0	0	0	0
Exhaust Heat		-39	-39	0		
Sup. Fan Heat			181	1		
Ret. Fan Heat		0	0	0		
Duct Heat Pkup		0	0	0		
Underflr Sup Ht Pkup			0	0		
Supply Air Leakage		0	0	0		
Grand Total ==>	30,492	1,926	32,599	100.00	30,052	100.00

HEATING COIL PEAK

Mo/Hr: Heating Design; OADB: 22

	Space Peak Space Sens Btu/h	Coil Peak Tot Sens Btu/h	Percent Of Total (%)
Envelope Loads			
Skylite Solar	0	0	0.00
Skylite Cond	0	0	0.00
Roof Cond	0	-1,214	26.86
Glass Solar	0	0	0.00
Glass/Door Cond	0	0	0.00
Wall Cond	-1,835	-2,540	56.20
Partition/Door	0	0	0.00
Floor	0	0	0.00
Adjacent Floor	0	0	0
Infiltration	-796	-796	17.62
Sub Total ==>	-2,631	-4,550	100.68
Internal Loads			
Lights	0	0	0.00
People	0	0	0.00
Misc	0	0	0.00
Sub Total ==>	0	0	0.00
Ceiling Load	-362	0	0.00
Ventilation Load	0	0	0.00
Adj Air Trans Heat	0	0	0
Ov/Undr Sizing	0	0	0.00
Exhaust Heat		31	-0.68
OA Preheat Diff.		0	0.00
RA Preheat Diff.		0	0.00
Additional Reheat		0	0.00
Underflr Sup Ht Pkup		0	0.00
Supply Air Leakage		0	0.00
Grand Total ==>	-2,993	-4,520	100.00

TEMPERATURES

	Cooling	Heating
SADB	55.0	57.5
Ra Plenum	81.6	53.7
Return	81.6	53.7
Ret/OA	81.6	53.7
Fn MtrTD	0.0	0.0
Fn BldTD	0.0	0.0
Fn Frict	0.1	0.0

AIRFLOWS

	Cooling	Heating
Diffuser	1,121	1,121
Terminal	1,121	1,121
Main Fan	1,121	1,121
Sec Fan	0	0
Nom Vent	0	0
AHU Vent	0	0
Infil	23	23
MinStop/Rh	0	0
Return	1,143	1,143
Exhaust	23	23
Rm Exh	0	0
Auxiliary	0	0
Leakage Dwn	0	0
Leakage Ups	0	0

ENGINEERING CKS

	Cooling	Heating
% OA	0.0	0.0
cfm/ft²	1.25	1.25
cfm/ton	412.51	
ft²/ton	331.30	
Btu/hr-ft²	36.22	-5.02
No. People	0	

COOLING COIL SELECTION

	Total Capacity ton	Total Capacity MBh	Sens Cap. MBh	Coil Airflow cfm	Enter DB °F	Enter WB °F	Enter HR gr/lb	Leave DB °F	Leave WB °F	Leave HR gr/lb
Main Clg	2.7	32.6	32.2	1,121	81.8	60.5	48.0	55.0	49.9	47.2
Aux Clg	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Opt Vent	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Total	2.7	32.6								

AREAS

	Gross Total	Glass ft²	Glass (%)
Floor	900		
Part	0		
Int Door	0		
ExFlr	0		
Roof	900	0	0
Wall	1,200	0	0
Ext Door	0	0	0

HEATING COIL SELECTION

	Capacity MBh	Coil Airflow cfm	Ent °F	Lvg °F
Main Htg	-4.5	1,121	53.7	57.5
Aux Htg	0.0	0	0.0	0.0
Preheat	-1.4	1,121	53.7	54.9
Humidif	0.0	0	0.0	0.0
Opt Vent	0.0	0	0.0	0.0
Total	-4.5			

System Checksums

top floor

Fan Coil

COOLING COIL PEAK / CLG SPACE PEAK

Peaked at Time: Mo/Hr: 7 / 15 — CLG Space Peak Mo/Hr: Sum of

Outside Air: OADB/WB/HR: 92 / 74 / 102 — CLG Space Peak OADB: Peaks

	Space Sens. + Lat. Btu/h	Plenum Sens. + Lat Btu/h	Net Total Btu/h	Percent Of Total (%)	Space Sensible Btu/h	Percent Of Total (%)
Envelope Loads						
Skylite Solar	0	0	0	0	0	0
Skylite Cond	0	0	0	0	0	0
Roof Cond	0	67,911	67,911	12	0	0
Glass Solar	57,404	0	57,404	10	134,973	33
Glass/Door Cond	25,757	0	25,757	5	30,146	7
Wall Cond	6,217	4,501	10,718	2	4,397	1
Partition/Door	0		0	0	0	0
Floor	0		0	0	0	0
Adjacent Floor	0	0	0	0	0	0
Infiltration	0		0	0	0	0
Sub Total ==>	89,378	72,411	161,789	29	169,516	41
Internal Loads						
Lights	74,542	18,635	93,177	16	74,542	18
People	69,017	0	69,017	12	38,343	9
Misc	110,604	0	110,604	20	109,492	26
Sub Total ==>	254,163	18,635	272,798	48	222,376	54
Ceiling Load	25,228	-25,228	0	0	22,470	5
Ventilation Load	0	0	102,176	18	0	0
Adj Air Trans Heat	0		0	0	0	0
Dehumid. Ov Sizing			0	0		
Ov/Undr Sizing	7		7	0	7	0
Exhaust Heat		-7,362	-7,362	-1		
Sup. Fan Heat			35,469	6		
Ret. Fan Heat		0	0	0		
Duct Heat Pkup		0	0	0		
Underflr Sup Ht Pkup			0	0		
Supply Air Leakage		0	0	0		
Grand Total ==>	368,776	58,456	564,877	100.00	414,369	100.00

HEATING COIL PEAK

Mo/Hr: Heating Design

OADB: 22

	Space Peak Space Sens Btu/h	Coil Peak Tot Sens Btu/h	Percent Of Total (%)
Envelope Loads			
Skylite Solar	0	0	0.00
Skylite Cond	0	0	0.00
Roof Cond	0	-47,287	21.63
Glass Solar	0	0	0.00
Glass/Door Cond	-43,757	-43,757	20.01
Wall Cond	-10,025	-17,814	8.15
Partition/Door	0	0	0.00
Floor	0	0	0.00
Adjacent Floor	0	0	0
Infiltration	0	0	0.00
Sub Total ==>	-53,782	-108,859	49.79
Internal Loads			
Lights	0	0	0.00
People	0	0	0.00
Misc	0	0	0.00
Sub Total ==>	0	0	0.00
Ceiling Load	-14,936	0	0.00
Ventilation Load	0	-35,665	16.31
Adj Air Trans Heat	0	0	0
Ov/Undr Sizing	0	0	0.00
Exhaust Heat		4,359	-1.99
OA Preheat Diff.		-78,463	35.89
RA Preheat Diff.		0	0.00
Additional Reheat		0	0.00
Underflr Sup Ht Pkup		0	0.00
Supply Air Leakage		0	0.00
Grand Total ==>	-68,718	-218,628	100.00

TEMPERATURES

	Cooling	Heating
SADB	55.0	73.3
Ra Plenum	78.3	68.1
Return	78.3	68.1
Ret/OA	79.9	66.6
Fn MtrTD	0.1	0.0
Fn BldTD	0.4	0.0
Fn Frict	1.2	0.0

AIRFLOWS

	Cooling	Heating
Diffuser	19,315	19,315
Terminal	19,315	19,315
Main Fan	19,315	19,315
Sec Fan	0	0
Nom Vent	2,217	2,217
AHU Vent	2,217	2,217
Infil	0	0
MinStop/Rh	0	0
Return	19,181	19,181
Exhaust	2,083	2,083
Rm Exh	134	134
Auxiliary	0	0
Leakage Dwn	0	0
Leakage Ups	0	0

ENGINEERING CKS

	Cooling	Heating
% OA	11.5	11.5
cfm/ft²	0.80	0.80
cfm/ton	410.31	
ft²/ton	513.29	
Btu/hr·ft²	23.38	-9.05
No. People	153	

COOLING COIL SELECTION

	Total Capacity ton	Total Capacity MBh	Sens Cap. MBh	Coil Airflow cfm	Enter DB °F	Enter WB °F	Enter HR gr/lb	Leave DB °F	Leave WB °F	Leave HR gr/lb
Main Clg	47.1	564.9	472.5	19,315	81.6	64.2	65.6	55.0	54.3	64.5
Aux Clg	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Opt Vent	0.0	0.0	0.0	2,217	90.9	70.7	84.7	90.9	70.7	84.7
Total	47.1	564.9								

AREAS

	Gross Total	Glass ft²	Glass (%)
Floor	24,162		
Part	0		
Int Door	0		
ExFlr	0		
Roof	24,162	0	0
Wall	9,128	3,300	36
Ext Door	0	0	0

HEATING COIL SELECTION

	Capacity MBh	Coil Airflow cfm	Ent °F	Lvg °F
Main Htg	-140.2	19,315	66.6	73.3
Aux Htg	0.0	0	0.0	0.0
Preheat	0.0	0	0.0	0.0
Humidif	0.0	0	0.0	0.0
Opt Vent	-78.5	2,217	22.0	55.0
Total	-218.6			

System Checksums

TYP FLOOR 2_3_4_5

Fan Coil

COOLING COIL PEAK / CLG SPACE PEAK

Peaked at Time: Mo/Hr: 8 / 16 — Outside Air: OADB/WB/HR: 92 / 73 / 99

CLG SPACE PEAK: Mo/Hr: Sum of — OADB: Peaks

	Space Sens. + Lat. Btu/h	Plenum Sens. + Lat Btu/h	Net Total Btu/h	Percent Of Total (%)	Space Sensible Btu/h	Percent Of Total (%)
Envelope Loads						
Skylite Solar	0	0	0	0	0	0
Skylite Cond	0	0	0	0	0	0
Roof Cond	0	0	0	0	0	0
Glass Solar	264,136	0	264,136	13	554,914	35
Glass/Door Cond	102,987	0	102,987	5	118,606	7
Wall Cond	27,300	21,523	48,823	2	16,283	1
Partition/Door	0		0	0	0	0
Floor	0		0	0	0	0
Adjacent Floor	0	0	0	0	0	0
Infiltration	0		0	0	0	0
Sub Total ==>	394,423	21,523	415,946	21	689,803	43
Internal Loads						
Lights	298,168	74,542	372,709	18	298,168	19
People	276,067	0	276,067	14	153,371	10
Misc	443,041	0	443,041	22	439,921	27
Sub Total ==>	1,017,276	74,542	1,091,818	54	891,460	55
Ceiling Load	27,228	-27,228	0	0	26,875	2
Ventilation Load	0	0	386,737	19	0	0
Adj Air Trans Heat	0		0	0	0	0
Dehumid. Ov Sizing			0	0		
Ov/Undr Sizing	0		0	0	0	0
Exhaust Heat		-7,946	-7,946	0		
Sup. Fan Heat			131,278	7		
Ret. Fan Heat		0	0	0		
Duct Heat Pkup		0	0	0		
Underflr Sup Ht Pkup			0	0		
Supply Air Leakage		0	0	0		
Grand Total ==>	1,438,927	60,892	2,017,834	100.00	1,608,137	100.00

HEATING COIL PEAK

Mo/Hr: Heating Design — OADB: 22

	Space Peak Space Sens Btu/h	Coil Peak Tot Sens Btu/h	Percent Of Total (%)
Envelope Loads			
Skylite Solar	0	0	0.00
Skylite Cond	0	0	0.00
Roof Cond	0	0	0.00
Glass Solar	0	0	0.00
Glass/Door Cond	-175,029	-175,029	24.96
Wall Cond	-40,099	-72,380	10.32
Partition/Door	0	0	0.00
Floor	0	0	0.00
Adjacent Floor	0	0	0
Infiltration	0	0	0.00
Sub Total ==>	-215,128	-247,408	35.28
Internal Loads			
Lights	0	0	0.00
People	0	0	0.00
Misc	0	0	0.00
Sub Total ==>	0	0	0.00
Ceiling Load	-8,950	0	0.00
Ventilation Load	0	-142,660	20.34
Adj Air Trans Heat	0	0	0
Ov/Undr Sizing	0	0	0.00
Exhaust Heat		2,612	-0.37
OA Preheat Diff.		-313,853	44.75
RA Preheat Diff.		0	0.00
Additional Reheat		0	0.00
Underflr Sup Ht Pkup		0	0.00
Supply Air Leakage		0	0.00
Grand Total ==>	-224,078	-701,310	100.00

TEMPERATURES

	Cooling	Heating
SADB	55.0	72.8
Ra Plenum	75.9	69.7
Return	75.9	69.7
Ret/OA	77.8	68.0
Fn MtrTD	0.1	0.0
Fn BldTD	0.4	0.0
Fn Frict	1.2	0.0

AIRFLOWS

	Cooling	Heating
Diffuser	74,959	74,959
Terminal	74,959	74,959
Main Fan	74,959	74,959
Sec Fan	0	0
Nom Vent	8,866	8,866
AHU Vent	8,866	8,866
Infil	0	0
MinStop/Rh	0	0
Return	74,424	74,424
Exhaust	8,331	8,331
Rm Exh	535	535
Auxiliary	0	0
Leakage Dwn	0	0
Leakage Ups	0	0

ENGINEERING CKS

	Cooling	Heating
% OA	11.8	11.8
cfm/ft²	0.78	0.78
cfm/ton	445.78	
ft²/ton	574.76	
Btu/hr-ft²	20.88	-7.26
No. People	613	

COOLING COIL SELECTION

	Total Capacity ton	Total Capacity MBh	Sens Cap. MBh	Coil Airflow cfm	Enter DB °F	Enter WB °F	Enter HR gr/lb	Leave DB °F	Leave WB °F	Leave HR gr/lb
Main Clg	168.2	2,017.8	1,668.2	74,959	79.4	63.4	65.2	55.0	54.2	64.0
Aux Clg	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Opt Vent	0.0	0.0	0.0	8,866	90.9	70.7	84.7	90.9	70.7	84.7
Total	168.2	2,017.8								

AREAS

	Gross Total	Glass ft²	Glass (%)
Floor	96,648		
Part	0		
Int Door	0		
ExFlr	0		
Roof	0	0	0
Wall	36,512	13,200	36
Ext Door	0	0	0

HEATING COIL SELECTION

	Capacity MBh	Coil Airflow cfm	Ent °F	Lvg °F
Main Htg	-387.5	74,959	68.0	72.8
Aux Htg	0.0	0	0.0	0.0
Preheat	0.0	0	0.0	0.0
Humidif	0.0	0	0.0	0.0
Opt Vent	-313.9	8,866	22.0	55.0
Total	-701.3			

EQUIPMENT ENERGY CONSUMPTION

Alternative: 1 Self-contained+VAV+PFP

Equipment - Utility		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
		------- Monthly Consumption -------												
Lights														
	Electric (kWh)	48,882.2	44,557.6	52,617.2	47,710.9	50,749.7	50,553.1	47,907.5	52,617.1	47,710.9	50,749.7	48,685.7	47,907.5	590,649.1
	Peak (kW)	163.8	163.8	163.8	163.8	163.8	163.8	163.8	163.8	163.8	163.8	163.8	163.8	163.8
MISC LD														
	Electric (kWh)	56,079.8	51,133.5	60,322.2	54,789.5	58,200.9	57,966.4	55,024.1	60,322.2	54,789.5	58,201.0	55,845.1	55,024.0	677,698.1
	Peak (kW)	195.5	195.5	195.5	195.5	195.5	195.5	195.5	195.5	195.5	195.5	195.5	195.5	195.5
Cooling Coil Condensate														
	Recoverable Water (1000gal)	0.3	0.2	0.2	5.1	10.0	20.6	24.3	25.9	15.0	2.4	1.8	0.9	106.6
	Peak (1000gal/Hr)	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.1
Bsu 1: water heater														
	Electric (kWh)	1,433.1	1,296.6	1,569.6	1,364.9	1,501.4	1,501.4	1,364.9	1,569.6	1,364.9	1,501.4	1,433.1	1,364.9	17,265.7
	Peak (kW)	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7
Bsu 2: Hot Water Recirc Pump														
	Electric (kWh)	14.8	13.4	16.2	14.1	15.5	15.5	14.1	16.2	14.1	15.5	14.8	14.1	178.4
	Peak (kW)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Bsu 3: exterior lighting														
	Electric (kWh)	2,849.2	2,573.5	2,849.2	2,757.3	2,849.2	2,757.3	2,849.2	2,849.2	2,757.3	2,849.2	2,757.3	2,849.2	33,547.2
	Peak (kW)	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1
Bsu 4: elevator motor														
	Electric (kWh)	11,044.5	10,119.5	11,969.5	10,915.0	11,507.0	11,507.0	10,915.0	11,969.5	10,915.0	11,507.0	11,044.5	10,915.0	134,328.5
	Peak (kW)	59.2	59.2	59.2	59.2	59.2	59.2	59.2	59.2	59.2	59.2	59.2	59.2	59.2
Cpl 1: Elevator Machine Rm [Sum of dsn coil capacities=2.72 tons]														
Elevator Machine Room Split [Clg Nominal Capacity/F.L.Rate=5 tons / 4.15 kW] (Cooling Equipment)														
	Electric (kWh)	114.7	107.7	185.5	227.3	298.6	383.6	348.3	377.3	306.9	217.6	185.1	138.7	2,891.4
	Peak (kW)	1.1	1.0	1.2	1.4	1.6	1.9	1.8	1.8	1.7	1.3	1.2	1.1	1.9
Cond fan for Recip < 15ton														
	Electric (kWh)	32.1	30.1	50.2	57.1	70.8	85.1	79.1	85.8	71.5	55.7	48.6	38.8	704.6
	Peak (kW)	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.4
Cntl panel & interlocks - 0.125 KW (Misc Accessory Equipment)														
	Electric (kWh)	24.8	23.4	36.9	42.9	52.5	66.3	61.8	63.9	51.4	41.6	38.4	30.3	533.9
	Peak (kW)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Cpl 2: Dedicated OA [Sum of dsn coil capacities=0.00 tons]														
Cpl 3: WSCS Units [Sum of dsn coil capacities=269.0 tons]														

Project Name:
ataset Name: CASE STUDY.TRC

Alternative - 1 Equipment Energy Consumption report page 1 of 15

EQUIPMENT ENERGY CONSUMPTION

Alternative: 1 Self-contained+VAV+PFP

Equipment - Utility	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
					------- Monthly Consumption -------								
Cpl 3: WSCS Units [Sum of dsn coil capacities=269.0 tons]													
Whole Building WCSC [Clg Nominal Capacity/F.L.Rate=269.0 tons / 207.9 kW] (Cooling Equipment)													
Electric (kWh)	17,171.1	15,746.6	20,464.2	24,617.5	35,547.8	52,812.3	52,235.6	55,753.9	39,852.4	22,818.2	20,593.9	17,897.9	375,511.4
Peak (kW)	72.5	70.8	85.2	143.3	183.5	205.5	207.6	207.4	189.5	106.2	96.5	80.0	207.6
Ballantyne 6 story													
Electric (kWh)	1,722.8	1,710.3	1,786.6	2,993.5	5,407.8	6,560.6	6,431.9	6,524.4	5,695.9	2,546.3	2,148.7	1,614.5	45,132.0
Peak (kW)	11.6	12.2	6.8	13.2	13.2	13.2	13.2	13.2	13.2	13.2	10.5	5.5	13.2
Ballantyne 6 story													
Recoverable Water (1000gal)	48.1	43.9	56.8	66.9	92.7	126.6	123.4	132.4	99.9	63.2	57.2	49.4	960.5
Peak (1000gal/Hr)	0.2	0.2	0.2	0.4	0.5	0.5	0.5	0.5	0.5	0.3	0.3	0.2	0.5
VV Cond Wtr Pump (12 F Delta T) (Misc Accessory Equipment)													
Electric (kWh)	1,053.7	962.9	1,277.0	1,741.7	2,818.0	5,028.7	5,029.0	5,371.2	3,378.3	1,512.9	1,331.5	1,095.3	30,600.1
Peak (kW)	4.8	4.6	6.2	14.0	23.8	23.8	23.8	23.8	23.8	8.6	7.6	5.6	23.8
Cntl panel & interlocks - 1 KW (Misc Accessory Equipment)													
Electric (kWh)	378.0	372.0	423.0	385.0	475.0	496.0	487.0	494.0	463.0	409.0	401.0	400.0	5,183.0
Peak (kW)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Hpl 1: Electric [Sum of dsn coil capacities=1,895 mbh]													
Electric Resistance - 001 [Nominal Capacity/F.L.Rate=2,064 mbh / 605 kW] (Heating Equipment)													
Electric (kWh)	43,936.8	43,062.3	15,224.8	915.2	0.0	0.0	0.0	0.0	0.0	4,804.0	10,059.9	25,860.0	143,863.0
Peak (kW)	309.8	316.4	236.6	61.7	0.0	0.0	0.0	0.0	0.0	108.5	170.3	259.3	316.4
Sys 1: top floor													
FC w/VFD Crit. Zone Reset [DsnAirflow/F.L.Rate=16,501 cfm / 12.50 kW] (Main Clg Fan)													
Electric (kWh)	538.0	494.9	744.0	877.4	1,373.0	1,995.9	1,747.0	1,984.9	1,356.7	810.1	727.2	570.7	13,219.8
Peak (kW)	2.5	2.5	4.1	12.5	12.5	12.5	12.5	12.5	12.5	5.7	4.9	3.2	12.5
Parallel Fan Powered VAV [DsnAirflow/F.L.Rate=5,160 cfm / 0.25 kW] (Main Htg Fan)													
Electric (kWh)	46.3	38.6	6.4	0.0	0.0	0.0	0.0	0.0	0.0	0.8	6.0	33.1	131.2
Peak (kW)	0.3	0.3	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.3	0.3
FC Centrifugal var freq drv [DsnAirflow/F.L.Rate=700 cfm / 0.30 kW] (Room Exhaust Fan)													
Electric (kWh)	2.8	2.6	3.0	2.8	2.9	2.9	2.7	3.0	2.7	2.9	2.8	2.7	33.7
Peak (kW)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FC Centrifugal var freq drv [DsnAirflow/F.L.Rate=3,164 cfm / 2.15 kW] (System Exhaust Fan)													
Electric (kWh)	407.9	373.1	444.4	399.5	427.6	430.7	404.3	448.1	405.6	426.2	409.8	400.8	4,977.8
Peak (kW)	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3

EQUIPMENT ENERGY CONSUMPTION

Alternative: 1 Self-contained+VAV+PFP

Equipment - Utility	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
					------- Monthly Consumption -------								
Sys 1: top floor													
FC Centrifugal var freq drv [DsnAirflow/F.L.Rate=2,955 cfm / 1.87 kW] (Opt. Ventilation Fan)													
Electric (kWh)	604.7	552.3	657.3	592.0	628.0	630.5	592.5	656.1	592.8	631.2	605.0	592.5	7,335.0
Peak (kW)	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9
Sys 2: TYP FLOOR 2_3_4_5													
FC w/VFD Crit. Zone Reset [DsnAirflow/F.L.Rate=62,400 cfm / 45.29 kW] (Main Clg Fan)													
Electric (kWh)	3,382.7	3,087.3	3,725.5	3,914.0	5,965.4	8,080.3	6,986.8	7,761.4	5,838.2	3,678.9	3,498.0	3,345.3	59,263.7
Peak (kW)	12.7	11.9	14.4	32.8	45.3	45.3	45.3	45.3	45.3	19.0	17.4	13.6	45.3
Parallel Fan Powered VAV [DsnAirflow/F.L.Rate=16,021 cfm / 0.25 kW] (Main Htg Fan)													
Electric (kWh)	58.4	50.2	20.2	0.4	0.0	0.0	0.0	0.0	0.0	6.3	18.9	44.6	198.9
Peak (kW)	0.3	0.3	0.3	0.2	0.0	0.0	0.0	0.0	0.0	0.2	0.3	0.3	0.3
FC Centrifugal var freq drv [DsnAirflow/F.L.Rate=2,800 cfm / 1.19 kW] (Room Exhaust Fan)													
Electric (kWh)	10.5	9.6	11.4	10.7	11.1	10.6	10.1	11.1	10.3	11.0	10.4	10.3	127.1
Peak (kW)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FC Centrifugal var freq drv [DsnAirflow/F.L.Rate=12,656 cfm / 8.58 kW] (System Exhaust Fan)													
Electric (kWh)	1,641.8	1,501.3	1,786.9	1,602.1	1,727.1	1,734.5	1,612.1	1,804.9	1,626.8	1,714.7	1,643.6	1,608.0	20,003.6
Peak (kW)	5.2	5.1	5.2	5.2	5.2	5.3	5.3	5.3	5.2	5.2	5.2	5.2	5.3
FC Centrifugal var freq drv [DsnAirflow/F.L.Rate=11,821 cfm / 7.50 kW] (Opt. Ventilation Fan)													
Electric (kWh)	2,396.8	2,188.5	2,606.3	2,342.7	2,501.0	2,499.4	2,322.5	2,604.4	2,346.1	2,502.8	2,397.6	2,343.0	29,050.9
Peak (kW)	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Sys 3: 1st fl													
FC w/VFD Crit. Zone Reset [DsnAirflow/F.L.Rate=15,128 cfm / 9.02 kW] (Main Clg Fan)													
Electric (kWh)	392.7	358.5	477.9	644.8	955.9	1,314.7	1,167.2	1,287.5	964.5	556.1	471.1	399.1	8,990.0
Peak (kW)	1.6	1.5	2.0	7.1	9.0	9.0	9.0	9.0	9.0	2.9	2.5	1.7	9.0
Parallel Fan Powered VAV [DsnAirflow/F.L.Rate=18,067 cfm / 7.65 kW] (Main Htg Fan)													
Electric (kWh)	2,981.7	2,756.6	2,873.5	2,688.9	3,121.6	3,226.9	3,136.0	3,248.2	2,988.3	2,748.3	2,692.7	2,874.0	35,336.6
Peak (kW)	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7
FC Centrifugal var freq drv [DsnAirflow/F.L.Rate=700 cfm / 0.30 kW] (Room Exhaust Fan)													
Electric (kWh)	2.3	2.2	2.6	2.2	2.3	2.2	2.1	2.3	2.1	2.4	2.3	2.3	27.2
Peak (kW)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FC Centrifugal var freq drv [DsnAirflow/F.L.Rate=2,741 cfm / 1.86 kW] (System Exhaust Fan)													
Electric (kWh)	330.4	302.6	359.3	328.5	353.4	356.4	335.7	370.4	334.8	348.4	331.2	325.5	4,076.8
Peak (kW)	1.1	1.0	1.0	1.1	1.1	1.1	1.1	1.1	1.1	1.0	1.0	1.0	1.1

Project Name:
ataset Name: CASE STUDY.TRC

Alternative - 1 Equipment Energy Consumption report page 3 of 15

EQUIPMENT ENERGY CONSUMPTION

Alternative: 1 Self-contained+VAV+PFP

------- Monthly Consumption -------

Equipment - Utility	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Sys 3: 1st fl													
FC Centrifugal var freq drv [DsnAirflow/F.L.Rate=2,510 cfm / 1.59 kW] (Opt. Ventilation Fan)													
Electric (kWh)	518.6	474.3	563.1	508.5	542.7	542.9	511.7	565.0	511.6	543.4	518.8	509.5	6,310.1
Peak (kW)	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Sys 4: elevator machine room													
FC Centrifugal const vol [DsnAirflow/F.L.Rate=1,120 cfm / 0.51 kW] (Main Clg Fan)													
Electric (kWh)	182.1	158.1	189.7	174.1	186.4	190.3	178.9	196.4	176.8	183.5	175.3	171.2	2,162.8
Peak (kW)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5

EQUIPMENT ENERGY CONSUMPTION

Alternative: 2 90_1 Appendix G Chilled Water VAV

------- Monthly Consumption -------

Equipment - Utility		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Lights														
	Electric (kWh)	50,663.5	46,181.2	54,534.6	49,449.6	52,599.0	52,395.3	49,653.3	54,534.6	49,449.6	52,599.1	50,459.8	49,653.3	612,172.8
	Peak (kW)	169.8	169.8	169.8	169.8	169.8	169.8	169.8	169.8	169.8	169.8	169.8	169.8	169.8
MISC LD														
	Electric (kWh)	56,079.8	51,133.5	60,322.2	54,789.5	58,200.9	57,966.4	55,024.1	60,322.2	54,789.5	58,201.0	55,845.1	55,024.0	677,698.1
	Peak (kW)	195.5	195.5	195.5	195.5	195.5	195.5	195.5	195.5	195.5	195.5	195.5	195.5	195.5
Cooling Coil Condensate														
	Recoverable Water (1000gal)	0.6	0.5	0.6	4.3	9.1	19.9	23.8	25.3	14.2	1.8	1.7	1.0	102.7
	Peak (1000gal/Hr)	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.1
Bsu 1: water heater														
	Electric (kWh)	1,433.1	1,296.6	1,569.6	1,364.9	1,501.4	1,501.4	1,364.9	1,569.6	1,364.9	1,501.4	1,433.1	1,364.9	17,265.7
	Peak (kW)	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7
Bsu 2: Hot Water Recirc Pump														
	Electric (kWh)	14.8	13.4	16.2	14.1	15.5	15.5	14.1	16.2	14.1	15.5	14.8	14.1	178.4
	Peak (kW)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Bsu 3: exterior lighting														
	Electric (kWh)	2,849.2	2,573.5	2,849.2	2,757.3	2,849.2	2,757.3	2,849.2	2,849.2	2,757.3	2,849.2	2,757.3	2,849.2	33,547.2
	Peak (kW)	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1
Bsu 4: elevator motor														
	Electric (kWh)	11,044.5	10,119.5	11,969.5	10,915.0	11,507.0	11,507.0	10,915.0	11,969.5	10,915.0	11,507.0	11,044.5	10,915.0	134,328.5
	Peak (kW)	59.2	59.2	59.2	59.2	59.2	59.2	59.2	59.2	59.2	59.2	59.2	59.2	59.2
Cpl 1: Elevator Machine Rm [Sum of dsn coil capacities=3.05 tons]														
Elevator Machine Room Split [Clg Nominal Capacity/F.L.Rate=5 tons / 4.15 kW] (Cooling Equipment)														
	Electric (kWh)	78.1	68.8	150.6	209.3	296.4	406.4	364.2	391.5	308.4	192.3	155.6	102.4	2,723.8
	Peak (kW)	1.0	1.0	1.2	1.4	1.7	2.0	2.0	2.0	1.8	1.4	1.3	1.1	2.0
Cond fan for Recip < 15ton														
	Electric (kWh)	21.7	19.1	40.5	52.3	70.1	90.0	82.6	89.0	71.8	48.9	40.6	28.6	655.3
	Peak (kW)	0.3	0.3	0.3	0.4	0.4	0.5	0.4	0.4	0.4	0.4	0.3	0.3	0.5
Cntl panel & interlocks - 0.125 KW (Misc Accessory Equipment)														
	Electric (kWh)	20.8	19.0	27.9	34.6	45.8	56.0	54.5	56.5	45.6	30.9	28.0	23.6	443.1
	Peak (kW)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Cpl 2: Air-Cooled Chiller [Sum of dsn coil capacities=342.2 tons]														

Project Name:
ataset Name: CASE STUDY.TRC

Alternative - 2 Equipment Energy Consumption report page 5 of 15

EQUIPMENT ENERGY CONSUMPTION

Alternative: 2 90_1 Appendix G Chilled Water VAV

------- Monthly Consumption -------

Equipment - Utility	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Cpl 2: Air-Cooled Chiller [Sum of dsn coil capacities=342.2 tons]													
Air-cooled chiller - 004 [Clg Nominal Capacity/F.L.Rate=342.2 tons / 342.2 kW] (Cooling Equipment)													
Electric (kWh)	12,323.1	11,090.2	15,549.4	22,322.8	35,685.6	57,971.8	52,892.6	56,749.6	40,240.9	19,811.2	16,927.4	12,598.5	354,163.1
Peak (kW)	59.0	58.7	65.9	124.2	181.5	247.4	232.0	233.5	196.7	100.5	80.3	59.7	247.4
MZ packaged rooftop cond fan													
Electric (kWh)	2,816.7	2,548.0	3,358.7	3,991.4	5,463.4	7,718.5	7,328.5	7,877.3	5,860.3	3,744.2	3,365.4	2,848.2	56,920.4
Peak (kW)	12.1	12.1	12.5	18.7	23.1	30.0	29.5	29.6	25.0	15.9	13.6	12.3	30.0
Cnst vol chill water pump (Misc Accessory Equipment)													
Electric (kWh)	2,666.1	2,573.6	2,958.9	2,866.4	3,521.4	3,598.4	3,660.1	3,652.4	3,428.9	2,951.2	2,774.0	2,858.7	37,509.9
Peak (kW)	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7
Cntl panel & interlocks - 0.1 KW (Misc Accessory Equipment)													
Electric (kWh)	34.6	33.4	38.4	37.2	45.7	46.7	47.5	47.4	44.5	38.3	36.0	37.1	486.8
Peak (kW)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Hpl 1: Electric [Sum of dsn coil capacities=2,637 mbh]													
Electric Resistance - 001 [Nominal Capacity/F.L.Rate=2,064 mbh / 605 kW] (Heating Equipment)													
Electric (kWh)	98,262.4	92,587.5	50,596.1	17,894.2	4,817.3	0.0	0.0	0.0	1,218.8	27,032.9	38,599.1	71,068.1	402,076.4
Peak (kW)	438.8	445.9	384.8	306.8	231.9	0.0	0.0	0.0	104.0	331.0	353.5	386.3	445.9
Sys 1: top floor													
90.1-04 Min VAV FC Centrifugal [DsnAirflow/F.L.Rate=20,794 cfm / 25.59 kW] (Main Clg Fan)													
Electric (kWh)	1,649.7	1,482.2	2,113.6	2,534.0	3,217.7	4,291.9	3,690.6	4,078.9	3,262.3	2,187.4	2,018.0	1,749.7	32,276.0
Peak (kW)	7.1	7.1	8.2	20.9	25.6	25.6	25.6	25.6	25.6	9.0	8.3	7.6	25.6
Parallel Fan Powered VAV [DsnAirflow/F.L.Rate=6,053 cfm / 2.49 kW] (Main Htg Fan)													
Electric (kWh)	928.0	807.6	468.2	171.9	4.4	0.0	0.0	0.0	0.0	256.6	396.3	751.6	3,784.7
Peak (kW)	2.5	2.5	2.5	2.3	0.4	0.0	0.0	0.0	0.0	2.5	2.5	2.5	2.5
FC Centrifugal vav/inlet vn [DsnAirflow/F.L.Rate=700 cfm / 0.52 kW] (Room Exhaust Fan)													
Electric (kWh)	4.7	4.3	5.6	5.4	5.9	5.7	5.5	5.9	5.3	5.4	5.0	4.8	63.4
Peak (kW)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FC Centrifugal vav/inlet vn [DsnAirflow/F.L.Rate=3,143 cfm / 2.81 kW] (System Exhaust Fan)													
Electric (kWh)	616.4	564.6	663.0	597.6	632.4	635.0	599.2	660.3	600.6	635.5	611.6	605.5	7,421.7
Peak (kW)	2.0	2.0	2.0	2.0	1.9	1.9	1.9	1.9	1.9	2.0	2.0	2.0	2.0
FC Centrifugal vav/inlet vn [DsnAirflow/F.L.Rate=2,955 cfm / 3.12 kW] (Opt. Ventilation Fan)													
Electric (kWh)	1,030.1	942.7	1,117.5	1,014.6	1,075.0	1,075.8	1,017.0	1,119.4	1,016.2	1,074.0	1,030.1	1,014.5	12,526.9
Peak (kW)	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1

EQUIPMENT ENERGY CONSUMPTION

Alternative: 2 90_1 Appendix G Chilled Water VAV

------- Monthly Consumption -------

Equipment - Utility	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Sys 2: TYP FLOOR 2_3_4_5													
90.1-04 Min VAV FC Centrifugal [DsnAirflow/F.L.Rate=78,749 cfm / 92.44 kW] (Main Clg Fan)													
Electric (kWh)	6,644.9	6,014.4	7,943.1	7,764.2	9,638.0	13,807.9	11,439.5	12,470.0	9,679.4	7,810.1	7,351.3	6,752.8	107,315.6
Peak (kW)	24.3	24.2	39.5	33.4	45.9	92.4	64.8	64.8	44.8	29.0	27.9	26.1	92.4
Parallel Fan Powered VAV [DsnAirflow/F.L.Rate=20,334 cfm / 8.37 kW] (Main Htg Fan)													
Electric (kWh)	3,686.0	3,283.4	2,047.8	868.3	260.6	0.0	0.0	0.0	61.3	1,182.9	1,680.1	3,113.4	16,183.6
Peak (kW)	8.4	8.4	8.4	8.4	8.4	0.0	0.0	0.0	5.6	8.4	8.4	8.4	8.4
FC Centrifugal vav/inlet vn [DsnAirflow/F.L.Rate=2,800 cfm / 2.07 kW] (Room Exhaust Fan)													
Electric (kWh)	25.0	23.1	26.5	23.0	23.3	20.4	19.9	21.7	20.9	24.9	24.2	24.2	276.9
Peak (kW)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
FC Centrifugal vav/inlet vn [DsnAirflow/F.L.Rate=12,572 cfm / 11.24 kW] (System Exhaust Fan)													
Electric (kWh)	2,383.6	2,183.5	2,594.3	2,370.2	2,531.8	2,568.9	2,421.5	2,663.3	2,409.8	2,498.4	2,391.9	2,357.2	29,374.3
Peak (kW)	7.5	7.5	7.6	7.6	7.6	7.7	7.6	7.6	7.6	7.6	7.5	7.5	7.7
FC Centrifugal vav/inlet vn [DsnAirflow/F.L.Rate=11,821 cfm / 12.47 kW] (Opt. Ventilation Fan)													
Electric (kWh)	4,122.2	3,774.3	4,472.9	4,063.1	4,301.9	4,303.7	4,067.9	4,477.4	4,066.0	4,300.0	4,123.8	4,062.3	50,135.5
Peak (kW)	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
Sys 3: 1st fl													
90.1-04 Min VAV FC Centrifugal [DsnAirflow/F.L.Rate=19,787 cfm / 22.12 kW] (Main Clg Fan)													
Electric (kWh)	1,466.3	1,327.3	1,750.0	1,747.6	2,389.0	3,210.4	2,776.2	3,036.4	2,377.9	1,729.8	1,634.1	1,492.8	24,937.8
Peak (kW)	5.4	5.3	8.1	7.5	18.0	22.1	22.1	22.1	20.4	6.6	6.2	5.8	22.1
Parallel Fan Powered VAV [DsnAirflow/F.L.Rate=5,227 cfm / 2.15 kW] (Main Htg Fan)													
Electric (kWh)	937.1	833.9	525.8	228.2	62.4	0.0	0.0	0.0	24.3	322.2	427.8	802.4	4,164.0
Peak (kW)	2.2	2.2	2.2	2.2	2.2	0.0	0.0	0.0	1.3	2.2	2.2	2.2	2.2
FC Centrifugal vav/inlet vn [DsnAirflow/F.L.Rate=700 cfm / 0.52 kW] (Room Exhaust Fan)													
Electric (kWh)	4.8	4.4	5.1	4.5	4.6	4.1	4.0	4.4	4.2	4.8	4.6	4.6	54.0
Peak (kW)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FC Centrifugal vav/inlet vn [DsnAirflow/F.L.Rate=3,105 cfm / 2.78 kW] (System Exhaust Fan)													
Electric (kWh)	570.3	522.6	620.8	567.0	606.3	613.9	579.0	636.6	577.1	597.6	572.2	564.0	7,027.5
Peak (kW)	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
FC Centrifugal vav/inlet vn [DsnAirflow/F.L.Rate=2,874 cfm / 3.03 kW] (Opt. Ventilation Fan)													
Electric (kWh)	1,002.3	917.7	1,087.6	988.0	1,046.1	1,046.5	989.2	1,088.7	988.8	1,045.5	1,002.6	987.8	12,190.7
Peak (kW)	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Sys 4: elevator machine room													

Project Name:
ataset Name: CASE STUDY.TRC

EQUIPMENT ENERGY CONSUMPTION

Alternative: 2 90_1 Appendix G Chilled Water VAV

Equipment - Utility	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
					------- Monthly Consumption -------								
Sys 4: elevator machine room													
FC Centrifugal const vol [DsnAirflow/F.L.Rate=1,220 cfm / 0.14 kW] (Main Clg Fan)													
Electric (kWh)	52.1	46.1	53.2	48.8	52.2	53.4	50.2	55.1	49.5	51.4	49.1	48.4	609.5
Peak (kW)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

EQUIPMENT ENERGY CONSUMPTION

Alternative: 3   Water Source Heat Pump+VAV+SPF

Equipment - Utility		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
		------- Monthly Consumption -------												
Lights														
	Electric (kWh)	48,882.2	44,557.6	52,617.2	47,710.9	50,749.7	50,553.1	47,907.5	52,617.1	47,710.9	50,749.7	48,685.7	47,907.5	590,649.1
	Peak (kW)	163.8	163.8	163.8	163.8	163.8	163.8	163.8	163.8	163.8	163.8	163.8	163.8	163.8
MISC LD														
	Electric (kWh)	56,079.8	51,133.5	60,322.2	54,789.5	58,200.9	57,966.4	55,024.1	60,322.2	54,789.5	58,201.0	55,845.1	55,024.0	677,698.1
	Peak (kW)	195.5	195.5	195.5	195.5	195.5	195.5	195.5	195.5	195.5	195.5	195.5	195.5	195.5
Cooling Coil Condensate														
	Recoverable Water (1000gal)	0.2	0.2	0.3	5.0	9.6	19.1	22.5	23.9	14.1	2.5	1.9	0.9	100.1
	Peak (1000gal/Hr)	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.1
Bsu 1: water heater														
	Electric (kWh)	1,433.1	1,296.6	1,569.6	1,364.9	1,501.4	1,501.4	1,364.9	1,569.6	1,364.9	1,501.4	1,433.1	1,364.9	17,265.7
	Peak (kW)	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7
Bsu 2: Hot Water Recirc Pump														
	Electric (kWh)	14.8	13.4	16.2	14.1	15.5	15.5	14.1	16.2	14.1	15.5	14.8	14.1	178.4
	Peak (kW)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Bsu 3: exterior lighting														
	Electric (kWh)	2,849.2	2,573.5	2,849.2	2,757.3	2,849.2	2,757.3	2,849.2	2,849.2	2,757.3	2,849.2	2,757.3	2,849.2	33,547.2
	Peak (kW)	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1
Bsu 4: elevator motor														
	Electric (kWh)	11,044.5	10,119.5	11,969.5	10,915.0	11,507.0	11,507.0	10,915.0	11,969.5	10,915.0	11,507.0	11,044.5	10,915.0	134,328.5
	Peak (kW)	59.2	59.2	59.2	59.2	59.2	59.2	59.2	59.2	59.2	59.2	59.2	59.2	59.2
Cpl 1: Elevator Machine Rm [Sum of dsn coil capacities=2.72 tons]														
Elevator Machine Room Split [Clg Nominal Capacity/F.L.Rate=5 tons / 4.15 kW] (Cooling Equipment)														
	Electric (kWh)	114.7	107.7	185.5	227.3	298.6	383.6	348.3	377.3	306.9	217.6	185.1	138.7	2,891.4
	Peak (kW)	1.1	1.0	1.2	1.4	1.6	1.9	1.8	1.8	1.7	1.3	1.2	1.1	1.9
Cond fan for Recip < 15ton														
	Electric (kWh)	32.1	30.1	50.2	57.1	70.8	85.1	79.1	85.8	71.5	55.7	48.6	38.8	704.6
	Peak (kW)	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.4
Cntl panel & interlocks - 0.125 KW (Misc Accessory Equipment)														
	Electric (kWh)	24.8	23.4	36.9	42.9	52.5	66.3	61.8	63.9	51.4	41.6	38.4	30.3	533.9
	Peak (kW)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Cpl 2: Dedicated OA [Sum of dsn coil capacities=0.00 tons]														
Cpl 3: WSHP [Sum of dsn coil capacities=261.9 tons]														

EQUIPMENT ENERGY CONSUMPTION

Alternative: 3 Water Source Heat Pump+VAV+SPF

------- Monthly Consumption -------

Equipment - Utility	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Cpl 3: WSHP [Sum of dsn coil capacities=261.9 tons]													
Water Source Heat Pump [Clg Nominal Capacity/F.L.Rate=261.9 tons / 240.9 kW] (Cooling Equipment - Cooling Mode)													
Electric (kWh)	21,609.0	19,888.0	27,183.1	34,494.8	46,748.0	62,319.9	60,474.0	64,950.5	49,808.7	31,682.6	27,722.0	23,048.4	469,928.9
Peak (kW)	88.8	88.0	113.1	187.4	239.7	240.9	240.9	240.9	240.9	144.1	130.4	101.3	240.9
Water Source Heat Pump [Htg Nominal Capacity/F.L.Rate=3,142 mbh / 229.4 kW] (Cooling Equipment - Heating Mode)													
Electric (kWh)	8,223.8	7,968.8	1,923.4	150.7	0.0	0.0	0.0	0.0	0.0	526.6	1,118.5	4,392.8	24,304.7
Peak (kW)	76.1	77.3	43.7	2.9	0.0	0.0	0.0	0.0	0.0	16.9	26.2	55.7	77.3
WSHP - Cooling tower													
Electric (kWh)	1,491.1	1,361.5	2,169.1	2,382.5	3,104.1	3,830.4	3,943.4	3,991.5	3,186.2	2,353.8	2,116.1	1,665.1	31,594.7
Peak (kW)	5.6	5.6	6.2	8.1	9.5	11.5	11.9	11.9	10.4	6.9	6.6	6.0	11.9
WSHP - Cooling tower													
Recoverable Water (1000gal)	75.6	66.9	112.9	150.9	205.2	273.5	265.4	285.0	218.6	137.2	118.1	90.4	1,999.6
Peak (1000gal/Hr)	0.4	0.4	0.5	0.8	1.1	1.1	1.1	1.1	1.1	0.6	0.6	0.4	1.1
Eq5032 - VV Cond Wtr Pump (12 F Delta T) (Misc Accessory Equipment)													
Electric (kWh)	112.4	103.0	139.5	208.2	332.2	572.7	571.7	609.4	393.0	173.8	146.5	118.4	3,480.7
Peak (kW)	0.5	0.4	0.6	1.6	2.9	2.9	2.9	2.9	2.9	1.0	0.8	0.5	2.9
Wshpcntl - WS heat pump control (Misc Accessory Equipment)													
Electric (kWh)	15.9	13.8	11.6	9.9	11.9	11.8	11.9	11.9	11.2	10.6	11.0	15.2	146.4
Peak (kW)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sys 1: top floor													
FC w/VFD Crit. Zone Reset [DsnAirflow/F.L.Rate=16,501 cfm / 12.50 kW] (Main Clg Fan)													
Electric (kWh)	464.2	428.4	669.4	876.7	1,302.3	1,870.4	1,624.4	1,792.3	1,341.1	785.2	654.1	507.5	12,315.9
Peak (kW)	2.3	2.2	3.4	11.2	12.5	12.5	12.5	12.5	12.5	5.3	4.1	2.7	12.5
Series Fan Powered VAV [DsnAirflow/F.L.Rate=19,488 cfm / 7.34 kW] (Main Htg Fan)													
Electric (kWh)	2,678.6	2,465.0	2,575.3	2,346.7	2,752.7	3,037.8	2,878.7	2,998.4	2,668.5	2,447.5	2,371.0	2,614.0	31,834.2
Peak (kW)	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3
FC Centrifugal var freq drv [DsnAirflow/F.L.Rate=700 cfm / 0.30 kW] (Room Exhaust Fan)													
Electric (kWh)	2.8	2.5	2.8	2.5	2.7	2.6	2.5	2.7	2.5	2.7	2.6	2.6	31.5
Peak (kW)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FC Centrifugal var freq drv [DsnAirflow/F.L.Rate=2,663 cfm / 1.81 kW] (System Exhaust Fan)													
Electric (kWh)	313.7	288.9	349.3	314.8	336.5	337.7	317.5	352.5	319.1	336.2	321.6	313.1	3,899.8
Peak (kW)	1.0	1.0	1.1	1.1	1.1	1.0	1.1	1.1	1.1	1.1	1.1	1.0	1.1

Project Name:
ataset Name: CASE STUDY.TRC

EQUIPMENT ENERGY CONSUMPTION

Alternative: 3 Water Source Heat Pump+VAV+SPF

------- Monthly Consumption -------

Equipment - Utility	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Sys 1: top floor													
FC Centrifugal var freq drv [DsnAirflow/F.L.Rate=2,454 cfm / 1.56 kW] (Opt. Ventilation Fan)													
Electric (kWh)	506.2	463.9	553.8	498.3	530.5	527.6	496.4	552.5	500.3	532.2	510.0	500.1	6,171.8
Peak (kW)	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Sys 2: TYP FLOOR 2_3_4_5													
FC w/VFD Crit. Zone Reset [DsnAirflow/F.L.Rate=62,400 cfm / 45.29 kW] (Main Clg Fan)													
Electric (kWh)	2,143.2	1,951.3	2,646.5	3,328.1	4,902.9	6,707.3	6,031.9	6,633.1	4,878.4	2,946.1	2,589.8	2,191.9	46,950.6
Peak (kW)	8.5	8.4	11.2	32.0	45.3	45.3	45.3	45.3	45.3	17.0	12.6	9.5	45.3
Series Fan Powered VAV [DsnAirflow/F.L.Rate=75,269 cfm / 28.34 kW] (Main Htg Fan)													
Electric (kWh)	11,348.5	10,492.1	10,698.5	9,890.0	11,548.3	11,874.1	11,580.7	12,011.9	11,117.2	10,244.8	10,031.3	10,920.6	131,758.0
Peak (kW)	28.3	28.3	28.3	28.3	28.3	28.3	28.3	28.3	28.3	28.3	28.3	28.3	28.3
FC Centrifugal var freq drv [DsnAirflow/F.L.Rate=2,800 cfm / 1.19 kW] (Room Exhaust Fan)													
Electric (kWh)	10.7	9.9	11.6	10.1	10.3	9.8	9.3	10.3	9.6	10.7	10.5	10.6	123.4
Peak (kW)	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.1	0.1	0.1	0.0	0.0	0.1
FC Centrifugal var freq drv [DsnAirflow/F.L.Rate=11,178 cfm / 7.58 kW] (System Exhaust Fan)													
Electric (kWh)	1,320.7	1,208.4	1,441.4	1,324.8	1,425.4	1,440.8	1,358.4	1,498.7	1,350.1	1,399.1	1,329.4	1,301.1	16,398.2
Peak (kW)	4.5	4.3	4.3	4.4	4.5	4.5	4.5	4.5	4.5	4.5	4.3	4.3	4.5
FC Centrifugal var freq drv [DsnAirflow/F.L.Rate=10,343 cfm / 6.56 kW] (Opt. Ventilation Fan)													
Electric (kWh)	2,019.0	1,845.5	2,194.8	2,003.8	2,132.7	2,139.5	2,018.2	2,228.9	2,009.3	2,128.8	2,022.2	1,982.8	24,725.4
Peak (kW)	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
Sys 3: 1st fl													
FC w/VFD Crit. Zone Reset [DsnAirflow/F.L.Rate=15,128 cfm / 9.02 kW] (Main Clg Fan)													
Electric (kWh)	392.7	358.5	477.9	644.8	955.9	1,314.7	1,167.2	1,287.5	964.5	556.1	471.1	399.1	8,990.0
Peak (kW)	1.6	1.5	2.0	7.1	9.0	9.0	9.0	9.0	9.0	2.9	2.5	1.7	9.0
Series Fan Powered VAV [DsnAirflow/F.L.Rate=18,067 cfm / 6.80 kW] (Main Htg Fan)													
Electric (kWh)	2,650.5	2,450.3	2,554.2	2,390.1	2,774.8	2,868.3	2,787.6	2,887.3	2,656.3	2,442.9	2,393.5	2,554.7	31,410.5
Peak (kW)	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8
FC Centrifugal var freq drv [DsnAirflow/F.L.Rate=700 cfm / 0.30 kW] (Room Exhaust Fan)													
Electric (kWh)	2.3	2.2	2.6	2.2	2.3	2.2	2.1	2.3	2.1	2.4	2.3	2.3	27.2
Peak (kW)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FC Centrifugal var freq drv [DsnAirflow/F.L.Rate=2,741 cfm / 1.86 kW] (System Exhaust Fan)													
Electric (kWh)	330.4	302.6	369.3	328.5	353.4	356.4	335.7	370.4	334.8	348.4	331.2	325.5	4,076.8
Peak (kW)	1.1	1.0	1.0	1.1	1.1	1.1	1.1	1.1	1.1	1.0	1.0	1.0	1.1

Project Name:
ataset Name: CASE STUDY.TRC

EQUIPMENT ENERGY CONSUMPTION

Alternative: 3 Water Source Heat Pump+VAV+SPF

------- Monthly Consumption -------

Equipment - Utility	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Sys 3: 1st fl													
FC Centrifugal var freq drv [DsnAirflow/F.L.Rate=2,510 cfm / 1.59 kW] (Opt. Ventilation Fan)													
Electric (kWh)	518.6	474.3	563.1	508.5	542.7	542.9	511.7	565.0	511.6	543.4	518.8	509.5	6,310.1
Peak (kW)	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Sys 4: elevator machine room													
FC Centrifugal const vol [DsnAirflow/F.L.Rate=1,120 cfm / 0.51 kW] (Main Clg Fan)													
Electric (kWh)	182.1	158.1	189.7	174.1	186.4	190.3	178.9	196.4	176.8	183.5	175.3	171.2	2,162.8
Peak (kW)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5

EQUIPMENT ENERGY CONSUMPTION

Alternative: 4 Air-Cooled Chiller+Fan Coil

Equipment - Utility		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
		------- Monthly Consumption -------												
Lights														
	Electric (kWh)	48,882.2	44,557.6	52,617.2	47,710.9	50,749.7	50,553.1	47,907.5	52,617.1	47,710.9	50,749.7	48,685.7	47,907.5	590,649.1
	Peak (kW)	163.8	163.8	163.8	163.8	163.8	163.8	163.8	163.8	163.8	163.8	163.8	163.8	163.8
MISC LD														
	Electric (kWh)	56,079.8	51,133.5	60,322.2	54,789.5	58,200.9	57,966.4	55,024.1	60,322.2	54,789.5	58,201.0	55,846.1	55,024.0	677,698.1
	Peak (kW)	195.5	195.5	195.5	195.5	195.5	195.5	195.5	195.5	195.5	195.5	195.5	195.5	195.5
Cooling Coil Condensate														
	Recoverable Water (1000gal)	0.2	0.2	0.2	2.8	6.4	14.2	17.1	18.2	10.3	1.3	1.0	0.5	72.2
	Peak (1000gal/Hr)	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.1
Bsu 1: water heater														
	Electric (kWh)	1,433.1	1,296.6	1,569.6	1,364.9	1,501.4	1,501.4	1,364.9	1,569.6	1,364.9	1,501.4	1,433.1	1,364.9	17,265.7
	Peak (kW)	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7
Bsu 2: Hot Water Recirc Pump														
	Electric (kWh)	14.8	13.4	16.2	14.1	15.5	15.5	14.1	16.2	14.1	15.5	14.8	14.1	178.4
	Peak (kW)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Bsu 3: exterior lighting														
	Electric (kWh)	2,849.2	2,573.5	2,849.2	2,757.3	2,849.2	2,757.3	2,849.2	2,849.2	2,757.3	2,849.2	2,757.3	2,849.2	33,547.2
	Peak (kW)	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1
Bsu 4: elevator motor														
	Electric (kWh)	11,044.5	10,119.5	11,969.5	10,915.0	11,507.0	11,507.0	10,915.0	11,969.5	10,915.0	11,507.0	11,044.5	10,915.0	134,328.5
	Peak (kW)	59.2	59.2	59.2	59.2	59.2	59.2	59.2	59.2	59.2	59.2	59.2	59.2	59.2
Cpl 1: Elevator Machine Rm [Sum of dsn coil capacities=2.72 tons]														
Elevator Machine Room Split [Clg Nominal Capacity/F.L.Rate=5 tons / 4.15 kW] (Cooling Equipment)														
	Electric (kWh)	114.7	107.7	185.5	227.3	298.6	383.6	348.3	377.3	306.9	217.6	185.1	138.7	2,891.4
	Peak (kW)	1.1	1.0	1.2	1.4	1.6	1.9	1.8	1.8	1.7	1.3	1.2	1.1	1.9
Cond fan for Recip < 15ton														
	Electric (kWh)	32.1	30.1	50.2	57.1	70.8	85.1	79.1	85.8	71.5	55.7	48.6	38.8	704.6
	Peak (kW)	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.4
Cntl panel & interlocks - 0.125 KW (Misc Accessory Equipment)														
	Electric (kWh)	24.8	23.4	36.9	42.9	52.5	66.3	61.8	63.9	51.4	41.6	38.4	30.3	533.9
	Peak (kW)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Cpl 2: Air-Cooled Chiller [Sum of dsn coil capacities=255.8 tons]														

EQUIPMENT ENERGY CONSUMPTION

Alternative: 4 Air-Cooled Chiller+Fan Coil

------- Monthly Consumption -------

Equipment - Utility	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Cpl 2: Air-Cooled Chiller [Sum of dsn coil capacities=255.8 tons]													
Air-cooled chiller - 004 [Clg Nominal Capacity/F.L.Rate=255.8 tons / 255.8 kW] (Cooling Equipment)													
Electric (kWh)	9,805.3	8,944.3	14,003.9	20,397.8	31,193.1	48,717.3	45,126.8	48,346.5	35,114.6	18,434.4	15,059.7	10,591.3	305,735.0
Peak (kW)	52.3	51.9	81.5	159.0	209.7	228.9	216.0	216.2	213.5	123.6	102.5	61.5	228.9
MZ packaged rooftop cond fan													
Electric (kWh)	2,210.2	2,026.2	2,985.2	3,655.2	4,971.7	6,644.9	6,361.1	6,854.4	5,279.8	3,443.3	2,983.8	2,349.6	49,765.4
Peak (kW)	10.6	10.6	16.0	23.9	26.5	27.0	26.7	26.7	26.6	19.8	17.5	12.5	27.0
Cnst vol chill water pump (Misc Accessory Equipment)													
Electric (kWh)	2,154.6	2,114.3	2,506.0	2,281.3	2,724.9	2,845.9	2,776.8	2,805.6	2,655.8	2,442.6	2,385.0	2,264.0	29,956.7
Peak (kW)	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8
Cntl panel & interlocks - 0.1 KW (Misc Accessory Equipment)													
Electric (kWh)	37.4	36.7	43.5	39.6	47.3	49.4	48.2	48.7	46.1	42.4	41.4	39.3	520.0
Peak (kW)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Hpl 1: Electric [Sum of dsn coil capacities=1,117 mbh]													
Electric Resistance - 001 [Nominal Capacity/F.L.Rate=2,064 mbh / 605 kW] (Heating Equipment)													
Electric (kWh)	22,192.8	22,257.3	6,254.9	622.6	0.0	0.0	0.0	0.0	0.0	2,068.3	3,211.0	9,321.9	65,928.7
Peak (kW)	192.9	195.1	80.9	9.8	0.0	0.0	0.0	0.0	0.0	25.9	54.3	123.2	195.1
Sys 1: top floor													
FC Centrifugal const vol [DsnAirflow/F.L.Rate=19,314 cfm / 21.35 kW] (Main Clg Fan)													
Electric (kWh)	8,190.9	7,296.4	7,790.6	7,122.2	7,839.7	8,153.0	7,729.0	8,412.4	7,500.2	7,484.8	7,218.2	7,515.5	92,252.6
Peak (kW)	21.4	21.4	21.4	21.4	21.4	21.4	21.4	21.4	21.4	21.4	21.4	21.4	21.4
FC Centrifugal var freq drv [DsnAirflow/F.L.Rate=700 cfm / 0.30 kW] (Room Exhaust Fan)													
Electric (kWh)	3.6	3.1	3.2	3.1	3.6	3.7	3.5	3.9	3.4	3.1	3.0	3.2	40.4
Peak (kW)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FC Centrifugal var freq drv [DsnAirflow/F.L.Rate=2,425 cfm / 1.64 kW] (System Exhaust Fan)													
Electric (kWh)	269.8	247.3	292.9	266.2	283.5	282.8	267.5	294.2	268.5	281.0	269.5	266.2	3,289.4
Peak (kW)	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
FC Centrifugal var freq drv [DsnAirflow/F.L.Rate=2,216 cfm / 1.41 kW] (Opt. Ventilation Fan)													
Electric (kWh)	463.2	423.7	501.5	455.6	482.6	482.8	456.2	502.5	456.0	481.9	462.3	455.7	5,623.9
Peak (kW)	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Sys 2: TYP FLOOR 2_3_4_5													

EQUIPMENT ENERGY CONSUMPTION

Alternative: 4 Air-Cooled Chiller+Fan Coil

------- Monthly Consumption -------

Equipment - Utility	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Sys 2: TYP FLOOR 2_3_4_5													
FC Centrifugal const vol [DsnAirflow/F.L.Rate=74,958 cfm / 79.01 kW] (Main Clg Fan)													
Electric (kWh)	29,705.1	26,783.5	29,739.9	26,898.3	29,225.5	30,014.8	28,514.2	31,108.7	27,893.5	28,371.7	27,559.9	28,148.2	343,963.3
Peak (kW)	79.0	79.0	79.0	79.0	79.0	79.0	79.0	79.0	79.0	79.0	79.0	79.0	79.0
FC Centrifugal var freq drv [DsnAirflow/F.L.Rate=2,800 cfm / 1.19 kW] (Room Exhaust Fan)													
Electric (kWh)	14.3	13.2	15.6	14.2	15.0	15.0	14.2	15.6	14.2	15.0	14.4	14.2	174.8
Peak (kW)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FC Centrifugal var freq drv [DsnAirflow/F.L.Rate=9,700 cfm / 6.58 kW] (System Exhaust Fan)													
Electric (kWh)	1,079.1	989.2	1,171.7	1,064.7	1,134.1	1,131.3	1,070.1	1,176.7	1,074.0	1,124.0	1,078.2	1,064.7	13,157.6
Peak (kW)	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2
FC Centrifugal var freq drv [DsnAirflow/F.L.Rate=8,866 cfm / 5.62 kW] (Opt. Ventilation Fan)													
Electric (kWh)	1,852.6	1,695.5	2,009.9	1,824.7	1,931.4	1,931.3	1,824.7	2,009.9	1,824.7	1,931.3	1,852.7	1,824.7	22,513.4
Peak (kW)	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6
Sys 3: 1st fl													
FC Centrifugal const vol [DsnAirflow/F.L.Rate=17,998 cfm / 17.93 kW] (Main Clg Fan)													
Electric (kWh)	6,593.8	5,975.5	6,721.9	6,112.6	6,662.9	6,846.8	6,505.7	7,084.3	6,358.7	6,430.3	6,224.3	6,310.8	77,827.5
Peak (kW)	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9	17.9
FC Centrifugal var freq drv [DsnAirflow/F.L.Rate=700 cfm / 0.30 kW] (Room Exhaust Fan)													
Electric (kWh)	3.0	2.8	3.3	3.0	3.2	3.2	3.0	3.3	3.0	3.2	3.0	3.0	36.7
Peak (kW)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FC Centrifugal var freq drv [DsnAirflow/F.L.Rate=2,387 cfm / 1.62 kW] (System Exhaust Fan)													
Electric (kWh)	260.7	239.0	283.1	257.3	274.3	273.5	258.8	284.5	259.9	271.5	260.4	257.3	3,180.3
Peak (kW)	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
FC Centrifugal var freq drv [DsnAirflow/F.L.Rate=2,155 cfm / 1.37 kW] (Opt. Ventilation Fan)													
Electric (kWh)	450.4	412.2	488.6	443.6	469.5	469.5	443.6	488.6	443.6	469.5	450.4	443.6	5,473.0
Peak (kW)	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Sys 4: elevator machine room													
FC Centrifugal const vol [DsnAirflow/F.L.Rate=1,120 cfm / 0.11 kW] (Main Clg Fan)													
Electric (kWh)	39.2	34.0	40.8	37.5	40.1	40.9	38.5	42.3	38.0	39.5	37.7	36.8	465.3
Peak (kW)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

Project Name:
Dataset Name: CASE STUDY.TRC

ENERGY CONSUMPTION SUMMARY

	Elect Cons. (kWh)	Water Cons. (1000 gals)	% of Total Building Energy	Total Building Energy (kBtu/yr)	Total Source Energy* (kBtu/yr)
Alternative 1					
Primary heating					
Primary heating	143,863		6.4 %	491,005	1,473,161
Other Htg Accessories			0.0 %	0	0
Heating Subtotal	**143,863**		**6.4 %**	**491,005**	**1,473,161**
Primary cooling					
Cooling Compressor	378,403		16.8 %	1,291,489	3,874,854
Tower/Cond Fans	45,837	960	2.0 %	156,440	469,368
Condenser Pump	30,600		1.4 %	104,438	313,346
Other Clg Accessories	5,717		0.3 %	19,512	58,541
Cooling Subtotal....	**460,558**	**960**	**20.5 %**	**1,571,879**	**4,716,109**
Auxiliary					
Supply Fans	191,245		8.5 %	652,719	1,958,354
Pumps			0.0 %	0	0
Stand-alone Base Utilities	185,320		8.2 %	632,496	1,897,679
Aux Subtotal....	376,565		16.7 %	1,285,216	3,856,033
Lighting					
Lighting	590,649		26.3 %	2,015,885	6,048,259
Receptacle					
Receptacles	677,698		30.1 %	2,312,983	6,939,644
Cogeneration					
Cogeneration			0.0 %	0	0
Totals					
Totals**	**2,249,331**	**960**	**100.0 %**	**7,676,968**	**23,033,206**

* Note: Resource Utilization factors are included in the Total Source Energy value.
** Note: This report can display a maximum of 7 utilities. If additional utilities are used, they will be included in the total.

Dataset Name: CASE STUDY.TRC

Alternative - 1 Energy Consumption Summary report page 1

ENERGY CONSUMPTION SUMMARY

	Elect Cons. (kWh)	% of Total Building Energy	Total Building Energy (kBtu/yr)	Total Source Energy* (kBtu/yr)
Alternative 2				
Primary heating				
Primary heating	402,076	15.2 %	1,372,287	4,117,272
Other Htg Accessories		0.0 %	0	0
Heating Subtotal	**402,076**	**15.2 %**	**1,372,287**	**4,117,272**
Primary cooling				
Cooling Compressor	356,887	13.5 %	1,218,055	3,654,531
Tower/Cond Fans	57,576	2.2 %	196,506	589,576
Condenser Pump		0.0 %	0	0
Other Clg Accessories	930	0.0 %	3,174	9,522
Cooling Subtotal....	**415,393**	**15.7 %**	**1,417,736**	**4,253,630**
Auxiliary				
Supply Fans	308,342	11.7 %	1,052,372	3,157,431
Pumps	37,510	1.4 %	128,021	384,102
Stand-alone Base Utilities	185,320	7.0 %	632,496	1,897,679
Aux Subtotal....	531,172	20.1 %	1,812,890	5,439,213
Lighting				
Lighting	612,173	23.2 %	2,089,346	6,268,664
Receptacle				
Receptacles	677,698	25.7 %	2,312,983	6,939,644
Cogeneration				
Cogeneration		0.0 %	0	0
Totals				
Totals**	**2,638,512**	**100.0 %**	**9,005,240**	**27,018,420**

* Note: Resource Utilization factors are included in the Total Source Energy value.
** Note: This report can display a maximum of 7 utilities. If additional utilities are used, they will be included in the total.

Project Name:
Dataset Name: CASE STUDY.TRC

TRACE® 700 v6.2.4 calculated at 12:22 PM on 06/04/2010
Alternative - 2 Energy Consumption Summary report page 1

ENERGY CONSUMPTION SUMMARY

	Elect Cons. (kWh)	Water Cons. (1000 gals)	% of Total Building Energy	Total Building Energy (kBtu/yr)	Total Source Energy* (kBtu/yr)
Alternative 3					
Primary heating					
Primary heating	33,759		1.5 %	115,219	345,691
Other Htg Accessories	7		0.0 %	25	74
Heating Subtotal	**33,766**		**1.5 %**	**115,244**	**345,765**
Primary cooling					
Cooling Compressor	472,820		20.4 %	1,613,736	4,841,692
Tower/Cond Fans	32,299	2,000	1.4 %	110,238	330,746
Condenser Pump	3,310		0.1 %	11,295	33,889
Other Clg Accessories	673		0.0 %	2,297	6,892
Cooling Subtotal....	**509,102**	**2,000**	**21.9 %**	**1,737,566**	**5,213,219**
Auxiliary					
Supply Fans	327,186		14.1 %	1,116,686	3,350,394
Pumps	171		0.0 %	584	1,753
Stand-alone Base Utilities	185,320		8.0 %	632,496	1,897,679
Aux Subtotal....	512,677		22.1 %	1,749,767	5,249,825
Lighting					
Lighting	590,649		25.4 %	2,015,885	6,048,259
Receptacle					
Receptacles	677,698		29.2 %	2,312,983	6,939,644
Cogeneration					
Cogeneration			0.0 %	0	0
Totals					
Totals**	**2,323,892**	**2,000**	**100.0 %**	**7,931,444**	**23,796,712**

* Note: Resource Utilization factors are included in the Total Source Energy value.
** Note: This report can display a maximum of 7 utilities. If additional utilities are used, they will be included in the total.

Project Name:
Dataset Name: CASE STUDY.TRC

TRACE® 700 v6.2.4 calculated at 12:22 PM on 06/04/2010
Alternative - 3 Energy Consumption Summary report page 1

ENERGY CONSUMPTION SUMMARY

	Elect Cons. (kWh)	% of Total Building Energy	Total Building Energy (kBtu/yr)	Total Source Energy* (kBtu/yr)
Alternative 4				
Primary heating				
Primary heating	65,929	2.7 %	225,015	675,112
Other Htg Accessories		0.0 %	0	0
Heating Subtotal	**65,929**	**2.7 %**	**225,016**	**675,112**
Primary cooling				
Cooling Compressor	308,626	12.5 %	1,053,342	3,160,342
Tower/Cond Fans	50,470	2.0 %	172,254	516,814
Condenser Pump		0.0 %	0	0
Other Clg Accessories	1,054	0.0 %	3,597	10,792
Cooling Subtotal....	**360,150**	**14.5 %**	**1,229,193**	**3,687,948**
Auxiliary				
Supply Fans	567,998	22.9 %	1,938,578	5,816,316
Pumps	29,957	1.2 %	102,242	306,758
Stand-alone Base Utilities	185,320	7.5 %	632,496	1,897,679
Aux Subtotal....	783,275	31.6 %	2,673,317	8,020,752
Lighting				
Lighting	590,649	23.8 %	2,015,885	6,048,259
Receptacle				
Receptacles	677,698	27.4 %	2,312,983	6,939,644
Cogeneration				
Cogeneration		0.0 %	0	0
Totals				
Totals**	**2,477,701**	**100.0 %**	**8,456,393**	**25,371,714**

* Note: Resource Utilization factors are included in the Total Source Energy value.
** Note: This report can display a maximum of 7 utilities. If additional utilities are used, they will be included in the total.

Project Name:
Dataset Name: CASE STUDY.TRC

TRACE® 700 v6.2.4 calculated at 12:22 PM on 06/04/2010
Alternative - 4 Energy Consumption Summary report page 1

APPENDIX B
PERFORMANCE RATING DETAILS

Performance Rating Details

Project Name: CASE STUDY	Date:
City: Atlanta, GA	Weather Data: Atlanta, Georgia

Performance Rating Method Alternative: Alt-2 90_1 Appendix G Chilled Water VAV

		0° Rotation		90° Rotation		180° Rotation		270° Rotation		Average	
		Energy 10^6 Btu/yr	Peak kBtuh	Energy 10^6 Btu/yr	Peak kBtuh	Energy 10^6 Btu/yr	Peak kBtuh	Energy 10^6 Btu/yr	Peak kBtuh	Energy 10^6 Btu/yr	Peak kBtuh
Lighting - Conditioned	Electricity	2,089.4	579	2,089.4	579	2,089.4	579	2,089.4	579	2,089.4	579
Space Heating	Electricity	1,372.3	1,522	1,345.6	1,498	1,372.2	1,520	1,346.4	1,496	1,359.1	1,509
Space Cooling	Electricity	1,221.2	852	1,246.7	695	1,257.4	685	1,246.6	695	1,243.0	732
Pumps	Electricity	128.0	26	621.3	164	623.4	162	621.3	164	498.5	129
Heat Rejection	Electricity	196.5	104	165.9	82	166.3	82	165.9	82	173.7	88
Fans - Conditioned	Electricity	1,052.4	626	851.5	460	847.3	472	851.5	460	900.7	505
Receptacles - Conditioned	Electricity	2,313.0	667	2,313.0	667	2,313.0	667	2,313.0	667	2,313.0	667
Stand-alone Base Utilities	Electricity	632.5	256	779.8	290	779.8	290	779.8	290	743.0	281
Total Building Consumption		9,005.3	4,633	9,413.1	4,436	9,448.8	4,468	9,413.9	4,434	9,320.3	4,490

	0° Rotation	90° Rotation	180° Rotation	270° Rotation	Average
Electric ($)	$178,190	$184,993	$185,581	$185,017	$183,445
Total Building Cost ($)	$178,190	$184,993	$185,581	$185,017	$183,445

APPENDIX C
ENERGY COST BUDGET

Energy Cost Budget / PRM Summary

Project Name: Case Stuy		Date: June 04, 2010
City: Atlanta, GA	Weather Data: Atlanta, Georgia	

Note: The percentage displayed for the "Proposed/ Base %" column of the base case is actually the percentage of the total energy consumption.

* Denotes the base alternative for the ECB study.

		* Alt-2 90_1 Appendix G Chilled			Alt-1 Self-contained+VAV+PFP			Alt-3 Water Source Heat Pump+			Alt-4 Air-Cooled Chiller+Fan Co		
		Energy 10^6 Btu/yr	Proposed / Base %	Peak kBtuh	Energy 10^6 Btu/yr	Proposed / Base %	Peak kBtuh	Energy 10^6 Btu/yr	Proposed / Base %	Peak kBtuh	Energy 10^6 Btu/yr	Proposed / Base %	Peak kBtuh
Lighting - Conditioned	Electricity	2,089.3	22	579	2,015.9	96	559	2,015.9	96	559	2,015.9	96	559
Space Heating	Electricity	1,359.1	15	1,509	491.0	36	1,080	115.2	8	381	225.0	17	666
Space Cooling	Electricity	1,243.0	13	732	1,311.0	105	719	1,616.0	130	789	1,056.9	85	788
Pumps	Electricity	498.5	5	129	104.4	21	81	11.9	2	10	102.2	21	20
Heat Rejection	Electricity	173.6	2	88	156.4	90	46	110.2	63	42	172.3	99	93
Fans - Conditioned	Electricity	900.7	10	505	652.7	72	321	1,116.7	124	431	1,938.6	215	449
Receptacles - Conditioned	Electricity	2,313.0	25	667	2,313.0	100	667	2,313.0	100	667	2,313.0	100	667
Stand-alone Base Utilities	Electricity	743.0	8	281	632.5	85	256	632.5	85	256	632.5	85	256
Total Building Consumption		$\boxed{9,320.3}$			$\boxed{7,677.0}$			$\boxed{7,931.4}$			$\boxed{8,456.4}$		

		* Alt-2 90_1 Appendix G Chilled	Alt-1 Self-contained+VAV+PFP	Alt-3 Water Source Heat Pump+	Alt-4 Air-Cooled Chiller+Fan Co
Total	**Number of hours heating load not met**	9	28	0	0
	Number of hours cooling load not met	0	2	4	22

	* Alt-2 90_1 Appendix G Chilled		Alt-1 Self-contained+VAV+PFP		Alt-3 Water Source Heat Pump+		Alt-4 Air-Cooled Chiller+Fan Co	
	Energy 10^6 Btu/yr	Cost/yr $/yr	Energy 10^6 Btu/yr	Cost/yr $/yr	Energy 10^6 Btu/yr	Cost/yr $/yr	Energy 10^6 Btu/yr	Cost/yr $/yr
Electricity	9,320.3	183,462	7,677.0	153,993	7,931.4	158,601	8,456.4	168,333
Total	**9,320**	**183,462**	**7,677**	**153,993**	**7,931**	**158,601**	**8,456**	**168,333**

Project Name:
Dataset Name: CASE STUDY.TRC

Energy Cost Budget Report Page 1 of 1

APPENDIX D
ECONOMIC COST

ECONOMIC PARAMETERS

Project Name:
Location:
Building Owner:
Program User:
Company:
Comments:

Study Life:	20 Yrs
Mortgage Life:	20 Yrs
Depreciation Life:	20 Yrs
Mortgage Interest Rate:	10.0 %
Percent Financed:	0.0 %
Depreciation Method:	None
Declining Balance Taxes:	100.0 %

Income Tax Rate:	0.0 %
Cost of Capital:	10.0 %
Property tax rate:	0.0 %
Insurance Expense rate:	0.0 %

<u>Annual Inflation Rate Of</u>

Maintenance Expense	2.0 %
Replacement Expense	2.0 %
Property Taxes	0.0 %
Insurance Expense	0.0 %

Alt #	First Cost ($/ton)	First Cost ($/ft²)	Additional First Cost	Total First Cost	Maintenance Cost ($/ton)	Maintenance Cost ($/ft²)	Total Maint. Cost	Total Alt. Cost
4	4,822.27	9.00	0.00	1,310,337.00	70.15	0.13	19,061.57	1,329,398.57
3	4,386.84	8.15	0.00	1,186,562.88	81.72	0.15	22,205.44	1,208,768.32
2	4,217.49	10.00	0.00	1,455,930.00	74.25	0.18	25,632.05	1,481,562.05
1	4,686.32	8.75	0.00	1,273,938.75	72.81	0.14	19,784.36	1,293,723.11

Project Name:
Dataset Name: CASE STUDY.TRC

Economic Parameters report Page 1 of 1

MONTHLY UTILITY COSTS

Utility	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
					------- Monthly Utility Costs -------								
Alternative 1													
Electric													
On-Pk Cons. ($)	10,925	10,154	10,111	9,386	10,787	12,118	11,608	12,580	10,630	9,885	9,698	9,846	127,729
On-Pk Demand ($)	2,306	2,399	2,063	2,013	2,178	2,394	2,395	2,411	2,248	1,929	1,853	2,076	26,264
Total ($):	13,231	12,553	12,174	11,399	12,965	14,513	14,003	14,992	12,877	11,813	11,551	11,922	153,993
Water													
On-Pk Cons. ($)	322	294	380	447	617	841	820	880	664	422	382	331	6,399
Monthly Total ($):	13,552	12,847	12,554	11,846	13,582	15,354	14,823	15,871	13,542	12,236	11,933	12,253	160,392
Building Area =	145,593 ft²												
Utility Cost Per Area =	1.10 $/ft²												
Alternative 2 - 0° Rotation													
Electric													
On-Pk Cons. ($)	14,276	13,185	12,620	10,924	11,630	12,936	12,083	13,127	11,216	11,750	11,895	12,856	148,499
On-Pk Demand ($)	2,684	2,777	2,412	2,169	2,438	2,695	2,608	2,626	2,493	2,168	2,239	2,383	29,691
Total ($):	16,960	15,962	15,031	13,092	14,069	15,631	14,692	15,753	13,709	13,918	14,134	15,238	178,190
Water													
On-Pk Cons. ($)	4	4	4	4	4	4	4	4	4	4	4	4	43
Monthly Total ($):	16,964	15,965	15,035	13,096	14,072	15,635	14,695	15,757	13,713	13,922	14,138	15,242	178,233
Building Area =	145,593 ft²												
Utility Cost Per Area =	1.22 $/ft²												

Project Name:
lataset Name: CASE STUDY.TRC

Monthly Utility Costs report Page 1 of 4

YEARLY CASH FLOW

Alternative: 1
Life Cycle Cost: $2,832,130.79

Year	Utility Cost ($)	Maint. Cost ($)	Interest Cost ($)	Principal Cost ($)	Property Taxes ($)	Insurance Cost ($)	Revenue Penalty ($)	Replace. Expenses ($)	Deprec. Tax ($)	Cash Flow Effect ($)	Present Value ($)
0	0	0	0	1,273,939	0	0	0	0	0	1,273,939	1,273,939
1	160,392	19,784	0	0	0	0	0	0	0	180,177	163,797
2	160,392	20,180	0	0	0	0	0	0	0	180,573	149,233
3	160,392	20,584	0	0	0	0	0	0	0	180,976	135,970
4	160,392	20,995	0	0	0	0	0	0	0	181,388	123,890
5	160,392	21,415	0	0	0	0	0	0	0	181,808	112,888
6	160,392	21,844	0	0	0	0	0	0	0	182,236	102,867
7	160,392	22,280	0	0	0	0	0	0	0	182,673	93,740
8	160,392	22,726	0	0	0	0	0	0	0	183,118	85,426
9	160,392	23,181	0	0	0	0	0	0	0	183,573	77,853
10	160,392	23,644	0	0	0	0	0	0	0	184,037	70,954
11	160,392	24,117	0	0	0	0	0	0	0	184,509	64,669
12	160,392	24,599	0	0	0	0	0	0	0	184,992	58,944
13	160,392	25,091	0	0	0	0	0	0	0	185,484	53,728
14	160,392	25,593	0	0	0	0	0	0	0	185,986	48,976
15	160,392	26,105	0	0	0	0	0	0	0	186,498	44,646
16	160,392	26,627	0	0	0	0	0	0	0	187,020	40,701
17	160,392	27,160	0	0	0	0	0	0	0	187,552	37,106
18	160,392	27,703	0	0	0	0	0	0	0	188,095	33,831
19	160,392	28,257	0	0	0	0	0	0	0	188,649	30,846
20	160,392	28,822	0	0	0	0	0	0	0	189,215	28,126

Alternative: 2
Life Cycle Cost: $3,339,121.91

Year	Utility Cost ($)	Maint. Cost ($)	Interest Cost ($)	Principal Cost ($)	Property Taxes ($)	Insurance Cost ($)	Revenue Penalty ($)	Replace. Expenses ($)	Deprec. Tax ($)	Cash Flow Effect ($)	Present Value ($)
0	0	0	0	1,455,930	0	0	0	0	0	1,455,930	1,455,930
1	191,877	25,632	0	0	0	0	0	0	0	217,509	197,736
2	191,877	26,145	0	0	0	0	0	0	0	218,022	180,184
3	191,877	26,668	0	0	0	0	0	0	0	218,545	164,196
4	191,877	27,201	0	0	0	0	0	0	0	219,078	149,633
5	191,877	27,745	0	0	0	0	0	0	0	219,622	136,368
6	191,877	28,300	0	0	0	0	0	0	0	220,177	124,284
7	191,877	28,866	0	0	0	0	0	0	0	220,743	113,276
8	191,877	29,443	0	0	0	0	0	0	0	221,321	103,248
9	191,877	30,032	0	0	0	0	0	0	0	221,909	94,111
10	191,877	30,633	0	0	0	0	0	0	0	222,510	85,787
11	191,877	31,245	0	0	0	0	0	0	0	223,123	78,203
12	191,877	31,870	0	0	0	0	0	0	0	223,748	71,293
13	191,877	32,508	0	0	0	0	0	0	0	224,385	64,996
14	191,877	33,158	0	0	0	0	0	0	0	225,035	59,259
15	191,877	33,821	0	0	0	0	0	0	0	225,698	54,030
16	191,877	34,497	0	0	0	0	0	0	0	226,375	49,266
17	191,877	35,187	0	0	0	0	0	0	0	227,065	44,924
18	191,877	35,891	0	0	0	0	0	0	0	227,768	40,968
19	191,877	36,609	0	0	0	0	0	0	0	228,486	37,359
20	191,877	37,341	0	0	0	0	0	0	0	229,218	34,072

Project Name:
Dataset Name: CASE STUDY.TRC

Yearly Cash Flow report Page 1 of 2

YEARLY CASH FLOW

By MCI

Alternative: 3
Life Cycle Cost: $2,888,129.34

Year	Utility Cost ($)	Maint. Cost ($)	Interest Cost ($)	Principal Cost ($)	Property Taxes ($)	Insurance Cost ($)	Revenue Penalty ($)	Replace. Expenses ($)	Deprec. Tax ($)	Cash Flow Effect ($)	Present Value ($)
0	0	0	0	1,188,583	0	0	0	0	0	1,188,583	1,188,583
1	171,877	22,205	0	0	0	0	0	0	0	194,083	176,439
2	171,877	22,650	0	0	0	0	0	0	0	194,527	160,766
3	171,877	23,103	0	0	0	0	0	0	0	194,980	146,491
4	171,877	23,565	0	0	0	0	0	0	0	195,442	133,469
5	171,877	24,036	0	0	0	0	0	0	0	195,913	121,647
6	171,877	24,517	0	0	0	0	0	0	0	196,394	110,859
7	171,877	25,007	0	0	0	0	0	0	0	196,884	101,033
8	171,877	25,507	0	0	0	0	0	0	0	197,384	92,081
9	171,877	26,017	0	0	0	0	0	0	0	197,894	83,927
10	171,877	26,538	0	0	0	0	0	0	0	198,415	76,497
11	171,877	27,068	0	0	0	0	0	0	0	198,945	69,729
12	171,877	27,610	0	0	0	0	0	0	0	199,487	63,563
13	171,877	28,162	0	0	0	0	0	0	0	200,039	57,944
14	171,877	28,725	0	0	0	0	0	0	0	200,602	52,825
15	171,877	29,300	0	0	0	0	0	0	0	201,177	48,160
16	171,877	29,886	0	0	0	0	0	0	0	201,763	43,909
17	171,877	30,483	0	0	0	0	0	0	0	202,360	40,036
18	171,877	31,093	0	0	0	0	0	0	0	202,970	36,506
19	171,877	31,715	0	0	0	0	0	0	0	203,592	33,289
20	171,877	32,349	0	0	0	0	0	0	0	204,226	30,357

Alternative: 4
Life Cycle Cost: $2,929,459.97

Year	Utility Cost ($)	Maint. Cost ($)	Interest Cost ($)	Principal Cost ($)	Property Taxes ($)	Insurance Cost ($)	Revenue Penalty ($)	Replace. Expenses ($)	Deprec. Tax ($)	Cash Flow Effect ($)	Present Value ($)
0	0	0	0	1,310,337	0	0	0	0	0	1,310,337	1,310,337
1	168,376	19,062	0	0	0	0	0	0	0	187,438	170,398
2	168,376	19,443	0	0	0	0	0	0	0	187,819	155,222
3	168,376	19,832	0	0	0	0	0	0	0	188,208	141,403
4	168,376	20,228	0	0	0	0	0	0	0	188,605	128,819
5	168,376	20,633	0	0	0	0	0	0	0	189,009	117,360
6	168,376	21,046	0	0	0	0	0	0	0	189,422	106,924
7	168,376	21,466	0	0	0	0	0	0	0	189,843	97,419
8	168,376	21,896	0	0	0	0	0	0	0	190,272	88,763
9	168,376	22,334	0	0	0	0	0	0	0	190,710	80,880
10	168,376	22,780	0	0	0	0	0	0	0	191,157	73,699
11	168,376	23,236	0	0	0	0	0	0	0	191,612	67,159
12	168,376	23,701	0	0	0	0	0	0	0	192,077	61,202
13	168,376	24,175	0	0	0	0	0	0	0	192,551	55,775
14	168,376	24,658	0	0	0	0	0	0	0	193,034	50,832
15	168,376	25,151	0	0	0	0	0	0	0	193,528	46,329
16	168,376	25,654	0	0	0	0	0	0	0	194,031	42,227
17	168,376	26,167	0	0	0	0	0	0	0	194,544	38,489
18	168,376	26,691	0	0	0	0	0	0	0	195,067	35,085
19	168,376	27,225	0	0	0	0	0	0	0	195,601	31,982
20	168,376	27,769	0	0	0	0	0	0	0	196,145	29,156

MONTHLY UTILITY COSTS

Utility	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
					------- Monthly Utility Costs -------								
Alternative 2 - 90° Rotation													
Electric													
On-Pk Cons. ($)	14,862	13,781	13,335	11,474	12,070	13,173	12,598	13,583	11,687	12,420	12,555	13,502	155,039
On-Pk Demand ($)	2,801	2,957	2,555	2,155	2,318	2,533	2,544	2,555	2,411	2,268	2,338	2,518	29,954
Total ($):	17,663	16,738	15,890	13,629	14,388	15,706	15,142	16,138	14,098	14,689	14,892	16,019	184,993
Water													
On-Pk Cons. ($)	583	529	692	791	1,050	1,457	1,398	1,508	1,129	758	686	591	11,170
Monthly Total ($):	18,246	17,267	16,582	14,420	15,438	17,163	16,540	17,646	15,227	15,446	15,578	16,610	196,163

Building Area = 145,593 ft²

Utility Cost Per Area = 1.35 $/ft²

Utility	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Alternative 2 - 180° Rotation													
Electric													
On-Pk Cons. ($)	14,978	13,874	13,359	11,517	12,130	13,203	12,643	13,609	11,687	12,428	12,600	13,593	155,619
On-Pk Demand ($)	2,822	2,915	2,523	2,160	2,334	2,553	2,532	2,550	2,401	2,279	2,374	2,520	29,962
Total ($):	17,800	16,789	15,881	13,676	14,465	15,755	15,176	16,158	14,088	14,706	14,974	16,112	185,581
Water													
On-Pk Cons. ($)	590	535	697	800	1,066	1,476	1,415	1,522	1,134	759	689	595	11,277
Monthly Total ($):	18,390	17,324	16,578	14,477	15,531	17,231	16,591	17,680	15,222	15,465	15,662	16,707	196,858

Building Area = 145,593 ft²

Utility Cost Per Area = 1.35 $/ft²

MONTHLY UTILITY COSTS

Utility	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
					------- Monthly Utility Costs -------								
Alternative 2 - 270° Rotation													
Electric													
On-Pk Cons. ($)	14,864	13,783	13,336	11,475	12,068	13,172	12,598	13,582	11,687	12,419	12,557	13,504	155,046
On-Pk Demand ($)	2,805	2,961	2,558	2,156	2,318	2,534	2,544	2,556	2,411	2,270	2,339	2,521	29,972
Total ($):	17,669	16,744	15,894	13,631	14,387	15,706	15,142	16,137	14,098	14,689	14,896	16,024	185,017
Water													
On-Pk Cons. ($)	583	529	692	791	1,050	1,457	1,398	1,507	1,129	758	686	591	11,170
Monthly Total ($):	18,252	17,273	16,586	14,421	15,437	17,163	16,540	17,645	15,227	15,447	15,581	16,615	196,187

Building Area = 145,593 ft²

Utility Cost Per Area = 1.35 $/ft²

Utility	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Alternative 3													
Electric													
On-Pk Cons. ($)	9,997	9,131	10,279	10,360	11,804	12,851	12,293	13,306	11,515	10,645	10,084	9,597	131,861
On-Pk Demand ($)	1,973	1,994	2,020	2,232	2,359	2,534	2,524	2,536	2,413	2,143	2,049	1,961	26,740
Total ($):	11,970	11,125	12,299	12,591	14,163	15,386	14,817	15,843	13,928	12,789	12,133	11,558	158,601
Water													
On-Pk Cons. ($)	504	446	751	1,002	1,361	1,813	1,760	1,890	1,450	912	785	602	13,276
Monthly Total ($):	12,474	11,572	13,050	13,593	15,524	17,199	16,576	17,733	15,378	13,700	12,918	12,160	171,877

Building Area = 145,593 ft²

Utility Cost Per Area = 1.18 $/ft²

Project Name:

ataset Name: CASE STUDY.TRC

Economic Summary

Project Information

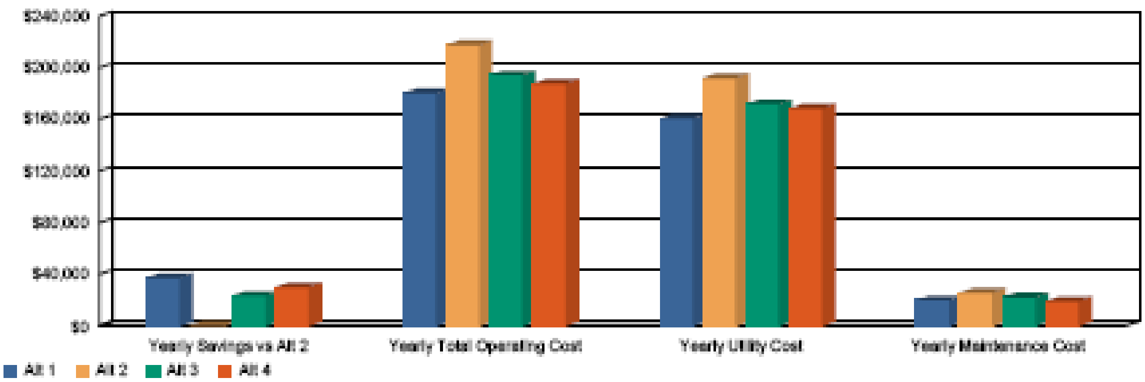
Location	Atlanta, GA
Project Name	CASE STUDY
User	
Company	
Comments	

Study Life:	20 years
Cost of Capital:	10 %
Alternative 1:	Self-contained+VAV+PFP
Alternative 2:	90_1 Appendix G Chilled Water VAV
Alternative 3:	Water Source Heat Pump+VAV+SPF
Alternative 4:	Air-Cooled Chiller+Fan Coil

Economic Comparison of Alternatives

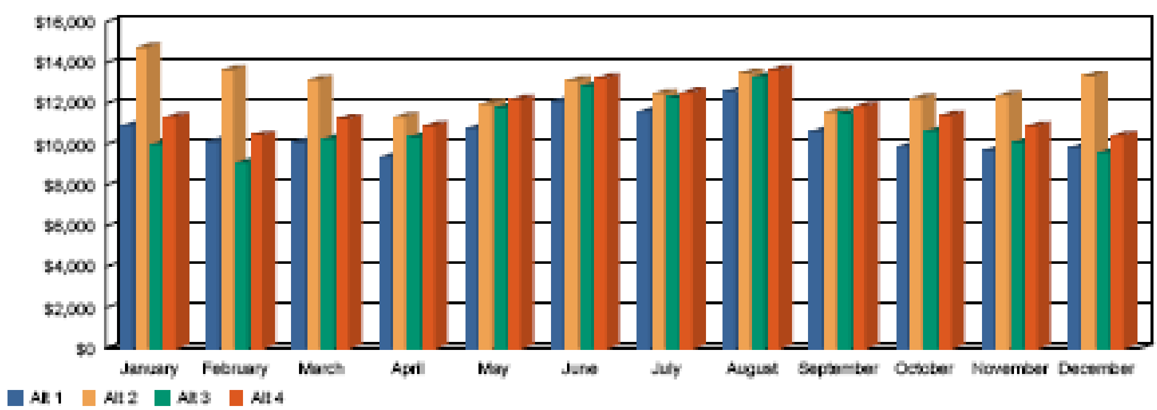
	Yearly Savings ($)	First Cost Difference ($)	Cumulative Cash Flow Difference ($)	Simple Payback (yrs.)	Net Present Value ($)	Life Cycle Payback (yrs.)	Internal Rate of Return (%)
Alt 2 vs Alt 1	23,427	181,891	-1,039,988	-1.0	-543,682	No Payback	Does Not Payback
Alt 1 vs Alt 3	0	87,356	201,163	6.3	33,999	10.1	15.3
Alt 4 vs Alt 1	0	38,398	-178,512	-1.0	-97,329	No Payback	Does Not Payback
Alt 2 vs Alt 3	23,427	269,347	-838,805	-1.0	-509,684	No Payback	Does Not Payback
Alt 2 vs Alt 4	23,427	145,593	-881,457	-1.0	-446,353	No Payback	Does Not Payback
Alt 4 vs Alt 3	0	123,754	22,652	18.6	-63,331	No Payback	1.6

Annual Operating Costs



	Yearly Savings vs Alt 2	Yearly Total Operating Cost ($)	Yearly Utility Cost ($)	Yearly Maintenance Cost ($)
Alt 1	37,333	180,177	160,393	19,784
Alt 2	0	217,510	191,877	25,632
Alt 3	23,427	194,083	171,877	22,205
Alt 4	30,072	187,438	168,376	19,062

Monthly Utility Costs



Project Name:
Dataset Name: CASE STUDY.TRC

APPENDIX E
BLCC INPUTS AND SUMMARY

NIST BLCC 5.3-09: Input Data Listing

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

General Information

File Name:	C:\Program Files (x86)\BLCC5\projects\Case Study_Dissertation.xml
Date of Study:	Sun Jun 06 16:40:40 EDT 2010
Analysis Type:	FEMP Analysis, Energy Project
Project Name:	Case Study
Project Location:	Georgia
Analyst:	
Base Date:	May 1, 2010
Service Date:	May 1, 2010
Study Period:	20 years 0 months (May 1, 2010 through April 30, 2030)
Discount Rate:	3%
Discounting Convention:	End-of-Year

Discount and Escalation Rates are REAL (exclusive of general inflation)

Escalation Rates

From Date	Duration	Escalation
April 1, 2009	1 year 0 months	-6.52%
April 1, 2010	1 year 0 months	1.07%
April 1, 2011	1 year 0 months	1.51%
April 1, 2012	1 year 0 months	1.04%
April 1, 2013	1 year 0 months	1.48%
April 1, 2014	1 year 0 months	0.61%
April 1, 2015	1 year 0 months	0.74%
April 1, 2016	1 year 0 months	1.2%
April 1, 2017	1 year 0 months	1.09%
April 1, 2018	1 year 0 months	0.78%
April 1, 2019	1 year 0 months	1.40%
April 1, 2020	1 year 0 months	1.44%
April 1, 2021	1 year 0 months	0.88%
April 1, 2022	1 year 0 months	0.31%
April 1, 2023	1 year 0 months	0.31%
April 1, 2024	1 year 0 months	0%
April 1, 2025	1 year 0 months	0%
April 1, 2026	1 year 0 months	1.02%
April 1, 2027	1 year 0 months	1.30%
April 1, 2028	1 year 0 months	1.36%
April 1, 2029	1 year 0 months	1.07%
April 1, 2030	1 year 0 months	0.83%
April 1, 2031	1 year 0 months	0.73%
April 1, 2032	1 year 0 months	0.79%
April 1, 2033	1 year 0 months	0.75%
April 1, 2034	1 year 0 months	0.77%
April 1, 2035	1 year 0 months	0.74%
April 1, 2036	1 year 0 months	0.76%
April 1, 2037	1 year 0 months	0.76%
April 1, 2038	1 year 0 months	0.76%
April 1, 2039	Remaining	0.76%

Alternative: Alt1 Self-contained VAV System

Energy: Electricity

Annual Consumption:	1.0 kWh
Price per Unit:	$153993.00000
Demand Charge:	$0
Utility Rebate:	$0
Location:	U.S. Average
Rate Schedule:	Residential
State:	Georgia

Usage Indices

From Date	Duration	Usage Index
May 1, 2010	Remaining	100%

Water: Water Cost - Alt.1

	Annual Usage		Annual Disposal	
	Units/Year	Price/Unit	Units/Year	Price/Unit
@Summer Rates	1.0 L	$6399.00000	0.0 L	$0.00000
@Winter Rates	0.0 L	$0.00000	0.0 L	$0.00000

Escalation Rates - Usage

From Date	Duration	Usage Cost Escalation
May 1, 2010	Remaining	0%

Escalation Rates - Disposal

From Date	Duration	Disposal Cost Escalation
May 1, 2010	Remaining	0%

Usage Indices - Usage

From Date	Duration	Index
May 1, 2010	Remaining	100%

Component:

Initial Investment

Initial Cost (base-year $):	$1,273,939
Annual Rate of Increase:	0%
Expected Asset Life:	0 years 0 months
Residual Value Factor:	0%

Cost-Phasing

Cost Adjustment Factor: 0%

Years/Months (from Date)	Date	Portion
0 years 0 months	May 1, 2010	100%

Recurring OM&R: Alt 1

Amount	$19,784
Annual Rate of Increase:	2%

Usage Indices

From Date	Duration	Factor
May 1, 2010	Remaining	100%

Alternative: Alt2 Water source heat pump VAV System

Energy: Copy of: Electricity

Annual Consumption:	1.0 kWh
Price per Unit:	$158601.00000
Demand Charge:	$0
Utility Rebate:	$0
Location:	U.S. Average
Rate Schedule:	Residential
State:	North Carolina

Usage Indices

From Date	Duration	Usage Index
May 1, 2010	Remaining	100%

Component: Copy of:

Initial Investment

Initial Cost (base-year $):	$1,186,583
Annual Rate of Increase:	0%
Expected Asset Life:	0 years 0 months
Residual Value Factor:	0%

Cost-Phasing

Cost Adjustment Factor: 0%

Years/Months (from Date)	Date	Portion
0 years 0 months	May 1, 2010	100%

Recurring OM&R: Alt 2

Amount:	$22,205
Annual Rate of Increase:	2%

Usage Indices

From Date	Duration	Factor
May 1, 2010	Remaining	100%

Water: Water cost - Alt.2

	Annual Usage		Annual Disposal	
	Units/Year	Price/Unit	Units/Year	Price/Unit
@Summer Rates	1.0 L	$13276.00000	0.0 L	$0.00000
@Winter Rates	0.0 L	$0.00000	0.0 L	$0.00000

Escalation Rates - Usage

From Date	Duration	Usage Cost Escalation
May 1, 2010	Remaining	0%

Escalation Rates - Disposal

From Date	Duration	Disposal Cost Escalation
May 1, 2010	Remaining	0%

Usage Indices - Usage

From Date	Duration	Index
May 1, 2010	Remaining	100%

Usage Indices - Disposal

From Date	Duration	Index
May 1, 2010	Remaining	100%

Alternative: Alt3 Air-cooled chiller FC system

Energy: Copy of: Electricity

Annual Consumption:	1.0 kWh
Price per Unit:	$168333.00000
Demand Charge:	$0
Utility Rebate:	$0
Location:	U.S. Average
Rate Schedule:	Residential
State:	North Carolina

Usage Indices

From Date	Duration	Usage Index
May 1, 2010	Remaining	100%

Water: Water cost - Alt.3

	Annual Usage		Annual Disposal	
	Units/Year	Price/Unit	Units/Year	Price/Unit
@Summer Rates	1.0 L	$43.00000	0.0 L	$0.00000
@Winter Rates	0.0 L	$0.00000	0.0 L	$0.00000

Escalation Rates - Usage

From Date	Duration	Usage Cost Escalation
May 1, 2010	Remaining	0%

Usage Indices - Usage

From Date	Duration	Index
May 1, 2010	Remaining	100%

Escalation Rates - Disposal

From Date	Duration	Disposal Cost Escalation
May 1, 2010	Remaining	0%

Usage Indices - Disposal

From Date	Duration	Index
May 1, 2010	Remaining	100%

Component: Copy of:

Initial Investment

Initial Cost (base-year $):	$1,310,337
Annual Rate of Increase:	0%
Expected Asset Life:	0 years 0 months
Residual Value Factor:	0%

Cost-Phasing

Cost Adjustment Factor: 0%

Years/Months (from Date)	Date	Portion
0 years 0 months	May 1, 2010	100%

Recurring OM&R: Alt. 3

Amount: $19,062

Annual Rate of Increase: 2%

NIST BLCC 5.3-09: Summary LCC

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

General Information

File Name:	C:\Program Files (x86)\BLCC5\projects\Case Study_Dissertation.xml
Date of Study:	Sun Jun 06 17:00:57 EDT 2010
Analysis Type:	FEMP Analysis, Energy Project
Project Name:	Case Study
Project Location:	Georgia
Analyst:	
Base Date:	May 1, 2010
Service Date:	May 1, 2010
Study Period:	20 years 0 months (May 1, 2010 through April 30, 2030)
Discount Rate:	3%
Discounting Convention:	End-of-Year

Discount and Escalation Rates are REAL (exclusive of general inflation)

Alternative: Alt1Self-contained VAV System

LCC Summary

	Present Value	Annual Value
Initial Cost	$1,273,939	$85,637
Energy Consumption Costs	$2,525,062	$169,741
Energy Demand Costs	$0	$0
Energy Utility Rebates	$0	$0
Water Usage Costs	$95,208	$6,400
Water Disposal Costs	$0	$0
Annually Recurring OM&R Costs	$357,728	$24,047
Non-Annually Recurring OM&R Costs	$0	$0
Replacement Costs	$0	$0
Less Remaining Value	$0	$0
	------------	------------
Total Life-Cycle Cost	$4,251,937	$285,825

Alternative: Alt2 Water source heat pump VAV System

LCC Summary

	Present Value	Annual Value
Initial Cost	$1,186,583	$79,765
Energy Consumption Costs	$2,600,621	$174,820
Energy Demand Costs	$0	$0
Energy Utility Rebates	$0	$0
Water Usage Costs	$197,528	$13,278
Water Disposal Costs	$0	$0
Annually Recurring OM&R Costs	$401,504	$26,990
Non-Annually Recurring OM&R Costs	$0	$0
Replacement Costs	$0	$0
Less Remaining Value	$0	$0
	------------	------------
Total Life-Cycle Cost	$4,386,235	$294,853

Alternative: Alt3 Air-cooled chiller FC system

LCC Summary

	Present Value	Annual Value
Initial Cost	$1,310,337	$88,084
Energy Consumption Costs	$2,760,199	$185,547
Energy Demand Costs	$0	$0
Energy Utility Rebates	$0	$0
Water Usage Costs	$640	$43
Water Disposal Costs	$0	$0
Annually Recurring OM&R Costs	$344,673	$23,170
Non-Annually Recurring OM&R Costs	$0	$0
Replacement Costs	$0	$0
Less Remaining Value	$0	$0
	------------	------------
Total Life-Cycle Cost	$4,415,848	$296,844

APPENDIX F
DECISION-MAKING MODEL PROGRAM

1. INPUT

a. Important judgment matrix of Criteria layer and Sub-criteria layer

Criteria layer

C1. Technical requirement

C2. Economical performence

C3. Environmental performence

C4. LEED performance

Input matirx for weighting of criteria layer

$$
\begin{array}{c}
\begin{pmatrix} C1 & C2 & C3 & C4 \end{pmatrix} \\
IM0 := \begin{pmatrix} 1 & \frac{1}{3} & \frac{1}{5} & \frac{1}{5} \\ 3 & 1 & \frac{1}{3} & \frac{1}{3} \\ 5 & 3 & 1 & 1 \\ 5 & 3 & 1 & 1 \end{pmatrix} \quad \begin{pmatrix} C1 \\ C2 \\ C3 \\ C4 \end{pmatrix}
\end{array}
$$

Sub-criteria layer

C1. Technical requirement

C11. Full load effectiveness

C12. Part load effectiveness

C13. Reliability

C14. Maintainability

C15. Spatial requirement

Input matirx for weighting of technical requirement

$$
\begin{array}{c}
\begin{pmatrix} C11 & C12 & C13 & C14 & C15 \end{pmatrix} \\
IM1 := \begin{pmatrix} 1 & 1 & 5 & 5 & 7 \\ 1 & 1 & 5 & 5 & 7 \\ \frac{1}{5} & \frac{1}{5} & 1 & 1 & 3 \\ \frac{1}{5} & \frac{1}{5} & 1 & 1 & 3 \\ \frac{1}{7} & \frac{1}{7} & \frac{1}{3} & \frac{1}{3} & 1 \end{pmatrix} \quad \begin{pmatrix} C11 \\ C12 \\ C13 \\ C14 \\ C15 \end{pmatrix}
\end{array}
$$

C2. Economical performence

C21. Life cycle costing

Input matirx for weighting of economical performence

$IM2 := 1$

C3. Environmental performence

C31. Human health

C32. Ecosystem quality

C33. Climate Change

C34. Resources

Input matirx for weighting of environmental performence

$$\begin{array}{cc} & (C31 \;\; C32 \;\; C33 \;\; C34) \\ IM3 := & \begin{pmatrix} 1 & 2 & 2 & 2 \\ 0.5 & 1 & 2 & 2 \\ 0.5 & 0.5 & 1 & 2 \\ 0.5 & 0.5 & 0.5 & 1 \end{pmatrix} \end{array} \qquad \begin{pmatrix} C31 \\ C32 \\ C33 \\ C34 \end{pmatrix}$$

C4. LEED perfomance

C4.1. Optimized energy performance

C4.2. Enhanced refrigerant management

Input matirx for weighting of environmental performence

$$IM4 := \begin{pmatrix} 1 & 2 \\ 0.5 & 1 \end{pmatrix} \qquad \begin{pmatrix} C41 \\ C42 \end{pmatrix}$$

b. Pairwise comparison matrix for the alternative layer

Max ,Min and ture value for C1. Technical requirement

$$(C11 \;\; C12 \;\; C13 \;\; C14 \;\; C15)$$

$$C1_{Ture1} := (3 \;\; 4 \;\; 4 \;\; 2 \;\; 2)^T$$

$$C1_{Ture2} := (3 \;\; 3 \;\; 4 \;\; 1 \;\; 2)^T$$

$$C1_{Ture3} := (3 \;\; 1 \;\; 2 \;\; 3 \;\; 3)^T$$

$$C1_{Max} := (4 \;\; 4 \;\; 4 \;\; 4 \;\; 4)$$

$$C1_{Min} := (1 \;\; 1 \;\; 1 \;\; 1 \;\; 1)$$

Max and Min for C2. Ecnomical performence

C21

$C2_{Ture1} := (153993)$

$C2_{Ture2} := (158601)$

$C2_{Ture3} := (168333)$

$$C2_{mean} := \left[\frac{(C2_{Ture1} + C2_{Ture2} + C2_{Ture3})}{3}\right] = \left(1.603 \times 10^{5}\right)$$

$$C2_{st} := \left(\text{Stdev}\left(C2_{Ture1}, C2_{Ture2}, C2_{Ture3}\right)\right) = \left(7.321 \times 10^{3}\right)$$

$$C2_{Max} := C2_{mean} + 3 \cdot C2_{st} = \left(1.823 \times 10^{5}\right)$$

$$C2_{Min} := C2_{mean} - 3 \cdot C2_{st} = \left(1.383 \times 10^{5}\right)$$

Max and Min for C3. Environmental performence

$(C31 \quad C32 \quad C33 \quad C34)$

$C3_{Ture1} := (84 \quad 5 \quad 72 \quad 78)^{T}$ C31. Human health

$C3_{Ture2} := (73 \quad 5 \quad 61.5 \quad 66)^{T}$ C32. Ecosystem quality

C33. Climate Change

$C3_{Ture3} := (78 \quad 7.5 \quad 41 \quad 47)^{T}$ C34. Resources

$$C3_{mean} := \left[\frac{(C3_{Ture1} + C3_{Ture2} + C3_{Ture3})}{3}\right]^{T} = (78.333 \quad 5.833 \quad 58.167 \quad 63.667)$$

$$C3_{s}(g) := \text{Stdev}\left(C3_{Ture1_{g}}, C3_{Ture2_{g}}, C3_{Ture3_{g}}\right)$$

$$C3_{st} := \left(C3_{s}(0) \quad C3_{s}(1) \quad C3_{s}(2) \quad C3_{s}(3)\right) = (5.508 \quad 1.443 \quad 15.767 \quad 15.631)$$

$$C3_{Max} := C3_{mean} + 3 \cdot C3_{st} = (94.856 \quad 10.163 \quad 105.466 \quad 110.56)$$

$$C3_{Min} := C3_{mean} - 3 \cdot C3_{st} = (61.811 \quad 1.503 \quad 10.867 \quad 16.773)$$

Max and Min for C4. LEED performance

$$\begin{array}{l} \\ C4_{Ture1} := \end{array}\begin{array}{c} (C41 \quad C42) \\ (3 \quad 1)^T \end{array}$$

$$C4_{Ture2} := (1 \quad 1)^T$$

$$C4_{Ture3} := (0 \quad 0)^T$$

C4.1. Optimized energy performance

C4.2. Enhanced refrigerant management

$$C4_{Max} := (10 \quad 1)$$

$$C4_{Min} := (0 \quad 0)$$

2. PREFERENCE WEIGHTING FOR CRITERIA AND SUB-CRITERIA

Criteria layer

$k := 0 .. 3$

The Weighting of criteria w_{ck} is

$$W_{Criteria_k} := \frac{\left[\prod_{j=0}^{3} \left(IM0_{k,j}\right)\right]^{\frac{1}{4}}}{\sum_{i=0}^{3} \left[\prod_{j=0}^{3} \left(IM0_{i,j}\right)\right]^{\frac{1}{4}}}$$

$$W_{Criteria} = \begin{pmatrix} 0.067 \\ 0.151 \\ 0.391 \\ 0.391 \end{pmatrix} \begin{pmatrix} W1 \\ W2 \\ W3 \\ W4 \end{pmatrix}$$

C1. Technical requirement

C2. Economical perfomence

C3. Environmental perfomence

C4. LEED performance

Sub-criteria layer

C1. Technical requirement

$m := 0..4$

The weighting of sub-criteria w_{c1} is

$$W_{C1_m} := \frac{\left[\prod_{j=0}^{4}\left(IM1_{m,j}\right)\right]^{\frac{1}{5}}}{\sum_{i=0}^{4}\left[\prod_{j=0}^{4}\left(IM1_{i,j}\right)\right]^{\frac{1}{5}}}$$

$$W_{C1} = \begin{pmatrix} 0.389 \\ 0.389 \\ 0.091 \\ 0.091 \\ 0.041 \end{pmatrix} \qquad \begin{pmatrix} W11 \\ W12 \\ W13 \\ W14 \\ W15 \end{pmatrix}$$

C11. Full load effectiveness
C12. Part load effectiveness
C13. Reliability
C14. Maintainability
C15. Spatial requirement

C2. Economical performence

$W_{C2} := 1 \qquad W21$ C21. Life cycle costing

C3. Environmental performence

$n := 0..3$

The weighting of sub-criteria w_{c3} is

$$W_{C3} := \begin{pmatrix} 0.301 \\ 0.021 \\ 0.352 \\ 0.326 \end{pmatrix} \qquad \begin{pmatrix} W31 \\ W32 \\ W33 \\ W34 \end{pmatrix}$$

C31. Human health
C32. Ecosystem quality
C33. Climate Change
C34. Resources

C4. LEED performance

$q := 0..1$

The weighting of sub-criteria w_{c4} is

$$W_{C4} := \begin{pmatrix} 0.9048 \\ 0.0952 \end{pmatrix} \qquad \begin{pmatrix} W41 \\ W42 \end{pmatrix}$$

C41. Optimized energy performance
C42. Enhanced refrigerant management

Total weighting

$$W_{total} := \text{stack}\left(W_{Criteria_0} \cdot W_{C1}, W_{Criteria_1} \cdot W_{C2}, W_{Criteria_2} \cdot W_{C3}, W_{Criteria_3} \cdot W_{C4}\right)$$

$W_{total} =$ (· %)

	0
0	2.625
1	2.625
2	0.611
3	0.611
4	0.276
5	15.089
6	11.763
7	0.821
8	13.757
9	12.741
10	35.361
11	3.721

$$\begin{pmatrix} W11 \\ W12 \\ W13 \\ W14 \\ W15 \\ W21 \\ W31 \\ W32 \\ W33 \\ W34 \\ W41 \\ W42 \end{pmatrix}$$

C11. Full load effectiveness
C12. Part load effectiveness
C13. Reliability
C14. Maintainability
C15. Spatial requirement
C21. Life cycle costing
C31. Human health
C32. Ecosystem quality
C33. Climate Change
C34. Resources
C41. Optimized energy performance
C42. Enhanced refrigerant management

3. CONSISTENCY CHECK

Criteria layer

Size of the matrix $n_c := 4$

Random consistency index $RI_c := 0.9$

Eigenvalue of the matrix $\lambda_c := \mathrm{eigenvals}(IM0)$

Max eigenvalue of the matrix

$$\lambda_{maxc} := \max\left(\mathrm{Re}\left(\lambda_{c_0}\right), \mathrm{Re}\left(\lambda_{c_1}\right), \mathrm{Re}\left(\lambda_{c_2}\right), \mathrm{Re}\left(\lambda_{c_3}\right)\right) = 4.043$$

Consistency index $CI_c := \dfrac{\lambda_{maxc} - n_c}{n_c - 1} = 0.014$

Consistency ratio $CR_c := \dfrac{CI_c}{RI_c} = 0.016$

Sub-criteria layer

C1. Technical requirement

Size of the matrix $n_s := 5$

Random consistency index $RI_s := 1.12$

Eigenvalue of the matrix $\lambda_s := \mathrm{eigenvals}(IM1)$

Max eigenvalue of the matrix

$$\lambda_{maxs} := \max\left(\mathrm{Re}\left(\lambda_{s_0}\right), \mathrm{Re}\left(\lambda_{s_1}\right), \mathrm{Re}\left(\lambda_{s_2}\right), \mathrm{Re}\left(\lambda_{s_3}\right)\right) = 5.094$$

Consistency index $CI_s := \dfrac{\lambda_{maxs} - n_s}{n_s - 1} = 0.023$

Consistency ratio $CR_s := \dfrac{CI_s}{RI_s} = 0.021$

4. Overall performance

The max ,min and ture value matrix

$C_{Max} := augment(C1_{Max}, C2_{Max}, C3_{Max}, C4_{Max})$ Combine all the max value

$C_{Min} := augment(C1_{Min}, C2_{Min}, C3_{Min}, C4_{Min})$ Combine all the min value

$C_{Ture1} := augment\left(C1_{Ture1}^{T}, C2_{Ture1}^{T}, C3_{Ture1}^{T}, C4_{Ture1}^{T}\right)$ Combine all the alternative 1 value

$C_{Ture2} := augment\left(C1_{Ture2}^{T}, C2_{Ture2}^{T}, C3_{Ture2}^{T}, C4_{Ture2}^{T}\right)$ Combine all the alternative 2 value

$C_{Ture3} := augment\left(C1_{Ture3}^{T}, C2_{Ture3}^{T}, C3_{Ture3}^{T}, C4_{Ture3}^{T}\right)$ Combine all the alternative 3 value

Evaluation value for alternative 1

$$E1 := diag\left[\left(C_{Ture1}^{T} - C_{Min}^{T}\right)\cdot\left(\frac{9-1}{C_{Max} - C_{Min}}\right) + 1\right]$$

E1 =

	0	
0	6.333	C11. Full load effectiveness
1	9	C12. Part load effectiveness
2	9	C13. Reliability
3	3.667	C14. Maintainability
4	3.667	C15. Spatial requirement
5	3.85	C21. Life cycle costing
6	6.372	C31. Human health
7	4.23	C32. Ecosystem quality
8	6.17	C33. Climate Change
9	6.223	C34. Resources
10	3.4	C41. Optimized energy performance
11	9	C42. Enhanced refrigerant management

Evaluation value for alternative 2

$$E2 := \mathrm{diag}\left[\left(C_{Ture2}^{T} - C_{Min}^{T}\right)\cdot\left(\frac{9-1}{C_{Max} - C_{Min}}\right) + 1\right]$$

E2 =

	0
0	6.333
1	6.333
2	9
3	1
4	3.667
5	4.689
6	3.709
7	4.23
8	5.282
9	5.199
10	1.8
11	9

C11. Full load effectiveness
C12. Part load effectiveness
C13. Reliability
C14. Maintainability
C15. Spatial requirement
C21. Life cycle costing
C31. Human health
C32. Ecosystem quality
C33. Climate Change
C34. Resources
C41. Optimized energy performance
C42. Enhanced refrigerant management

Evaluation value for alternative 3

$$E3 := \mathrm{diag}\left[\left(C_{Ture3}^{T} - C_{Min}^{T}\right)\cdot\left(\frac{9-1}{C_{Max} - C_{Min}}\right) + 1\right]$$

E3 =

	0
0	6.333
1	1
2	3.667
3	6.333
4	6.333
5	6.461
6	4.919
7	6.54
8	3.548
9	3.578
10	1
11	1

C11. Full load effectiveness
C12. Part load effectiveness
C13. Reliability
C14. Maintainability
C15. Spatial requirement
C21. Life cycle costing
C31. Human health
C32. Ecosystem quality
C33. Climate Change
C34. Resources
C41. Optimized energy performance
C42. Enhanced refrigerant management

Overall score

$$OS1 := \sum_{z=0}^{11} diag\left(E1 \cdot W_{total}^{T}\right)_z = 5.034$$ Alternative 1

$$OS2 := \sum_{z=0}^{11} diag\left(E2 \cdot W_{total}^{T}\right)_z = 3.943$$ Alternative 2

$$OS3 := \sum_{z=0}^{11} diag\left(E3 \cdot W_{total}^{T}\right)_z = 3.213$$ Alternative 3

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BIOGRAPHICAL SKETCH

Xun was born and grew up in Dalian, a coastal city in northeast of China. She received her bachelor of engineering degree from Dalian University of Technology, China, in June 2005 and began her PH.D program in Department of Mechanical Engineering at University of Florida after she got her master's degree in the same department in December 2007. She is also pursuing a minor in building construction at the University of Florida for Sustainable Green Building Design. Xun has two internship experiences in mechanical consulting, energy modeling as well as energy saving development in HVAC design companies. Xun is a LEED Accredited Professional and EIT engineer.