SYRACUSE UNIVERSITY
BUILDING ENERGY AND ENVIRONMENTAL SYSTEMS LABORATORY (BEESL)
DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING
263 Link Hall, Syracuse University, Syracuse, NY 13244-1240; http://BEESL.Syr.Edu

Virtual Design Studio (VDS) -

Development of an Integrated Computer Simulation Environment for Performance Based Design of Very-Low Energy and High IEQ Buildings

Final Research Report*

Prepared for

U.S. Department of Energy

(Award Number: DE-EE0003844)

Prepared by

Yixing Chen[1], Jianshun Zhang[1] (PI), Michael Pelken[2] (Co-PI), Lixing Gu[3] (Co-PI), Daniel Rice[1], Zhaozhou Meng[1], Shewangizaw Semahegn[1], Wei Feng[1], Francesca Ling[2], Jun Shi[1], Hugh Henderson[4] (Co-PI)

1. Building Energy and Environmental Systems Laboratory (BEESL), Syracuse, NY 13244
2. School of Architecture, Syracuse University, Syracuse, NY 13244
3. Florida Solar Energy Center, 1679 Clearlake Road, Cocoa, FL 32922
4. CDH Energy Corp, 2695 Bingley Road, Cazenovia, NY 13035

September 2013

* This report is suitable for public release.

Executive Summary

The objective of this study was to develop a "Virtual Design Studio (VDS)": a software platform for integrated, coordinated and optimized design of green building systems with low energy consumption, high indoor environmental quality (IEQ), and high level of sustainability. This VDS is intended to assist collaborating architects, engineers and project management team members throughout from the early phases to the detailed building design stages. It can be used to plan design tasks and workflow, and evaluate the potential impacts of various green building strategies on the building performance by using the state of the art simulation tools as well as industrial/professional standards and guidelines for green building system design.

Engaged in the development of VDS was a multi-disciplinary research team that included architects, engineers, and software developers. Based on the review and analysis of how existing professional practices in building systems design operate, particularly those used in the U.S., Germany and UK, a generic process for performance-based building design, construction and operation was proposed. It distinguishes the whole process into five distinct stages: Assess, Define, Design, Apply, and Monitoring (ADDAM). The current VDS is focused on the first three stages.

The VDS considers building design as a multi-dimensional process, involving multiple design teams, design factors, and design stages. The intersection among these three dimensions defines a specific design task in terms of "who", "what" and "when". It also considers building design as a multi-objective process that aims to enhance the five aspects of performance for green building systems: site sustainability, materials and resource efficiency, water utilization

efficiency, energy efficiency and impacts to the atmospheric environment, and IEQ. The current VDS development has been limited to energy efficiency and IEQ performance, with particular focus on evaluating thermal performance, air quality and lighting environmental quality because of their strong interaction with the energy performance of buildings.

The VDS software framework contains four major functions:

1) Design coordination: It enables users to define tasks using the Input-Process-Output flow approach, which specifies the anticipated activities (i.e., the process), required input and output information, and anticipated interactions with other tasks. It also allows task scheduling to define the work flow, and sharing of the design data and information via the internet.

2) Modeling and simulation: It enables users to perform building simulations to predict the energy consumption and IEQ conditions at any of the design stages by using EnergyPlus and a combined heat, air, moisture and pollutant simulation (CHAMPS) model. A method for co-simulation was developed to allow the use of both models at the same time step for the combined energy and indoor air quality analysis.

3) Results visualization: It enables users to display a 3-D geometric design of the building by reading BIM (building information model) file generated by design software such as SketchUp, and the predicted results of heat, air, moisture, pollutant and light distributions in the building.

4) Performance evaluation: It enables the users to compare the performance of a proposed building design against a reference building that is defined for the same type of buildings

under the same climate condition, and predicts the percent of improvements over the minimum requirements specified in ASHRAE Standard 55-2010, 62.1-2010 and 90.1-2010. An approach was developed to estimate the potential impact of a design factor on the whole building performance, and hence can assist the user to identify areas that have most pay back for investment.

The VDS software was developed by using C++ with the conventional Model, View and Control (MVC) software architecture. The software has been verified by using a simple 3-zone case building. The application of the VDS concepts and framework for building design and performance analysis has been illustrated by using a medium-sized, five story office building that received LEED Platinum Certification from USGBC.

Acknowledgements

We gratefully acknowledge the financial support from the United States Department of Energy under Award Number: DE-EE0003844, and the additional funding from the Syracuse Center of Excellence in Environmental and Energy Systems.

We are grateful to the Department of Mechanical and Aerospace Engineering and the School of Architecture in Syracuse University for their support.

We would like to thank the Syracuse Center of Excellence in Environmental and Energy Systems for providing comprehensive project information for the VDS case study. We would also like to thank Prof. John Haymaker of Georgia Institute of Technology and Dr. Reid Senescu for the access to the PIP source code.

We also wish to give our deep appreciation to those who participated in our workshops and working sessions for their ideas, suggestions and feedback.

Acknowledgment: "This material is based upon work supported by the Department of Energy under Award Numbers DE-EE0003844."

Contents

List of Figures

List of Tables

Acronym

ASHRAE - American Society of Heating, Refrigerating and Air Conditioning Engineers

BCVTB - Building Controls Virtual Test Bed

BDA - Building Design Advisor

BIM - Building Information Modeling

CHAMPS - Coupled Heat, Air, Moisture and Pollutant Simulation

DeST - Designer's Simulation Toolkit

DOE - Department of energy

EIA - Energy information administration

EPA - Environmental protection agency

GUI - Graphical user interface

IAQ -Indoor air quality

IEQ - Indoor environmental quality

KBES - Knowledge-based expert system

LEED - Leadership in Energy & Environmental Design

NREL -National Renewable Energy Laboratory

ODE -Ordinary differential equation

SyracuseCoE - Syracuse Center of Excellence

USGBC -U.S. Green Building Council

VDS - Virtual design studio

Chapter 1. Introduction

1.1. Background and problem definition

Buildings consume a large share of the total energy consumption in the U.S. Buildings, including both residential and commercial, consume about 41% of the total energy consumption in US (Figure 1-1). Figure 1-2 shows the total energy consumption by end-use sector in US from 1949 to 2011. The building energy consumption has increased significantly over time and is a large percentage of the total energy consumption. With the increasing concerns regarding energy use and climate change, the concepts of "Low Carbon", "Energy Efficiency" and "Environmental Friendliness" have to be considered and applied throughout the full life cycle of buildings, including conception, planning, design, construction, operation, retrofitting, reuse or demolition and dis-assembly.

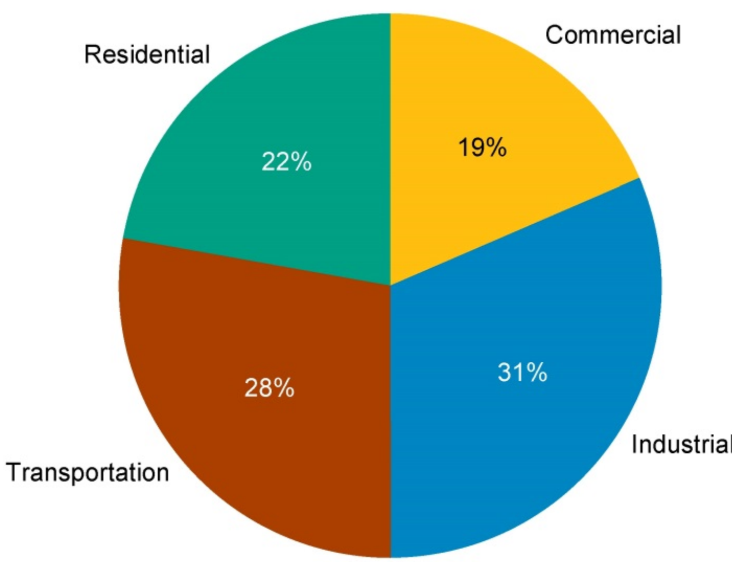


Figure 1-1 End-use sector shares of total energy consumption in 2011 (US EIA, 2013d)

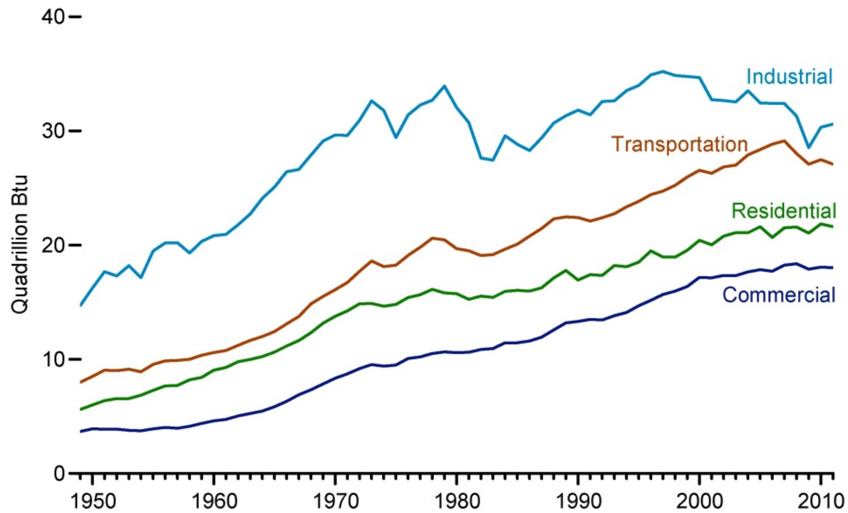


Figure 1-2 Total energy consumption by end-use sector in the US from 1949 to 2011 (US EIA, 2013d)

The majority of energy consumed in buildings is for conditioning the space for occupants, including heating, cooling, lighting and ventilation (Figure 1-3). People spend approximately 90% of their time indoors (US EPA, 1989). The indoor environmental quality (IEQ) in buildings affects occupants' health, comfort, and performance. It is, therefore, very important to create a healthy, comfortable and productive indoor environment for occupants, while striving to maximize energy efficiency of buildings.

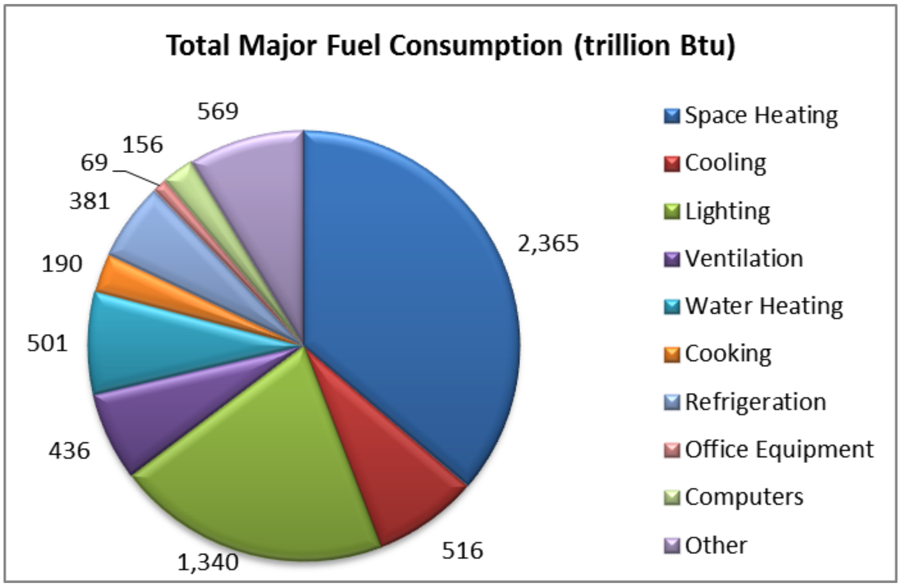


Figure 1-3 Major fuel consumption by end use for all buildings in US, 2003 (US EIA, 2013b)

There are many areas for improving building energy efficiencies and IEQ: building materials and enclosure, HVAC equipment and systems, better design integration, and control of operation. This research focuses on the development of a whole building simulation software platform to assist the performance based design of very-low energy and high IEQ new buildings, here after called high performance buildings.

There are many existing simulation programs developed to simulate building energy and IEQ performance. These simulation programs do not integrate with practice related design processes as part of their framework. They require detailed input parameters throughout the design processes. As the design information is very limited in the early design stages, these simulation tools are predominantly suitable for the detailed design stage in which various design parameters have been specified. Moreover, these simulation programs have either energy simulation capacity or IEQ simulation capacity. They cannot be used readily for integrated energy and IEQ simulation and analysis.

Different tools are often used by different disciplines in the same design to evaluate different performance aspects, such as energy consumption, day lighting, air quality, acoustical quality, durability, cost, and contribution to greenhouse gas emissions. These tools share same building information such as climate data, building geometry, and constructions and materials; however, they normally do not use the same data format. Users, therefore, need to input the same building information multiple times in order to perform simulations and analysis. Moreover, these tools are isolated; they cannot evaluate the combined energy and IEQ performance.

Building design is a multi-disciplinary process requiring coordination among all participating disciplines such as architectural, engineering and management team members. It is hence critical to be able to represent various forms of architectural and engineering production/documentation, and allow for different ways in viewing the design and simulation results.

Buildings designed and constructed using a performance-based energy and IEQ design process that optimizes the interaction between the building envelope, HVAC and lighting systems, among other design aspects, can save significant energy costs while providing better indoor climate and air quality. High performance buildings can be constructed for the same or nearly the same present cost as a non-energy-efficient buildings. However, the performance-based energy and IEQ design process may not be reached using existing simulation tools and collaborative methodologies.

The simulation platform developed in this research is designed to simulate and analyze energy and IEQ performance to assist the multi-disciplinary design teams from conceptual to detail design stages. The platform is also intended to overcome the disciplinary boundaries by using the same tool, more coherent representation and display of simulation results and predicted performance, and a server-based documents repository system for the dissemination of planning and design results, the predicted performance, and identifications of areas for possible improvements to architectural and system design.

1.2. Objectives

The objectives of this research were to:

1) Develop a method for integrating conceptual to detailed design processes, with which designers can quantitatively evaluate the predicted performance of various design options; then iterate and optimize the design;

2) Develop a user friendly environment/platform that also integrates well with existing Building Information Models (BIM).

3) Develop an integrated simulation environment for energy efficiency and IEQ analysis, which enables simulations of combined heat, air, moisture and pollutant transport for whole building energy and environmental analysis (CHAMPS-WholeBuilding);

4) Develop and enhance the multizone simulation model CHAMPS-Multizone for integration into the platform; and

5) Develop and implement relevant EnergyPlus (E+) components and coupling method for integration with CHAMPS-Multizone model.

1.3. Scope

The above research objectives were accomplished through the development of a "Virtual Design Studio" (VDS): a digital platform for the coordinated, integrated and optimized design process in high performance buildings. VDS is intended to assist collaborating architects, engineers and project management team members throughout from early phases to detailed building design development. Moreover, it helps facilitate the workflow and processing of information in combination with a range of appropriate, task-based performance simulation.

Figure 1-4 shows the composition of VDS. It is designed to include a knowledge-based expert system (KBES), a suite of performance simulation models, a "virtual building" database containing all building related information (i.e., a building information model or BIM), and a knowledge base of architectural design principles to help achieving a fully coordinated, integrated and optimized building design. This research focuses on the development of the performance simulation models and the knowledge base of architectural design principles.

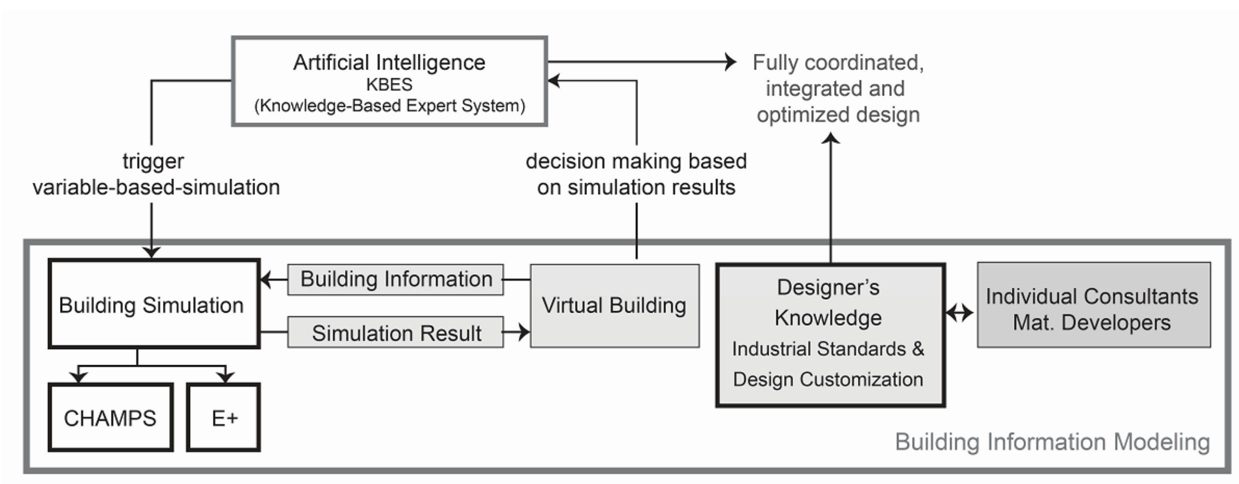


Figure 1-4 Composition of VDS

The present project was focused on evaluating the energy efficiency and IEQ aspects of a building design, especially thermal, IAQ and lighting, because of their close link to building energy consumption. The VDS's software architecture is, however, designed to also accommodate future implementation of additional capabilities such as 1) models: onsite renewable energy supply and storage; 2) structure and process for team work, and coordination; 3) connections to a knowledge based expert system; and 4) connection to a server-based database that documents the experienced design sequence and simulation results in a case study format, and offers the inclusion of building energy and environmental monitoring system for comparisons between the predicted and actual building performance.

Through the present research, a prototype of the VDS software has been developed. It includes the following major components:

1) A process module for planning and defining the design tasks for various design stages and teams, including input and output variables for each task and the relationship among tasks;
2) An input module for entering design parameters in a systematic manner covering site and climate, form and massing, internal programmatic zoning, external enclosure, and HVAC system;
3) A whole building simulation engine for combined energy and IEQ simulation and analysis;
4) A result module for displaying the architectural design outcomes in combination with the zone air fields and envelope fluxes of heat, air, moisture and pollutants; and
5) A performance module for displaying the overall building performance in comparison with existing minimum energy and IEQ standards (ASHRAE 55-2010 (ASHRAE,

2010a), 62.1-2010 (ASHRAE, 2010b), and 90.1-2010 (ASHRAE, 2010c)), green building standard (LEED (USGBC, 2009)), and advanced energy standard (ASHRAE 189.1 (ASHRAE, 2009)).

6) A web-based, performance related document sharing system for collaboration and project coordination.

1.4. Organization of the report

This report is organized into 6 chapters in the following sequence:

Chapter 1 introduces the background and problem definition, research objectives, research scope, and the organization of the present project. The limitations of current simulation tools are discussed and the concepts of VDS are introduced.

Chapter 2 provides the literature review, which consists of the following: (1) existing leading building design and simulation tools; (2) performance-based design methodologies; (3) building design process; (4) Building performance evaluation systems. Finally, the knowledge gap identified in this study is presented.

Chapter 3 presents the overall framework of VDS. The multi-dimensional design process is introduced as the basis for VDS development. The software framework is introduced including software architecture, data model, control method, and viewer/GUI.

Chapter 4 discusses in detail the implementation of a whole building performance simulation model which integrates an enhanced CHAMPS-Multizone model and EnergyPlus. Both CHAMPS-Multizone and EnergyPlus are introduced. The method of integrating the two by using the Building Controls Virtual Test Bed (BCVTB) is also discussed.

Chapter 5 shows the method and procedure for performance evaluation. First, it introduces the overall framework of the performance evaluation model. It then presents the baseline building definition. Furthermore, the performance evaluation method is presented. Finally, the performance evaluation model is tested and verified by a case study.

Chapter 6 presents a case study using a LEED platinum building: the Syracuse COE headquarters. The methods introduced in chapter 3, chapter 4 and chapter 5 are demonstrated with the assistance of the VDS software developed.

Chapter 7 summarizes the conclusions from this study and suggests areas for further research and development on the subject and platform development.

Chapter 2. Literature Review

This chapter reviews the following: 1) existing leading tools in building design and simulation, 2) performance-based design methodologies, 3) building design processes, 4) existing building performance criteria and assessment systems. At the end, the resulting knowledge gap is identified.

2.1. Existing leading building design and simulation tools

Several software platforms have been developed to advance performance-based building design practices. The US Department of Energy (DOE) provides a directory of 402 building software tools for evaluating energy efficiency, renewable energy, and sustainability in buildings (US DOE, 2013a). This section provides a review of some existing leading building design and simulation tools related to this research.

The Designer's Simulation Toolkit (DeST) (Yan, Xia, Tang, Song, Zhang, & Jiang, 2008) can be used to simulate and analyze both HVAC systems and the overall building energy consumption. It has a Graphic User Interface (GUI) developed based on AutoCAD's format for data input, and the simulation results are given in Excel table formats. It has a ventilation module based on a multi-zone network model, and an IAQ simulation module to predict multi-zone pollutant transport. However, it does not differentiate the needs of different design stages and also does not have the capability to perform IAQ analysis.

The Building Design Advisor (BDA) (LBNL, 2013b) uses an object-oriented design method to model building systems and simulates building energy and lighting performance. BDA has a GUI to model building geometry. It can read environmental condition files as well as integrate DOE2 (LBNL, 1993) for detailed building energy analysis and COMIS (Feustel & Rayner-Hooson , 1990) for IAQ analysis. The object oriented model of this software provides a basic concept for building component modeling. However, integration between the detailed simulation models and whole building performance model is very limited. Also, BDA is based on separate energy and IAQ simulation, while the combined effects of energy and IAQ are not considered.

Another building design-based simulation tool is the Green Building Studio (GBS) (Autodesk, 2013b). GBS is intended to help architects evaluate building performance based on building information modeling (BIM). It reads BIM files generated by Revit for detailed building geometry inputs, in addition to user input on building energy usage and environmental conditions. GBS also uses DOE2 as a detailed simulation engine, which does not have IAQ simulation capability. ECOTECT is another sustainable design analysis tool (Autodesk, 2013a). It has a powerful geometry import function which can read building geometry information from most of the 3D drawing formats such as DXF and 3DS, and can provide daylighting analysis, solar radiation analysis, as well as shadow and reflection analysis. However, ECOTECT can only provide simple energy simulation and thermal performance analysis. Also, it does not have IAQ simulation capability.

A more recently developed drawing and 3D modeling tool for designers is SketchUp and its optional simulation tool EnergyPlus plug-in, OpenStudio (Ellis & Torcellini, 2008). SketchUp (Google, 2013), a 3D graphical software tool, can be used by architects for conceptual design and analysis; while EnergyPlus (US DOE, 2012a) has comprehensive building energy simulation capabilities. OpenStudio (NREL, 2013) provides a bridge between SketchUp and EnergyPlus, which allows users to quickly create geometry using SketchUp and perform energy simulation using EnergyPlus. Comparing with Revit and its BIM method, SketchUp appears to be more intuitive to use. SketchUp and its energy simulation plug-in is a very promising software tool for this research, but it is currently limited to energy analysis as opposed to combined IEQ and energy analysis. Most recently, LBNL has been developing Graphical User Interfaces, called Simergy (LBNL, 2013e) for EnergyPlus, which is aimed at exploiting the comprehensive simulation capability of this program. Welle et al. (2011) also used EnergyPlus as the simulation engine for developing an automated BIM-based multidisciplinary thermal simulation for building design optimization.

Several commercially available design tools also use EnergyPlus as its simulation engine, including DesignBuilder (DesignBuilder Software Ltd., 2013) and BENTLEY's AECOsim Energy Simulator (Bentley, 2013). DesignBuilder has its own 3D graphic editor for geometry design, libraries of constructions, packaged HVAC systems and weather data, and ability to perform EnergyPlus simulation and display simulation results, all in the same platform. The most recent version also includes the ability to design detailed HVAC systems, making use of the detailed HVAC simulation capability of EnergyPlus. AECOsim Energy Simulator incorporates the EnergyPlus as a simulation engine for building performance calculations. Built on top of Bentley's BIM platform, it allows users to work seamlessly between industry CAD, BIM, and AEC applications such as MicroStation, AutoCAD, Revit, and supports standard file formats such as gbXML, DXF, DGN, and DWG. Moreover, AECOsim Energy Simulator features comprehensive HVAC systems capabilities. It is capable of performing dynamic thermal simulation for large and complex buildings; predict energy consumption, CO2 emissions, operating costs and occupant comfort.

Although there are many simulation programs developed to simulate building energy and IEQ performance, there are some limitations of existing tools:

1) These simulation tools do not integrate with design processes as part of their operational framework. These simulation tools require detailed input parameters throughout all design phases. As the design information is very limited in the early design stages, most of these simulation tools are suitable only for detailed design stages.
2) These simulation programs have either energy simulation capacity or IEQ simulation capacity. However they lack the capability of integrated energy and IEQ simulation and analysis.

2.2. Performance-based design methodologies

For high performance building design, it is critical to understand which performance criteria can be achieved and to what degree, through what strategies and the implementation of available and appropriate (active, passive and hybrid) building system components. A review of the state of art and established approaches has shown various ways of combining design and performance based working methodologies.

The "Ecological Circle of Buildings" (Daniels, 2003) demonstrates the methodology to correlate design considerations with performance criteria and system interactions. The graphical principle of the "Ecological Circle of Buildings" depicts a way of systematically organizing and correlating the expected or demonstrated performance relationships between exterior space, building fabric and technical installations.

The ongoing development of the “Ratcliff Green Matrix” (Ratcliff, 2007) elaborates on the relationships between areas of design consideration and standard US project stages. The “Green Matrix” shown in Figure 2-1 is designed to cross-reference topics of sustainability with standard phases of the project design, thereby illuminating appropriate strategies for a particular phase of work. Within the “Green Matrix” there is a horizontal heading for the five introduced sustainable topics: site, water, energy, materials, and indoor environment. Vertically listed are seven design phases: pro-forma, master planning, pre-design, schematic design, design development, construction documents, and construction/post occupancy. At the intersection of topics and phases are listed design strategies particular to that condition. The user “clicks” the intersection under consideration and is led to more specific information about the strategies and further resource links – some of which may reside on the web site itself, or may be linked to independent web sources. The “Green Matrix” therefore correlates four relevant areas: design stage, design consideration and suggested procedures, as well as internal and external references. However, there are not quantitative simulation capacities for the “Green Matrix”.

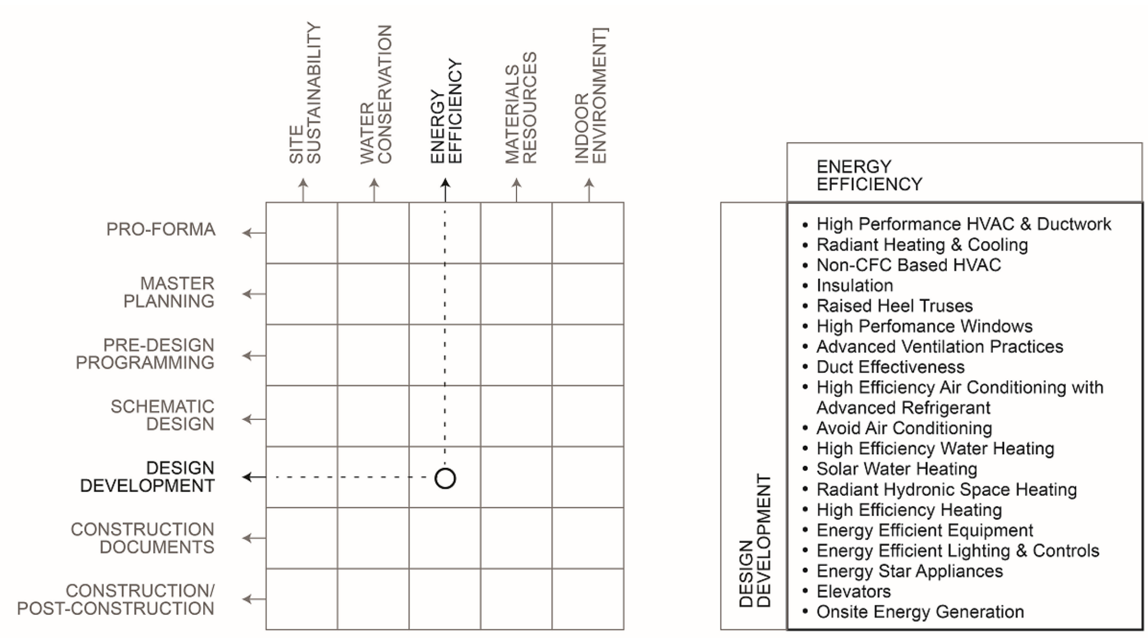


Figure 2-1 Green Matrix (Ratcliff, 2007)

Harputlugil and Hensen (Harputlugil & Hensen, 2006) discusses a similar approach that adds another dimension to the described organization of a two dimensional matrix. As in previous examples, the proposed methodology relates design criteria (in form of performance rating systems like LEED, BREEAM and BG-tool) to Building Process Phases and Design Stages in a project matrix. The structure correlates Pre-Design, Design, Construction, Operation and Renovation stages and sub-stages to respective assessment stages (Pre-design assessment, design assessment, construction assessment and operation assessment). The authors argue that "Since buildings are so diverse, serving many different types of occupancies or functions, any attempt to develop a single system to define and rate performance of these buildings will not be perfect and will even be unsatisfactory for many potential users (MacDonald 2000). Hence, it might be one strategy to at least define a flexible system that can have many possible configurations for dealing with the issues created by the diversity. MacDonald (2000) emphasized that major issues were related to: who will be the users of such a rating system; how any rating results will impact actions of building owners, operators, and other building industry actors; how such abilities will be deployed and maintained; and how quality will be assured."

In addition to the relationship of performance criteria and an appropriate assessment during all design stages, user diversity should also be considered as a third important aspect. In relation to the list of typical "standard" design team services, various specialists from different fields need to be involved depending on the complexity and building program, required planning input, as well as the expected building performance and environmental quality according to established industry and rating standards. *As a result, all three categories (design stage, design factor and involved actor) need to be correlated and facilitated by an integrated platform.*

An example of such an attempt is the "Sustainable Toolkit" (Parsons Brinckerhoff, 2013) that Parsons Brinckerhoff, a global consulting firm, has developed for different project types like Buildings, Highways, Transit and Ports. Also organized in a "Buildings Matrix" format, the "Sustainable Toolkit" structure provides guidance throughout the design stages by asking "What to do if you are… (a member of the project team working on a particular area)". The actors are hereby categorized by client / project management, various architectural team members, and a range of consulting engineering parties. In addition to the way all participating parties can now find their way through the process, a detailed overview of sustainability measures for all areas is provided. Next to this project specific and task related guidance, multiple links to external resources and references are provided in the different sections of the toolkit.

The design methodologies reviewed in this section organized the knowledge (design strategies, design guidance, and/or associated resources and references) for high performance building design by performance criteria, design teams, design factors, design stages, and/ or project types. However, there are not quantitative simulation capacities for these design methodologies.

For the assistance of an integrated and coordinated multi-disciplinary building design process of a given project type, VDS needs to also include three dimensions in representing respective steps: design team, design factors and design stages. For each task performed by a specific design team, at a specific design stage and for a specific design factor, all aspects of the building performance need to be assessed both qualitatively and quantitatively. There are five aspects of the building performance in VDS, including Site Sustainability, Water Efficiency, Energy & Atmosphere, Materials & Resources, and Indoor Environmental Quality (Table 2-3). This outcome constitutes a basic requirement and structure for the VDS platform development.

2.3. Building design process

This section provides a review and analysis of existing professional working stages in the US, UK and Germany to improve the understanding of design stages for the interdisciplinary design process.

In order to develop methodologies for a coordinated and fully integrated work flow, the architectural design process itself, as well as its planning parameters need to be understood. Furthermore the variety of building and project types, possible contractual configurations, the diversity of project specific team constellations as well as respective methodologies need to be considered. For these reasons, the platform needs to have the capability to be customized according to the project scope and the involved working methods.

At the beginning of every project a customized set up is required and facilitated by VDS. As the design process is typically not a linear sequence of planning steps, the expected changes and the development of design alterations need to be accommodated with feedback loops. The required comparison of alternative scenarios can be documented and compared for an optimized design.

For the architectural design process, different countries can have different professional practices in planning and design steps from the early to the final contractual stages leading to construction. Mandatory development stages are contractually binding for all participating parties according to various professional standards and liabilities. Thus the planning process is typically standardized according to the respective architectural chamber's legislative requirements and fee structure. As much as many other norms in the construction industry, these national and regional professional standards and respective methodologies can differ considerably.

As a design tool with a great degree of flexibility and opportunities for customization, these international differences should be considered and built into the predicted planning and simulation model. While similar in nature, different planning sequences and building standards do apply. In order to understand a simplified version of planning practices and to couple them with performance criteria and appropriate simulation techniques, project stages can be translated into generic performance assessment stages.

In general, the building process can be categorized into four overarching stages: 1) pre-design, 2) design and systems coordination, 3) construction and systems implementation, and 4) occupation, operation and maintenance. Industry standards cover all in-between steps and respective requirements in greater depth. As examples, professional working stages from US, UK and Germany were analyzed and compared (Table 2-1).

Table 2-1: Professional architectural working stages in the US, UK, and Germany

US (AIA)	Pre-Design Programming/ feasibility Service	Schematic Design	Design Development	Construction Documents/ Construction Procurement	Construction Contract Administration	Post Construction Services
England (RIBA) Scotland (RIAS)	Appraisal (A)	Strategic Briefing & Outline Proposals (B & C)	Detailed Proposal (D)	Final Proposals, Production Information & Tender Documentation (E, F, G, H)	Mobilization, Construction & Completion (J, K, L)	After Practice Completion (L)
Germany	Basic Investigation (LP1)	Preliminary Design (LP2)	Schematic Design & Planning Approval (LP3)	Authorization Planning (LP4) Executive Planning (LP5) Preparing the contract (LP6)	Cooperate Granting Contract (LP7) Site Supervision Monitoring (LP8) Maintaining Documentation (LP9)	Maintaining Documentation (LP9)

Although the mentioned planning stages are considered universal in nature, they can be further informed by the client structure and participating parties. US American Contract Documents are hereby divided into eight categories based on project type and / or the chosen delivery method, and suggest a wide range of possibilities for the project procurement (AIA, 2012). As another example, next to the nine prescribed planning stages, the German chamber's regulations prescribe a series of drawing scales that are aligned with the increased complexity and achieved project resolution (HOAI, 2009). Respectively, in the British system, planning stages foresee work on buildings and fit out projects carried out in eleven planning steps (RIBA, 2007).

The typical working stages discussed above can be simplified and further translated into performance evaluation stages that can now be seen as universal steps for a performance evaluation and implementation in VDS (Table 2-2).

Table 2-2 Professional project working stages simplified to the VDS ADDAM design stages

Simplified Professional Working Stages	Performance Assessment Stages
Pre-Design Pre-Design	**Assess** project and formulate strategic brief
Design Development and coordination Preliminary Design and Concept Development Schematic Design, Final Design, and Detail Development	**Define** performance scope and goals **Design** to meet and verify performance scope and goals
Construction	**Apply** and revisit scope and goals
Post-Construction / Operation Assessment Building Systems monitoring and supply of data base	**Monitor** performance / post construction verification

2.4. Building performance criteria and assessment systems

In addition to the above list of working stages and their respective deliverables, national and regional building codes form a highly specific planning frame work and inform all aspects of the individual design agenda. Code compliance is hereby mandatory to successfully design and construct the building. Among many others, they can regulate site related and civic planning aspects, building program related concerns, building massing, the use of materials, accessibility and environmental control issues. Recent changes to building codes internationally consider energy and environmental performance evaluations and certification as an additional area of consideration.

The US Environmental Protection Agency (EPA) provides a broad and holistic overview of recommendations in their Science & Technology: Sustainable Practices section. The EPA states that “Agency researchers and their partners from across a wide spectrum of investigative fields are working together to form a deeper understanding of the balance between the three pillars of sustainability—environment, society, and economy.” Various sustainability guidelines hereby address two categories: Urban and Local Sustainability and Industrial Sustainability (US EPA, 2012). Among others in the US, evaluation systems that more clearly address the building sector such as ASHRAE 189.1 (ASHRAE, 2009) and LEED (USGBC, 2009) standards are predominant in structuring environmental performance assessment methods for the built environment.

The National Institute of Building Sciences (NIBS, authorized by the U.S. Congress in the Housing and Community Development Act of 1974) provides guidance in various areas of construction. "The Institute's mission to serve the public interest is accomplished by supporting advances in building sciences and technologies for the purpose of improving the performance of our nation's buildings while reducing waste and conserving energy and resources" (NIBS, 2013). NIBS is organized by councils and committees that address a wide range of building performance related topics (Advanced Materials Council, Building Enclosure Council, Building Enclosure Technology and Environment Council, High Performance Building Council, etc.). NIBS's publications by various divisions support the dissemination of specific knowledge from individual areas of investigation. For instance, the "Journal of Building Enclosure Design" is an official publication of the Building Enclosure Technology and Environment Council (BETEC) of the NIBS. Further monthly E-Newsletters include the Journal of Advanced High-Performance Materials, Journal of Building Information Modeling, and the Journal of Hazard Mitigation and Risk Assessment.

Additionally, NIBS also offers United States National CAD and BIM Standards. The latest edition of "United States National CAD Standards" is currently available in Version 5. The "National BIM Standard - United States Version 2", by the NIBS building SMART alliance, "provides consensus based standards through referencing existing standards, documenting information exchanges and delivering best business practices for the entire built environment." (NIBS, 2013a)

The Building Seismic Safety Council (BSSC) and Multihazard Mitigation Council (MMC) are examples for nationally applicable, highly specific design provisions (BSSC, 2012). Among others, the Building Enclosure Technology and Environment Council (BETEC) and the High Performance Buildings Council (HPBC) represent the "Facility Performance and Sustainability Program". The HPBC states that the "Council's overall goal is to put standards in place to define the performance goals of a high performance building in order to facilitate the design, construction, financing, and operating buildings with an emphasis on life cycle issues rather than initial costs". The HPBC identifies the metrics and level of required performance for specific design objectives (energy, security, durability, moisture, acoustics, etc.) for building products, systems and subsystems, and references industry standards for validating these performance requirements (NIBS, 2011).

Furthermore, the National Institute of Standards and Technology (NIST) governs national industry standards for environmental performance, energy and a sustainable practice with "Standards for the Smart Grid, energy efficient lighting, photovoltaics, net-zero-energy buildings, software for "smart" buildings" (NIST, 2012). These are a few of the many NIST research areas related to energy use and conservation. Initiatives like the Improved Energy Performance Program, Measurement Science for Net-Zero Energy, High-Performance Buildings next to several other programs in the sustainability section provide suggestions in all relevant areas (NIST, 2012).

Various standards are defined by the German Energy Agency and other legislative agencies. Amongst others, the Energy Conservation Legislation (Energieeinsparungsgesetz EnEG and Energieeinsparverordnung EnEV 2009) provide guidelines for the efficiencies of buildings, as much as many national standards described in the German Industry Norms (Deutsche Industrie Norm DIN) like DIN V 18599 for the Evaluation of Energy in Buildings (DIN V 18599 Beiblatt 1 - Energy efficiency of buildings - Calculation of the net, final and primary energy demand for heating, cooling, ventilation, domestic hot water and lighting - Supplement 1 (2010): Balancing of demand and consumption) and (DIN V 18599 Beiblatt 2 - Energy efficiency of buildings - Calculation of the net, final and primary energy demand for heating, cooling, ventilation, domestic hot water and lighting - Supplement 2 (2012): Description of the application of values from DIN V 18599 for the certification according to the act on the promotion of renewable energies in the heat sector (EEWärmeG).

Other project type specific evaluation systems and planning advice are provided for instance by the Passivhaus (Passive House) Standards (Passivhaus, 2012). The International Passive House Association advises through their Passive House Planning Package (PHPP, 2012).

BREAM (the Building Research Environmental Assessment Method by the British Building Research Establishment (BREEAM, 2012a)), first launched in 1990, forms a predominant and comprehensive frame work for the performance planning and evaluation in the United Kingdom. The evaluation criteria have typically been differentiated by building program and type, and have been extended for an international application. “BREEAM is used in a range of formats from country specific schemes, adapted for local conditions, to international schemes intended for the certification of individual projects anywhere in the world (BREEAM, 2012b).

Amongst other information, case studies are available online for categories such as communities, datacenters, industrial, educational, offices, and mixed use developments (BREEAM, 2012c).

All the reviewed environmental assessment methodologies are based on the following three areas of consideration: the economy of resources (including energy conservation, water conservation and material conservation), Life Cycle Design (throughout the Pre-Building Phase, the Building Phase and the Post-Building Phase) and Humane Design considerations which are further defined as the Preservation of Natural Conditions, Urban and Site Planning Strategies, and the Design for Human Comfort (Kim, 1998).

For a comprehensive understanding of all design related issues, complex investigations on various scales are required. Planning considerations range from general sustainability aspects to a large number of highly specific site and building related topics.

Six fundamental principles have been identified for a "Whole Building Design Guide (WBDG)" by the US National Institute for Building Science (WBDG, 2013): 1) Optimize site and existing structure potentials, 2) Optimize energy use, 3) Protect and conserve water, 4) Use environmentally preferable products, 5) Enhance Indoor Environmental Quality (IEQ), and 6) Optimize operational and maintenance practices.

Similarly, the US Green Building Council's (USGBC's) LEED (Leadership in Energy and Environmental Design) certification program differentiates among various focus areas that include sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, location and linkages, awareness and education, innovation in design and regional priority (USGBC, 2012).

The LEED Rating System is further categorized for the evaluation of new construction, existing buildings, commercial interiors, healthcare, homes and neighborhood developments, amongst others (USGBC, 2012).

Another example for a well adopted evaluation system is ASHRAE's (American Society of Heating, Refrigerating and Air Conditioning Engineers) Standard 189.1 (ASHRAE, 2009) for the Design of High-Performance, Green Buildings. "Standard 189.1 provides a total building sustainability package for those who strive to design, build and operate green buildings. From site location to energy use to recycling, this standard sets the foundation for green buildings by addressing site sustainability, water use efficiency, energy efficiency, indoor environmental quality, and the building's impact on the atmosphere, materials and resources. Standard 189.1 serves as a compliance option in the 2012 International Green Construction Code™ (IgCC) published by the International Code Council. The IgCC regulates construction of new and remodeled commercial buildings." (ASHRAE, 2009).

Table 2-3 shows the five performance aspects considered by VDS and their relationship with those included in the various performance assessment systems reviewed. All aspects should be considered throughout the service life of the building from design to construction to operation.

Table 2-3 Performance aspects considered by VDS and existing assessment systems

VDS	LEED [LEED 2009]	ASHRAE 189.1 [ASHREA 2009]	BREEAM (UK) [BREEAM 2011]	DGNB(German) [DGNB.2008]	WBDG [PNNL2005]
Site Sustainability • Site selection • Mitigation of heat island effect • Reduction of light pollution	**Sustainable Sites** • Site Selection • Sitedevelopment • Alternative transportation • Stromwatermgt. • Landscape design and reduction of heat island • Light pollution Reduction	**Site Sustainability** • Site selection • Mitigation of heat island effect • Reduction of light pollution • Site development	**Land Use and Ecology** • Site selection • Site ecology • Ecological impact • Enhancing site ecology • Long term impact on biodiversity **Transport** • Transport accessibility • Proximity to amenities	**Ecological Quality** • Impacts on global and local environment **Quality of the Process** • Quality of the planning • Quality of the construction activities	**Transportation** • Regular Commute
Water Efficiency • Site water use reduction • Building water use reduction • Water cons measurement	**Water Efficiency** • Water efficient landscaping • Innovative waste water technologies • Water use reduction	**Water Use Efficiency** • Site water use reduction • Building water use reduction • Water cons measurement	**Water** • Watercons. • Water monitoring • Water leak prevention • Water efficient equipment	**Socio-cultural and Functional Quality** • Performance • Functionality **Technical Quality** • Quality of the technical implementation	**Water** • Total building water use • Indoor potable water use • Outdoor water use • Total storm sewer output
Energy and Atmosphere • Energy Efficiency measures • On-site renewable energy systems • Energycons. mgt.	**Energy and Atmosphere** • Commissioning of the building energy systems • Refrigerant mgt. • Optimizeenergy performance • On-Site renewable energy • Green power	**Energy Efficiency** • On-site renewable energy systems • Energycons. mgt. • Energy performanceof building systems	**Energy** • Reduction of CO2 emissions • Energy monitoring • External lighting • Low/ zero carbon technologies • Energy efficient systems	**Socio-cultural and Functional Quality** • Performance • Functionality **Technical Quality** • Quality of the technical implementation	**Energy** • Total building energy use • Source energy • Peak electricity demand
Indoor Environmental Quality • Indoor air quality • Thermal environmental condition • Acoustical control • Lighting	**Indoor Environmental Quality** • IAQ performance • Outdoor air monitoring • IAQ mgt. plan • Pollutant source control • Thermal comfort • Daylight & views	**Indoor Environmental Quality** • Indoor air quality • Thermal comfort • Acoustical control • Day lighting • Materials emissions	**Health & Wellbeing** • Visual comfort • Indoor air quality • Thermal comfort • Water quality • Acoustic performance • Safety and security	**Socio-cultural and Functional Quality** • Performance • Health, comfort and user satisfaction • Functionality **Technical Quality** • Quality of the technical implementation	**Occupant health and productivity** • Occupant turnover rate • Absenteeism • Building occupant satisfaction • Self-rated productivity
Materials and Resources • Isolation pollutants in the soil • Wastemgt. • Materials use Refrigerants use • Life-cycle assessment	**Materials and Resources** • Storage & collection of recyclables • Construction waste management • Materials reuse • Regional materials • Rapidly renewable materials	**Buildings Impact on the Atm., Materials and Resources** • Isolation pollutants in the the soil • Construction wastemgt. • Materials manufacturing • Refrigerants use • Life cycle assessment	**Material** • Life cycle impacts • Sourcing of materials • Insulation • Designing for robustness **Waste** • Construction waste management • Recycled aggregates **Pollution** • Refrigerants • NOx emissions • Surf. water runoff • Light pollution • Noise attenuation	**Ecological Quality** • Impacts on global and local environment • Utilization of resources and waste arising **Economical Quality** • Life cycle costs	**Waste Generation** • Solid sanitary waste • Hazardous waste • Recycled materials

2.5. Knowledge gap

While the simulation programs reviewed in section 2.1 have made it easier for designers to use existing energy simulation tools, they do not provide sufficient support for design coordination and integrated analysis of energy and IEQ performance from early to final design stage. Most of the simulation tools are not integrated with interdisciplinary design process requirements and respective collaborative practices. These simulation tools require detailed input parameters throughout the design processes. As the design information is very limited in the early design stages, these simulation tools are only suitable for detailed design stages. These simulation programs have either energy simulation capability or IEQ simulation capability. However, they lack of integration between energy and IEQ simulation.

The performance-based design methodologies reviewed in section 2.2 provide qualitative design strategies and design guidance integrated with the interdisciplinary design processes. However, there are not quantitative simulation capacities for these design methodologies.

Different tools are used by different disciplines in the same design to evaluate all above listed performance aspects such as energy consumption, day lighting, acoustical quality, air quality, thermal comfort, durability and costs. These tools share much of the same building information such as climate data, building geometry, and constructions and materials; however, they normally do not use the same data format. Users therefore need to input the same building information multiple times in order to perform the simulation and analysis. Moreover, these tools are isolated; therefore, they cannot evaluate the combined energy and IEQ performance together by including interactions between energy and IEQ simulations.

Building design is a multi-disciplinary process requiring the coordination among architectural, engineering and management team members. It is hence also critical to be able to represent various forms of architectural and engineering production/documentation, and allow for different ways in viewing the simulation results to evaluate and compare different design options.

The simulation platform developed in this research is designed to combine energy and IEQ simulation and analysis to assist the multi-disciplinary design teams from conceptual to detail design stages. The platform is also intended to overcome the disciplinary boundaries by using the same tool and a shared database for the dissemination of planning and design results, predicted performance, and identifications of areas for possible improvement in design.

Chapter 3. Virtual Design Studio: Development of the Framework

This chapter presents the framework of VDS including current development and implementation. First, it introduces the overall features of VDS. It then summarizes how VDS relates to the building design process and its typical project stages, performance-based design considerations, and respective performance optimization strategies. It outlines the methodology and scope for the organization, implementation and respective requirements for the VDS platform development based on the interdisciplinary design needs. Furthermore, it presents the VDS software framework and implementation methods. Finally, it shows the testing and verification of the VDS framework.

3.1. Introduction

Building design is a multi-dimensional process involving multi-disciplinary design teams, multi-design stages, multi-design factors, and multi-performance objectives. Designing a building is like solving a "magic cube" puzzle in which every step should be coordinated to reach the final solution efficiently. The designers at a given project stage need to consider the primary parameters for the current stage, but also the parameters that are further considered in the more detailed subsequent design stages. These parameters represent multi-design factors including Site & Climate, Form & Massing, Internal Configuration, External Enclosure, Environmental System (HVAC), Energy Supply-System, Water Supply-System, Materials, and their Interdependences. The impact of these design parameters on the building performance need to be evaluated and analyzed throughout the design process to optimize the design. Sufficient and timely iterations are necessary among the different design factors in different design stages for component trade-offs and whole building optimization.

VDS is a software platform for supporting an integrated, coordinated and optimized design of high performance buildings. It is intended to assist collaborating architects, engineers and project management team members throughout from the early phases to the detailed building design development. The platform helps to facilitate the workflow and the processing of information in combination with appropriate, task based performance simulation tools. It therefore needs to have the following major features:

1) Estimations of whole building performance at each design stage against minimum and advanced standards;

2) Event-driven simulations and iteration within and between design stages---i.e., the provision of feedback loops and the confirmation of consistency and optimized results;

3) Information/data flow cascades with evolving default settings to simplify the data entry and assisting the users in considering design options;

4) Comparison of design options and visualization of design and performance; and

5) Multi-disciplinary design coordination using building information models (BIM) for data sharing, and two-way data transfer between design/simulation software and BIM.

3.2. VDS building design process for performance evaluation

3.2.1. Multi-dimensional design process

Building design is a multi-dimensional process involving design teams, design factors and design stages. A 3-D matrix (named “Magic Cube”) is used as the fundamental structure of

VDS to facilitate multi-design teams, multi-design stages and multi-design factors, while considering multiple aspects of the building performance, and depicting a complex project set up (Figure 3-1). Within this matrix, all three areas of consideration are correlated to organize the workflow.

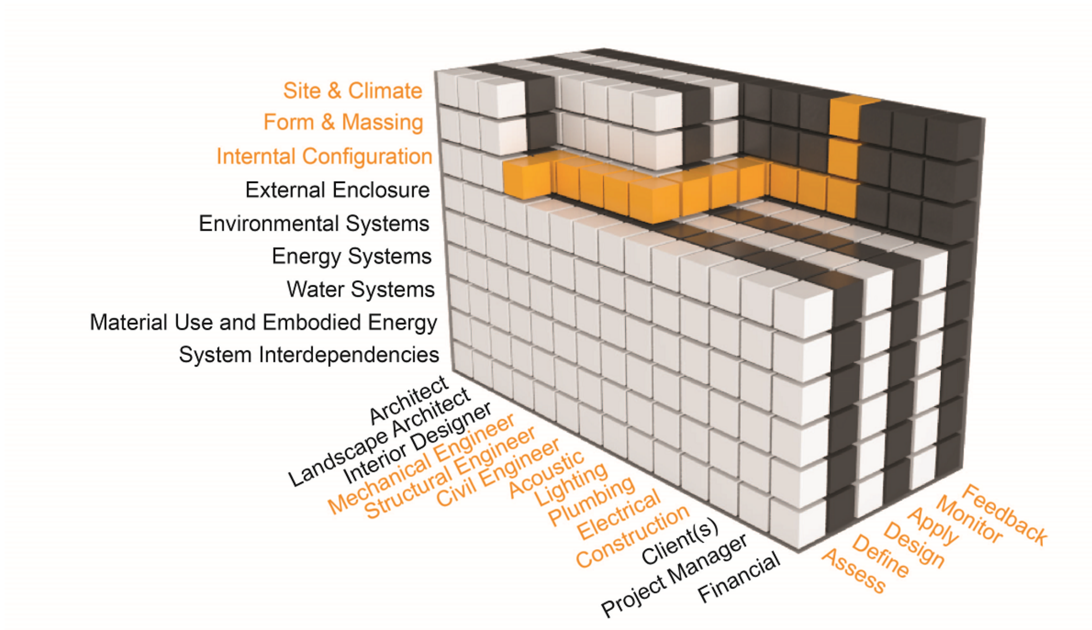


Figure 3-1 Three-dimensional “Magic Cube” matrix for VDS structure

3.2.1.1. Project customization and multi-disciplinary design teams

Because of the uncertainties regarding the project type and procurement as discussed in Section 2.3, the platform needs to provide flexibility in customizing each project set up. In order to structure the VDS platform, critical elements have to be correlated: project stage, design stage and performance criteria, and participating parties. A holistic systems thinking on multiple project scales in space and time is required, and is intended to be coordinated between the involved disciplines with the help of the VDS platform. For a custom project definition, three base team categories have been identified and can be further specified: architecture, systems design and project management. In the architectural design team, a base configuration of architects, interior designers and landscaping architects is offered, but can be altered by for instance including lighting or acoustics design consultants at any given stage. For the systems design team one assumes the participation of structural, HVAC, electrical and civic engineers. Given the contractual diversity, the project management team is specified according to client, contract form, project type, and management structure.

3.2.1.2. Design stages

As discussed in Section 2.3, the professional working stages can be translated into the five universal performance assessment stages used in the VDS's ADDAM structure:

1) "Assess"---Assess the project's needs, existing conditions and availability of resources and other constrains, and formulate a strategic brief for all areas of consideration (which corresponds to the advisory and negotiation working stage);
2) "Define"---Define the project's performance scope and goals, and propose possible strategies to achieve the performance goals (which corresponds to preliminary design and concept development working stages);
3) "Design"---Design the building and perform required analysis to meet and verify the previously defined performance scope and goals. It includes schematic design, final design and detail development working stage;
4) "Apply"---Apply the designed solutions and revisit/verify the defined scope and goals during construction working stages;
5) "Monitor"---Commission and monitor the achieved performance for verification, diagnose design-construction performance discrepancies, and document case study

results for possible feedbacks and to improve the future design of similar buildings.

3.2.1.3. Design factors

Based on the analysis of the established performance assessment systems in Section 2.4, the following design factors have been identified as key focus areas for VDS (i.e., the vertical axis in Figure 3-1):

1) an appropriate climactic and site specific design response (accessibility, site density, regional and local microclimates, site orientation and relationships to solar path and prevailing winds, ground conditions, background noise and air pollution, local renewable resources, bio-diversity, hard and soft landscaping, etc.);
2) the building form, orientation and massing (related to existing site context, proposed surface to volume ratio, orientation related to solar path and prevailing winds, noise and pollutant sources, etc.);
3) the external building enclosure including the roof area as well as the quantity and quality of openings (thermal properties, direct and indirect solar gain, air tightness, day lighting, natural ventilation, etc.);
4) the internal programmatic zoning related to occupant activities, building orientation and massing aspects, internal plug loads, moisture gains, and indoor pollutant sources;
5) all environmental control systems (active, passive and hybrid HVAC, mechanical, plumbing and electrical systems, etc.);
6) all energy systems (grid management, active, passive and hybrid energy and lighting systems, use of local renewable resources, energy storage and distribution solutions, etc.);

7) all water systems (supply and waste water management, local water collection and distribution, ground sources, artificial and natural water filtration systems, etc.);
8) material use and embodied energy including all phases of a building's life cycle; and
9) system interdependencies: overall system efficiencies related to individual subsystems and their coordination, integration, and operation throughout the seasons.

3.2.1.4. Multi-aspects of building performance

As discussed in Section 2.4, the building performance aspects considered by VDS are organized into five performance aspects:

1) Site Sustainability, including site accessibility, bio-system projection, mitigation of heat island effect, and reduction of light pollution.
2) Water Efficiency, including site water use reduction, building water use reduction, and water consumption measurement.
3) Energy and Atmosphere, including operational energy, on-site renewable energy, energy consumption measurement, and atmospheric protection.
4) Materials and Resources, including construction waste management, "Materials extraction, manufacture, or harvest", refrigerants, storage and collection of recyclables, and life cycle assessment.
5) Indoor Environmental Quality, including indoor air quality, thermal environmental condition, acoustical control, and lighting.

3.2.2. Input-process-output work flow

The above mentioned design factors address the range of scales, the increase in complexity and the required amount of information that needs to be facilitated. The timing of these interactions between all participating parties is typically organized in the form of a project management plan that can become part of the initial custom project set up. Who (from architecture, systems design or management) is working on what part of the project (as per design factors) at what point in time (as per design and performance target stages) and requires respective results? Each design consideration can be coupled with a design stage and a participating party, which defines a specific task. The work flow is thus formed by a series of expected inter-correlated and coordinated tasks throughout the entire design process. While an ideal process flow would be steady and linear, all expected required feedback loops can be facilitated via repeated or refined particular tasks at a given or later project stage.

In order to provide an overarching logic for all platform areas, the flow pattern of Input-Processing-and Output has been established (Figure 3-2 and Figure 3-3). The required input (by topic and discipline), suggestions for performance evaluation processes (by topic and suitable simulation tool), and the respectively suggested output (by topic and discipline) will be organized from site, whole building, mass, story and multi zone to detailed component investigations. The task specific output from one working stage hereby provides the required inputs for the next. The expected development of design options and alterations as well as the interactions between design teams are hereby incorporated into the VDS default structure (Figure 3-2) and respective task flows (Figure 3-3).

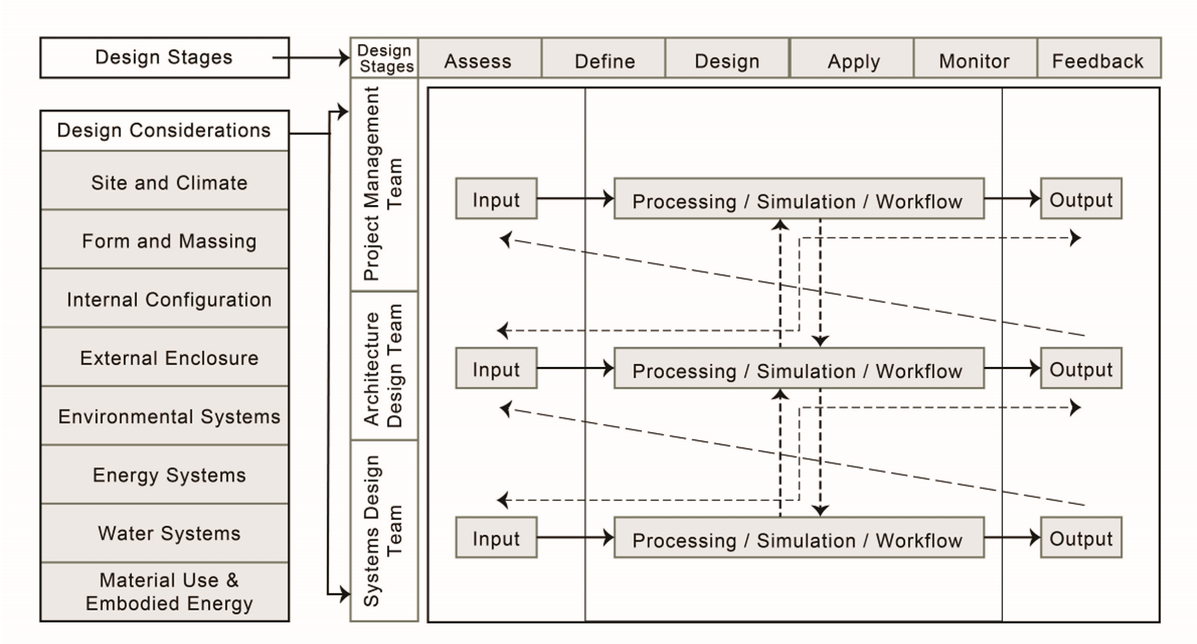


Figure 3-2 Input-Processing-Output methodology and feedback loops for VDS structure

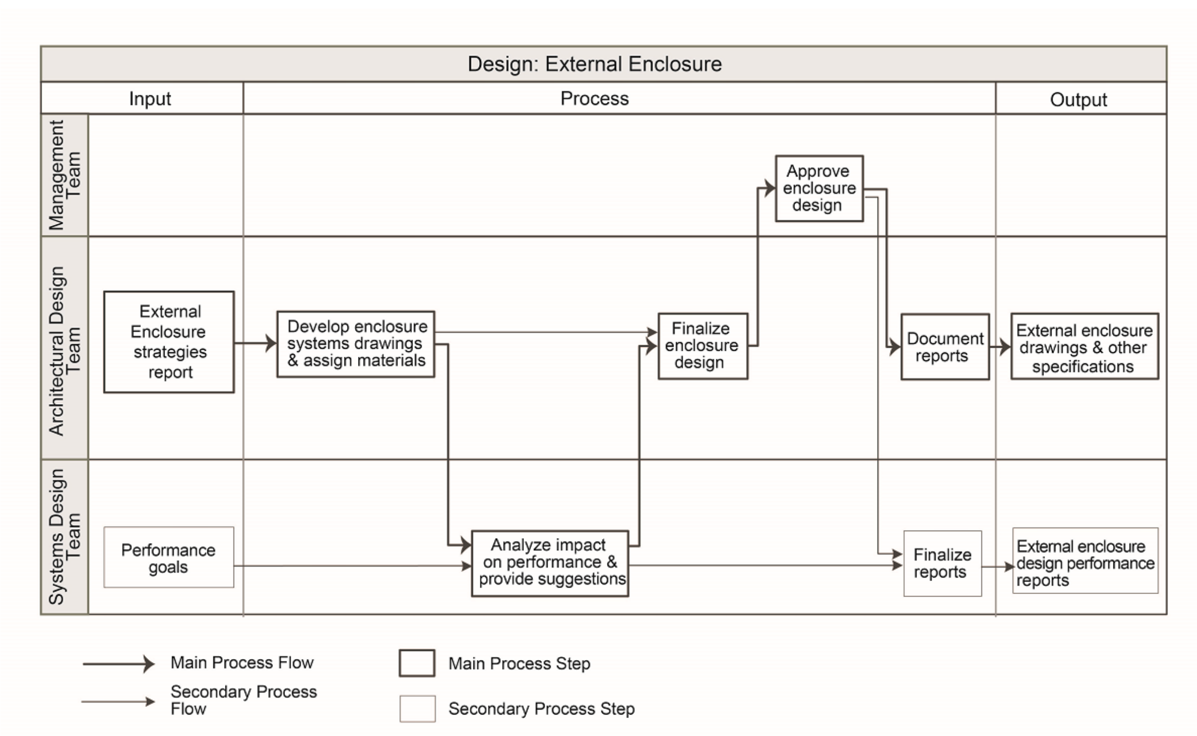


Figure 3-3 Developed Input-Processing-Output Rationale

3.2.3. System interdependencies

During each VDS-ADDAM stage, all relevant design factors and their relationships are investigated. Every aspect is hereby looked at in relation to programmatic needs and performance standards, as well as with regards to the impact the proposed solutions have on other areas of design and systems integration. For each given stage and design aspect, and according to the defined project intentions, the relationships between these crucial factors can vary significantly. For a particular area of investigation, all interdependencies are intended to be mapped and understood for one particular planning (for instance the Assessment) stage (Figure 3-4).

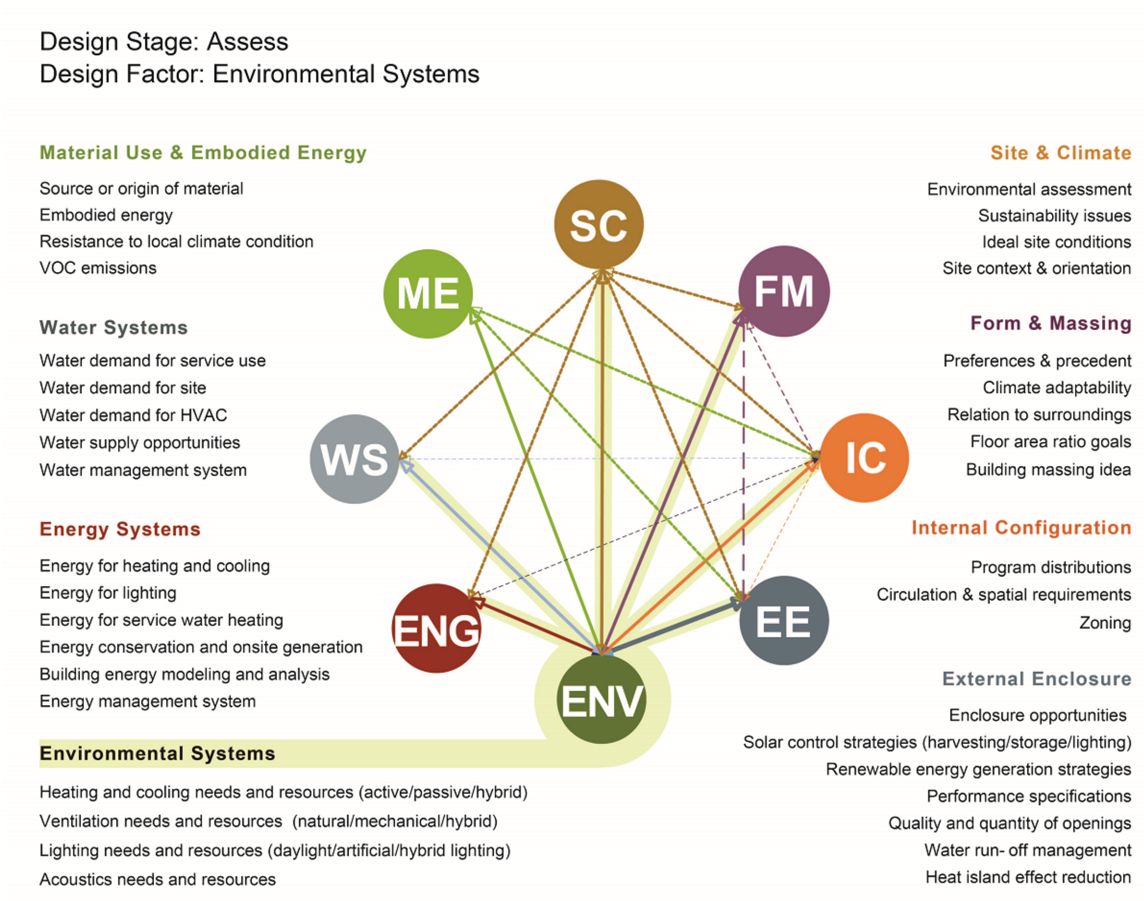


Figure 3-4 Interrelationships of design factors during the Assessment Stage

It is the intention to thus better understand system relationships between the wide range of criteria that are part of the planning and coordination process. The later described development of the actual platform structure and its Graphic User Interface (GUI) considers this complex set of information and will allow for suitable ways of accessing the required data according to all user's needs.

It is important to not see any of the mentioned factors in isolation. It is to be understood that almost all aspects of the design are closely related and will impact each other and the resulting system efficiencies (Figure 3-5). For example, the building location, its massing and its orientation determine a variety of efficiencies related to regional and local climate conditions such as thermal performance, daylight utilization, noise isolation, heat island effect, and visual quality.

The programmatic zoning and interior organization of a building impact system loads and external envelope characteristics. Alternative approaches for the use and combination of active, passive and hybrid HVAC systems, as well as energy and water conserving strategies are to be considered. Façade typologies and the quantity and quality of openings will determine thermal properties, impact energy and HVAC system efficiencies as well as the occupant's wellbeing and human comfort. Among many others, a life cycle assessment, the choice of materials and the use of renewable energy sources also impact viable financial models.

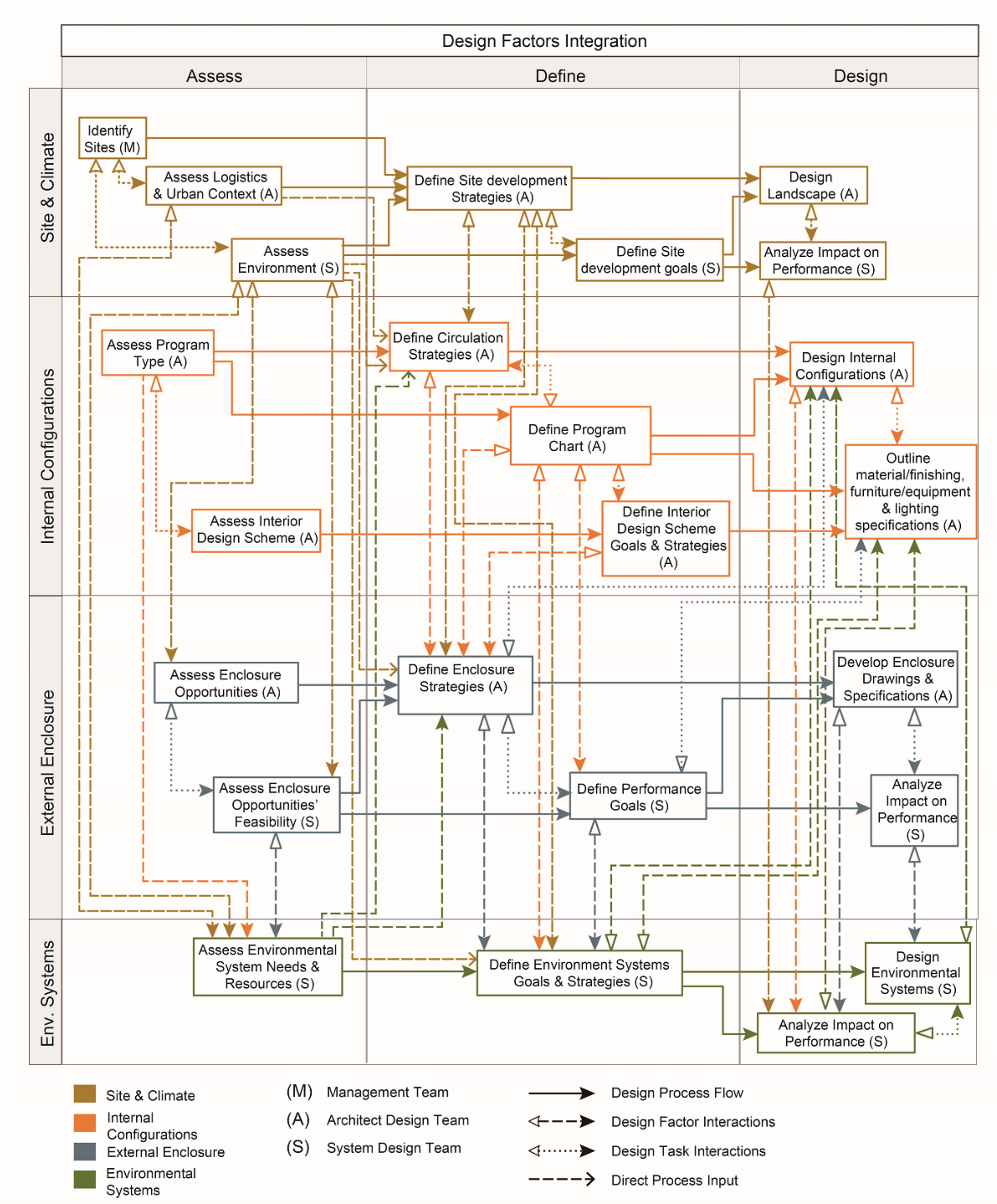


Figure 3-5 System Interdependencies and components cross-references in VDS structure

3.2.4. Web-based document sharing and extension to performance monitoring

In addition to the performance evaluation, a document sharing capability is required in order to allow for the coordination, exchange and processing of all available information. The platform will therefore provide a data repository that will be used during the design process, as well as a source for documentation. As part of this function, progress and stage concluding reports can be generated, that can also form a part of the usual concluding documentation at the end of each professional working stage. While different formats of files can be shared via the VDS platform, VDS will use Building Information Modeling (BIM) standards for the direct exchange of digital data.

After the project has been completed and once it is occupied and operational, the data collection via post-construction monitoring systems can allow for a direct comparison between predicted (assessed, defined and designed) and real time (applied and monitored) performance results. It is thus also possible to provide valuable feedback for design teams with a similar project in order to understand the simulation sequence as well as efficiencies of the documented workflow. The experienced variations and described feedback loops that differ from an ideal, linear process can therefore be understood and used for an optimization of the process itself internally and externally.

3.2.5. Impact of the multi-dimensional design processes on overall GUI development

The described scope directly informs a set of criteria for the GUI development (Figure 3-6). Given the described diversity of users and respective working methods, the GUI needs to facilitate a range of variables according to the role and responsibility of individuals on the project. This includes different tasks from the areas of architectural design, systems engineering and project management. The required information (Input), the suggested work flow (Processing) and the recommended results (Output) will hereby vary. In addition to a filtering-function that is intended to mask irrelevant or overly complex information according to the user's role, a range of different file formats need to be considered. The GUI will allow for an accustomed view port, as specified at the beginning of the project according to the user's responsibilities. It is the intention to only provide useful information that can be read and understood by the respective user, or offer selected views organized in a set of layers that are characterized by different complexities or ways of viewing the given information. Nested information that is relevant for the processing, but not needed for the chosen working methodology, can be hidden. For the specified tasks a processing diagram will be generated according to design stage, design factor and applicable standards. The previously discussed complexity of relationships within the matrix will be incorporated by differentiating the overall team coordination from specific and more detailed tasks, and thus allow for a focused and result oriented process.

In order to be able to correlate and simultaneously review all available information, the GUI has been provided with four separate viewing planes (Figure 3-6) combined in one screen interface. The proportions of this base set up can be adjusted according to user priorities and the complexity of the given information.

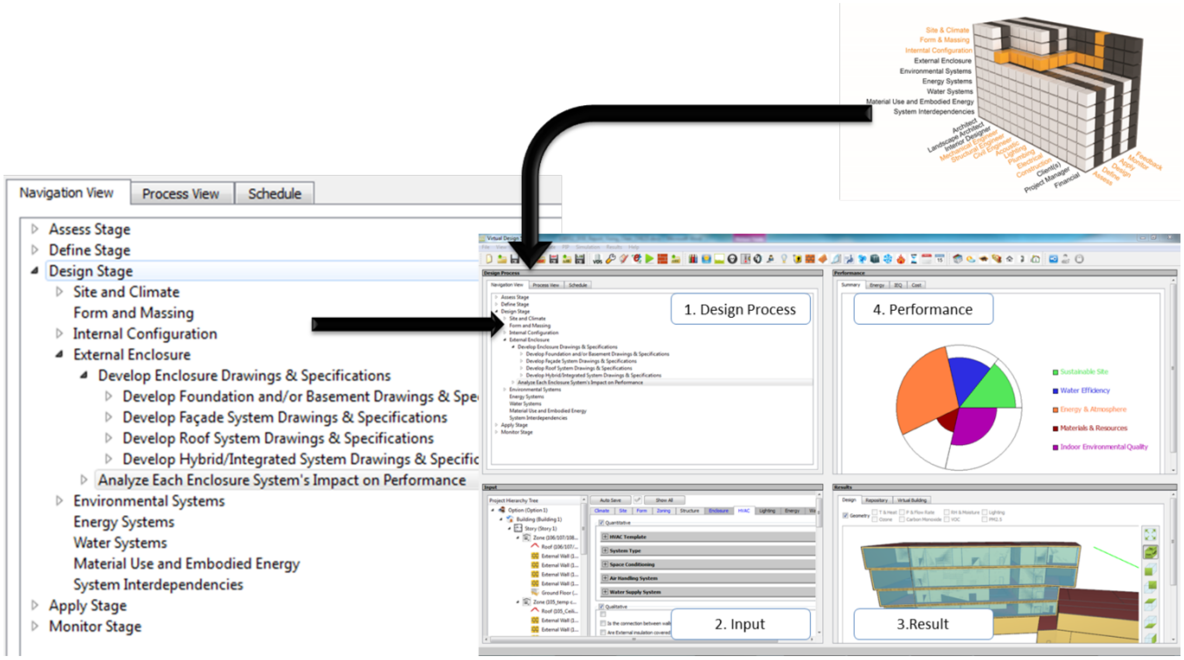


Figure 3-6 Development of VDS GUI based on established platform rationale

The “Design Process” Window (top left) shown in Figure 3-6 allows access to all information about the user’s role, the working stage related to design considerations and suggested processing steps. Depending on the chosen relationships, it provides an overview of required input, suggested processing and the recommended output for the next working stage.

The “Input” Window (bottom left) provides the opportunity to input all required data that will be needed for the processing.

The “Result” Window (bottom right) is equipped to view different digital and graphical information, so that the viewer can import different file formats. 2D drawings, 3D modeling results and other CAD information can be viewed. The window reacts to the chosen area of investigation specified in the “Design Process” Window, and the user input of the design parameters in the “Input” Window.

The “Performance” Window (top right) depicts design efficiencies in form of a pie chart (Figure 3-7). In response to established professional performance standards the VDS platform will facilitate simulation processes by offering a range of options for the project specific customization of prediction and simulation techniques. All output results are comparable with minimum requirements (e.g., ASHARE standards 55.1, 62.1and 90.1), green building certification standards (e.g., LEED and BREEAM) and advanced energy or IEQ standards/Guides (e.g., ASHRAE 189.1and ASHRAE Indoor Air Quality Guide), before providing valuable input for the next working stage. As part of this evaluation process, the platform will provide a comprehensive overview describing how the current planning state compares to the specified performance goals. The graph is broken down into groups of all relevant performance areas, and indicates the efficiencies related to applicable rating systems, including ASHRAE 90.1, ASHRAE 189.1, and LEED system. It is thus possible to easily understand where the defined performance criteria have been met, where the performance exceeds the users’ expected performance, or where respective shortcomings have been noted. The window reacts to the task specification in the “Design Process” Window and the design parameters in the “Input” Window.

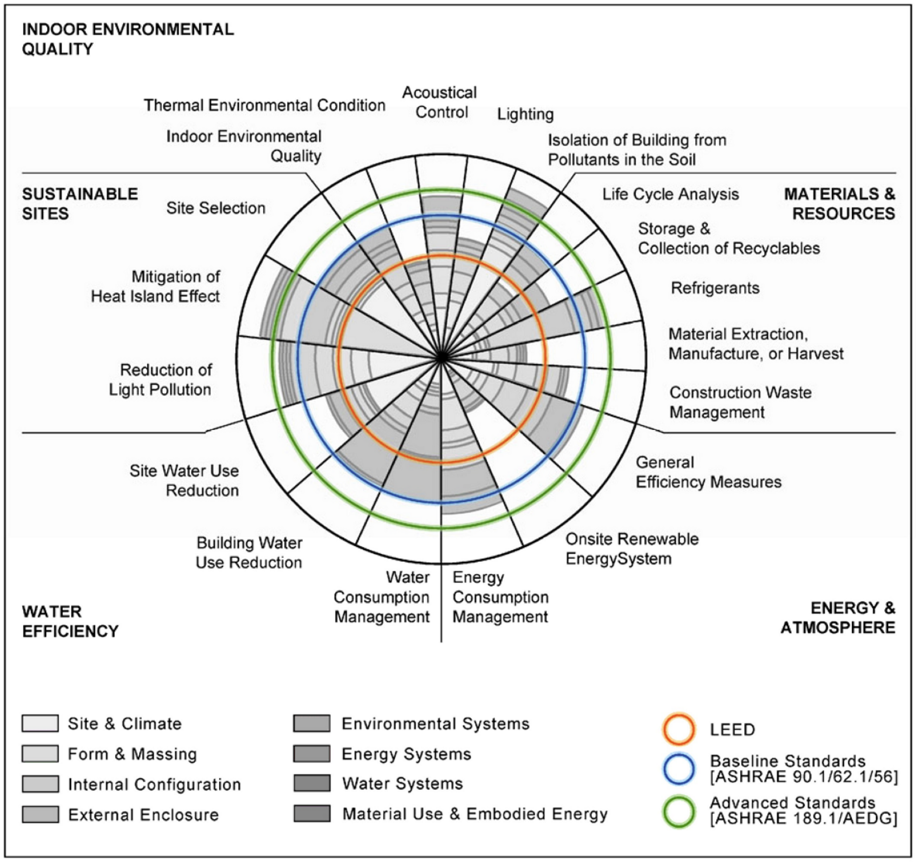


Figure 3-7 Pie chart for a systematic performance comparison

3.3. VDS software framework

This section presents an overview of the VDS design and method of software implementation; including system design, software architecture, GUI, data model, and external software integration.

3.3.1. System design

The VDS system is designed to include a KBES, a suite of building simulation models, a "Virtual Building" database containing all building related information, a knowledge base of architectural design principles and knowledge gained from industrial consultants and material developers (Figure 1-4). The "Building Simulation" component is a CHAMPS (Combined heat, air, moisture and pollutant simulations) suite that integrates models of building envelope, HVAC system, and room air, contaminant and energy flows together with shared databases (Zhang 2005; Nicolai et al. 2007; Feng et al. 2011). It emphasizes system level performance while providing linkages to detailed component models dealing with material and equipment level simulations. EnergyPlus (E+) is also incorporated for its comprehensive capability in energy and HVAC system simulations. The "Virtual Building" database provides data at various levels of details as required by different design stages (Kato et al. 2008). It is also used to store data collected from online monitoring systems, enabling direct comparison between predicted and real performance (Feng et al. 2009). This feature will facilitate the identification of design or construction deficiencies and provide feedbacks for future design improvement. A BIM protocol is used as the common vehicle for information sharing and exchange among different design teams to reduce the effort in repeated data entry and facilitate efficient and accurate feedbacks. It is also recognized that VDS is only an "assistant" to the designers. Human interactions coupled with traditional document sharing are also essential for a successful design in practice (Figure 3-8)

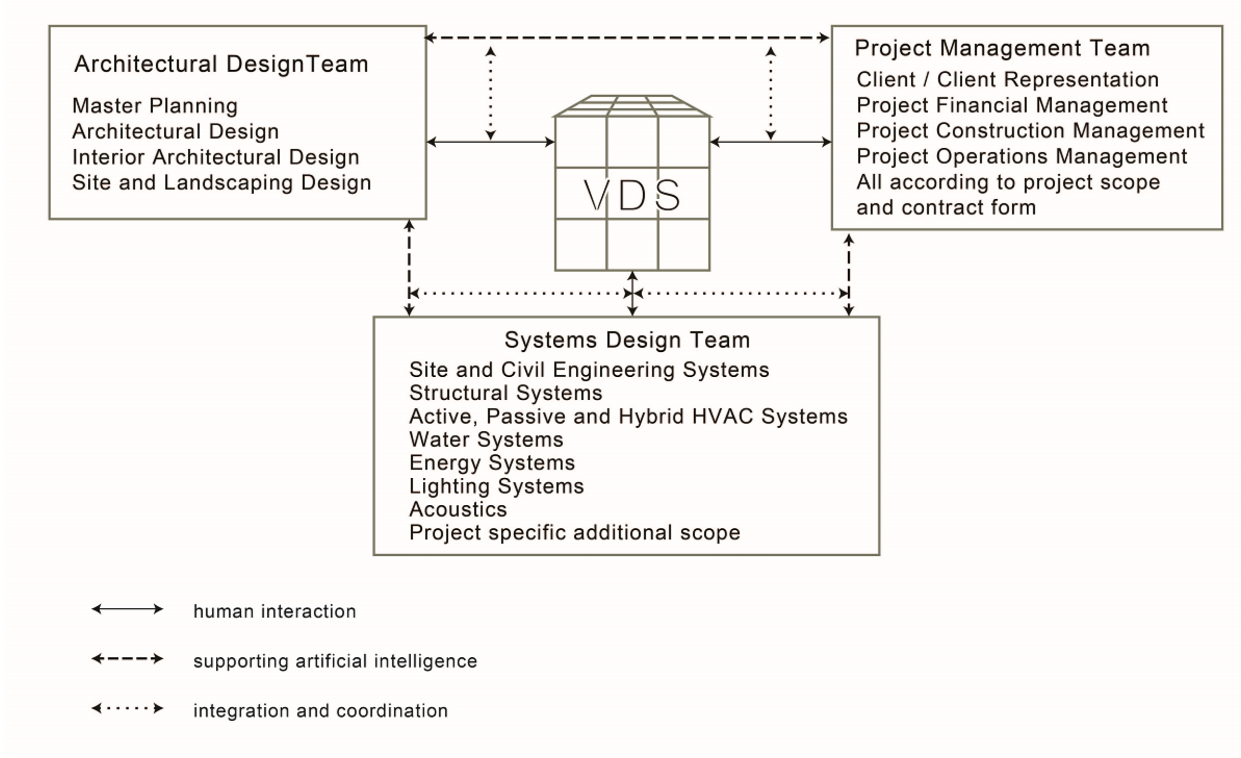


Figure 3-8 Coordination of Human Interaction and VDS supporting Artificial Intelligence

The current VDS development focuses on the building design process analysis and a framework that integrates several design and simulation software packages to realize the desired functionalities. Modular-based system architecture is adopted. It includes a VDS core, and externally linked standalone simulation and analysis software tools. The core contains a GUI, data model, a team work manager, and a simulation manager and two whole building simulation solvers (CHAMPS-Multizone and EnergyPlus to cover both energy and IEQ performance). The external standalone software tools are for more detailed analysis of envelope, HVAC, room environment, and life cycle cost, consultation with the Knowledge Base Expert System, or later comparisons between the monitored building performance and that predicted at the design stage (Figure 3-9).

Using the VDS platform, a building design created with an architectural or mechanical design software such as Revit (Autodesk, 2013c) or SketchUp with OpenStudio plug-in can be used to generate an Industrial Foundation Class (IFC) file or IDF (EnergyPlus's input file format) file. The IFC or IDF file can then be read into VDS data model. Moreover, VDS can run CHAMPS and EnergyPlus for whole building performance simulations. The VDS interfaces represent the multi-dimensional design processes, and consider both prescriptive and performance-based design approaches and relevant standards. A VDS simulation manager in combination with the expert knowledge of designers will help to decide when more detailed component simulations are necessary by calling upon envelope, HVAC, room, day-lighting or solar analysis models (Figure 3-9). Since most of the component models are available within the EnergyPlus (E+) software system, bridges (API modules) are developed to enable direct calling of the E+ or its modules from the simulation manager. Additional bridges will also be developed for the VDS simulation manager to interact with 1) the Virtual Building database for comparing predicted results with actual monitored data; 2) a KBES that contains heuristic reasoning rules for design evaluation and a KBES engine for reasoning; 3) an urban micro-climate simulation model (e.g., ENVI-Met (Bruse M. & Team, 2012)) for coupling with urban energy and environmental analysis; 4) and an optimization algorithm.

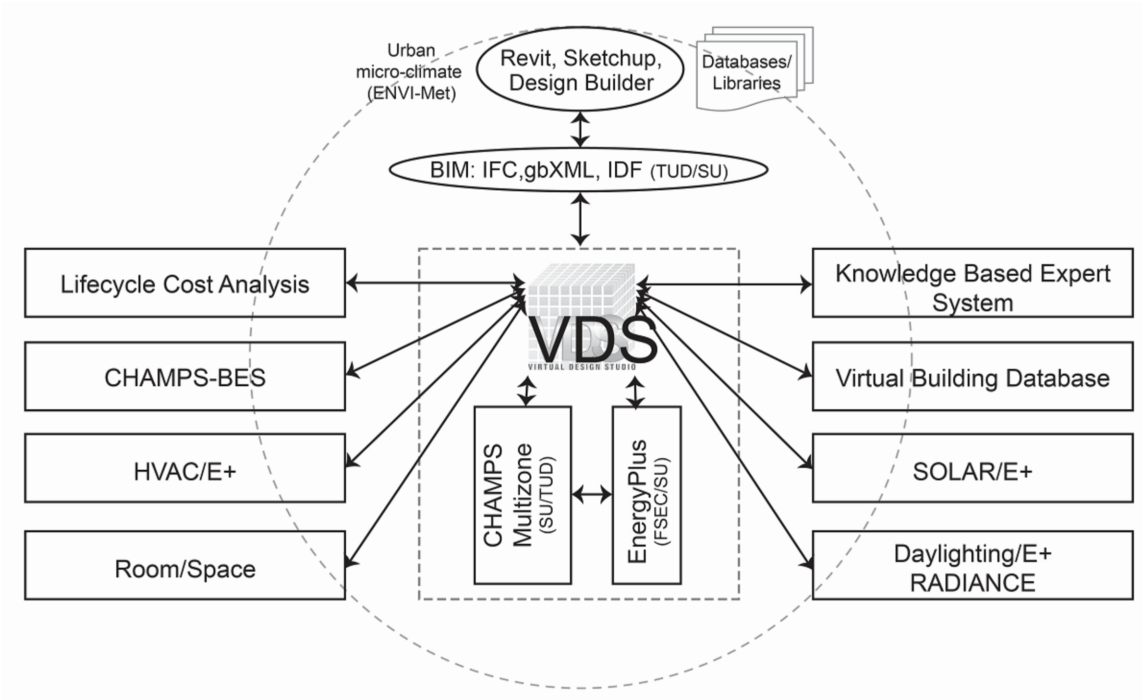


Figure 3-9 VDS Architecture and implementation plan

3.3.2. Model-view-control software architecture

The core of VDS is an object-oriented program developed by using the classic Model-View-Controller (MVC) software architecture (Figure 3-10). The Viewer is responsible for all interactions with the user. It updates the displayed data whenever a change of state in the data model is observed. The Data Model manages all behavior and data associated with the multi-dimensional design process and the building under design. The Controller is responsible for all application processes and Viewer action related events. The Viewer, the Controller and the Data Model correspond to the presentation, process, and data object layer, respectively. The fourth layer is the data persistence layer containing the input and output files, libraries and other documents managed or used by VDS (Figure 3-10). The VDS is implemented using Microsoft Visual Studio C++ 2010 with QT libraries version 4.8.0 (Nokia 2012).

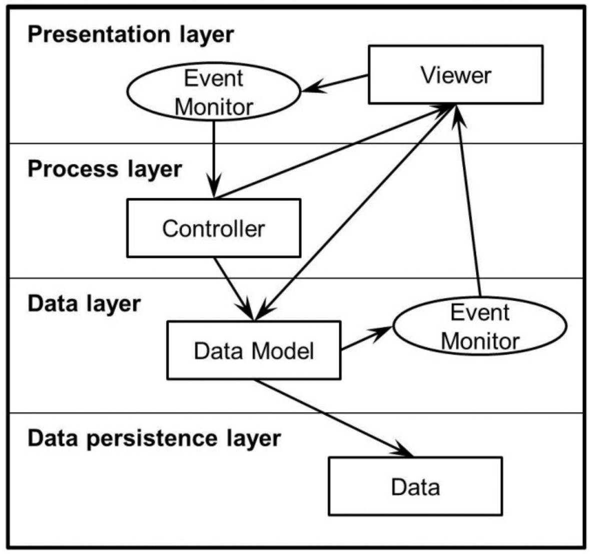


Figure 3-10 VDS MVC architecture pattern viewed in four software layers

3.3.3. The Viewer –GUI

The VDS GUI features four basic interactive windows in counter clockwise (Figure 3-11): Design Process, Input, Result and Performance. The size of each quad can be adjusted. Tab pages are used to present different categories of information in each quad using a layered-approach from high level to more detailed level. Within each tab page, further details regarding the information category are presented in forms that are most adequate for the category while consistence is sought whenever possible within the same quad.

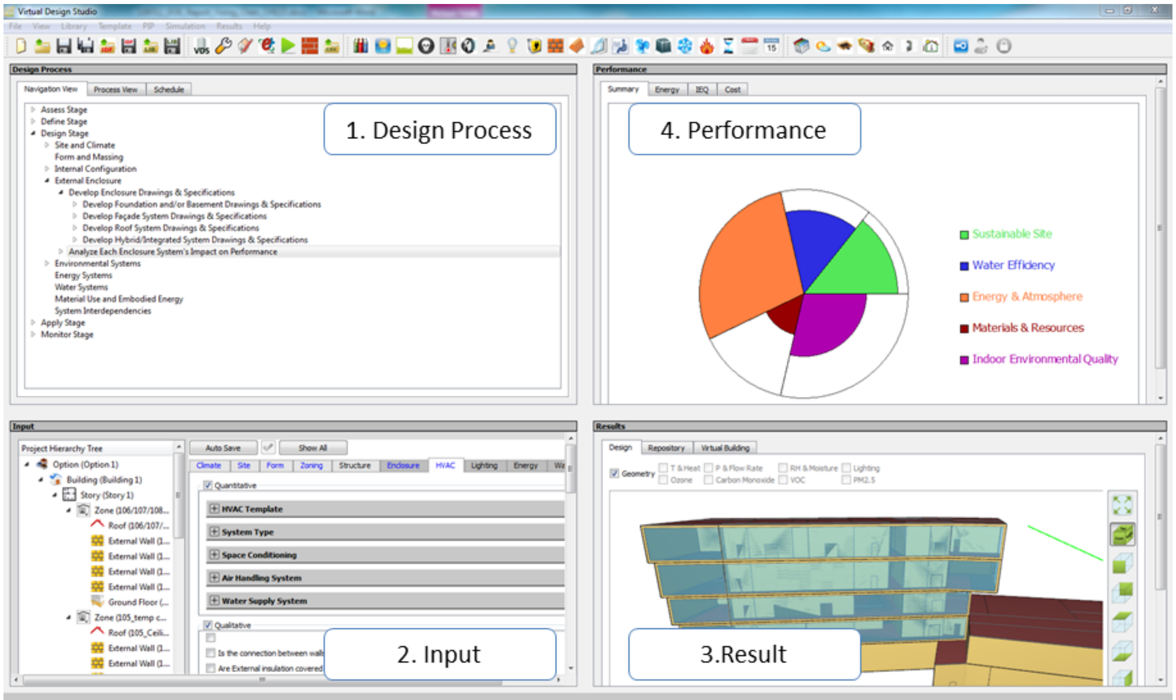


Figure 3-11 Four quads form (viewer) of VDS graphic user interface (GUI)

3.3.3.1. Design process representation

The "Design Process" window presents the design stages, actors, design consideration, associated tasks and schedule, and the input-process-output relationships among tasks, which also enables fast navigation through a complex design process. It includes a "navigation" tree (Figure 3-12) for task management (creation, deletion, and revision) as well as ease of navigation, a "process" page (Figure 3-13) for representing the relationships between tasks and the input and output of each task, and a "schedule" page (Figure 3-14) for tracking the task progress and completion. Figure 3-15 shows an example of the hierarchy of tasks and their associated inputs and outputs.

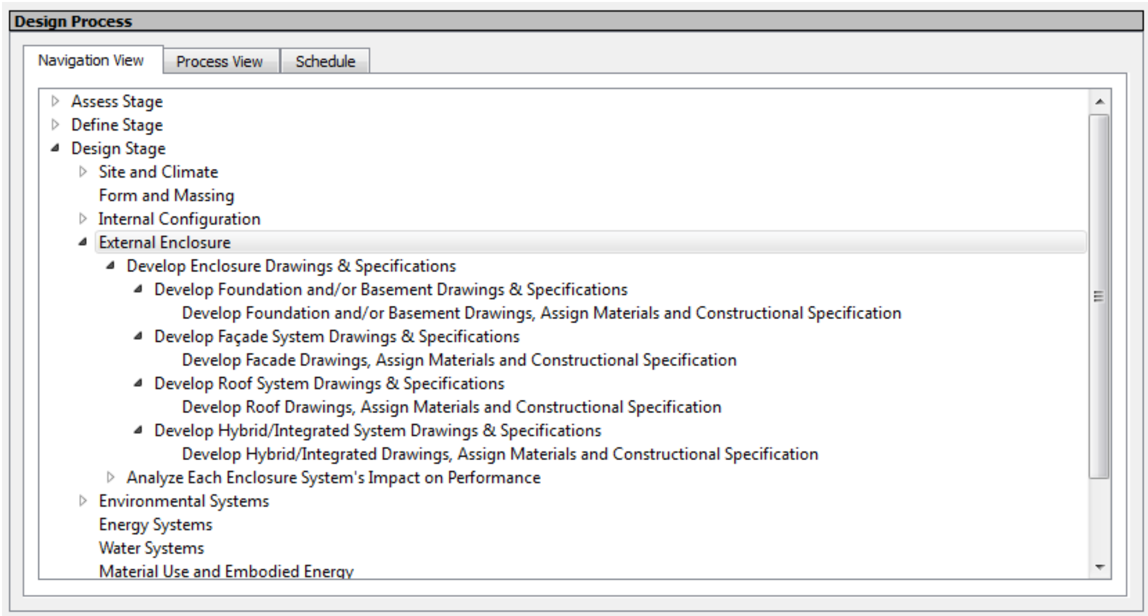


Figure 3-12 Navigation View in Design Process Window

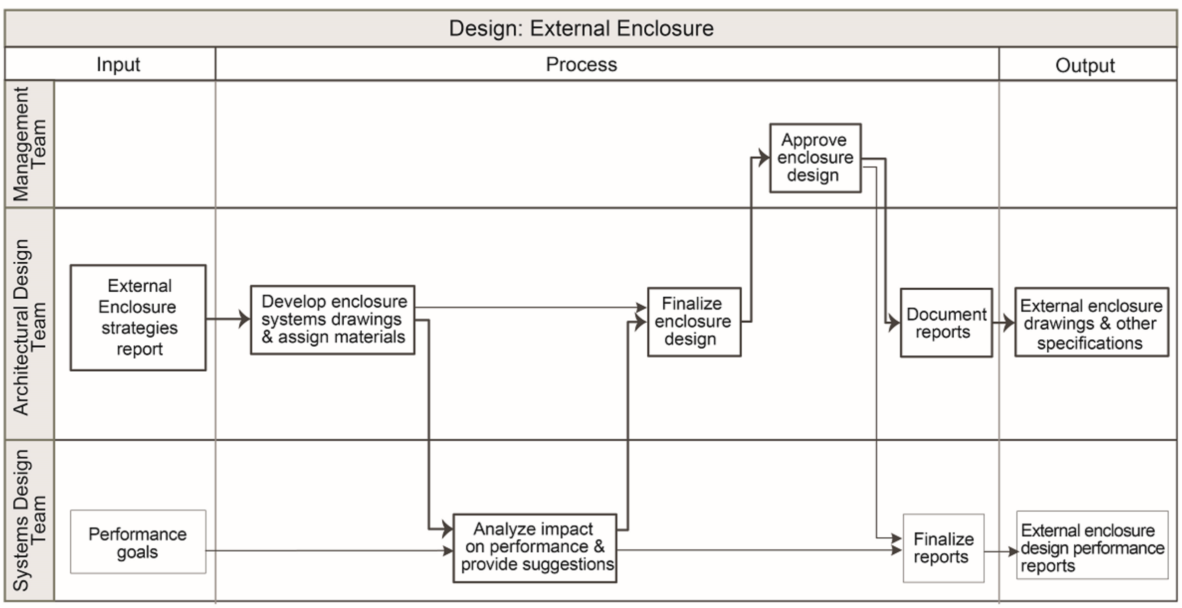


Figure 3-13 Sample of Process View in Design Process Window

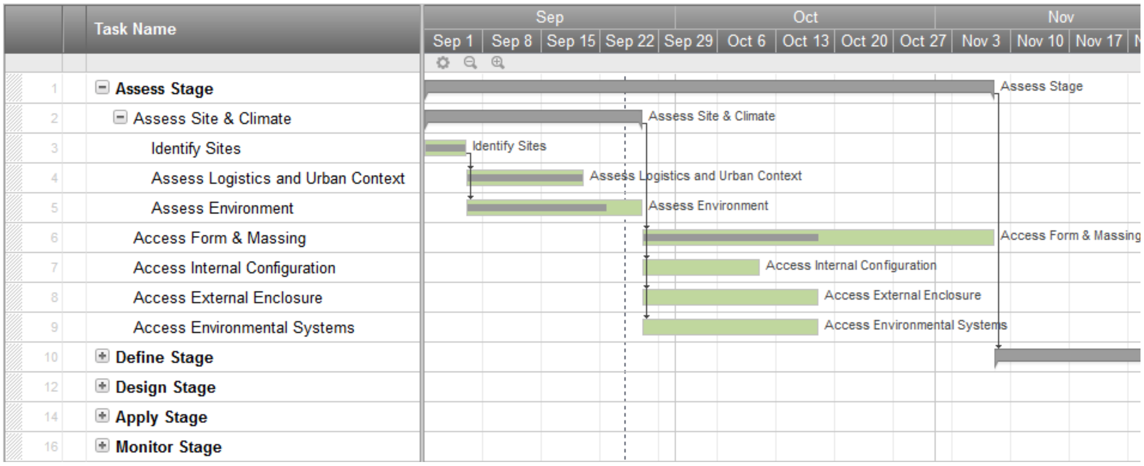


Figure 3-14 Sample of Schedule View in Design Process Window

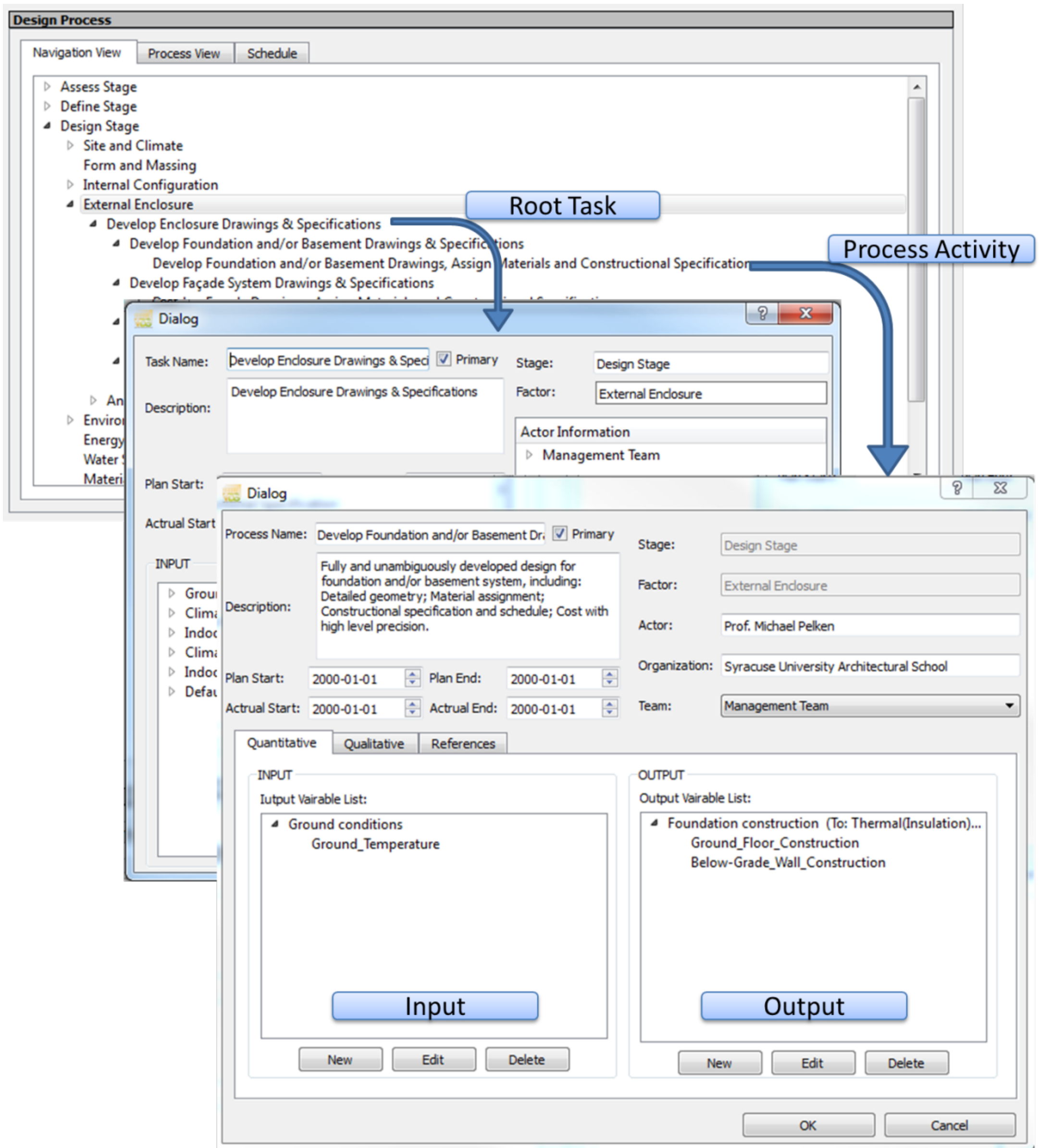


Figure 3-15 Hierarchy of tasks and their associated inputs and outputs

3.3.3.2. Design parameters representation

The "Input" window presents the opportunity to input all required design parameters (both quantitative and qualitative) and view supporting reference information. It includes a browsing tree on the left and tab pages on the right (Figure 3-16). The tree allows users to focus on a specific level in the building's hierarchical structure. Each tab page represents a category of input parameters of a specific design factor such as Climate, Site, Form, Zoning, Structure, Enclosure, HVAC, Lighting, Energy, Water, and Materials (embedded energy or carbon emission analysis). The quantitative design parameters in each category are further organized into groups. The value of a design parameter in a higher level can be “applied” to all its children; while the value in a lower level can obtain the value from its parent by clicking the “inherited” box.

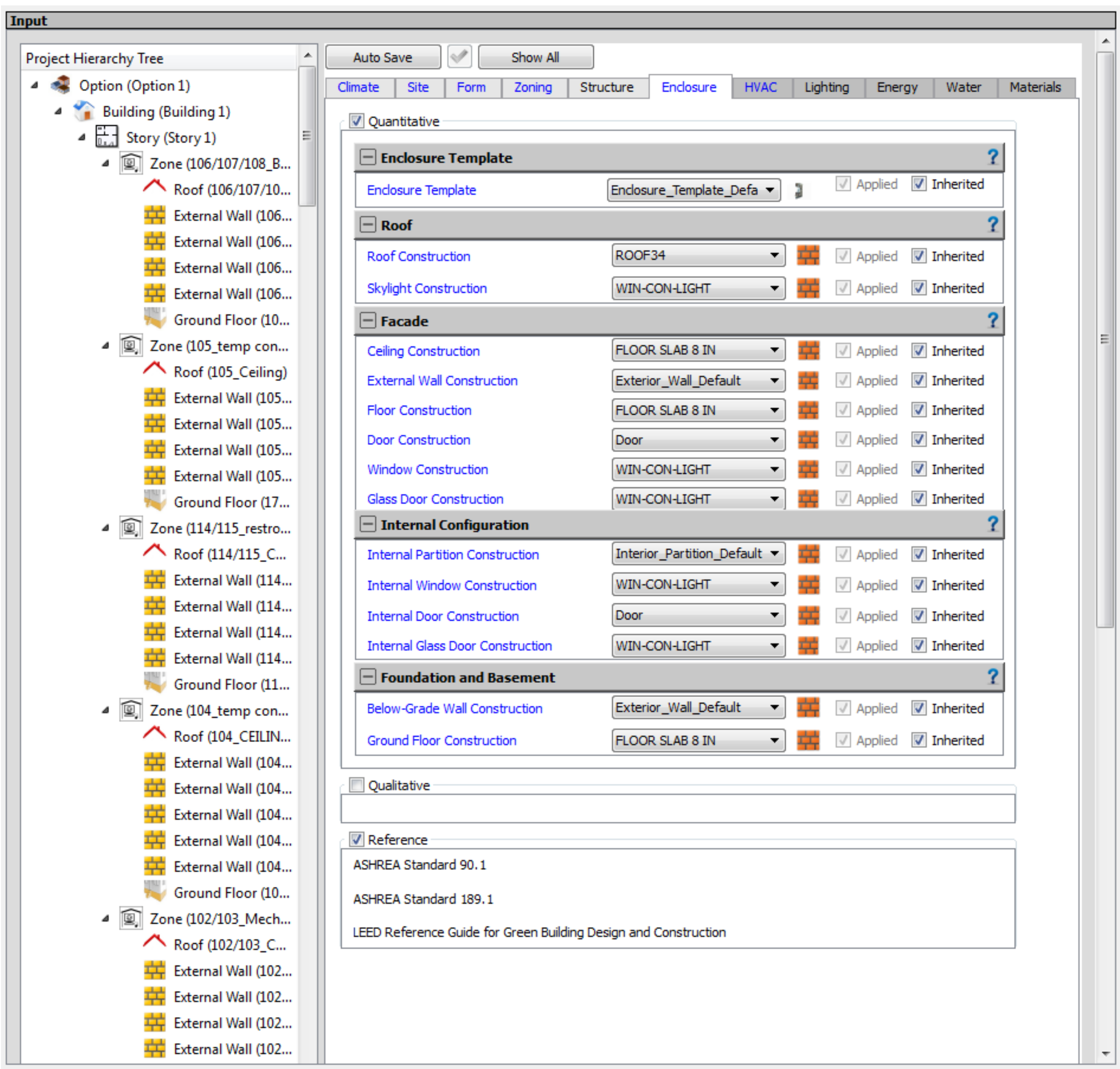


Figure 3-16 VDS design parameters organized by design factors (right) with displays filtered by design tasks and position in the hierarchical tree (left)

Table 3-1 provides a summary of the input parameters provided by the VDS. All the parameters in the same category are further organized into a “Template”---i.e., a form for systematically and logically presenting the design input parameters. For each “Template”, a pop-up window page provides a form for completing the input entries. The format of the pop-up window is standardized to have a library tree on the left for user to select a system type, and the entry form on the right. Each form is identified by a user definable “Name”, a “Type” selectable from the library on the left, a “Description” of entries, and associated parameter items organized in groups (i.e., rows in Table 3-1). For each parameter item (i.e., a bullet item in Table 3-1), a lower-layer pop-up window is provided for entering a set of variables, functions or input files that define the item. Figure 3-17 shows the input parameters for the HVAC Template, and Figure 3-18 shows the input parameters for Air Supply System Library as lower-layer pop-up window.

Table 3-1 Summary of VDS Input Parameters for Each Design Factors

Climate	Site/Building	Form/Massing	Zoning	Enclosure	HVAC
Template	**Template**	**Template**	**Template**	**Template**	**Template**
Climate zone • Climate Zone • Subzone*	**Location** • Latitude • Longitude • Elevation • Time zone • Shape and size*	**Shape** • Volume to surface ratio# • Building height# • Story height# • Shape function*	**IEQ Requirements** • Thermal comfort • Outdoor Ventilation rate • Daylighting Control • Acoustic quality*	• Envelope Type*	• **System Type**
Heating/cooling design conditions • Ground temperature • Winter design day • Summer design day • Other Design Days	**Building position** • Angle from north • X (E-W direction)* • Y (N-S direction)* • Z (Elevation)*	**Floor space** • Number of floors# • Number of zones# • Total floor area# •	**Occupancy** • Number of people • Activity • Schedule • H.A.M.P generation rates*	**Roof** • Roof • Skylight	**Space conditioning** • Supply air • Supply water * • Reheat coil • Room air distribution* • Standalone unit*
Detailed climate • EWP weather file • Temperature • RH • Wind speed • Wind direction • Air pressure • Solar radiation • Precipitation	**Landscape & surrounding environment** • Terrain type • Ground reflectance • Thermal radiation* • Shadowing* • Wind function* • Pollution function* • Noise function*	**External Surface** • Window fraction# • Wall area# • Window area # • Shading effect*	**Lighting** • Number of lights • Light type & power • Schedule • H.A.M.P generation rates*	**Façade** • Ceiling/floor • Exterior walls • Exterior windows • Exterior doors	**Air handling system** • Air supply system • Conditioning capacity* • System and components* • Control*
Atmosphere pollution • Ozone • Carbon monoxide • VOC • PM2.5 • Carbon dioxide* • Formaldehyde*			**Equipment (or process)** • Number of equipment • Equipment type & power • Schedule • H.A.M.P generation rates*	• **Internal Configuration** • Interior partitions • Interior windows • Interior doors	**Water supply system** • Hot water supply system • Chilled water supply system • System and components* • Control*
			Pollutant Source and Sink • Ozone • Carbon monoxide • VOC • PM2.5 • Carbon dioxide* • Formaldehyde*	**Foundation/ Basement** • Ground floor • Below-Grade wall	

Conditioning: heating, cooling, humidification and dehumidification;
H.A.M.P: heat, air, moisture and pollutants;
*: place holder for further implementation
#: calculated from geometry information

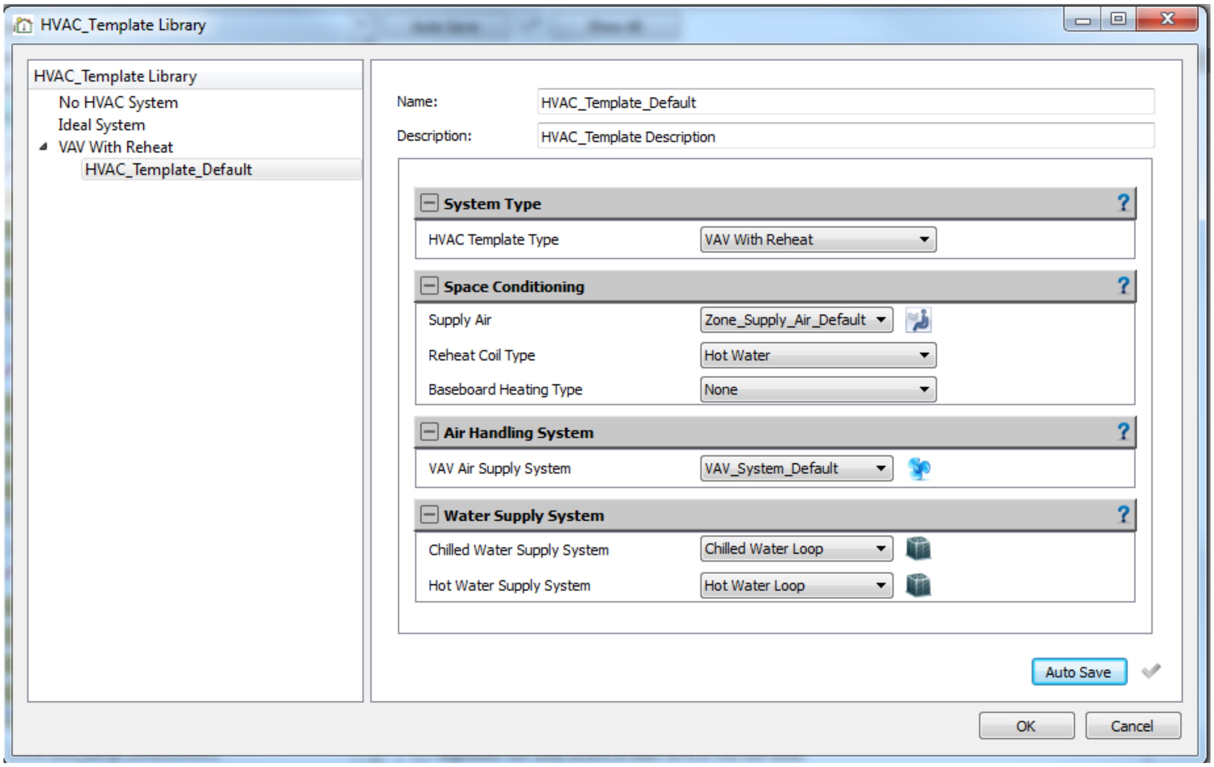


Figure 3-17 Input parameters for HVAC Template

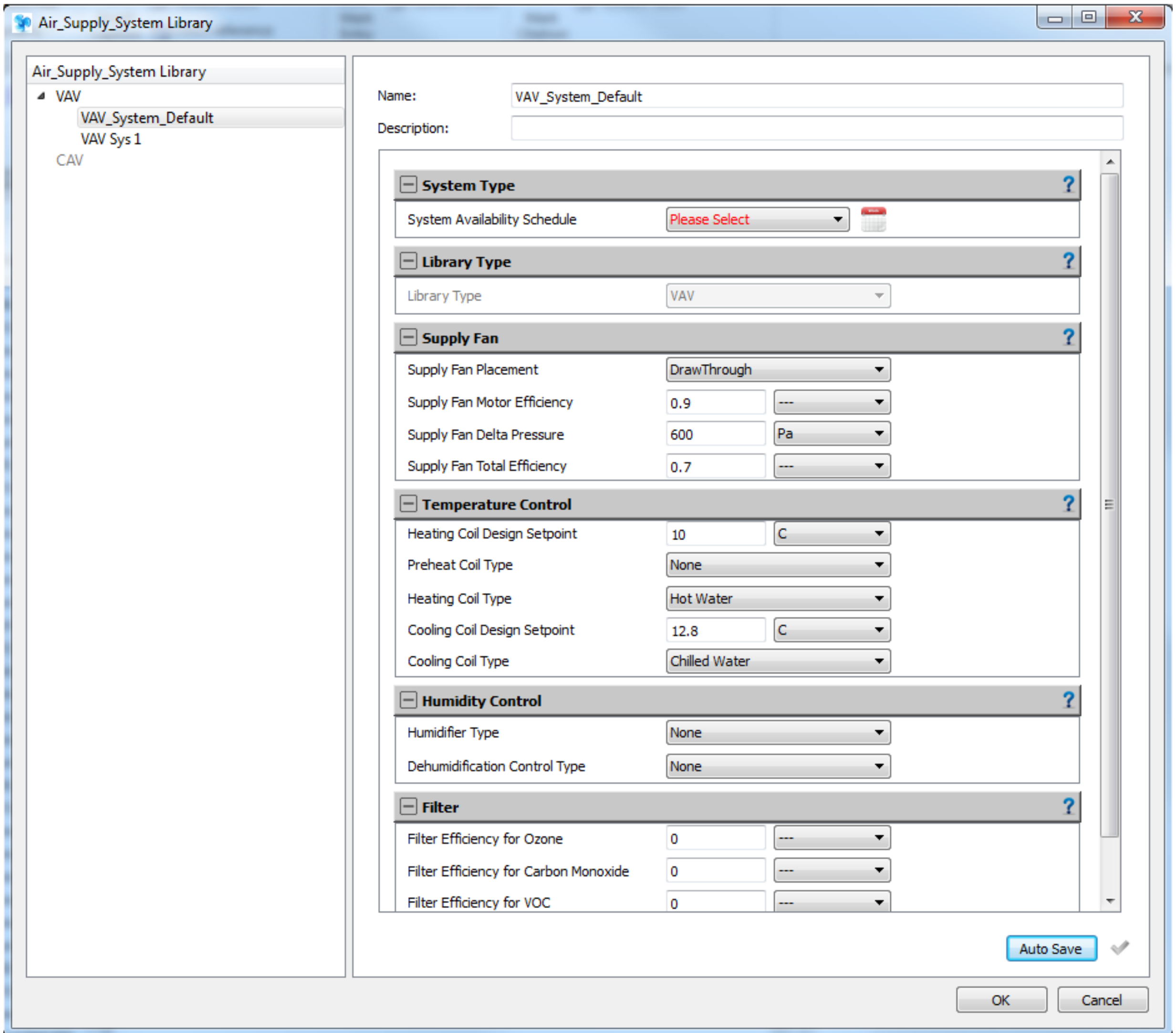


Figure 3-18 Input parameters for Air Supply System Library

3.3.3.3. Design result representation

The "Result" window presents the "Design" of the building in 3-D (Figure 3-19), the resulting conditions of heat (Figure 3-20), air, moisture, daylighting (Figure 3-21), and pollutants in the building, and a "Repository" (Figure 3-22) for document sharing over an internet server through the VDS-PIP. The "Heat", "Air", "Moisture" "Daylighting" and Pollutant" distributions are represented in the forms of contour maps and flux maps with architectural design overlay

(Figure 3-20 and Figure 3-21). The "Repository" page links directly to the VDS-PIP web interface.

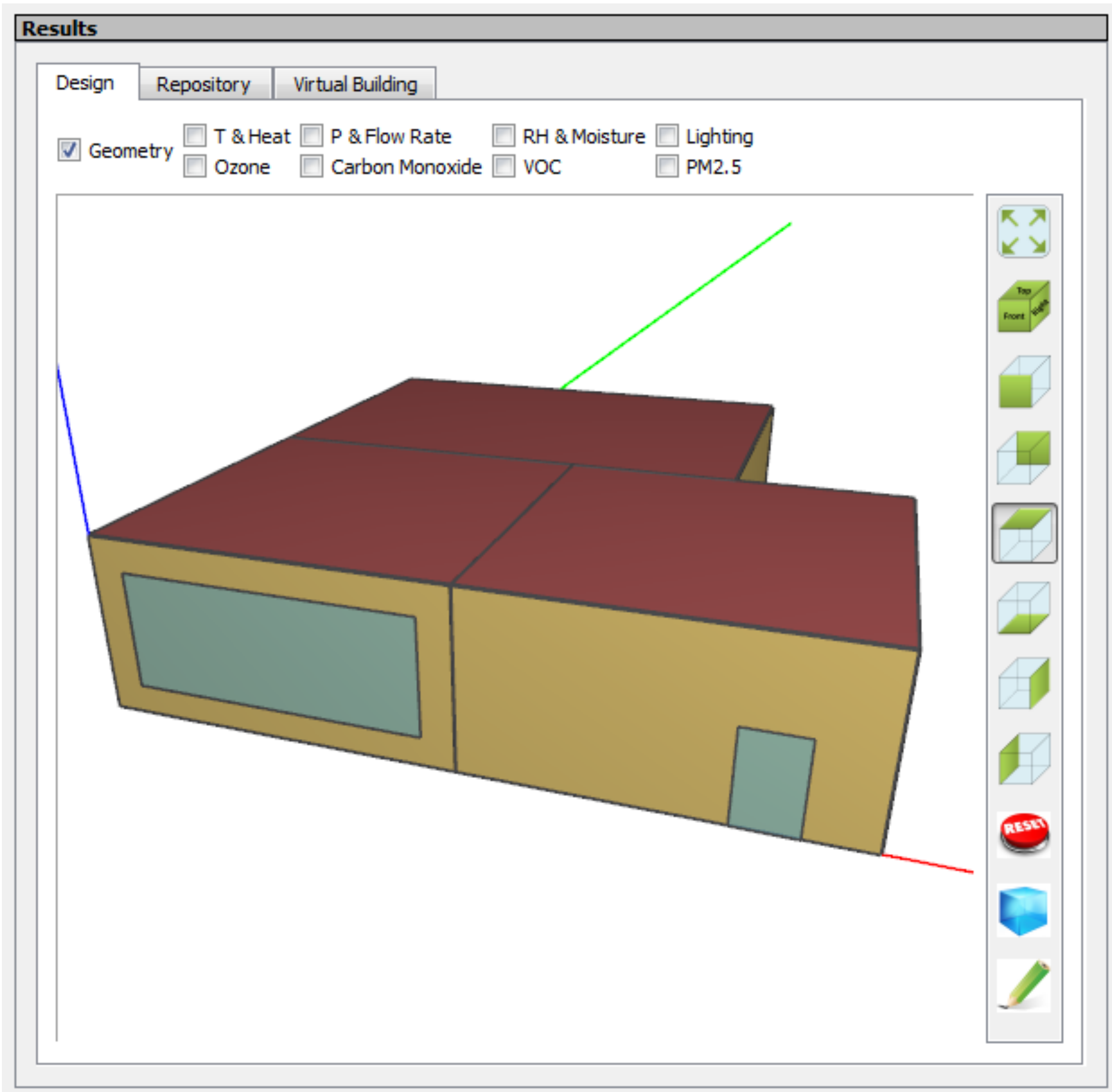


Figure 3-19 The "Design" of a 3-zone building in Result Window

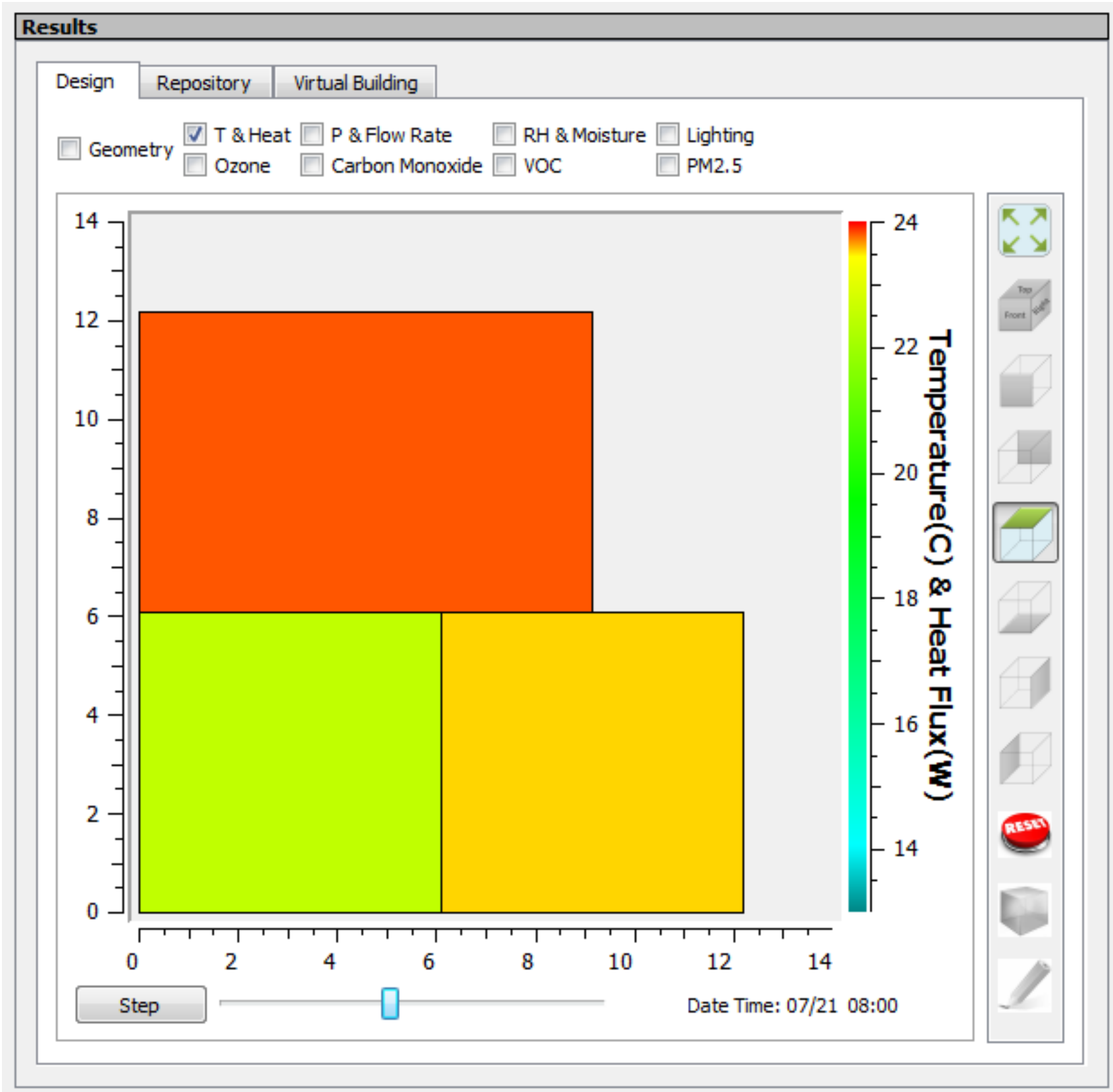


Figure 3-20 Temperature field of the 3-zone building at 8am on Jul. 21st in Result Window

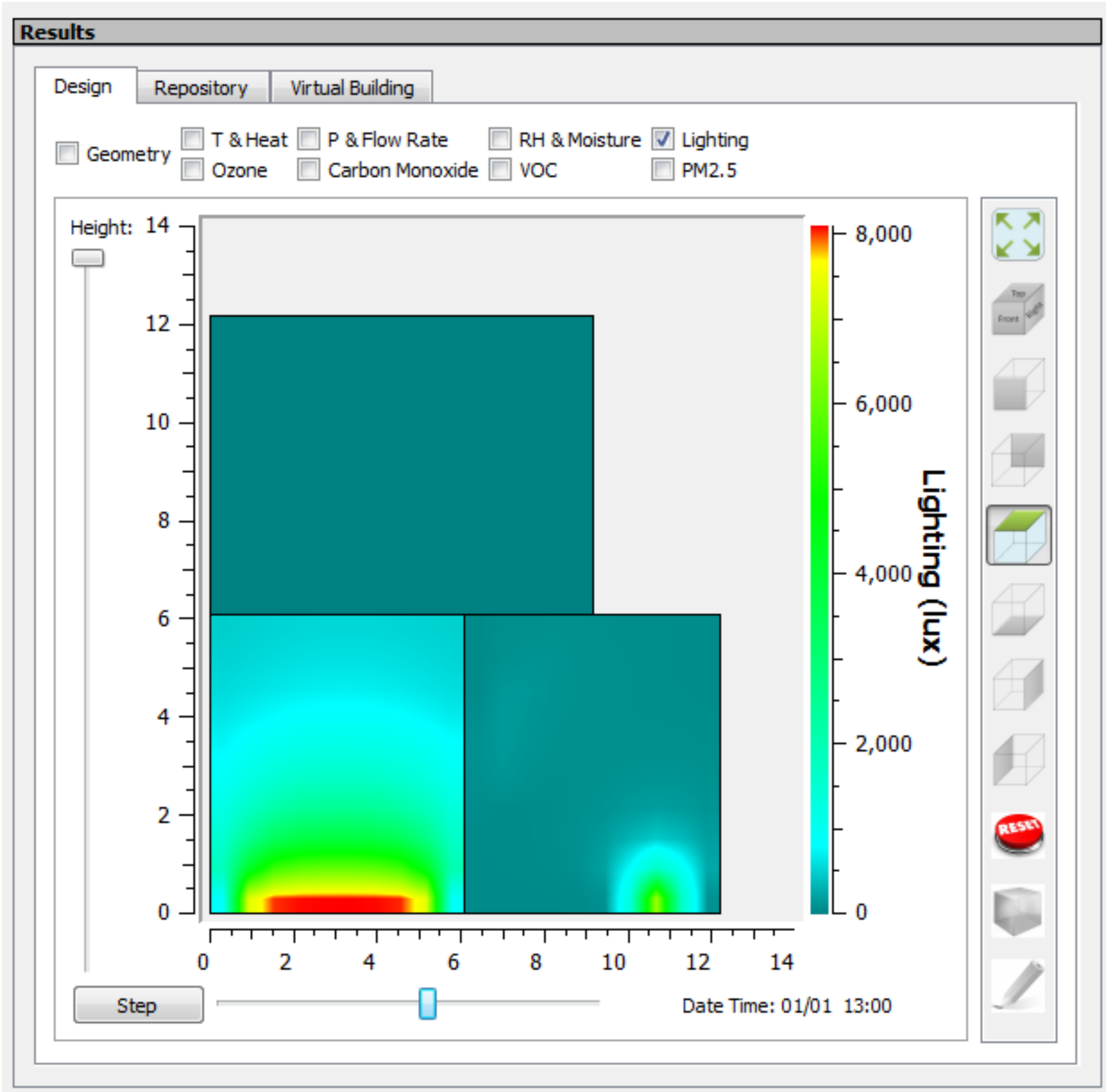


Figure 3-21 Lighting map of the 3-zone building at 1pm on Jan. 1st in Result Window

As discussed in Section 3.3.1, VDS has the capability to call external software tools for detailed analysis of envelope, HVAC, room environment, and life cycle cost. Figure 3-23 shows the sample results of the hygrothermal performance of a wall assembly simulated by CHAMPS-BES. The "Result" window should be able to display the simulation results generated by these external software tools.

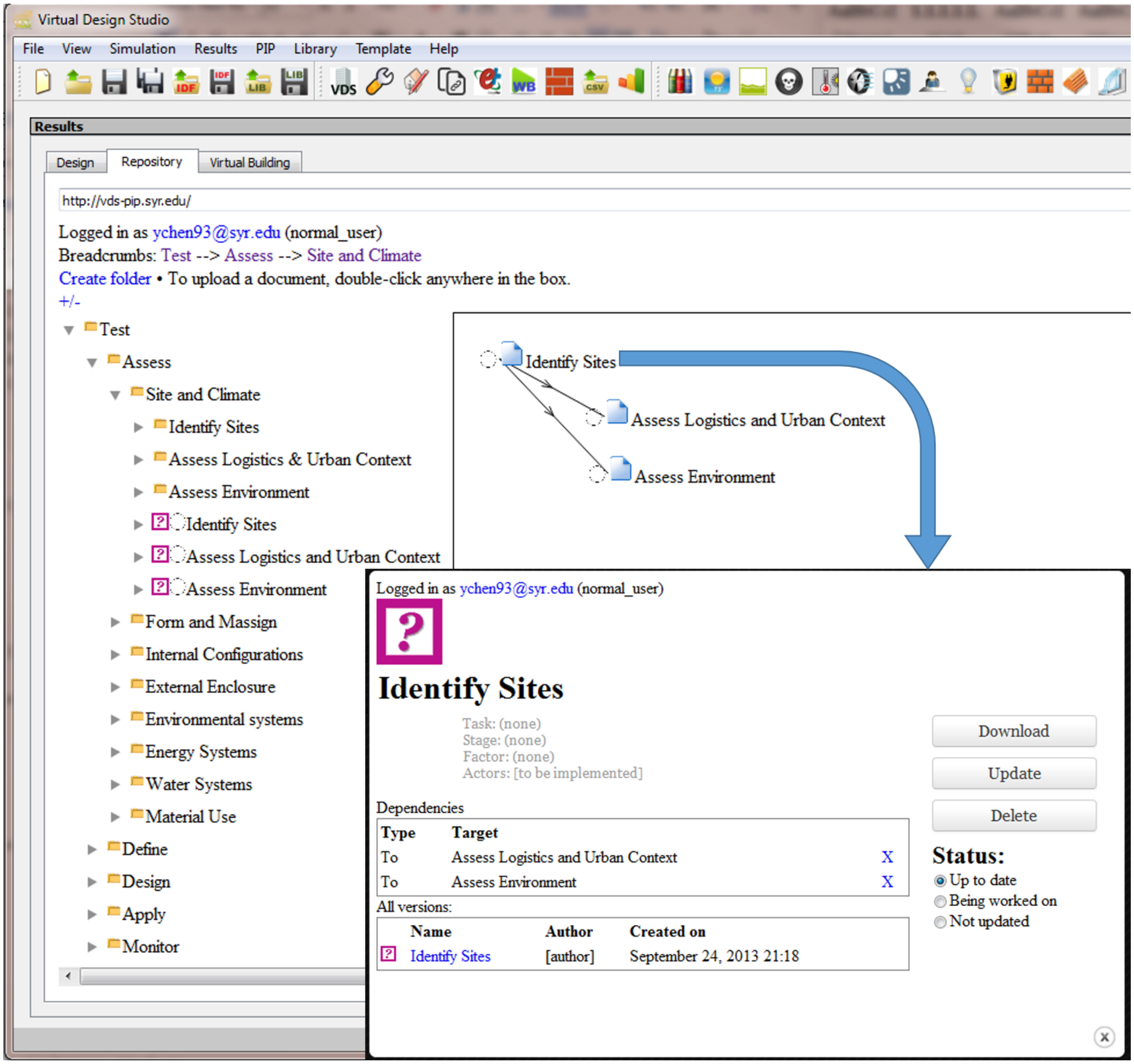
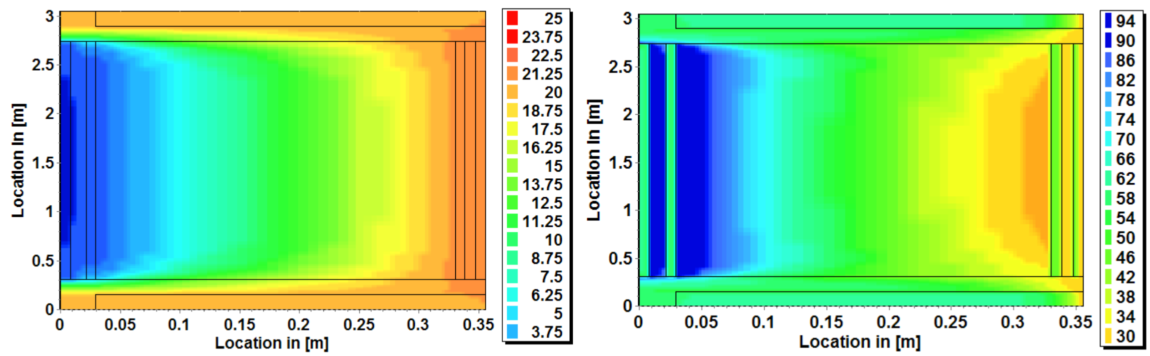


Figure 3-22 Repository Page in Result Window



(a) Temperature distribution (b) Relative Humidity distribution

Figure 3-23 Sample Results of hygrothermal performance of a wall assembly simulated by CHAMPS-BES

3.3.3.4. Performance representation

The "Performance" window represents the overall building performance (Figure 3-24), individual aspects of building performance (Energy, Figure 3-28), and cost information. By clicking on an aspect of the building performance in the summary view, the sub-performance aspects of the selected performance aspect will be shown (Figure 3-25). Furthermore, by clicking on a sub-performance aspect, the contributions of each design factor to the improvement of the sub-performance aspect are shown (Figure 3-26). Finally, by clicking on a design factor, the relationship map of the selected design factor with the other factors is shown (Figure 3-27). Future program extensions will include the confidence intervals for the predicted performance.

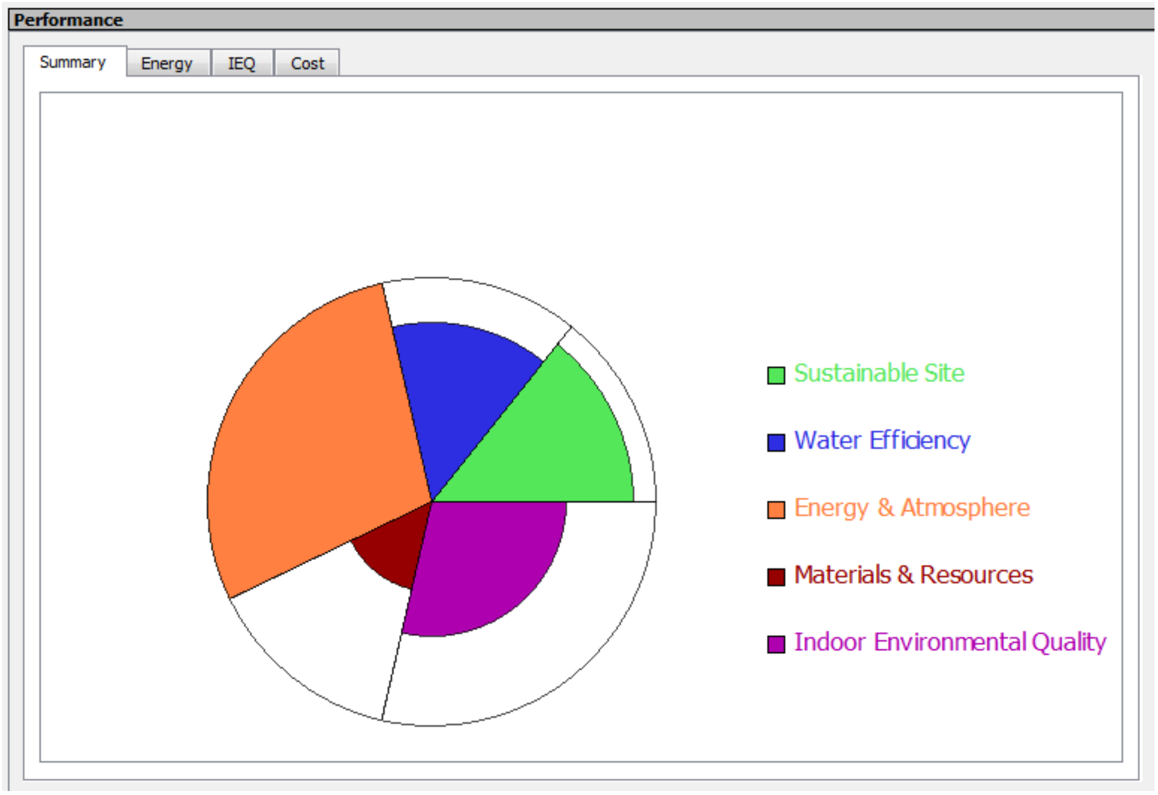


Figure 3-24 Proposed overall building performance summary view

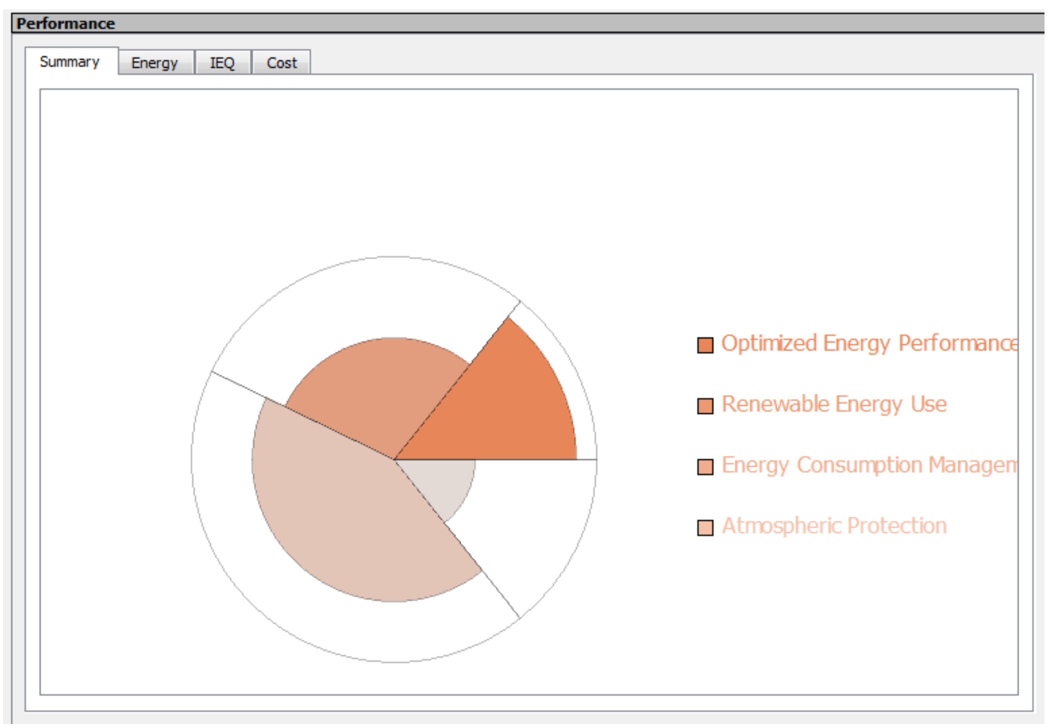


Figure 3-25 Energy & Atmosphere detail

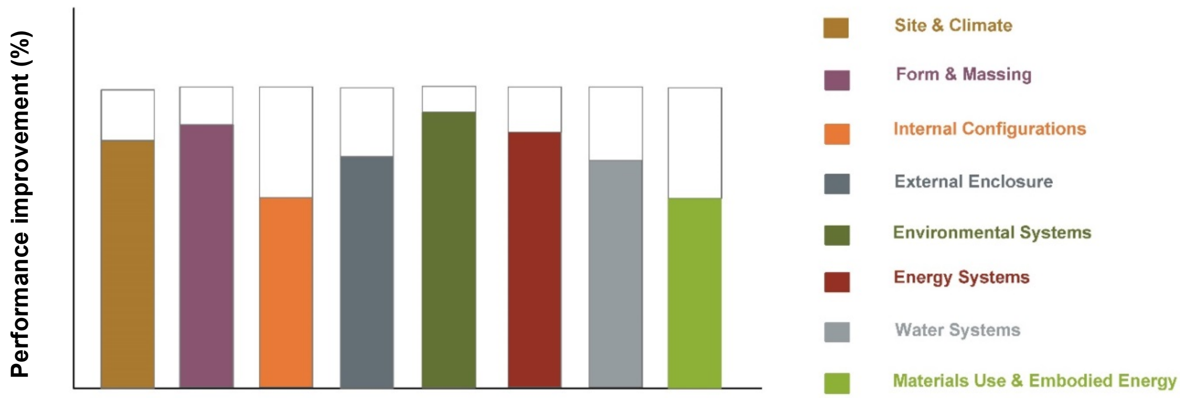


Figure 3-26 Performance improvement relative to reference building by design factor

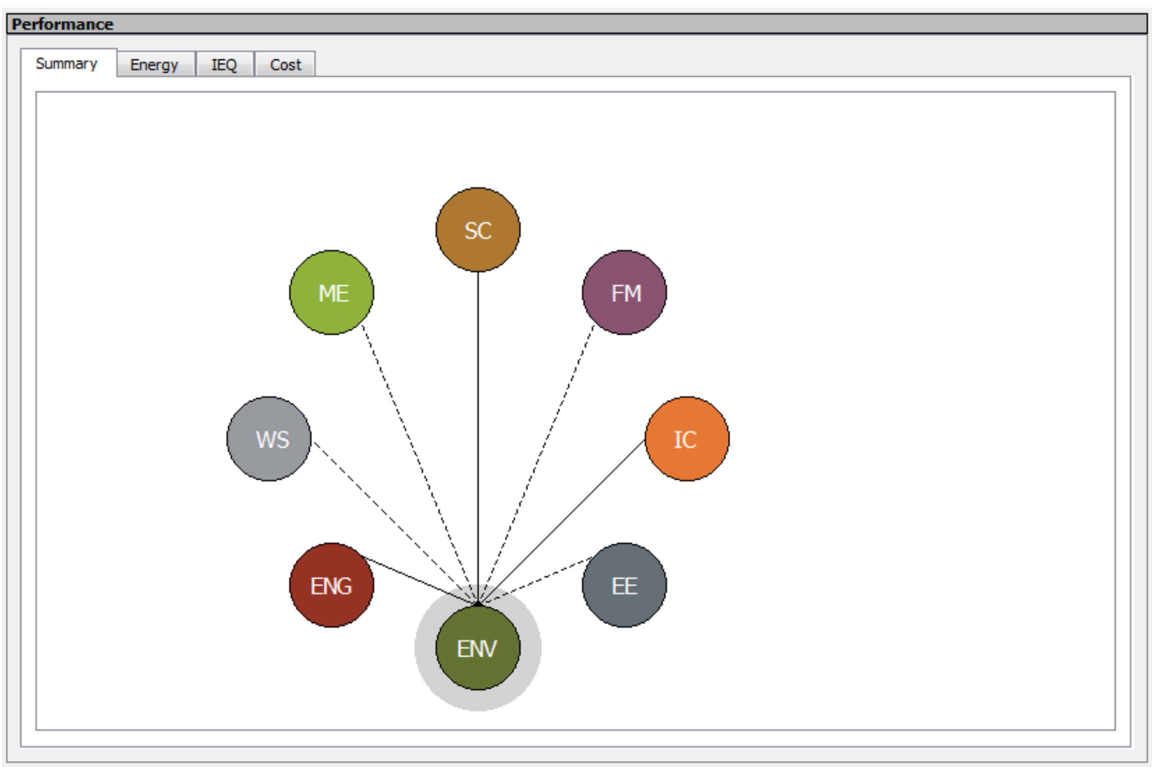


Figure 3-27 Design factor relationship map for the IAQ sub-performance aspect

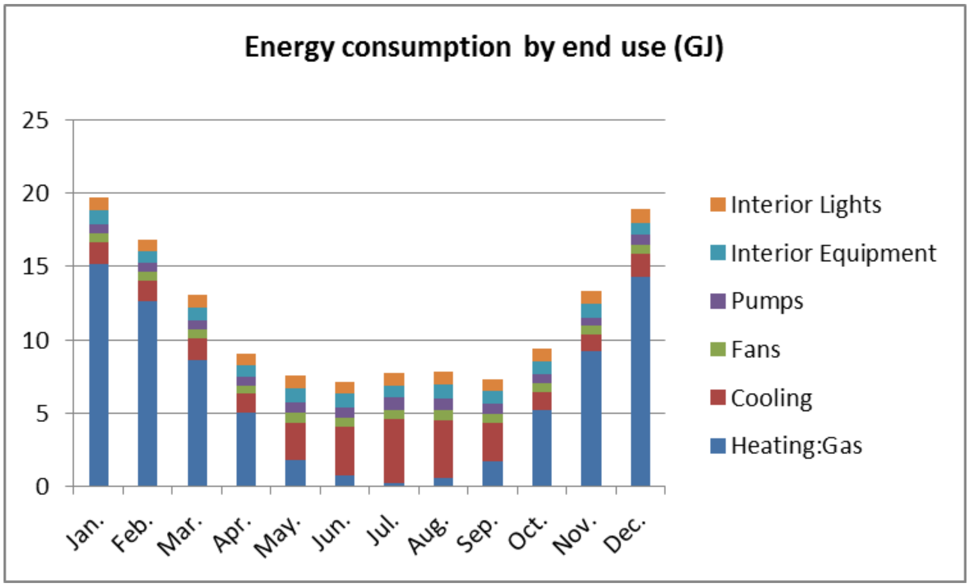


Figure 3-28 Sample of energy end use distribution in Performance Window

3.3.4. The Model – VDS data model

The VDS data model deals with two types of data. The first type represents the physical building system and components under design. VDS was first designed to display and store data according to tasks, but this would have resulted in over specification on what designers should do for each task, and redundancy in data storage. The present VDS design uses a common structure to represent and store the data for efficiency and convenient data sharing among different users (Figure 3-29). The data are organized and correlated by factors: Climate, Site, Form, Zoning, Structure, Enclosure, HVAC, Lighting, Energy and Water, consistent with the representation in the Viewer's parameter input window. A hierarchical structure is also adopted for representing a physical building from its climate and site level, to building level, floor, zone/room level, and to wall assembly level, which is similar to that adopted in the "Virtual Building" database (Kato et al. 2008) and CHMAPS-Multizone (Feng et al. 2011). This structure enables downward data inheritance from a higher to a lower level and upward aggregation from lower levels to a higher level. The downward inheritance is applied to the design parameters to reduce the effort of data entry by the user, and the upward aggregation is used by the simulation results and performances to enables the representation of summarized characteristics of a building component or whole building.

The second type of data represents the design process including design stages, design factors, design actors, design tasks and their inputs and outputs, relationships between tasks and task schedule. This type of data is represented in the "Magic Cube" data model (Figure 3-30). This data model enables the formation of the tree of design stages, factors and tasks that are decomposable to subtasks all way down to the "Process Activity"---an implementable task with all input and output parameters and actions defined (Figure 3-31). The task decomposition feature allows users to define and manage tasks according to the wide variety of project needs. The data model also enables the representation of the input-output dependencies between two different Process Activities (Figure 3-32).

Because tasks can be very different for different projects, and can be defined and managed in many ways, VDS allows the users to define their own custom tasks and establish project specific relationships between tasks, while providing a default template on objectives, tasks and associated input and output parameters for guidance.

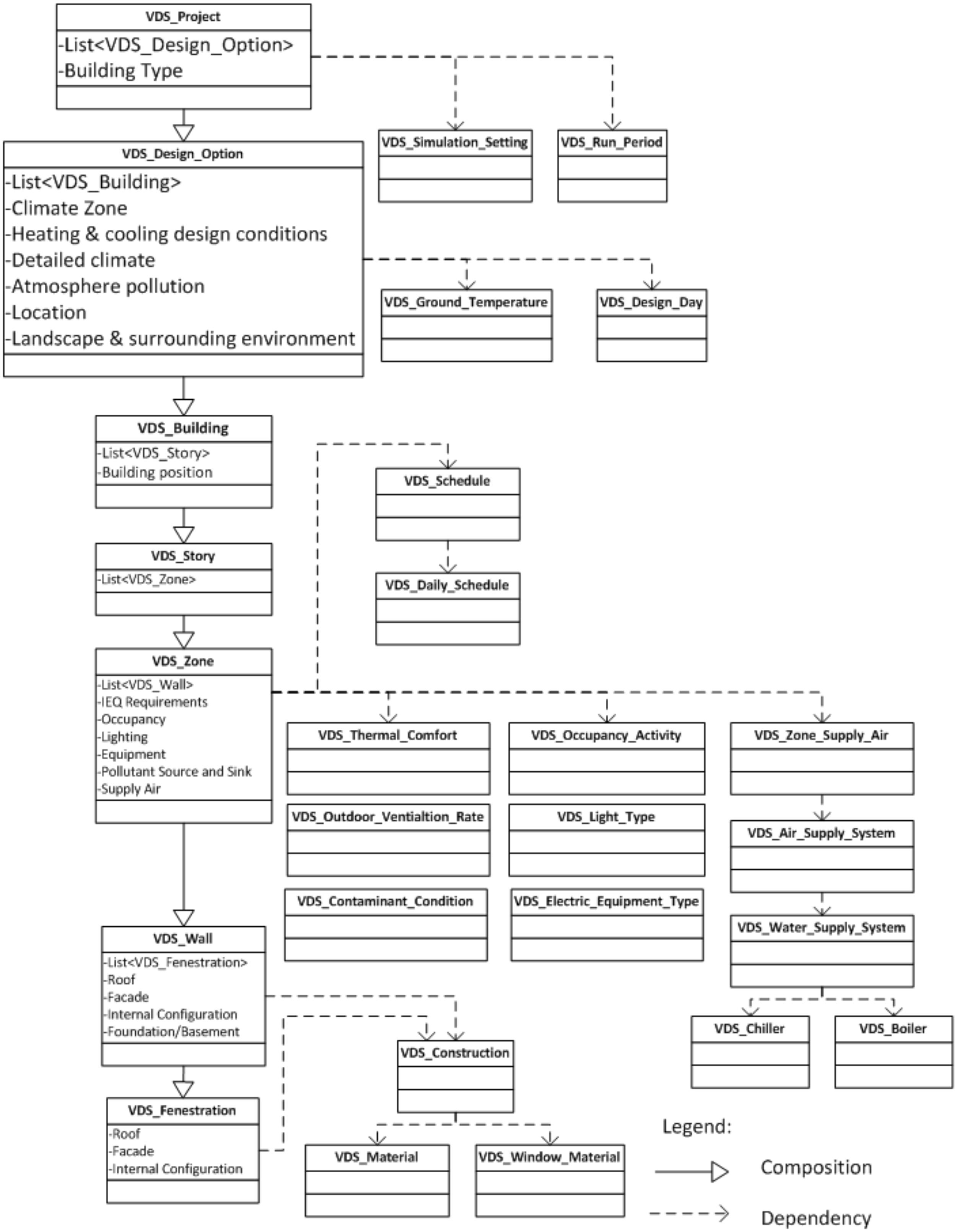


Figure 3-29 VDS data model: building related data

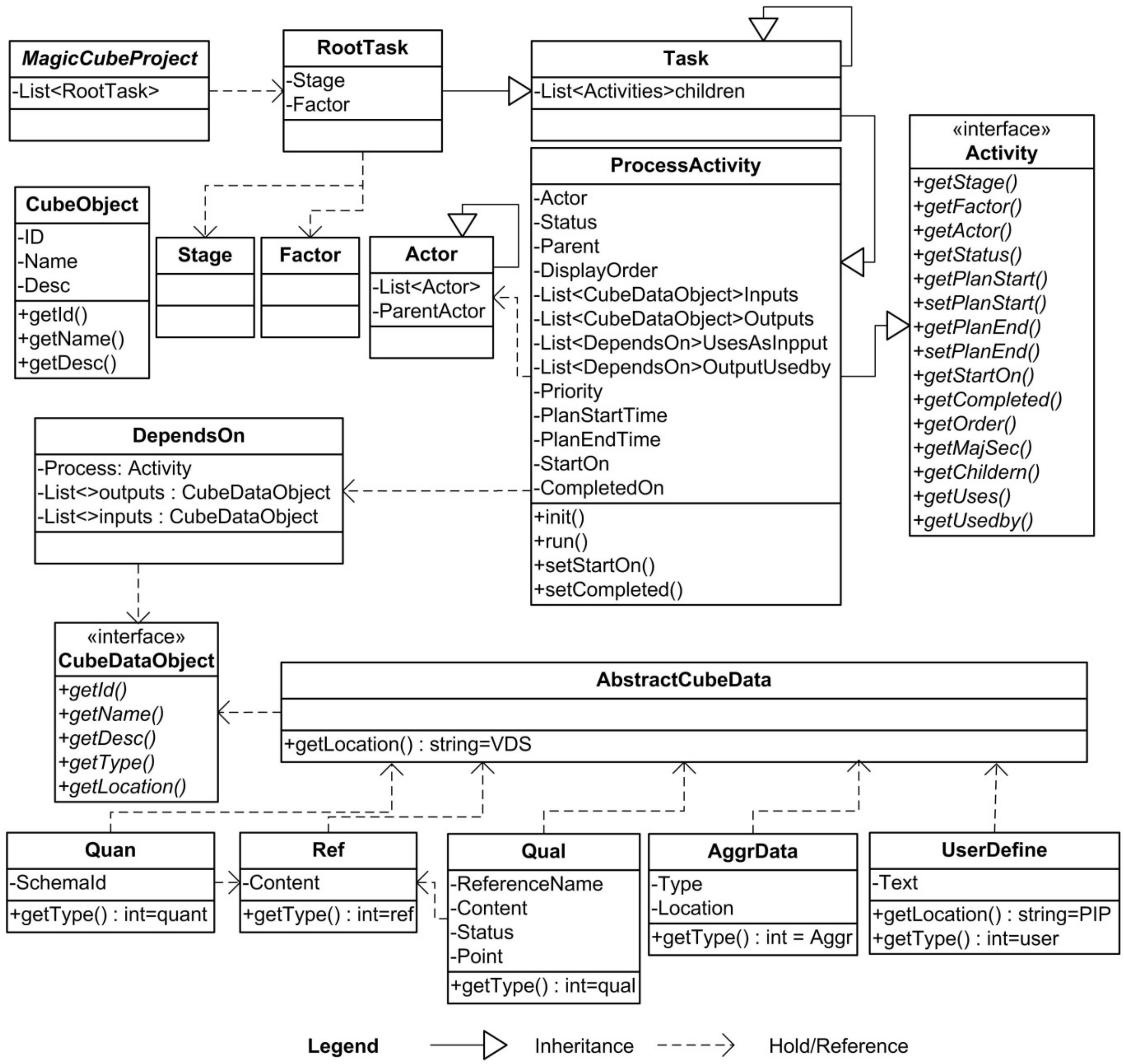


Figure 3-30 VDS data model: design process related data

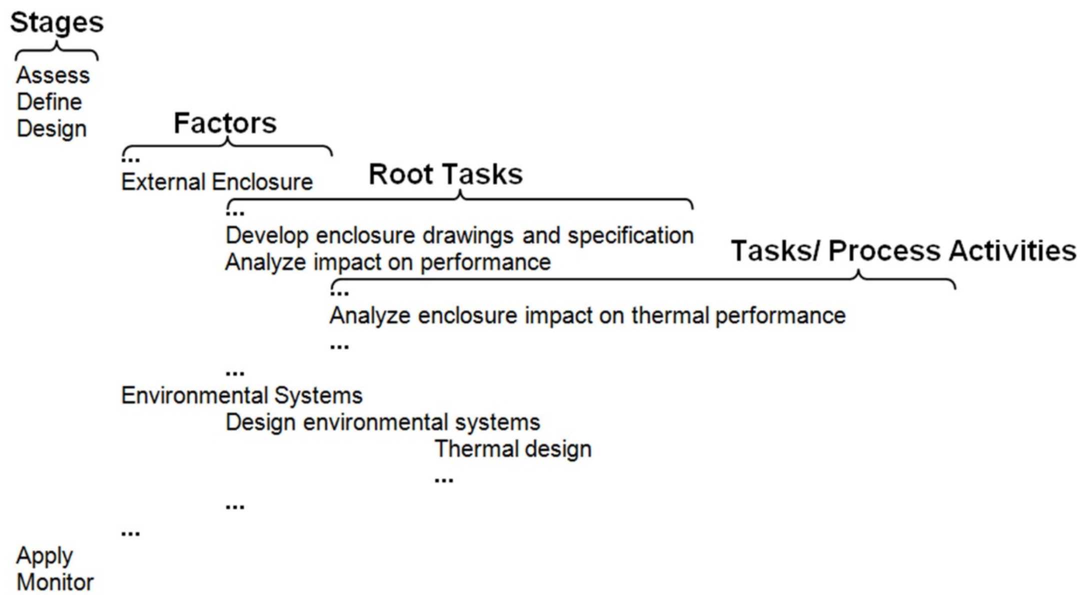


Figure 3-31 An example tree of stage, factor and tasks that are decomposed to subtasks until reaching the process activity level where all input and output parameters are defined

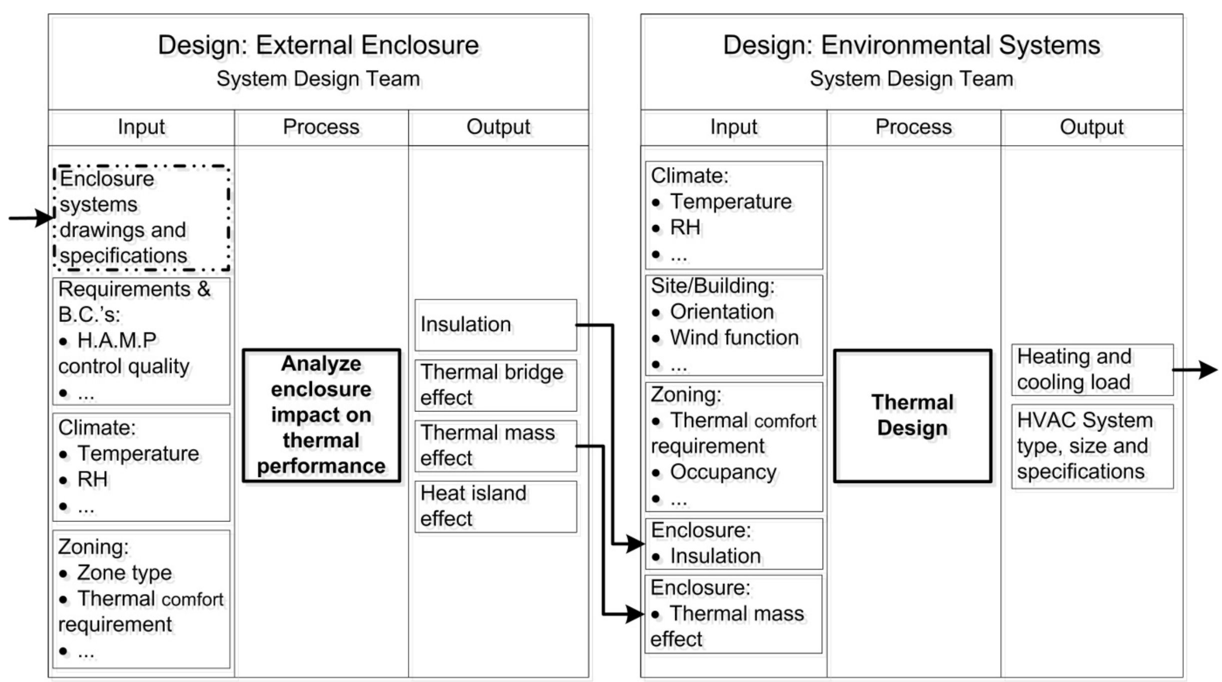


Figure 3-32 An example of the input-output dependency between two Process Activities

3.3.5. The Controller

The VDS Controller manages two types of data flows (including events), respectively. The first type is to assist the users in navigating through the complex design process and guide them to consider and enter essential data for a specific task. The navigation is also assisted by the hierarchical structure of the building model. For a specific task at a given design stage, a designer can access and manipulate the data closely related to the specific task as guided by the VDS. The designer can also access any other data regarding the building through the common structure, giving the user additional flexibility. The data access flexibility is especially useful for experienced users who already know where to find or enter data and what type of analysis is applicable and needed. The second type of data flow is the action of VDS in response to user input or command. This includes triggering required calculations (such as re-calculating the performance of a reference building when design geometry changed) or inferences, updating the data stored with the common data structure, and reflecting corresponding changes in the results and performance windows.

3.3.6. Software integration methods

As a digital platform for design, the VDS application will need to interact with external applications such as SketchUp, CHAMPS, EnergyPlus, and other software. To the extent possible, external applications will be tightly integrated and loosely coupled with VDS. This strategy will maximize usability and minimize software maintenance. Three levels of external application interactions are envisioned (Figure 3-33):

a) Encapsulation – wrap an external application using shared data files or memory to communicate between VDS and the application. This approach is used with design software such as Revit or SketchUp where VDS extracts building geometry data from the output files of the design software.

b) Incorporation – acquire the application source code and include desired components directly into the VDS system. Generally, this is the least desirable approach as it will require the greatest amount of maintenance effort. However, some codes such as CHAMPS-Multizone are internally maintained and will be incorporated as core software to VDS with enhanced functionality.

c) Integration – utilize a published application program interface (API) to make calls directly into the external application to perform a specific task. The API may be implemented using multiple technologies such as dynamic link libraries (DLL), Remote Procedure Call (RPC), COM, sockets, etc. This differs with "Encapsulation" in that the interactions occur at a task level rather than just data. That is VDS can control the execution behavior of the external application. The Building Controls Virtual Test Bed (BCVTB, LBNL 2012a) service in EnergyPlus is an example of the integration approach (Figure 3-34). Generally, this is the preferred method of interaction with external applications.

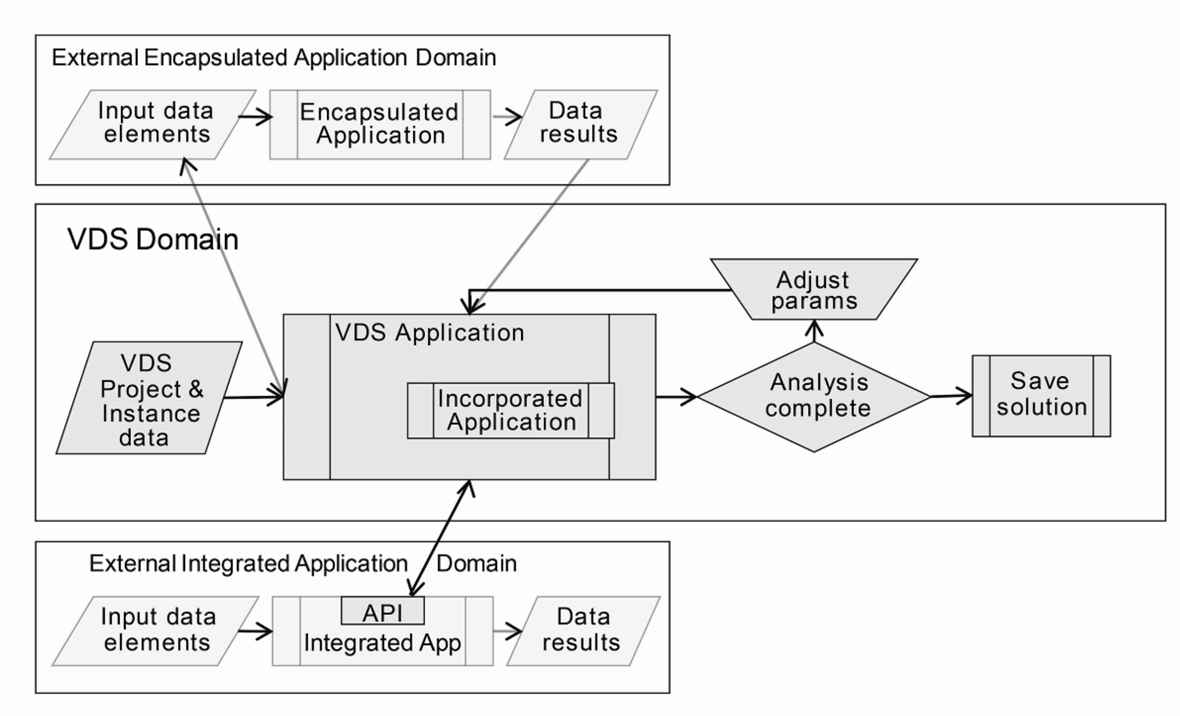


Figure 3-33 Three levels of external application interaction

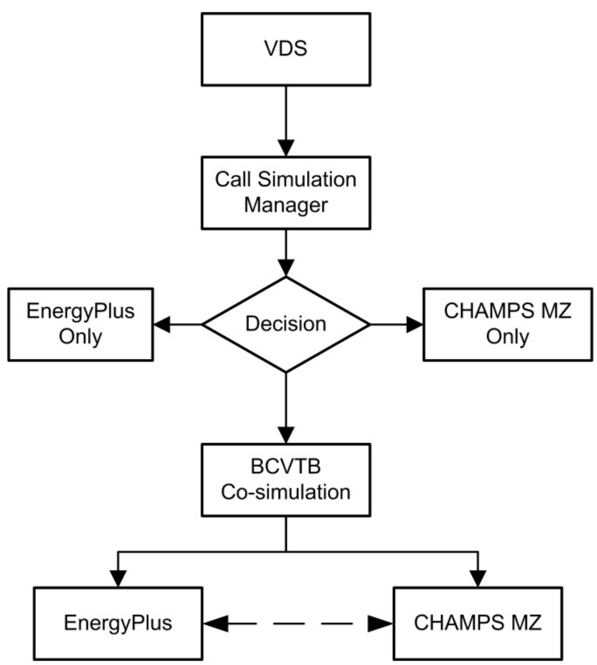


Figure 3-34 Integration of EnergyPlus and Incorporation of CHAMPS MZ into VDS

3.3.7. Multi-disciplinary design coordination and document sharing

A shared mental framework of project information can enhance a project team's performance by identifying information relationships and data dependencies to provide project teams with the right project data at the right time. The Process Integration Platform (PIP) (Senescu & Haymaker, 2013) provides this informational view by graphically representing project information or documents along with associated data dependencies using common web browsing technologies. VDS builds on these concepts by integrating project and task management features (VDS team manager) with PIP's document repository and information dependency features to provide teams with an enhanced collaboration environment. Further, since PIP document services are inherently shared, team members are provided with timely and consistent information among all members. Another benefit derived from PIP's document dependency capability is the ability to notify team members when upstream data changes creates a need to revisit dependent documents for accuracy in light of the data changes.

VDS-PIP is a web-based technology built using Ruby-on-Rails that is encapsulated within VDS using a QT Webview widget. The original source code was obtained from Professor John Haymaker and Dr. Reid Senescu. Messaging between VDS and PIP is accomplished through standard HTTP GET/POST protocols. In general, VDS is only required to authenticate the user and then display the associated PIP window within the VDS GUI. The task process structure of a VDS project is maintained by VDS and tasks are simply registered with PIP for the purpose of performing search functions. Initially, the task structure is populated in PIP using a project specific template based on the associated project tasks. Independently, the project information structure and associated information dependencies are maintained by PIP as user upload or create documents. This application-based role separation simplifies the system interface requirements between VDS and PIP greatly. That is, VDS manages the team's task relationships and PIP manages the data relationships created within the process. Documents are created in VDS-PIP by accessing the repository within VDS, selecting the associated task, and finally upload any document or URL name.

An example VDS-PIP display is shown in Figure 3-22. Here we see a project tree on the left with various documents for the Lighting Study task shown on the right. The arrowed lines connecting the documents represent informational relationships between the documents. In the event that an upstream document is modified, any document that has a dependency on that document would be highlighted as needing review by setting its status to "Not updated". For example, if the Shading Study was updated, then the Shading Analysis would need to be reviewed to see if the changes in the Shading Study required a new analysis to be conducted. Included in Figure 3-22 is an inset showing the document edit dialog. In addition to the basic document information, the insert shows the document's dependencies, status, and history. Document dependencies are created by dragging document icons from one document to another or from the tree to a document. A document history is automatically maintained by VDS-PIP for the user. Document search features will be added at a later time.

3.3.8. Software implementation scheme

Figure 3-35 shows the various modules designed for the VDS and their relationships. A number of key modules have been implemented to enable testing and demonstration of the VDS design concept and methodology. These modules include Data Persistence, Data Translator, Viewer, Model, Controller, Post Processing, and "Whole building and IEQ simulation manager and model" (which integrates CHAMPS-MZ and Energy Plus for combined energy and indoor environmental quality analysis). The model predicts the energy consumption of HVAC systems, lightings, and equipment as well as the temperature, RH, zone air pressure, air flow between zones, pollutant concentration, and lighting illumination level. Chapter 4 provides the detailed introduction of the model, including methodology, implementation, testing and verification.

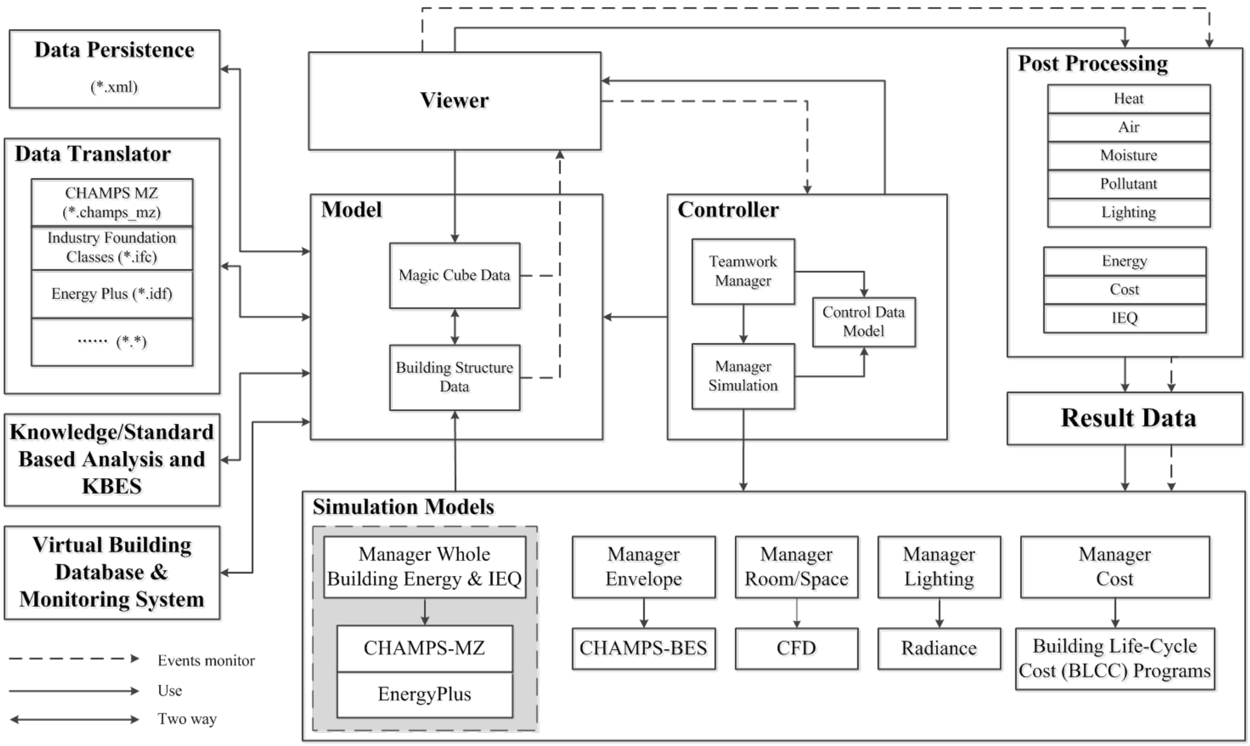


Figure 3-35 VDS software implementation scheme: modules and their relationships

3.4. Testing and verification

In order to test and verify the VDS framework, several workshops and working sessions have been organized to obtain the ideas, suggestions, and feedbacks from both architecture and engineering students and specialist in the area. At the beginning of this research, the workshops and working sessions focused on "Strategic Planning and Concept Verification". In the middle of the research, more issues related to software implementation are discussed. In the end of the research, a test version of VDS has been provided to the users and their feedbacks are used to debug the program as well as improve the GUI.

In the following, the functionality of VDS is illustrated through design development example: the evaluation of the building's External Enclosure and the use of internal Environmental Systems components at the "Design" stage.

As shown in Figure 3-36, the two design tasks are assumed to be concurrently performed by an architect and a consulting engineer. The architect leads the External Enclosure design based on the strategic brief, all relevant design consideration and industry standards, developed conceptual and preliminary schematic design solutions with feedbacks from the engineers regarding structural performance, thermal enclosure properties, impacts on possible weak linkages for thermal bridges and moisture condensation as well as overall energy savings and IEQ performance, the quantity and quality of openings (including windows and doors), daylighting conditions, acoustical properties and other criteria that may be project specific, while the engineer leads the Environmental Systems design with feedbacks from the architect on enclosure system properties, materials and assemblies.

Typically design options are evaluated with regards to its structure, materiality, build up and the resulting overall envelope performance. Performance aspects include: structural, thermal, air and moisture, acoustics, light penetration (quantity and quality of light) and the percentage and quality of openings such as windows and doors.

The façade is designed in response to the programmatic interior zoning and resulting requirements for its operation. Hereby, the façade has a direct impact on IEQ and for instance numerous work space related code / building regulations and specific performance compliant requirements.

In an interdisciplinary effort, the design options for the envelope related to all interior environmental control systems are qualitatively and quantitatively evaluated and compared. For improved energy performance, several building components can hereby be combined.

They could also explore and discuss opportunities for integrating enclosure design with environmental control system, e.g., the use of a hybrid system with controlled double wall façade for natural or hybrid ventilation.

Figure 3-37 illustrates a suggested VDS work flow by using two tasks at the Design stage, which are “Develop enclosure drawings” for the external enclosure design and “Design heating and cooling system” for the environmental systems design. First, the building design outcomes from previous design stages as well as outcomes from the current design stage for other design factors (i.e., Site & Climate, Form & Massing, and Internal Configuration, et al.) are all available for the present two tasks.

Based on the established input-process-output pattern, all previously generated results factors (i.e., Site & Climate, Form & Massing, and Internal Configuration, etc.) are available at this point of the development and form important information for the balanced and optimized development of both building envelope and HVAC system.

For example, the 3-D design model created with SketchUp can be imported and further analyzed with VDS as illustrated.

Both the architect and engineer respectively select the two previously defined tasks from the VDS Design Process window to perform the analysis and design, as illustrated in Figure 3-37.

For "Develop enclosure drawings", the architect would first introduce different options and design some candidate enclosure systems, and then enter relevant enclosure design parameters into VDS (e.g., type of assemblies and materials to be used, layout of windows, etc.).

VDS plays the role of an "engineering assistant" to assist the architect in predicting energy, IEQ, and other relevant performance aspects for the various design options as illustrated in the left portion of Figure 3-37. In addition to the assistance from VDS, the architect would discuss alternative design options with the systems design team that may suggest amendments or alternative solutions to further improve for instance energy and IEQ related performance, or gain some understanding on how a particular design affects the system efficiencies (which might help generating new design ideas) and other related systematic interdependencies. In other words, both person-VDS and person-person interactions are critical in the design process.

Similarly, for "Design heating and cooling system", the engineer would determine space requirements, propose systematic solutions and respective simulations, design the heating and cooling systems in greater detail, coordinate the impact (on for instance structure, floor and ceiling build ups, space layouts, and all required others) with the architect, and then enter the relevant design parameters into VDS to select and size the heating and cooling system properly to satisfy the requirements defined by the zoning, space usage and nature of the enclosure as established by the architect as illustrated on the right portion of Figure 3-37.

Engineer and architect would also explore and analyze other options for coordinated and fully integrated solutions, including enclosure design and environmental system design (e.g., hybrid ventilation, distributed multi-component environmental controls, and optimized zoning and conditioning) to achieve a better whole building performance.

The two designers can also use the PIP platform implemented in the VDS to share design documents as well as use other common communication methods. The PIP server also saves all the design data as a central repository.

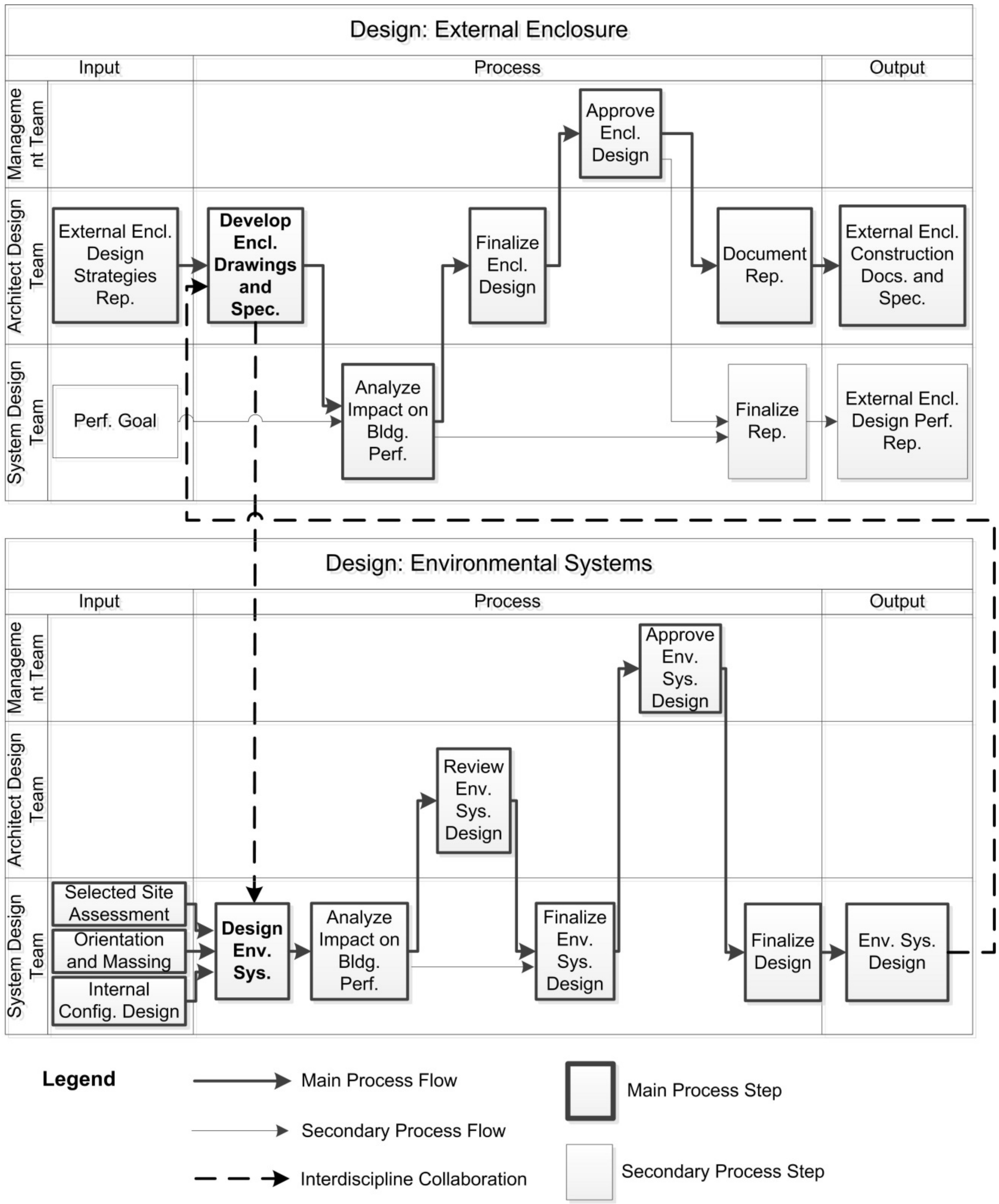


Figure 3-36 Illustration of the VDS-assisted collaborative design process for two design tasks

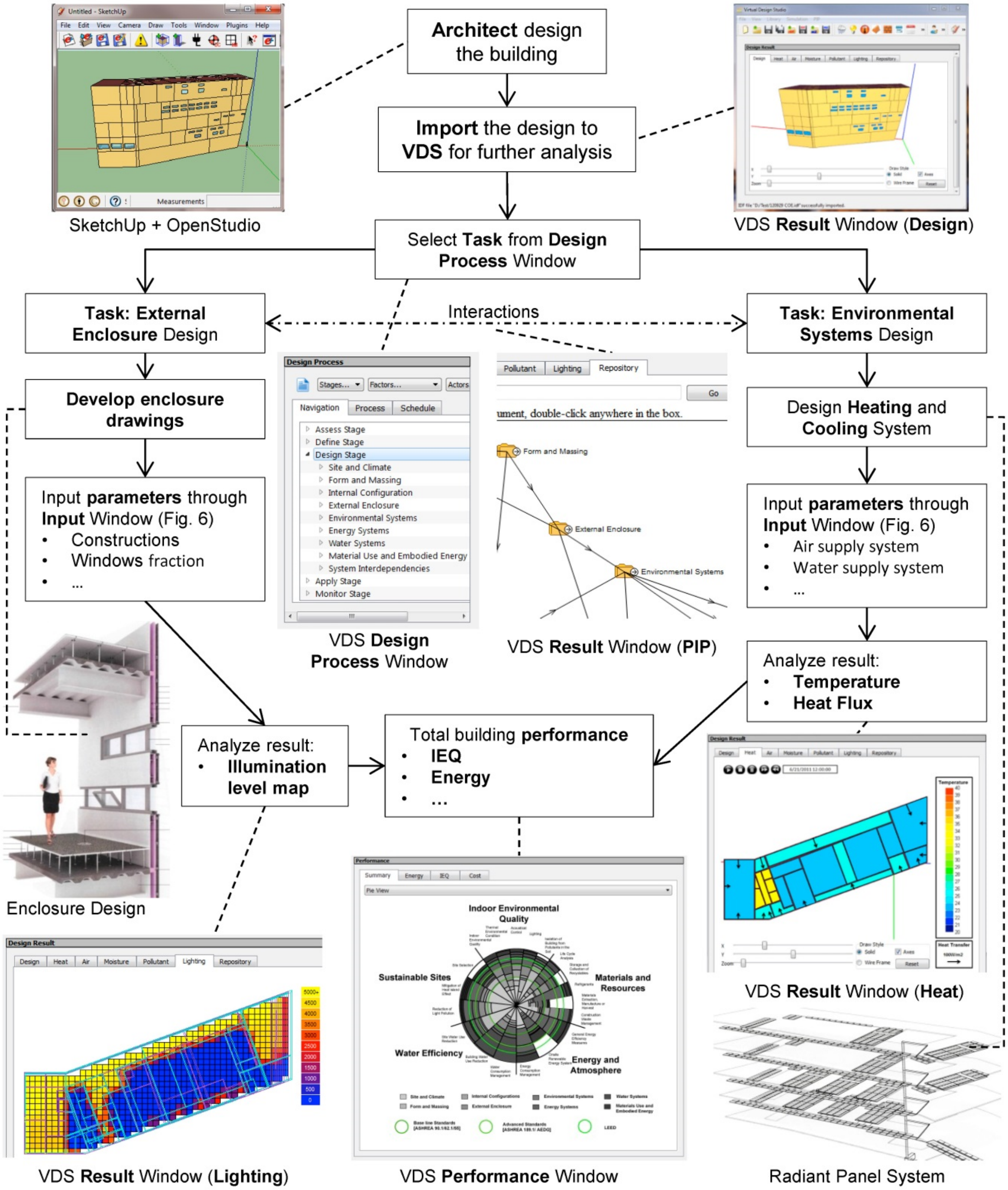


Figure 3-37 Illustration of a possible VDS work flow for two concurrent design tasks: external enclosure design lead by an architect and environmental system design lead by an engineer

3.5. Conclusions

A VDS overall framework for performance evaluation throughout the early to final design stages has been established based on the review and analysis of established professional working stages and performance assessment systems in US, UK, and Germany. It is designed to enable all participating parties (organized by architectural, systems design and project management teams) to correlate project specific working stages, design factors and performance criteria, and will help to coordinate the required input, an appropriate simulation methodology, and the respective desired output throughout all planning and design stages in an optimization process. This combination of system design methodologies with advanced simulation techniques, as in the developed VDS, will improve upon existing found models with a similar multi-scale, multi-staged, multi-disciplinary, and multi-objective optimization approach. The three-dimensional "Magic Cube" matrix represents an expansion to the existing two dimensional approaches found in the literature, and can be used for both the project customization and as a guidance tool for green building system design.

A VDS software framework is introduced and software implementation methodologies are discussed. Major VDS functionalities include: 1) representation of and navigation through multi-disciplinary, multi-stage and multi-design factor design process; 2) iteration between different design tasks throughout the various design stages to achieve optimal design; 3) combined energy and IEQ analysis; 4) coordination, information and document sharing among different design teams.

A design example illustrates that the VDS can potentially be an effective tool to assist fully coordinated, integrated, performance-based and optimized building design.

Through the present study, an overall framework of VDS has been developed with emphasis on the whole building's energy and IEQ performance simulation as well as the representation of architectural design principles. More researches are needed to extend the simulation capacities to include structural system, energy system, water system, and material usage and embodied energy system, and so on. VDS also needs to connect to a KBES which can provide suggestion for design iteration and optimization. Moreover, VDS needs to integrate with the monitoring system to compare between the predicted and actual results for validation and diagnosis of any discrepancies between the two, as well as for improving the simulation capability and providing suggestions for similar design projects in the future.

Chapter 4. Whole Building Performance Simulation Models

VDS is intended to analyze all five aspects of building performance, including Site Sustainability, Water Efficiency, Energy and Atmosphere, Materials and Resources, and IEQ. The current implementation focuses on "Energy and Atmosphere" and IEQ aspects, and includes the whole building simulation models for energy & IEQ, component simulation models for building envelope systems, room/space air distribution, and lighting, and cost analysis models (Figure 4-1). The Whole Building Energy & IEQ Simulation model integrates an enhanced CHAMPS-Multizone model and EnergyPlus to evaluate building energy performance, indoor air quality, thermal comfort, and daylighting performance as affected by the various design factors. The CHAMPS-BES (BEESL at Syracuse University, 2013) can be used to simulate 2-dimensional hygrothermal performance of building envelope systems. Computational fluid dynamics (CFD) can be used to analyze the zone air distribution. Radiance (LBNL, 2013d) can be used for lighting simulation. And Building Life-Cycle Cost (BLCC) programs (NIST, 2013) can be used for the analysis of capital investments in buildings.

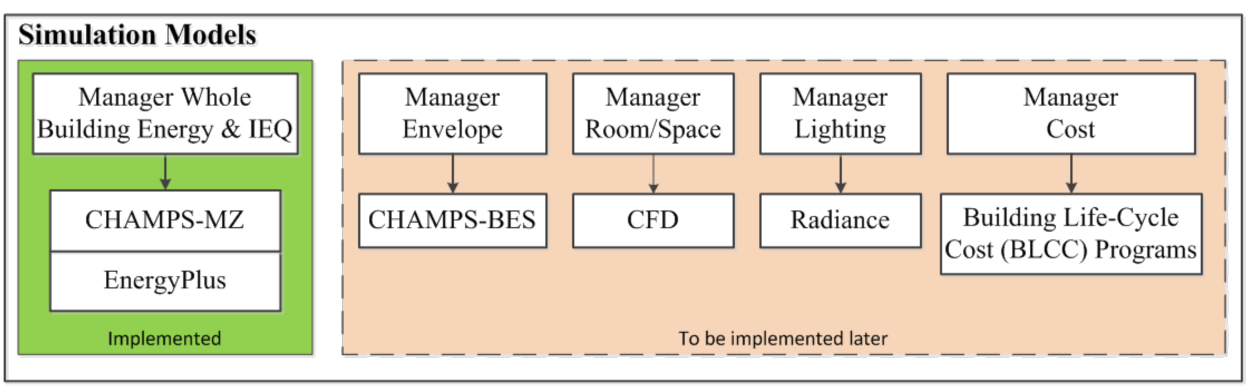


Figure 4-1 Simulation Models in VDS framework

This research focuses on the development of the Whole Building Energy & IEQ Simulation model. The following capabilities have been included in the current VDS implementation. The energy simulation model estimates the energy consumption of HVAC systems, lights, and electrical equipment. The IEQ simulation model predicts the indoor contaminate concentrations for indoor air quality, the zone air temperature and relative humidity for controlled zone conditions, the Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) for thermal comfort, and the illumination for daylighting. The energy, thermal comfort, and daylighting simulation are performed by EnergyPlus while the CHAMPS-Multizone is used for the IAQ simulation. Combined IEQ and energy analysis are performed by co-simulation with CHAMPS-Multizone (Feng et al. 2012) and EnergyPlus Version 7.2 (US DOE, 2012a).

This chapter shows the methodology and implementation of the Whole Building Energy & IEQ Simulation model. How the Whole Building Energy & IEQ Simulation models are applied to evaluate the building performance is discussed in Chapter 5.

We first introduce the functionalities and limitations of CHAMPS-Multizone and EnergyPlus, and then present the methodology to analyze both energy and IEQ performance by integrating CHAMPS-Multizone and EnergyPlus. It is then followed by discussion of the implementation methods. Finally, the simulation models are tested and verified by using a 3-zone building.

4.1. Introduction

CHAMPS-Multizone is a simulation program for whole building combined heat, air, moisture, and pollutant simulation (Feng, 2012; Zhang, 2005). Figure 4-2 shows the CHAMPS-

Multizone software structure. It has a graphical user interface (GUI) for users to input the design or control parameters. Then the simulation models are called to predict building performances. Figure 4-3 shows the flow chart of CHAMPS-Multizone. The solar radiation model, building envelope model, airflow network model, and zone and HVAC model are called to predict the energy and IEQ performances of a whole building.

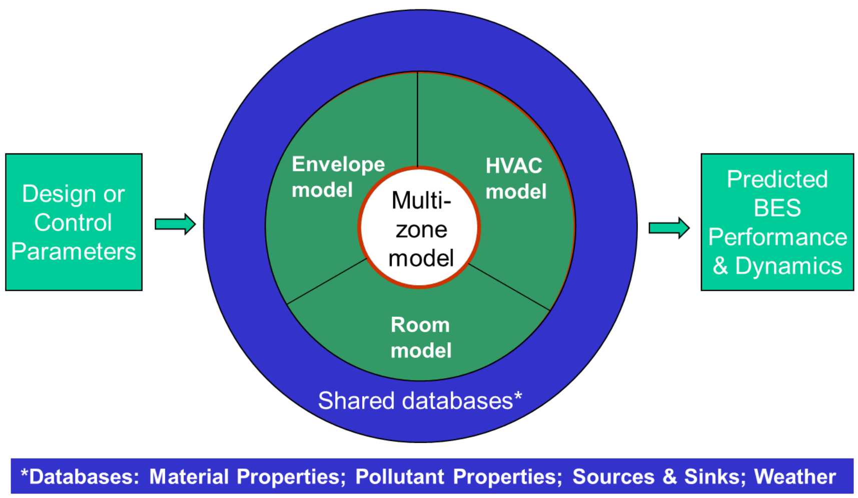


Figure 4-2 CHAMPS-Multizone software structure (Feng, 2012; Zhang, 2005)

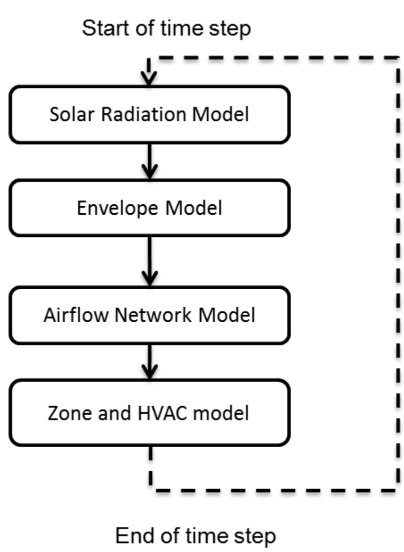


Figure 4-3 Flow chart of CHAMPS-Multizone

CHAMPS-Multizone is designed to predict both energy and IEQ performance. There are, however, several limitations:

1) There is no lighting simulation in CHAMPS-Multizone.
2) HVAC model in CHAMPS-Multizone is relatively simple. Currently, there are only air supply systems, including constant air volume (CAV) system and variable air volume (VAV) system. There is no HVAC plant system modeled in CHAMPS-Multizone.
3) The energy consumed by the air purifiers and filters are not simulated.
4) For pollutant transfer through envelope, only the transport by airflow is simulated. The transport by diffusion or liquid flow (water) is not simulated.
5) The pollutant balance in zones and air supply systems are predicted. However, the pollutant concentration information is not further used for combined IAQ and energy analysis. The CHAMPS-Multizone model needs to be enhanced to use the zone pollutant concentration information to control the outdoor ventilation rate for acceptable indoor air quality.

EnergyPlus is a whole building energy simulation program that engineers, architects, and researchers use to model energy use in buildings. Modeling the performance of a building with EnergyPlus enables building professionals to optimize the building design to minimize energy use. EnergyPlus models building envelope, heating, cooling, lighting, and ventilation systems (US DOE, 2012a).

EnergyPlus is a powerful simulation engine for energy and IEQ simulation. However, it currently does not have pollutant transport and detailed envelope's hygrothermal performance simulation capabilities.

One of the objectives of this research is to enhance the capability of the CHAMPS-Multizone model in the area of pollutant balance in the HVAC systems and outdoor ventilation rate control for acceptable IAQ, and integrate the enhanced CHAMPS-Multizone model and EnergyPlus for combined energy and IEQ analysis. For example, when indoor air quality strategies such as source control, ventilation and air cleaning are considered, designers would like to estimate their potential impacts on energy consumption. And when energy efficiency strategies such as tightening the building enclosures and use of energy recovery systems are considered, their potential impacts on the indoor environmental quality also need to be estimated. Persily & Emmerich (Persil & Emmerich, 2012) provided a comprehensive list of IEQ strategies that can have either negative or positive impacts on energy efficiencies. The integrated CHAMPS-EnergyPlus model, hereafter referred as CHAMPS-WholeBuilding, will have the capability for combined whole building heat, air, moisture, pollutant, and lighting simulation. EnergyPlus will focus on the heat, moisture, and lighting simulation, while CHAMPS-Multizone will focus on the air and pollutant simulation.

ASHRAE Standard 62.1-2010 (ASHRAE, 2010b) allows designers to use either prescriptive Ventilation Rate Procedure (VRP) or the Indoor Air Quality Procedure (IAQP) to meet the IAQ requirements. The Ventilation Rate Procedure defines the outdoor air requirement based on the program of the space, the number of people in the space, and the floor area of the space. The IAQ Procedure determines the outdoor airflow rate (i.e., the ventilation rate) based on the target contaminant concentration limits. The IAQ Procedure has the advantage of facilitating optimization of the IAQ strategies in terms of their effectiveness and energy efficiency. Currently, CHAMPS-Multizone and EnergyPlus both can use Ventilation Rate Procedure to determine the outdoor airflow rate. To our knowledge, no existing whole building performance simulation software except EnergyPlus can provide simulation based on the IAQ procedure or consider both Ventilation Rate Procedure and IAQ Procedure. For the IAQ procedure in EnergyPlus, there are, however, some limitations: 1) only CO_2 and a generic contaminant are considered; and 2) there is no air purification equipment modeled to control the IAQ. This research will enhance CHAMPS-Multizone and integrate it with EnergyPlus to determine outdoor airflow rate based on either the Ventilation Rate Procedure or the IAQ Procedure. The Whole Building Energy & IEQ simulation model will have the capability to simulate multiple contaminants and model air purification equipment to control the IAQ.

4.2. Methodology

Figure 4-4 shows the flow chart of VDS's Whole Building Energy and IEQ Simulation manager. The simulation manager will make the decision to call one of the simulation programs: EnergyPlus only, CHAMPS-Multizone only, or CHAMPS-WholeBuilding Co-Simulation. The following types of analyses can be performed with the whole building energy and IEQ simulation manager:

- Energy simulation: estimation of the energy consumption of HVAC systems, lights, and electrical equipment.
- IEQ simulation: predication of the indoor contaminates concentrations to determine the indoor air quality; simulation of the zone air temperature and relative humidity conditions;

calculation of the Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) for thermal comfort; and the illumination control for daylighting.

As shown in Figure 4-4, VDS provides three choices for designers to select which simulation model to be used. One of the choices is to perform simulations using EnergyPlus alone, since some users may want to perform only energy simulations to know building energy performance. The flow chart on the left in Figure 4-4 shows the calling sequences of EnergyPlus. The second choice is to perform simulations using CHAMPS-Multizone alone. The flow chart on the right in Figure 4-4 shows the calling sequences of CHAMPS Multizone. If users are mainly interested in indoor air quality with a simple HVAC system, CHAMPS-Multizone may be a better choice to simulate detailed heat, air, moisture, and pollutants transfer across building envelope and zone air balances. If users are interested in both energy and indoor air quality and would like to know interactions between both at every time step, CHAMPS-WholeBuilding Co-Simulation is a better choice. The flow chart in the middle of Figure 4-4 presents calling sequences of CHAMPS-WholeBuilding Co-Simulation. Therefore, VDS is able to process different users' request and provide various options for users to meet their different requirements. It can be used to evaluate various design options in different design stages.

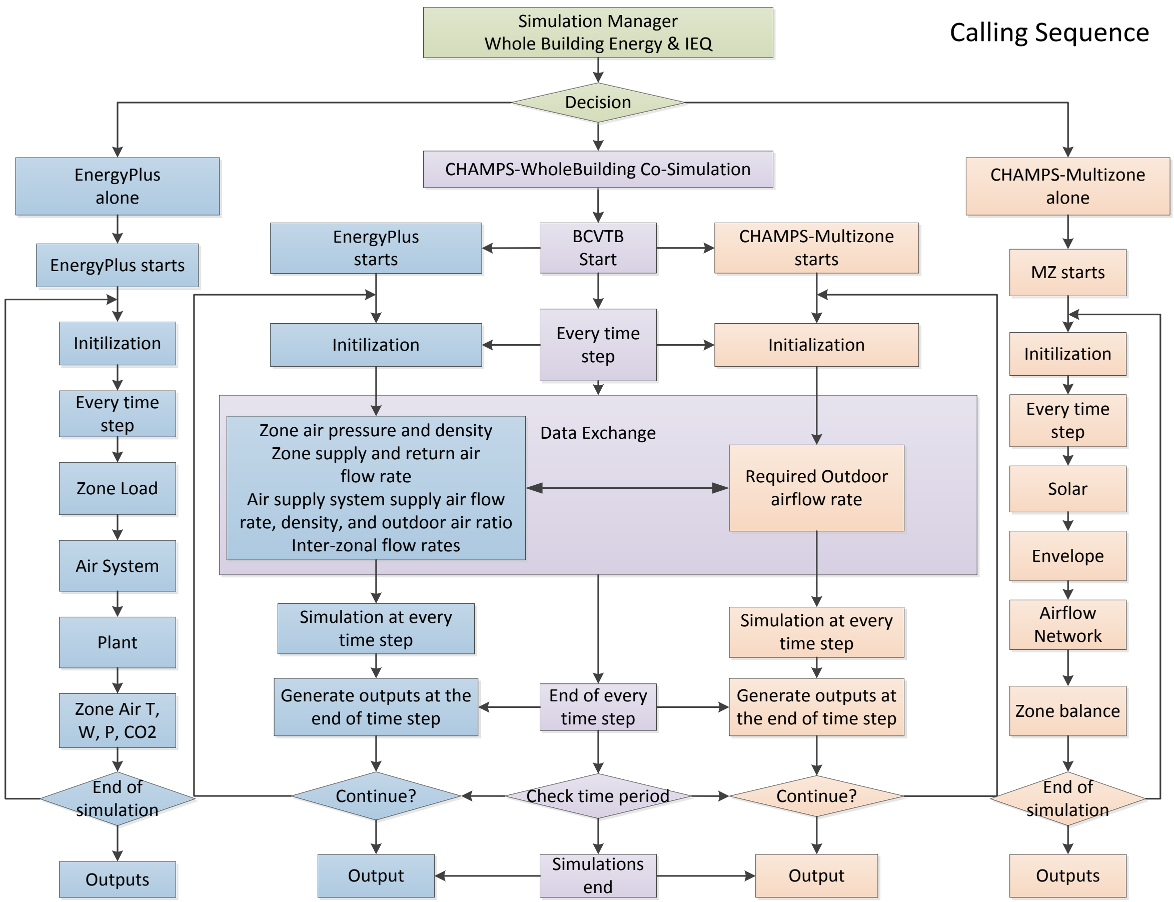


Figure 4-4 Flow chart of the Whole Building Energy and IEQ Simulation Manager

4.2.1. EnergyPlus only simulation

4.2.1.1. Simulation process

Figure 4-5 shows the flow chart of the EnergyPlus alone simulation. When designers want to perform EnergyPlus alone simulations, the Whole Building Energy & IEQ Simulation manager will first call VDS Data Transfer module to create an IDF input file for EnergyPlus from the existing VDS data model. The IDF input file and an EPW format weather file will then be used by EnergyPlus to perform the simulation. When the simulation is finished, the End of Simulation event will be captured by the Event Monitor. Figure 4-6 shows the flow chart of parsing the simulation results. The Whole Building Energy & IEQ simulation model will call the VDS Data Model to read the results. The results will then be displayed in VDS Results Quadrant and be further used by VDS Performance Evaluation Model to calculate the Building Performance (see Chapter 5). Finally, the performance results will be displayed in VDS Performance Quadrant. Figure 4-7 shows an example of daylighting illumination map in Results Quadrant, while Figure 4-8 presents an example of monthly summary plots in Performance Quadrant.

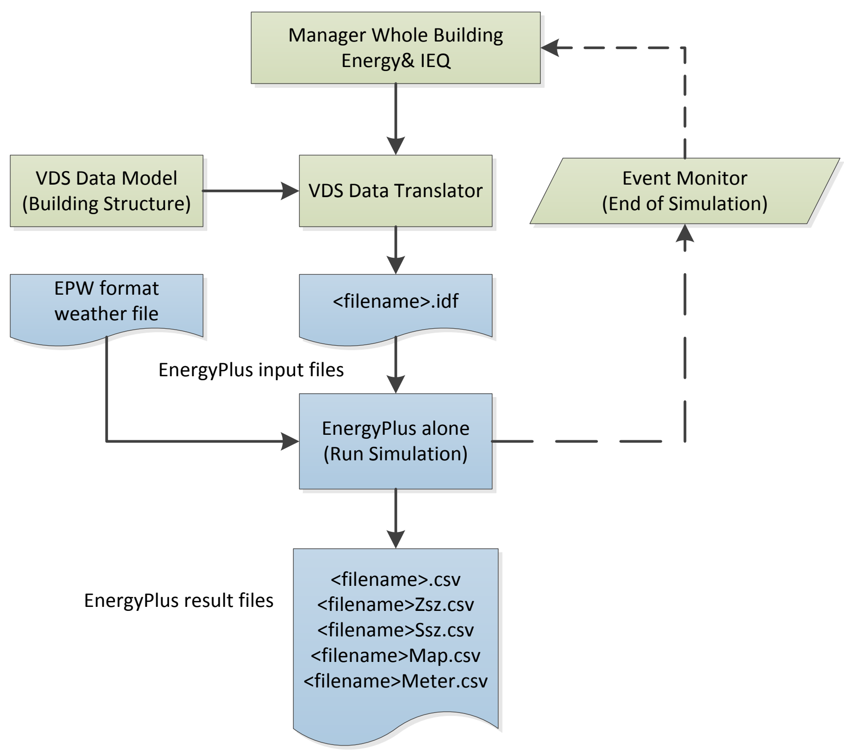


Figure 4-5 Flow chart of the EnergyPlus alone simulation

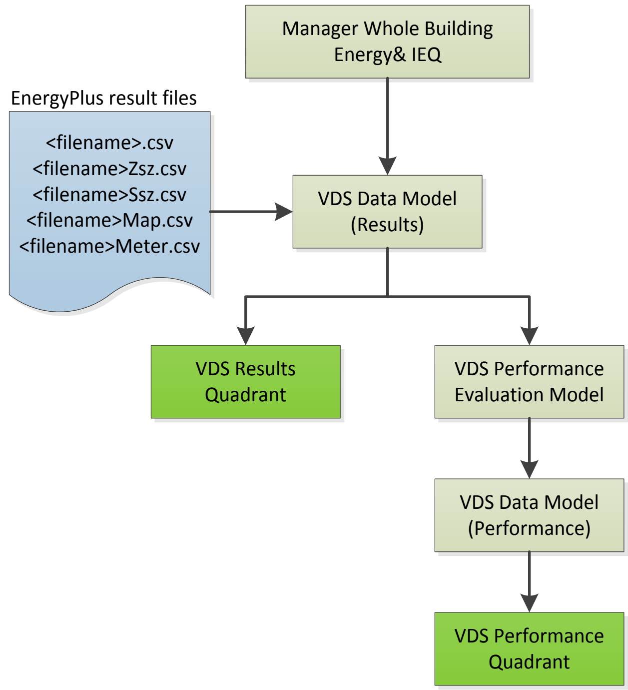


Figure 4-6 Flow chart of parsing EnergyPlus simulation results

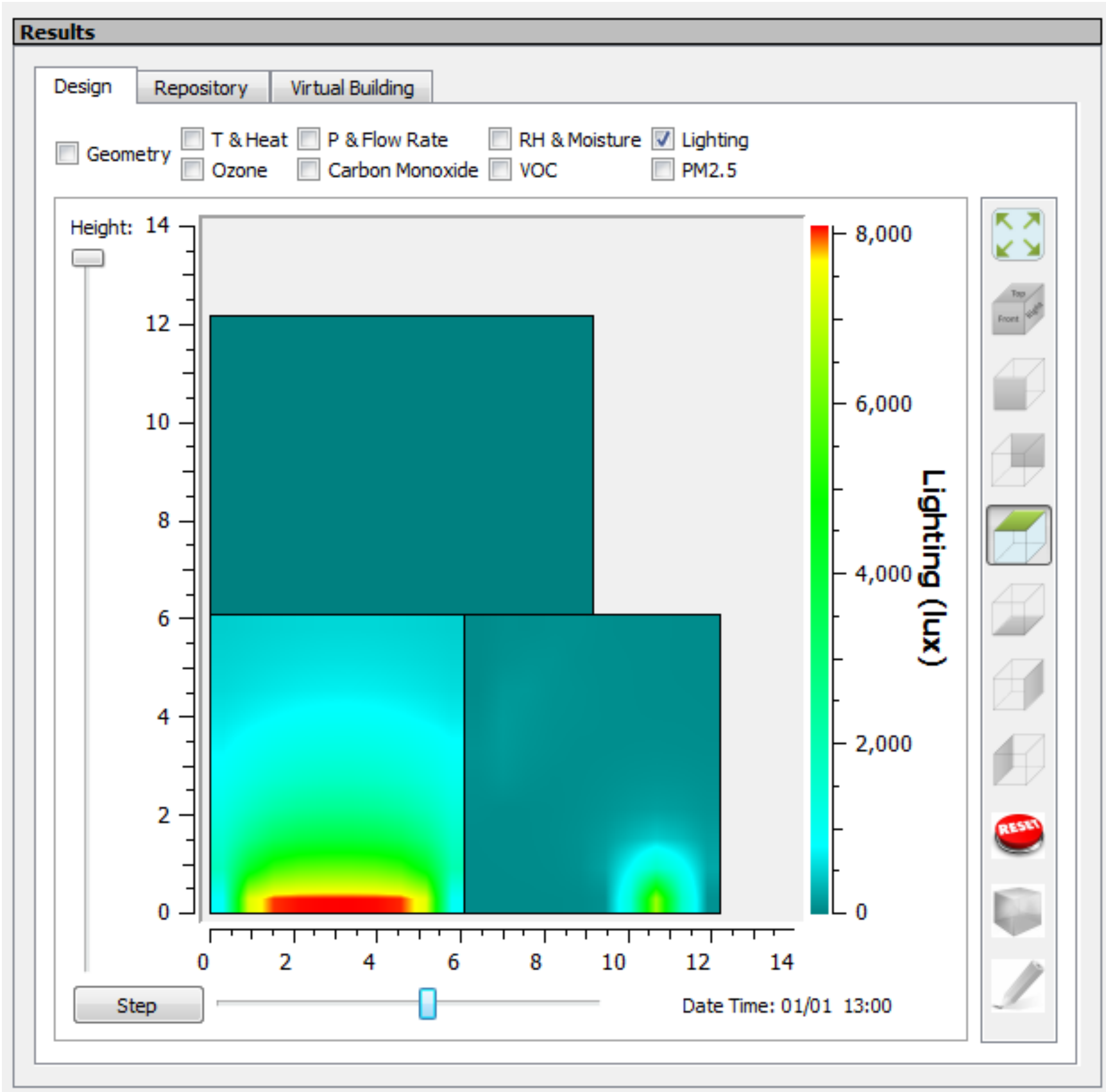


Figure 4-7 Example of daylighting illumination map in Results Quadrant

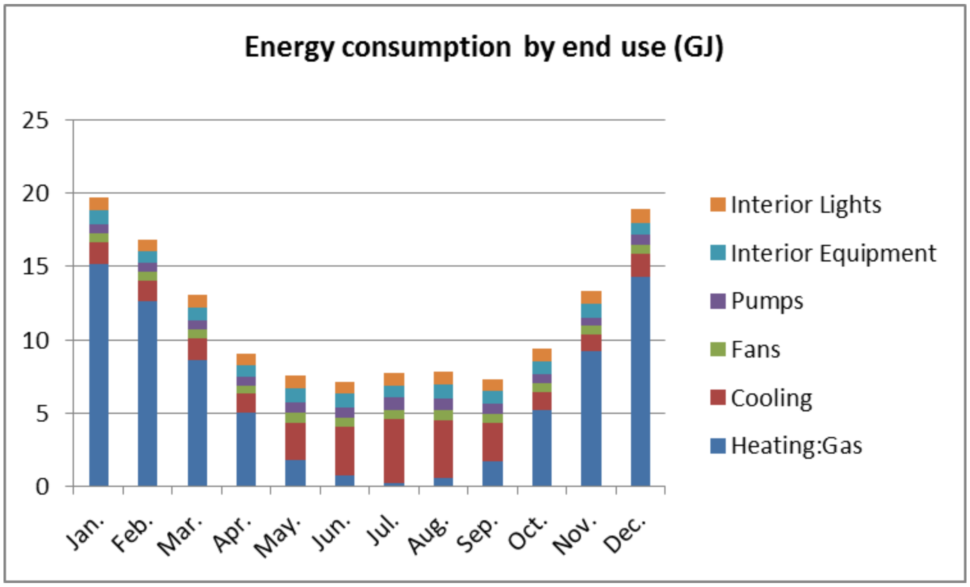


Figure 4-8 Example of monthly summary plots in Performance Quadrant

4.2.1.2. Essential inputs

As shown in Figure 4-5, in order to perform EnergyPlus alone simulation, an IDF file (EnergyPlus Input Data File) with essential inputs and an EPW (EnergyPlus Weather) format weather data file are required. Table 4-1 shows the list of essential inputs for EnergyPlus alone simulation organized by categories. The associate EnergyPlus objects for each input are also introduced. For HVAC systems, the "VAV (Variable Air Volume) systems with boilers and water-cooled chillers" template is presented. The mapping of VDS object and EnergyPlus object is not necessary one to one, as EnergyPlus and VDS have different ways of organizing the design parameters. For example, in VDS, the outdoor ventilation rate requirements are organized in the Zoning category while the zone supply air conditions are organized in the HVAC category. In EnergyPlus object, both the outdoor ventilation rate requirement and the zone supply air condition settings are all organized in the "HVAC Template: Zone: VAV" object for the "VAV systems with boilers and water-cooled chillers" template.

EnergyPlus also provides a simple way for users to model the HVAC systems by using HVAC templates. The HVAC template group of objects allows for the specification of simple zone thermostats and HVAC systems with automatically generated node names. The main objective is to simplify inputs by providing automatic node connections based on system components. However, all templates provide limited system types, compared to the whole capability of EnergyPlus. In order to use templates effectively, the CHAMPS-WholeBuilding uses existing system types. Table 4-2 shows the available system types and their HVAC template objects.

EnergyPlus provides powerful functions that allow users to model the HVAC systems in detailed equipment level. Users also need to model all the nodes, the connections among the equipment, and the connections between the equipment and the zones. It should be pointed out that the object based input is able to provide more flexibility and fulfill the use of all capabilities. However, due to input complexity, it is not easy to apply this approach for VDS. Therefore, the detailed object inputs are not adopted for the whole building performance simulation in CHAMPS-WholeBuilding. For detailed HVAC system and components simulation (e.g., for the purpose of HVAC system diagnostics and control), the component/equipment object-level modeling approach is recommended and should be performed by an engineer or modeler with adequate training in E+ modeling.

Table 4-1 Essential inputs for EnergyPlus alone simulation

Category	Essential Inputs	Associated EnergyPlus Objects
Climate	Design day conditions Ground temperature	SizingPeriod:DesignDay Site:GroundTemperature:BuildingSurface
Site	Site location Building position	Site:Location Building
Form	Zone position	Zone

	Wall geometry Window/door geometry	BuildingSurface:Detailed FenestrationSurface:Detailed
Zoning	Thermal Comfort Outdoor Ventilation Rate Daylighting Control Occupancy Lights Electrical equipment	HVACTemplate:Thermostat HVACTemplate:Zone:VAV Daylighting:Controls People Lights ElectricEquipment
Enclosure	Construction Materials	Construction Material Material:AirGap Material:Nomass WindowMaterial:Glazing WindowMaterial:Gas WindowMaterial:SimpleGlazingSystem
HVAC	VAV with reheat system	HVACTemplate:Zone:VAV HVACTemplate:System:VAV HVACTemplate:Plant:Chilledwaterloop HVACTemplate:Plant:Chiller HVACTemplate:Plant:Tower HVACTemplate:Plant:Hotwaterloop HVACTemplate:Plant:Boiler
	Simulation settings	TimeStep SurfaceConvertiionAlgorithm:Inside SurfaceConvertiionAlgorithm:Outside HeatBalanceAlgorithm SimulationControl RunPeriod GlobalGeometryRules Sizing:Parameters
	Schedule	ScheduleTypeLimits Schedule:Compact

Table 4-2 EnergyPlus objects for HVAC system templates (US DOE, 2012b)

HVAC System Templates	**Associate EnergyPlus Objects**
Simple ideal loads system	HVACTemplate:Thermostat HVACTemplate:Zone:IdealLoadsAirSystem
Packaged terminal air conditioner (PTAC) systems with optional hot water boiler	HVACTemplate:Thermostat HVACTemplate:Zone:PTAC HVACTemplate:Plant:HotWaterLoop (optional) HVACTemplate:Plant:Boiler (optional)
Packaged terminal air-to-air heat pump (PTHP)	HVACTemplate:Thermostat

systems	HVACTemplate:Zone:PTHP
Direct-expansion cooling, packaged and split system simulations	HVACTemplate:Thermostat HVACTemplate:Zone:Unitary HVACTemplate:System:Unitary
Direct-expansion heat pump systems	HVACTemplate:Thermostat HVACTemplate:Zone:Unitary HVACTemplate:System:UnitaryHeatPump:AirToAir
Packaged variable air volume systems using direct-expansion cooling	HVACTemplate:Thermostat HVACTemplate:Zone:VAV or VAV:FanPowered HVACTemplate:System:PackagedVAV HVACTemplate:Plant:HotWaterLoop HVACTemplate:Plant:Boiler
VAV systems with boilers and air-cooled chillers	HVACTemplate:Thermostat HVACTemplate:Zone:VAV or VAV:FanPowered HVACTemplate:System:VAV HVACTemplate:Plant:ChilledWaterLoop HVACTemplate:Plant:HotWaterLoop HVACTemplate:Plant:Chiller HVACTemplate:Plant:Boiler
Fan coil systems with boilers and chillers	HVACTemplate:Thermostat HVACTemplate:Zone:FanCoil HVACTemplate:Plant:ChilledWaterLoop HVACTemplate:Plant:HotWaterLoop HVACTemplate:Plant:Chiller HVACTemplate:Plant:Boiler HVACTemplate:Plant:Tower
Water to air heat pumps with boilers and cooling tower	HVACTemplate:Thermostat HVACTemplate:Zone:WaterToAirHeatPump HVACTemplate:Plant:MixedWaterLoop HVACTemplate:Plant:Boiler HVACTemplate:Plant:Tower
Dedicated outdoor air systems combined with fan coil systems with boilers and chillers	HVACTemplate:Thermostat HVACTemplate:Zone:FanCoil HVACTemplate:System:DedicatedOutdoorAir HVACTemplate:Plant:ChilledWaterLoop HVACTemplate:Plant:HotWaterLoop HVACTemplate:Plant:Chiller HVACTemplate:Plant:Boiler HVACTemplate:Plant:Tower

4.2.1.3. Simulation procedure and modules

The EnergyPlus program is a collection of many program modules (Figure 4-9) that work together to calculate the energy required for heating and cooling a building using a variety of systems and energy sources (US DOE, 2012b).

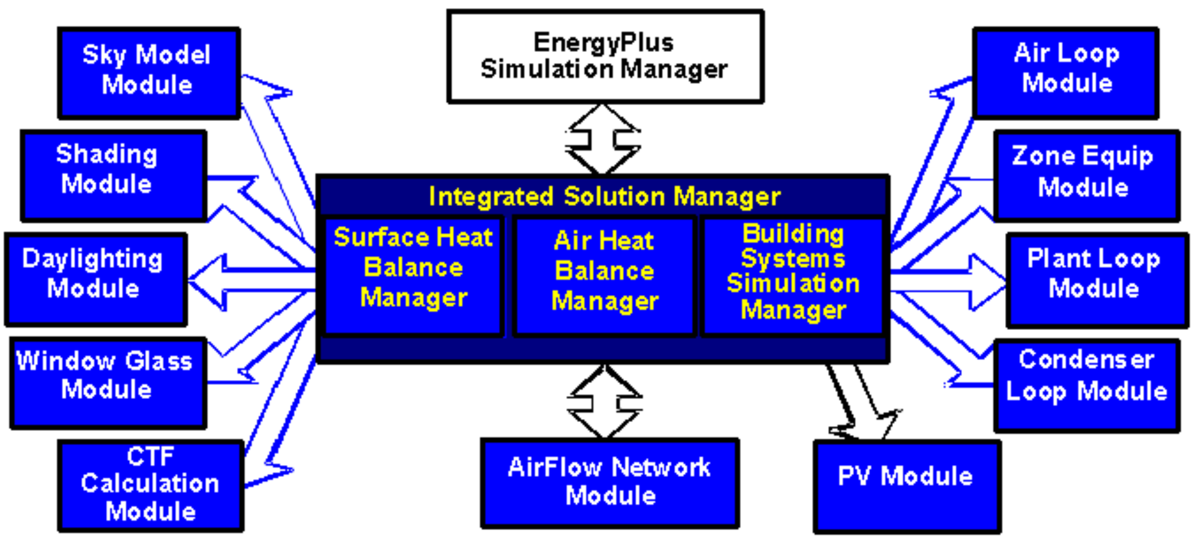


Figure 4-9 EnergyPlus program schematic (US DOE, 2012b)

As shown on the left of Figure 4-4, when EnergyPlus program starts, it reads an IDF input file and an EPW format weather file, and sets dynamic arrays for necessary variables accordingly. At the beginning of every time step, the program initializes every variable. The next step simulates heat and moisture transfer across each zone surface with given indoor and outdoor boundary conditions. The outdoor conditions are at the current time step given in the weather file. However, in order to speed-up calculation and avoid iteration, the indoor conditions at previous time steps are used. The main reason for this is that the heat transfer rate changes across the envelope are relatively slow and it is likely that the transfer rate remains unchanged or changed slightly if the indoor conditions change slightly. The partial-coupled approach increases calculation speed dramatically comparing to a fully coupled approach in which the envelope and zone balance models iterate at every time step. After interior surface conditions are determined from the envelope calculation, the program predicts system loads to maintain the desired indoor conditions set by thermostat and humidistat. The predicted system load determines whether heating or cooling is needed and if so, how much. Following this, the program performs HVAC system simulations based on the predictor's requested system loads. Iteration may be needed to finalize system performance. If a single system is used, iteration may be performed inside a single system module. When multiple systems are used, the iteration will be performed with all system modules, including plant if central plants are requested. After finalizing system performance and using a corrector, the program calculates the current indoor conditions by combining all zone loads and supply systems together. A full cycle of building simulation at each time step is completed. The program then moves to the next time step and checks whether the next period is still within the requested run period. If so, the simulation continues. If not, the program stops and outputs are generated.

It should be pointed out that the current indoor conditions are not necessary the desired indoor conditions. The desired indoor conditions are set by thermostat and humidistat, and used to determine the system load; while the current indoor conditions are calculated based on the zone balance model.

4.2.1.4. Simulation results

After the EnergyPlus standalone simulation is finished, the result files are generated in the same folder where the IDF input file is located. The result files imported by VDS are:

<filename>.csv, <filename>Zsz.csv, <filename>Ssz.csv, <filename>Map.csv, and <filename>Meter.csv, where the <filename> is the filename of the IDF input file without ".idf" extension.

The <filename>.csv result file contains the time series data at customized frequency of many output variables during a period specified by input. The output variables read by VDS include zone air temperature, relative humidity, and pressure, and surface heat flux.

The <filename>Zsz.csv result file show the sizing information of the zones, including the design day heating and cooling load, and the mass flow rate for heating and cooling.

The <filename>Ssz.csv result file show the sizing information of the air supply systems including the design day heating and cooling capacities, and the mass flow rate for heating and cooling.

The <filename>Map.csv result file show the daylighting illumination map data.

The <filename>Meter.csv result file provides time series data at customized frequency of the energy meters.

4.2.2. CHAMPS-Multizone only simulation

4.2.2.1. Simulation process

Figure 4-10 shows the flow chart of the CHAMPS-Multizone alone simulation. When designers want to performance CHAMPS-Multizone alone simulations, the Whole Building Energy & IEQ Simulation manager will first call VDS Data Transfer module to create an champs_mz input file for CHAMPS-Multizone from the existing VDS data model. The champs_mz input file, a CTF (Conduction Transfer Functions) file with CTF coefficients, and a list of CCD (Climate Condition Data) format weather files will then be used by CHAMPS-Multizone to perform the simulation.

When the simulation is finished, the End of Simulation event will be captured by the Event Monitor. Figure 4-11 shows the flow chart of parsing the simulation results. The Whole Building Energy & IEQ simulation model will call the VDS Data Model to read the results. The results will then be displayed in VDS Results Quadrant and be further used by VDS Performance Evaluation Model to calculate the Building Performance. Finally, the performance results will be displayed in VDS Performance Quadrant. Figure 4-12 shows an example of PM2.5 concentrations space distribution in Results Quadrant, while the summary plots as Figure 4-8 can be presented in Performance Quadrant.

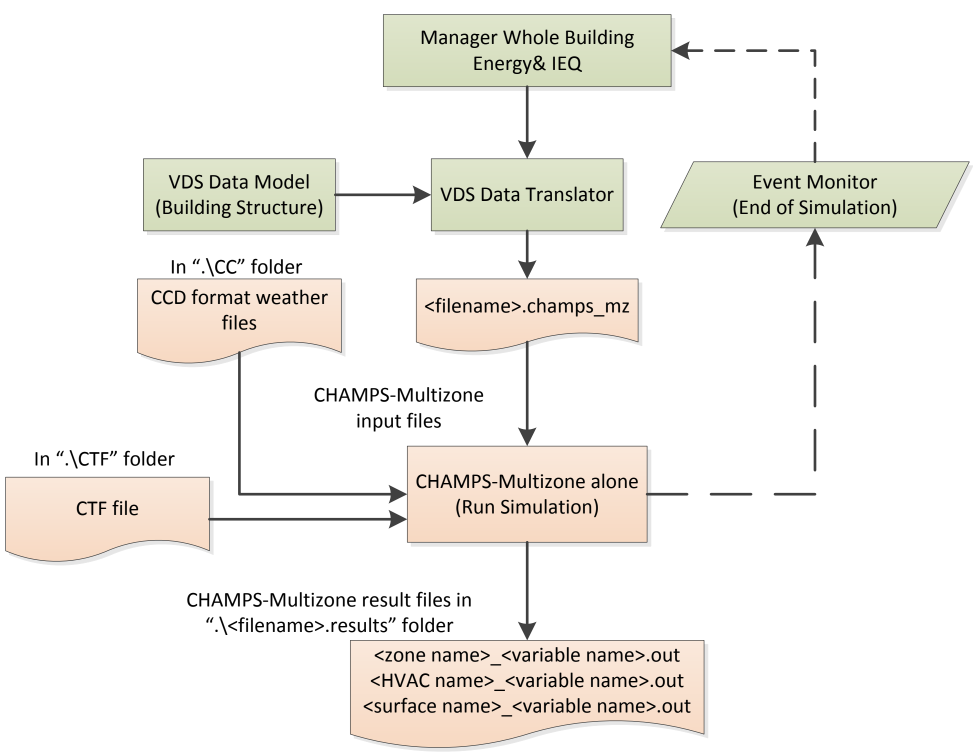


Figure 4-10 Flow chart of the CHAMPS-Multizone alone simulation

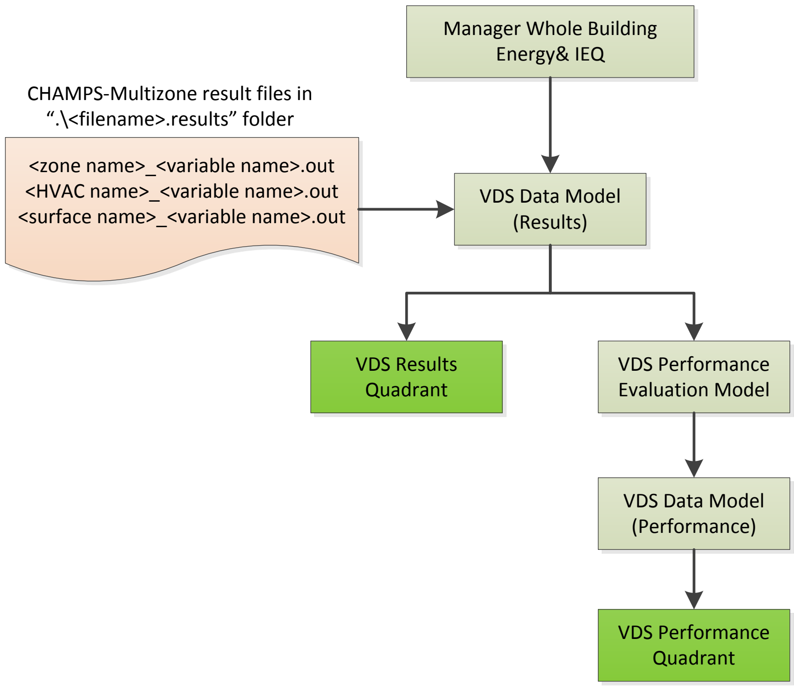


Figure 4-11 Flow chart of parsing CHAMPS-Multizone simulation results

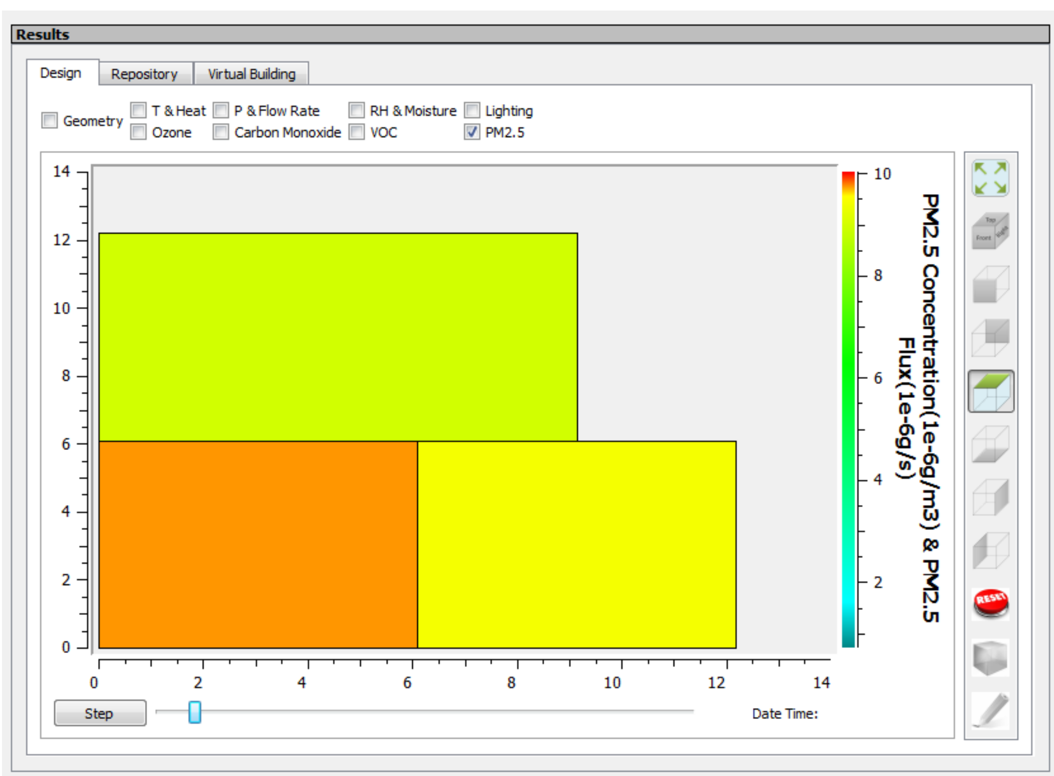


Figure 4-12 Example of PM2.5 concentrations in Results Quadrant

4.2.2.2. Essential inputs

The parameters list in Table 4-1 under Climate, Site, Form, Zoning, and Enclosure categories, and schedule are also essential inputs for CHAMPS-Multizone alone simulation. Table 4-3 shows the additional essential inputs for CHAMPS-Multizone alone simulation. The parameters are majorly for indoor air quality simulation, including atmosphere pollutant conditions, zone pollutant source and sink, zone pollutant limits, zone air purifier and filter, and HVAC system filters. The zone pollutant limits are used as the setpoints for IAQ control.

Table 4-3 Additional essential inputs for CHAMPS-Multizone alone simulation

Category	Essential Inputs	Associate CHAMPS-Multizone Parameters
Climate	Atmosphere pollutants	Outdoor ozone condition Outdoor PM2.5 condition Outdoor VOC condition Outdoor carbon monoxide condition
Zoning	Pollutant source and sink Windows and doors opening control Outdoor Ventilation Rate Zone air purifier Supply air filter	Ozone source and sink PM2.5 source and sink VOC source and sink Carbon monoxide source and sink Operation method and associated parameters Ozone limit PM2.5 limit VOC limit Carbon monoxide limit Zone Air purifier Filter
HVAC	Recirculated air filter Outdoor air filter Mixed air filter	Filter Filter Filter

4.2.2.3. Simulation procedure and modules

Figure 4-13 shows the CHAMPS-Multizone solver scheme. When CHAMPS-Multizone program starts, it reads a champs_mz file, a CTF file, and a list of CCD format weather files, and sets dynamic arrays for necessary variables accordingly. At the beginning of every time step, the solar solver is called to calculate incidental solar radiation (j_{sol}) on each construction surface. The incidental solar radiations are then used by building envelope solver to calculate the heat and mass balance on envelope surfaces based on the zone air conditions from previous time step. The solved surface temperature and mass density on the interior surfaces will be used by zone solver for heat/mass flux from building envelope. The air-flow solver solves the each zone's pressure air-flow relationship based on the zone air conditions from previous time step. The solved air-flow rate will be used by zone solver for infiltration, exfiltration, and/or inter-zonal airflow.

Furthermore, the zone & HVAC solver will calculate the heat, moisture and pollutants balances. A full cycle of building simulation at each time step is completed. The program then moves to the next time step and checks whether the next period is still within the requested run period. If so, the simulation continues. If not, the program stops and outputs are generated. Then, the End of Simulation event will be emitted.

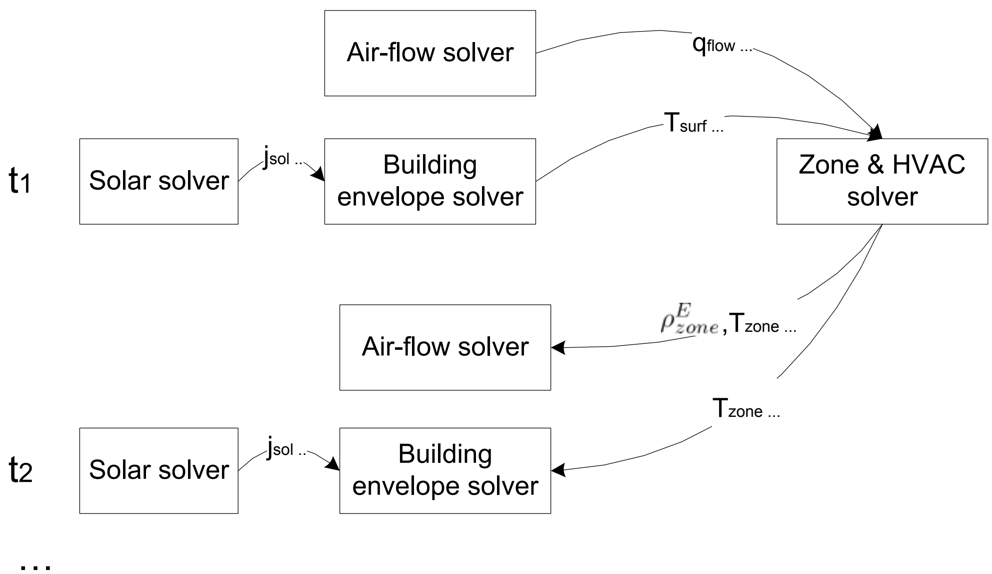


Figure 4-13 CHAMPS-Multizone solver scheme (Feng, 2012)

4.2.2.4. Simulation results

After the CHAMPS-Multizone alone simulation is finished, the result files are generated in the ".\<filename>.results" folder located in the same folder as the champs_mz input file. The result files imported by VDS are: <zone name>_<variable name>.out, <HVAC name>_<variable name>.out, and <surface name>_<variable name>.out.

The <zone name>_<variable name>.out result files contain the hourly time series data of zone status variables. The output variables read by VDS include zone air temperature and relative humidity, pressure, and pollutant concentrations.

The < HVAC name>_<variable name>.out result files contain the hourly time series data of HVAC status variables. The output variables read by VDS include HVAC supply and return conditions (temperature, relative humidity, and contaminant concentrations).

The < surface name>_<variable name>.out result files contain the hourly time series data of surface status variables. The output variables read by VDS include surface air flow, surface heat flux, surface moisture flux, pollutant transport fluxes.

4.2.3. CHAMPS-WholeBuilding co-simulation

As discussed in Section 4.1, one of the objectives of this research is to integrate CHAMPS-Multizone and EnergyPlus for combined energy and IEQ simulation and analysis. The combined capabilities are able to simulate building energy performance, thermal comfort and daylighting using EnergyPlus and to predict indoor air quality using CHAMPS-Multizone simultaneously through data exchange at each time step. The required data from EnergyPlus are zone supply and return air flow rates, zone air densities and pressures, air supply system conditions (supply air flow rate, supply air density, and outdoor air ratio), and inter-zonal flow rates. The required data from CHAMPS-Multizone are the required outdoor airflow rate based on either the Ventilation Rate Procedure or the IAQ Procedure. CHAMPS-Multizone uses imported data from EnergyPlus to calculate indoor pollutant balances and predict the amount of outdoor airflow rate required to maintain the indoor pollutants at or below the pollutant limits. EnergyPlus uses imported data from CHAMPS-Multizone to set the required outdoor airflow rate and include the sensible and latent loads in calculating the required system load. Coupling EnergyPlus and CHAMPS- Multizone provides a unique combination to simulate interactions between two programs, which cannot be realized by the use of a single program.

4.2.3.1. Building Controls Virtual Test Bed (BCVTB) for run time data exchange

In order to enable the co-simulation, the method for run-time data exchange needs to be developed. The run-time interface is an essential middle ware that enables CHAMPS-Multizone and EnergyPlus to communicate with each other at every time step. It is a command tool that synchronizes multiple programs to operate at the same time step.

The BCVTB (Wetter, 2010) is selected for the run-time data exchange between CHAMPS-Multizone and EnergyPlus. The BCVTB is a software environment that allows connecting different simulation programs to exchange data during time integration. The software architecture is a modular design based on Ptolemy II (LBNL, 2013f), a software environment for design and analysis of heterogeneous systems. Ptolemy II provides a graphical modeling environment, synchronizes the exchanged data and visualizes system evolution during run-time. The BCVTB provides additions to Ptolemy II. These allow the run-time coupling of different simulation programs for data exchange, including EnergyPlus, MATLAB, Simulink and the Modelica modeling and simulation environment Dymola. These additions also allow the execution of system commands, such as a script that executes a Radiance simulation. The link to a specific simulation program option allows the use of the simulation program which is best suited for the particular problem. This feature allows for the proper modeling of building heat transfer, HVAC system dynamics, and indoor air quality control.

4.2.3.2. Justification to select

There are many ways to couple different programs during run-time. Wetter (Wetter, 2010) listed many tools used in co-simulation. Based on existing capabilities, Wetter developed the BCVTB at LBNL and primarily focused on EnergyPlus applications. One of the design goals of the BCVTB was to provide users with a platform that allows them to link to their own simulation program or control interface. EnergyPlus was successfully linked with other programs via the BCVTB. Unfortunately, when BCVTB is used, a fixed synchronization time step is required to exchange data between EnergyPlus and other programs, which means the data exchange can only occur at the beginning or end of the time step and the two programs have to use the same time step. Because of this limitation, no iteration between the programs within a time step is allowed. Since the minimum time step is 1 minute in EnergyPlus, the values obtained from the previous time step imported from other programs will make insignificant differences. Therefore, CHAMPS-Multizone and EnergyPlus will exchange data once every time step and there is no iteration for data exchange within a time step for the present project. The CHAMPS-Multizone was modified to work with BCVTB for the data exchange.

4.2.3.3. Co-simulation implementation via BCVTB

Figure 4-14 shows the BCVTB GUI. It has a file menu and toolbar on the top, a library on the left, and the main development space on the right. This section introduces the procedures of developing the BCVTB project for CHAMPS-Multizone and EnergyPlus co-simulation. There are three parameters defined in BCVTB to control the simulation time, including Begin Time, End Time, and Time Step. These parameters have units of seconds and need to correspond with the begin time, time step and end time that are used in the simulation programs (i.e., CHAMPS-

BES and Energy-Plus). These three parameters are used to configure the Synchronous Data Flow (SDF) director, which defines the number of iterations and the period of the iteration.

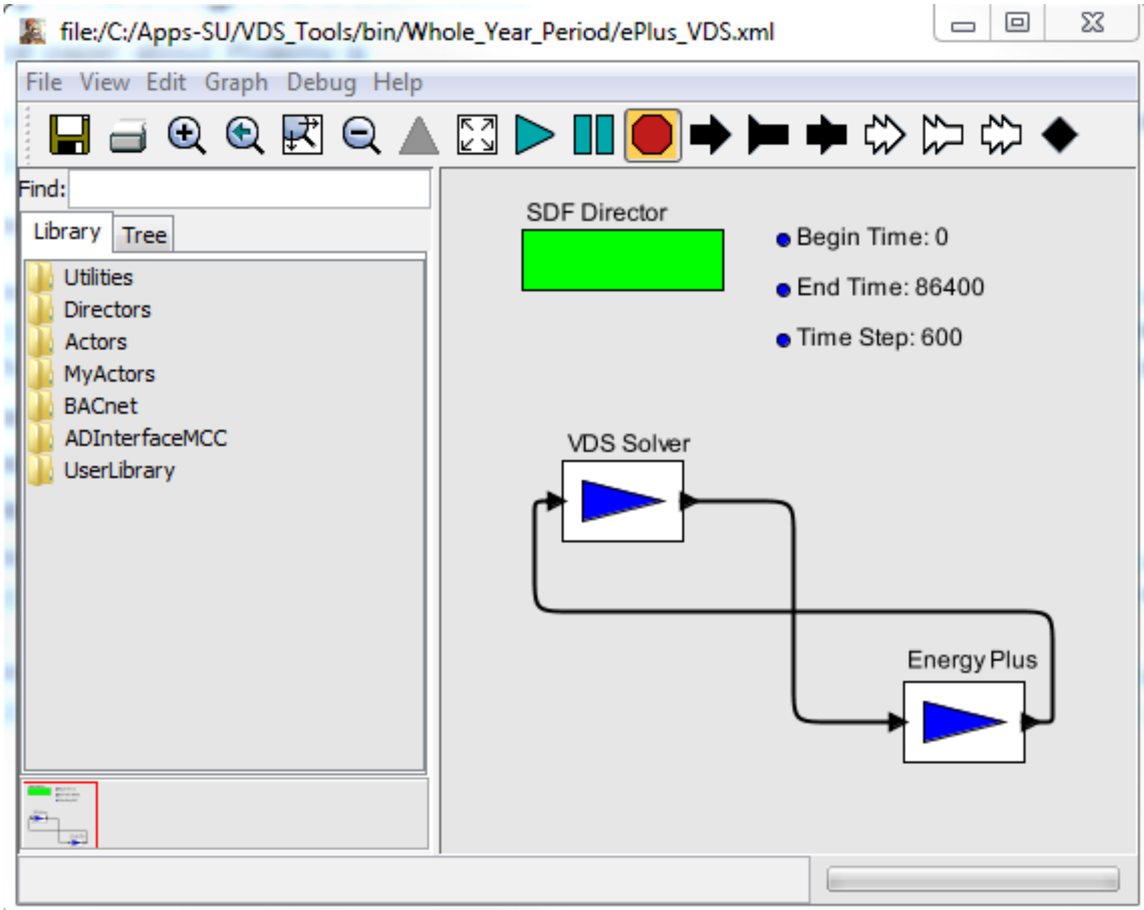


Figure 4-14 BCVTB GUI

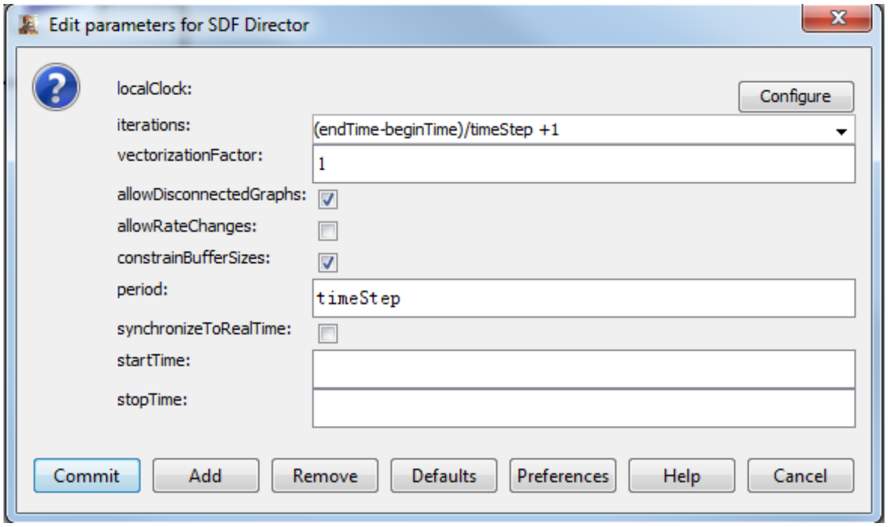


Figure 4-15 Configuration of the Synchronous Data Flow (SDF) director

BCVTB is developed with the Ptolemy II, an actor-oriented programming language for the development of interfacing sockets. Most (but not all) models of computation in Ptolemy II support actor-oriented design (Brooks, Lee, Liu, Neuendorffer, Zhao, & Zheng, 2008). This contrasts with (and complements) object-oriented design by emphasizing concurrency and communication between components. Components called actors execute and communicate with other actors in a model. Like objects, actors have a well-defined component interface. This interface abstracts the internal state and behavior of an actor, and restricts how an actor interacts with its environment. The interface includes ports that represent points of communication for an actor, and parameters that are used to configure the operation of an actor.

The actor used to model the co-simulation is the Simulator Actor. The Simulator Actor calls a simulation program of a dynamic system that is coupled to Ptolemy II. As shown in Figure 4-14, the port on the left of each Simulator Actor is input port while the port on the right is output port. Table 4-4 shows the list of parameters in Simulator Actor. At the start of the simulation, this actor fires a system command that is defined by the parameter “programName” with arguments "programArguments". It then initiates a socket connection and uses the socket to exchange data with the external simulation program each time the actor is fired. IBM (2013) provides more detailed information about how the socket works.

Table 4-4 Parameters in Simulator Actor

Parameters	Description
programName	Name of program that starts the simulation.
programArguments	Arguments of program that starts the simulation.
workingDirectory	Working directory of the simulation.
simulationLogFile	File name to which this actor writes the simulation log.
socketTimeout [milliseconds]	Socket time out in milliseconds.
showConsoleWindow	If *true* (the default), a window will be created that shows the console output.

There are two Simulator Actors used for CHAMPS-Multizone and EnergyPlus to model the co-simulation (Figure 4-14). Figure 4-16 shows the Simulator Actor for EnergyPlus including the configurations, while Figure 4-17 shows the Simulator Actor for CHAMPS-Multizone and its configurations. The two Simulator Actors are connected. The outputs from EnergyPlus become the inputs for CHAMPS-Multizone, while the outputs from CHAMPS-Multizone are the inputs for EnergyPlus during run-time simulation.

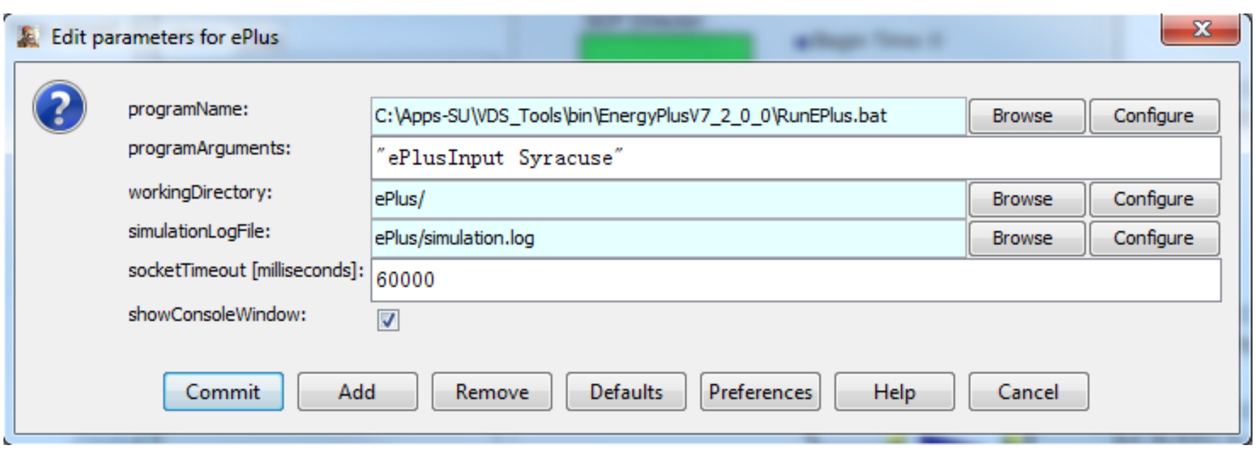


Figure 4-16 Simulator Actor for EnergyPlus in BCVTB

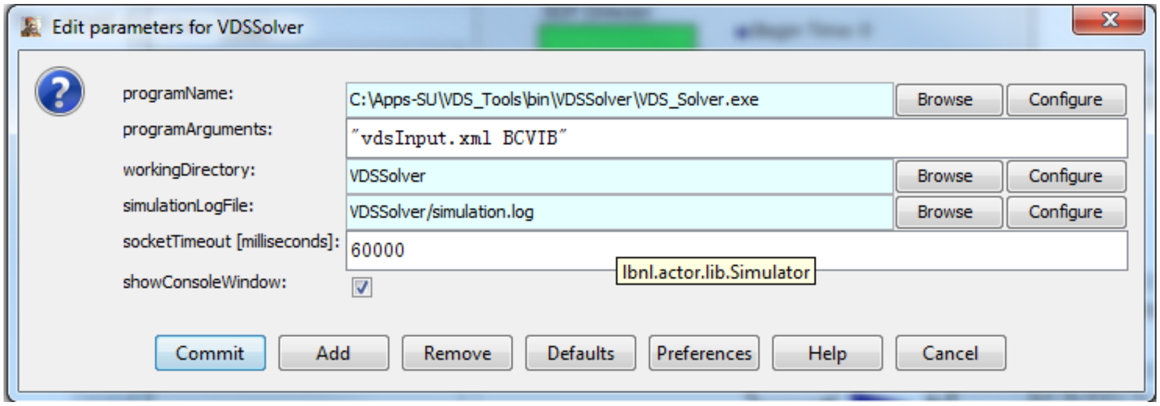


Figure 4-17 Simulator Actor for CHAMPS-Multizone in BCVTB

The model can be saved to an XML format file. BCVTB also can read an XML format file to create the model.

4.2.3.4. Overall flow of CHAMPS-WholeBuilding co-simulation

When VDS decides to perform CHAMPS-WholeBuilding co-simulation, CHAMPS-WholeBuilding will create the essential input files for CHAMPS-Multizone, EnergyPlus and BCVTB (Figure 4-18). The input files include an IDF input file (ePlusInput.idf) and a variables configuration file (variables.cfg) for EnergyPlus; an XML input file (vdsInput.xml) and a configuration file (configure.xml) for CHAMPS-Multizone; and a XML input file (ePlus_VDS.xml) for BCVTB. The IDF input file for EnergyPlus and the XML input file for CHAMPS-Multizone include all the essential inputs as introduced in sections 4.2.1.2 and 4.2.2.2. The XML input file for BCVTB includes all the information to generate the BCVTB project as introduced in section 4.2.3.3. The configuration file (configure.xml) for CHAMPS-Multizone includes the path of VDS XSD (XML Schema Definition) schema file and the path of the weather data folder. The variables configuration file (variables.cfg) for EnergyPlus defines the variables to be exchanged, including the parameters from EnergyPlus to CHAMPS-Multizone and the parameters from CHAMPS-Multizone to EnergyPlus. The detailed list of parameters is presented in Section 4.2.3.6.

After all the files are generated, CHAMPS-WholeBuilding calls BCVTB to run and BCVTB starts EnergyPlus and CHAMPS-Multizone simultaneously. First, EnergyPlus reads the input files and does the zone and system sizing calculation for the design days. The zone and system sizing result files (ePlusInputZsz.csv and ePlusInputSsz.csv) are generated. The sizing information includes the cooling and heating capacities and the maximum airflow rates.

After the sizing, the BCVTB will begin the run-time integration (Figure 4-19). At the beginning of every time step, BCVTB requests data exchange. EnergyPlus makes a call to the external interface with two vectors. One contains exported data, and the other has imported data. CHAMPS- Multizone does the same procedure by importing and exporting data through BCVTB with two vectors (Figure 4-20). The data specifications are listed in the configuration file (variables.cfg). The list of variables is presented in Section 4.2.3.6. The main criterion is that no duplication of efforts in both programs is performed, since both programs may have some common capabilities. In other words, in order to use the program effectively, the two programs are used to perform different tasks. For example, both programs can perform simulations of HVAC systems. Since EnergyPlus is a better tool to simulate HVAC systems, EnergyPlus is used to perform this task and export supply and return air conditions, while CHAMPS-Multizone imports supply and return airflow rates from EnergyPlus for contaminant calculations to determine an amount of outdoor air needed to keep indoor contaminant at or below the limits. The imported data of EnergyPlus from CHAMPS-Multizone are outdoor airflow rates required to maintain good indoor air quality. Based on the imported data, EnergyPlus will reset the outdoor flow rate regardless of its own inputs. The exported data of EnergyPlus are zone conditions, zone supply and return air conditions, air supply system conditions, and inter-zonal airflow rates. These data are used in CHAMPS-Multizone to perform zone pollutant balances to calculate required outdoor airflow rate to dilute indoor pollutants at or below the given limits.

After data exchange, each program performs its own calculations until the end of the time step (Figure 4-19). If one of programs reaches the end of the time step first, the faster program will be paused. When BCVTB receives signals from both programs to show that both programs have reached the end of time step, it issues a command to exchange data and start the next time step until the run period is reached.

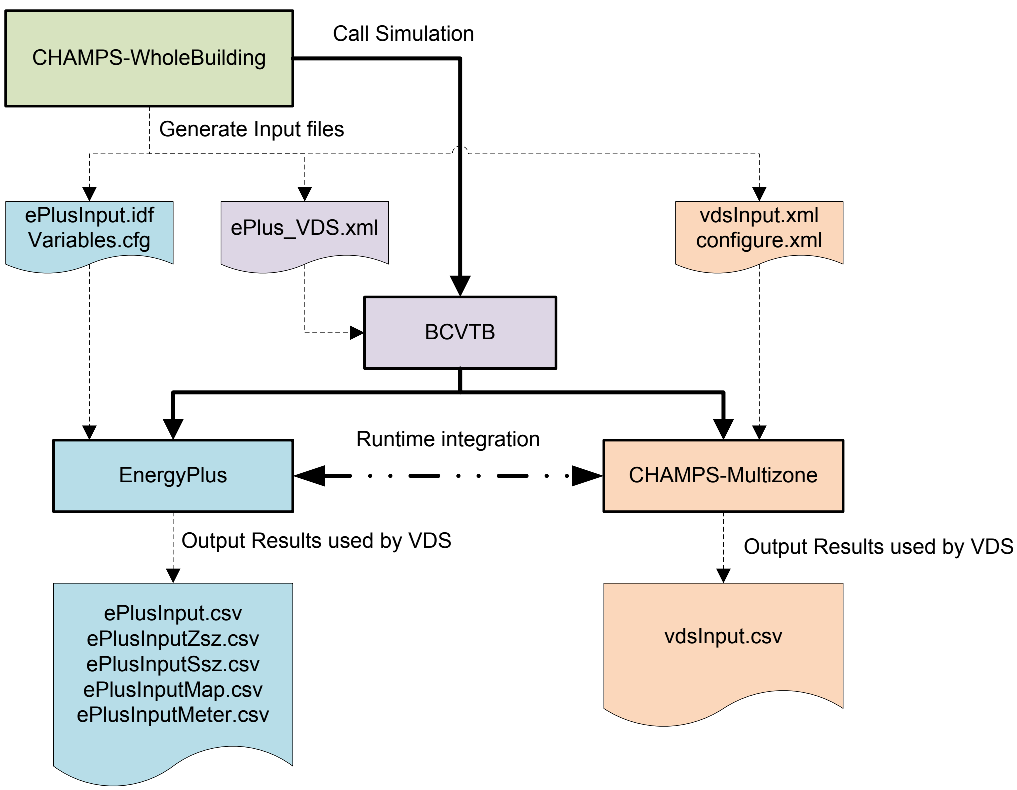


Figure 4-18 CHAMPS-WholeBuilding Co-Simulation flow

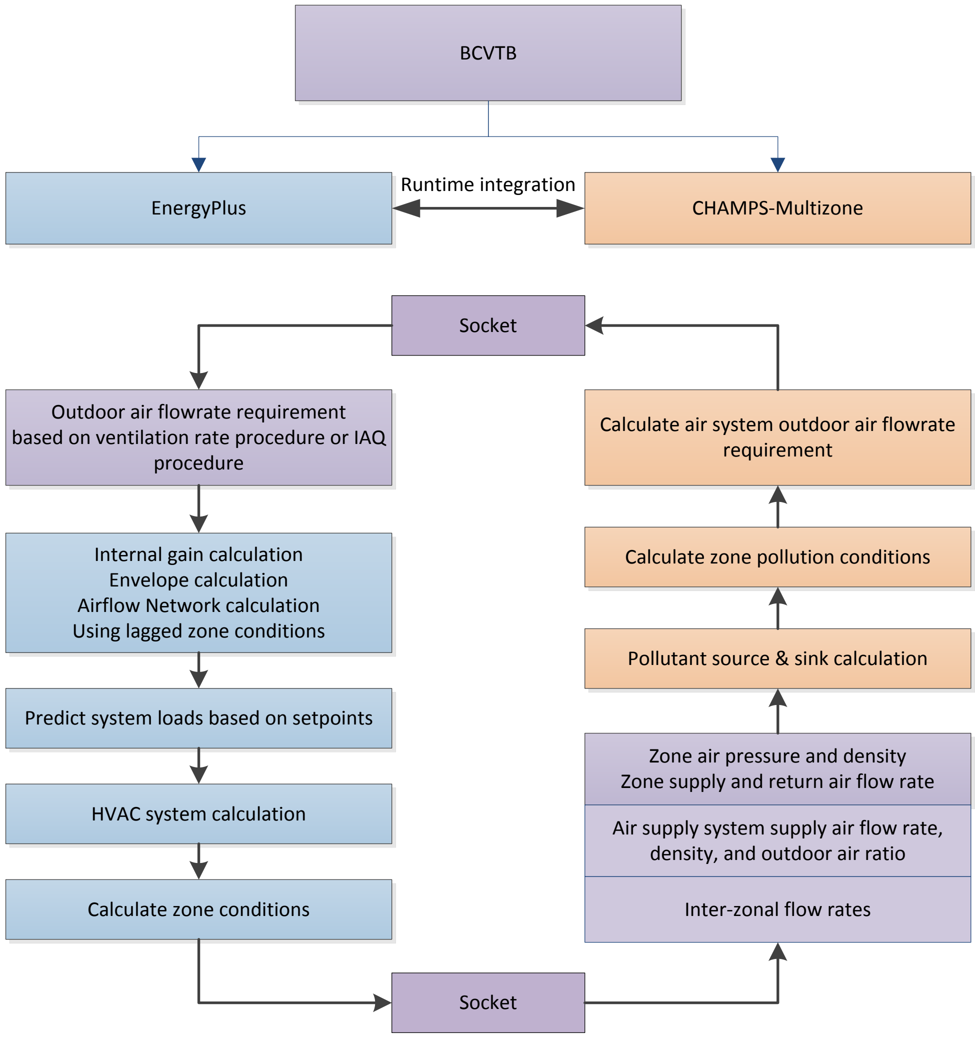


Figure 4-19 Runtime integration of EnergyPlus and CHAMPS-Multizone

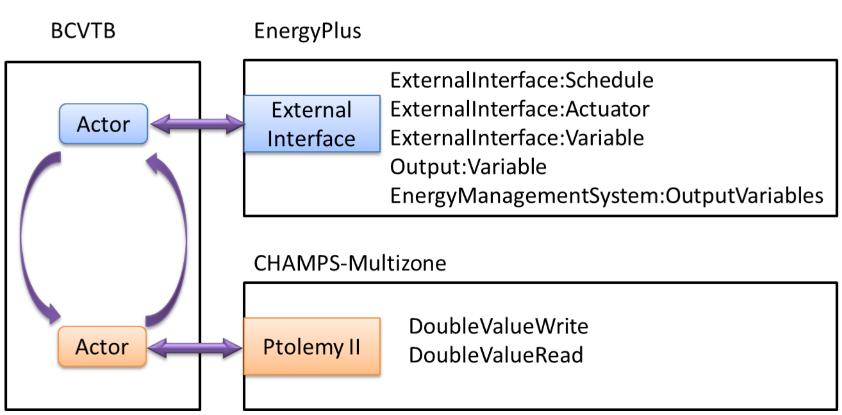


Figure 4-20 Data exchange architecture via BCVTB for EnergyPlus and CHAMPS-Multizone co-simulation

4.2.3.5. Co-simulation requirements

In order to use BCVTB to perform co-simulation, special requirements are needed for both EnergyPlus and CHAMPS-MZ programs.

4.2.3.5.1. Requirements of EnergyPlus

LBNL (US DOE, 2013b) developed a module of ExternalInterface in EnergyPlus. The module is called at the beginning of each time step to exchange data. The external interface module can map to three EnergyPlus input objects called ExternalInterface:Schedule, ExternalInterface: Actuator and ExternalInterface:Variable. The ExternalInterface:Schedule can be used to overwrite schedules, and the other two objects can be used in place of Energy Management System (EMS) actuators and EMS variables. The objects have similar functionality as the objects Schedule:Compact, EnergyManagementSystem:Actuator and EnergyManagementSystem:GlobalVariable, except that their numerical value is obtained from the external interface at the beginning of each zone time step, and will remain constant during this zone time step.

The object ExternalInterface:Actuator has an optional field called "initial value." If a value is specified for this field, then this value will be used during the warm-up period and the system sizing. If unspecified, then the numerical value for this object will only be used during time stepping. Since actuators always overwrite other objects (such as a schedule), all these objects have values that are defined during the warm-up and the system sizing even if no initial value is specified. For the objects ExternalInterface:Schedule and ExternalInterface:Variable, the field "initial value" is required, and its value will be used during the warm-up period and system-sizing. ExternalInterface:Variable is a global variable from the point of view of the EMS language. Thus, it can be used within any EnergyManagementSystem:Program in the same way as an EnergyManagementSystem:GlobalVariable or an EnergyManagementSystem:Sensor can be used.

Although variables of type ExternalInterface:Variable can be assigned to EnergyManagmentSystem:Actuator objects, for convenience, there is also an object called ExternalInterface:Actuator. This object behaves identically to EnergyManagmentSystem:Actuator, with the following exceptions:

- Its value is assigned by the external interface.
- Its value is fixed during the zone time step because this is the synchronization time step for the external interface.

The external interface can also map to the EnergyPlus objects Output:Variable and EnergyManagementSystem:OutputVariable. These objects can be used to send data from EnergyPlus to the BCVTB at each zone time step.

4.2.3.5.2. Requirement of CHAMPS-Multizone

The existing CHAMPS-Multizone does not have the capability to collaborate with Ptolemy II. Therefore, a modification of CHAMPS-Multizone is needed for use in co-simulation and to meet BCVTB requirements. A special function was created and is called at every time step in order to synchronize the EnergyPlus simulation time step. Ptolemy II is used at the external interface connection. Two data vectors are generated. The first vector is used to export data, and the second vector is used to import data. The dimension of each vector is determined in an EnergyPlus configuration file. It should be pointed out that the imported data were results obtained from EnergyPlus at the previous time step, and the exported data were also final results in CHAMPS- Multizone at the previous time step.

4.2.3.6. List of variables exchanged via BCVTB for the Co-Simulation

The data exchanged between EnergyPlus and CHAMPS-Multizone is defined in an XML file called “Variables.cfg”. The file is located in the same directory as the EnergyPlus IDF file. Figure 4-21 shows an example of the “Variables.cfg” file. The first two rows is the header. The third and last rows are the element of the form. The element contains child elements called “variable” that define the variable exchanged. The “variable” element has an attribute “source” and a child element called “EnergyPlus”. For the variables exchanged from EnergyPlus to CHAMPS-Multizone, the “source” attribute is set to “EnergyPlus”. On the other hand, it is set to “Ptolemy” when the variables are sent by CHAMPS-Multizone via Ptolemy II.

```
<?xml version="1.0" encoding="ISO-8859-1"?>
<!DOCTYPE BCVTB-variables SYSTEM "variables.dtd">
<BCVTB-variables>
  <variable source="EnergyPlus">
    <EnergyPlus name="Environment" type="Outdoor Barometric Pressure"/>
  </variable>
        .
        .
        .
  <variable source="Ptolemy">
    <EnergyPlus variable="VAV_System_Default_VDS_OA_Rate"/>
  </variable>
</BCVTB-variables>
```

Figure 4-21 Example of the “Variables.cfg” file

4.2.3.6.1. Variables from EnergyPlus to CHAMPS-Multizone

For each “variable” element from EnergyPlus, the child element “EnergyPlus” has two attributes, which are “name” and “type”. The “name” attributes needs to be the EnergyPlus key values, and the “type” attributes needs to be the EnergyPlus variables. Table 4-5 lists the variables exchanged from EnergyPlus to CHAMPS-Multizone, including outdoor air pressure and air density, zone air pressure and density, zone supply and return air mass flow rates, system supply air density and mass flow rate, system outdoor air ratio, inter-zonal air mass flow rates, and the pressure difference of the surfaces.

Table 4-5 Variables exchanged from EnergyPlus to CHAMPS-Multizone

Name	**Type**	**Note**
Environment	Outdoor Barometric Pressure	Outdoor air pressure
Environment	Outdoor Air Density	Outdoor air density
<Zone name>	AirflowNetwork Node Total Pressure	Zone air pressure
<Zone name> Zone Air Node	System Node Current Density	Zone air density
<Zone name> Supply Inlet	System Node MassFlowRate	Zone supply air mass flow rate
<Zone name> Return Inlet	System Node MassFlowRate	Zone return air mass flow rate
<Air supply system name>	AirLoopHVAC Actual Outdoor Air Fraction	Air supply system outdoor air ratio
<Air supply system name>	AirLoopHVAC Mixed Air Mass Flow Rate	Air supply system supply air mass flow rate
<Air supply system name> Supply Fan Outlet	System Node Current Density	Air supply system supply air density
<Surface name>	AirflowNetwork Mass Flow Rate from Node 2 to 1	Air mass flow rate from the external to the zone
<Surface name>	AirflowNetwork Mass Flow Rate from Node 1 to 2	Air mass flow rate from the zone to the external
<Surface name>	AirflowNetwork Linkage Pressure Difference	Pressure difference of the zone and the external

4.2.3.6.2. Variables from CHAMPS-Multizone to EnergyPlus

As shown in Figure 4-19, the variables exchanged from CHAMPS-Multizone to EnergyPlus are the outdoor air requirement for each air supply system. EnergyPlus provides the Energy Management System (EMS) (US DOE, 2012c) for advanced users to develop custom control and modeling routines for EnergyPlus models. Figure 4-22 shows the EMS code for controlling outdoor air mass flow rate from CHAMPS-Multizone. "VAV_System_Default" is the name of the air supply system.

The first object "ExternalInterface" identifies Ptolemy Server as the external interface.

The second object "EnergyManagementSystem:Actuator" creates an actuator named "VAV_System_Default_OA_Flow_Rate" that controls the outdoor air mass flow rate of the "VAV_System_Default" air supply system.

The third object "EnergyManagementSystem:Program" is a program that sets the system outdoor air mass flow rate to the value of "ExternalInterface:Variable" named "VAV_System_Default_VDS_OA_Rate".

The forth object "EnergyManagementSystem:ProgramCallingManager" indicates when the program named "Set_VAV_System_Default_OA_Flow_Rate" is called.

The last object "ExternalInterface:Variable" defines the name of the variable to be used in the "Variables.cfg" file and the initial value of the variable.

It should be pointed out that a single variable of outdoor air is applied to a single air loop system only. If multiple air loops are used in a building, multiple outdoor air variables have to be used.

For each "variable" element from CHAMPS-Multizone, the child element "EnergyPlus" has an attribute "variable". The "variable" attribute needs to be the same as the name of the "ExternalInterface:Variable" object in Figure 4-22.

```
ExternalInterface,
  PtolemyServer;                                          !- Name

EnergyManagementSystem:Actuator,
  VAV_System_Default_OA_Flow_Rate,                        !- Name
  VAV_System_Default OA Controller,                       !- Actuated Component Unique Name
  Outdoor Air Controller,                                 !- Actuated Component Type
  Air Mass Flow Rate;                                     !- Actuated Component Control Type

EnergyManagementSystem:Program,
  Set_VAV_System_Default_OA_Flow_Rate,                                          !- Name
  Set VAV_System_Default_OA_Flow_Rate = VAV_System_Default_VDS_OA_Rate;         !- Code

EnergyManagementSystem:ProgramCallingManager,
  Control_VAV_System_Default_OA_Flow_Rate,                !- Name
  AfterPredictorAfterHVACManagers,                        !- EnergyPlus Model Calling Point
  Set_VAV_System_Default_OA_Flow_Rate;                    !- Program Name 1

ExternalInterface:Variable,
  VAV_System_Default_VDS_OA_Rate,                         !- Name
  0;                                                      !- Initial Value
```

Figure 4-22 EMS code for controlling outdoor air mass flow rate

4.2.4. Enhanced CHAMPS-Multizone model

As introduced in Section 4.2.3, the current CHAMPS-Multizone does not incorporate Ptolemy II for BCVTB Co-Simulation. This section shows the modification of current CHAMPS-Multizone model for Co-Simulation. It first presents the flow chart of the enhanced CHAMPS-Multizone. The Ptolemy II functions are implemented to exchange data with BCVTB through a socket identified by BCVTB. Furthermore, it introduces the enhanced surface pollutant transport model, zone pollutant balance model, and air system pollutant balance model in CHAMPS-Multizone, which are used in the Co-Simulation for air quality analysis. Finally, the enhanced airflow network model in CHAMPS-Multizone is introduced, which is used by the CHAMPS-Multizone alone simulation. Both CHAMPS-Multizone and EnergyPlus have the airflow network simulation capability. As the airflow network model in EnergyPlus has been tested and validated more extensively, EnergyPlus is adopted in the VDS for co-simulation.

4.2.4.1. Incorporate Ptolemy II in CHAMPS-Multizone for data exchange with BCVTB

Figure 4-23 shows the flow chart of the enhanced CHAMPS-Multizone model. First, the VDS XML project file and the configuration file are read and the program is initialized. It then connects to the socket identified by BCVTB for data exchange. Moreover, two arrays "Write Array" and "Read Array" that contain the variables to be exchanged are created. The program then obtain the start time, end time and time step information from the VDS project file and initialize the result files for output. After these procedures, the program starts the loop to run the simulation for each time step. The CHAMPS-Multizone writes the output variables to the "Write Array". The program then calls the Ptolemy II function to exchange the data with BCVTB through the connected socket. After the data exchange process is finished, the information is saved in the "Read Array". CHAMPS-Multizone reads the variables from the array and performs the air system pollutant balance calculation, the zone pollutant balance calculation, and the required outdoor air flow rate calculation. The simulation results are saved to the result file. The program then moves to the next time step and checks whether the next period is still within the requested run period. If so, the simulation continues. If not, the program disconnects the socket and closes the result file.

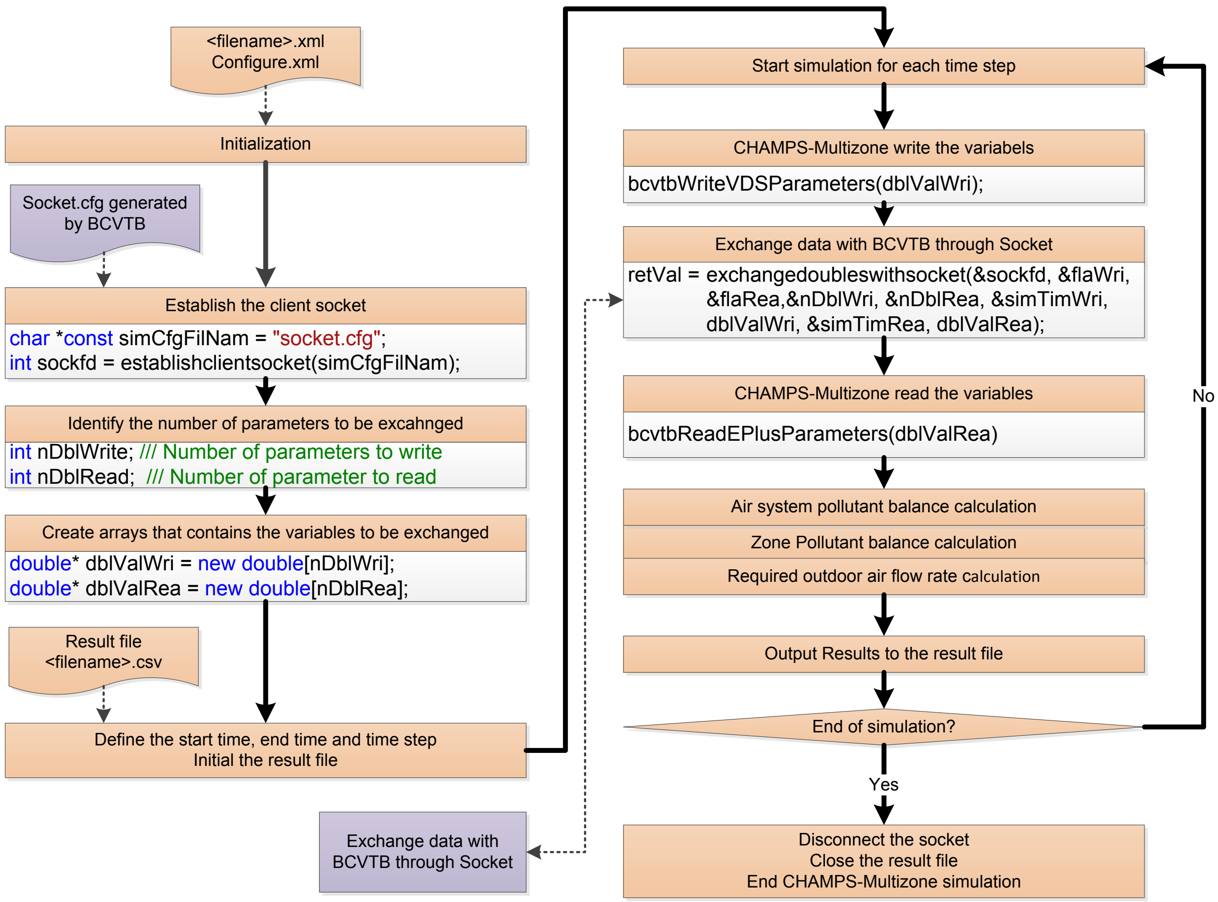


Figure 4-23 Flow chart of the enhanced CHAMPS-Multizone model

4.2.4.2. Pollutant source and sink model

Pollutant sources are used to generate pollutants in the zones, while pollutant sinks are used to remove pollutants from the zones. Sources can be used to simulate the impact of building materials, furniture and other emitters on IAQ. Sinks can be used to simulate the impact of air purification equipment, passive sorption media and other pollutant removers on IAQ.

There are several source models and sink models included in this research by referring to CONTAM user guide and documentation (Walton & Dols, 2013). The source and sink models in CONTAM includes: constant coefficient model, pressure driven source model, decaying source model, boundary layer diffusion model, burst source model, deposition with resuspension model, deposition velocity sink model, deposition rate sink model, NRCC power law model, and NRCC peak model. The current implementation includes the constant coefficient model, decaying source model, and boundary layer diffusion model.

4.2.4.2.1. Source/Sink model: constant coefficient model

The constant coefficient model can be used as both source and sink model. It can be used in both zone level and surface level.

$$S_{cc}(t) = G_{cc} - \frac{D}{\rho_a(t)} * \rho_c(t) \qquad \text{Equation 4-1}$$

Where:

$S_{cc}(t)$ = Net contaminant generation rate in a zone at time t [mg/s]. Positive value means "Source" while negative value means "Sink".

G_{cc} = Constant generation rate [mg/s]. The constant contaminant generation rate of the zone.

D = Effective removal rate [kg/s].The rate at which the air is removed from the zone.

$\rho_a(t)$ = Air density at time t [kg/m^3]

t = Current simulation time [s].

$\rho_c(t)$ = Pollutant concentration of the zone at time t [mg/m^3]

4.2.4.2.2. Source Model: Decaying Source Model

The decaying source model is intended to model the sources which decay with time. It can be used in both zone level and surface level.

$$S_{ds}(t) = G_{ds} e^{-\frac{t-t_0}{\tau_c}} \quad when\ t \geq t_0 \qquad \text{Equation 4-2}$$

$$S_{ds}(t) = 0 \quad when\ t < t_0 \qquad \text{Equation 4-3}$$

Where:

$S_{ds}(t)$ = Decaying source model contaminant source strength at time t [mg/s].

G_{ds} = Decaying source model initial generation rate [mg/s]

t_0 = Time of the emission since the start of the simulation [s]

τ_c = Time constant at which the generation rate reaches 0.37 of the original rate [s]

4.2.4.2.3. Source/Sink Model: Boundary Layer Diffusion Model

The boundary layer diffusion controlled reversible sink/source model with a linear sorption isotherm follows the descriptions presented in (Axley, 1991). The boundary layer refers to the region above the surface of a material through which a concentration gradient exists between the near-surface concentration and the air-phase concentration. It can be used in surface level.

The rate at which a contaminant is transferred onto a surface (sink) is defined as:

$$S_{bl}(t) = h \cdot d \cdot A \cdot \left[\frac{\rho_{cs}(t)}{\rho_m \cdot k} - \frac{\rho_{ca}(t)}{\rho_a(t)}\right] \quad when\ t \geq t_0 \qquad \text{Equation 4-4}$$

$$S(t) = 0 \quad when\ t < t_0 \qquad \text{Equation 4-5}$$

$$V_m \frac{\partial \rho_{cs}(t)}{\partial t} = -S_{bl}(t) \qquad \text{Equation 4-6}$$

Where:

$S_{bl}(t)$ = Boundary layer diffusion model contaminant source strength at time t [mg/s]. Positive value means "Source" while negative value means "Sink".

h = Film mass transfer coefficient over the sink [m/s]

d = Film density of dry air [kg/m^3]

A = Surface area of the adsorbent [m^2]

$\rho_a(t)$ = Zone air density at time t [kg/m^3]

ρ_m = Material density [kg/m^3]

V_m = Volume of the material [m^3]

$\rho_{ca}(t)$ = Pollutant concentration in the zone at time t [mg/m^3]

$\rho_{cs}(t)$ = Pollutant concentration in the adsorbent at time t [mg/m^3]

k = Henry adsorption constant or the partition coefficient [dimensionless]

4.2.4.3. Zone pollutant balance model

4.2.4.3.1. Zone pollutant balance calculation

For each contaminant in each zone, the governing equation for zone pollutant balance is

$$V\frac{\partial \rho_c(t)}{\partial t} = \sum_{i=1}^{n} \dot{m}c_i + \sum_{i=1}^{N_{cc}} S_{cc,i} + \sum_{i=1}^{N_{ds}} S_{ds,i} + \sum_{i=1}^{N_{bl}} S_{bl,i} + \dot{m}c_{sa} \qquad \text{Equation 4-7}$$

Where:

V = Volume of the zone [m^3]

$\dot{m}c_i$ = Contaminant mass flowrate from surface i [mg/s].

$S_{cc,i}$ = Contaminant mass flowrate from i-th constant coefficient model [mg/s].

$S_{ds,i}$ = Contaminant mass flowrate from i-th decaying source model [mg/s].

$S_{bl,i}$ = Contaminant mass flowrate from i-th boundary layer diffusion model [mg/s].

N_{cc} = Number of constant coefficient sources in the zone [dimensionless]

N_{ds} = Number of decaying source sources in the zone [dimensionless]

N_{bl} = Number of boundary layer diffusion sources in the zone [dimensionless]

$\dot{m}c_{sa}$ = Contaminant mass flowrate from supply air [mg/s].

The zone balance model is based on well mixed assumption and assumes the contaminant concentrations in the outgoing flows are all the same as the zone contaminant concentrations. As the zone air is incompressible, the amount of incoming flows will equal to the amount of outgoing flows. For each incoming flow, assume there is an outgoing flow with the same airflow rate as the incoming flow, and same contaminant concentrations as the zone contaminant concentrations. Objective of the model is to determine the contaminant fluxes between zones as well as the zone concentration. Therefore, only the incoming flows from the openings or air supply system are considered.

$$\dot{m}c_i = 0 \quad when\ \dot{m}_i \leq 0$$ Equation 4-8

$$\dot{m}c_i = \frac{\dot{m}_i}{\rho_a} \cdot [\rho_{ci} - \rho_c] \ when\ \dot{m}_i > 0$$ Equation 4-9

$$\dot{m}c_{sa} = \frac{\dot{m}_{sa}}{\rho_a} \cdot [\rho_{csa} \cdot (1 - \varepsilon_Z) - \rho_c]$$ Equation 4-10

Where:

$\dot{m}_i$ = Air mass flowrate from surface i to the zone [kg/s]. Positive value means the air from outside (or adjoin zone) to the zone, while the negative value means the air from the zone to the outside (or adjacent zone).

$\dot{m}_{sa}$ = Supply air mass flow rate [kg/s]

ρ_a = Air density [kg/m^3]

ρ_{ci} = Contaminant concentration of the other side of the surface [mg/m^3]. When the surface is an internal surface, the other side will be another zone. When the surface is an external surface, the other side will be the outdoor.

ρ_{csa} = Contaminant concentration of the supply air before the zone air filter [mg/m^3].

ε_Z = Efficiency of zone air filter [dimensionless]

4.2.4.3.2. Solve zone pollutant balance model using CVODE solver

The governing equations for zone pollutant balance (Equation 4-7) are an ordinary differential equation (ODE) system with initial value problem. The unknowns are the zone contaminant concentrations.

The SUNDIALS CVODE (Lawrence Livermore National Laboratory, 2013) solver is selected to solve the ODE system with initial value problem. The CVODE is a solver for stiff and nonstiff ODE systems (initial value problem) given in explicit form $y' = f(t, y)$. The methods used in CVODE are variable-order, variable-step multistep methods. The VDS zone pollutant balance governing equation is a nonstiff ODE system with initial value problem. For nonstiff problems, CVODE includes the Adams-Moulton formulas, with the order varying between 1 and 12. The resulting nonlinear system is solved (approximately) at each integration step. A direct linear solver (dense) is used to solve the problem, which uses Modified Newton iteration with fixed Jacobian.

4.2.4.4. Air system model

4.2.4.4.1. Filters for air supply system

The filters are constant efficiency filters. The contaminant concentration before and after the filter is:

$$\rho_{c-before} = \rho_{c-after} \cdot (1 - \varepsilon)$$

Where:

$\rho_{c-after}$ = Contaminant concentration after filter [mg/m^3]

$\rho_{c-before}$ = Contaminant concentration before filter [mg/m^3]

ε = Filter efficiency of the contaminant [dimensionless]

4.2.4.4.2. Air system pollutant balance calculation

Figure 4-24 shows the air supply system for pollutant balance calculation. The processes for pollutant balance calculation are: calculating return air conditions, calculating recirculated air conditions, calculating fresh air conditions, calculating mixed air conditions, and calculating supply air conditions. The detailed description and calculations are introduced in the follows.

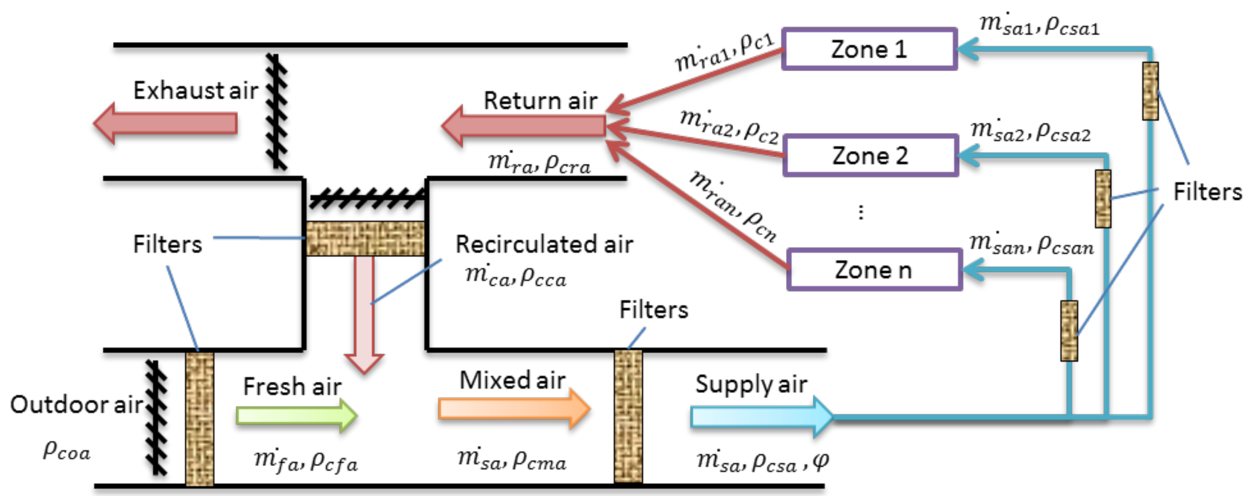


Figure 4-24 Schematic of the air supply system for pollutant balance calculation

- **Return air conditions calculation**

The return air is a mixture of return air from all zones served by the air supply system. For each contaminant, the contaminant concentration in return air is:

$$\rho_{cra} = \frac{\sum_{k=1}^{n}\left(\frac{\dot{m_{rak}}}{\rho_{ak}} \cdot \rho_{ck}\right)}{\sum_{k=1}^{n}\left(\frac{\dot{m_{rak}}}{\rho_{ak}}\right)} \qquad \text{Equation 4-11}$$

Where:

ρ_{cra} = Contaminant concentration in return air of the air supply system [mg/m^3]

$\dot{m_{rak}}$ = Return dry air mass flowrate of the zone k [kg/s]

ρ_{ak} = Air density of zone k [kg/m^3]

ρ_{ck} = Contaminant concentration in zone k [mg/m^3]

- **Recirculated air conditions calculation**

The recirculated air is the return air after the recirculated air filters. For each contaminant, the contaminant concentration in recirculated air is:

$$\rho_{cca} = \rho_{cra} \cdot (1 - \varepsilon_{ca}) \qquad \text{Equation 4-12}$$

Where:

ρ_{cca} = Contaminant concentration in recirculated air of the air supply system [mg/m^3]

ε_{ca} = Efficiency of recirculated air filter [dimensionless]

- **Fresh air conditions calculation**

The fresh air is the outdoor air after the outdoor air filters. For each contaminant, the contaminant concentration in fresh air is:

$$\rho_{cfa} = \rho_{coa} \cdot (1 - \varepsilon_{oa}) \qquad \text{Equation 4-13}$$

Where:

ρ_{cfa} = Contaminant concentration in fresh air of the air supply system [mg/m^3]

ε_{oa} = Efficiency of outdoor air filter [dimensionless]

- **Mixed air conditions calculation**

The mixed air is a mixture of the recirculated air and the fresh air. For each contaminant, the contaminant concentration in mixed air is:

$$\rho_{cma} = \frac{\frac{\dot{m}_{ca}}{\rho_a} \cdot \rho_{cca} + \frac{\dot{m}_{fa}}{\rho_a} \cdot \rho_{cfa}}{\frac{\dot{m}_{sa}}{\rho_a}} = \frac{\dot{m}_{ca} \cdot \rho_{cca} + \dot{m}_{fa} \cdot \rho_{cfa}}{\dot{m}_{sa}} \qquad \text{Equation 4-14}$$

$$\dot{m}_{ca} = \dot{m}_{sa} - \dot{m}_{fa} \qquad \text{Equation 4-15}$$

$$\varphi = \frac{\dot{m}_{fa}}{\dot{m}_{sa}} \qquad \text{Equation 4-16}$$

Where:

ρ_{cma} = Contaminant concentration in mixed air of the air supply system [mg/m^3]

$\dot{m}_{ca}$ = Recirculated dry air mass flow rate [kg/s]

$\dot{m}_{fa}$ = Outdoor/fresh air mass flow rate [kg/s]

$\dot{m}_{sa}$ = Supply air mass flow rate [kg/s]

φ = Outdoor air fraction [dimensionless]

The outdoor/fresh air flow rate is calculated in the following section. The supply air flow rate is calculated in EnergyPlus and exchanged through BCVTB.

- **Supply air condition calculation**

The supply air is the mixed air after the supply air filters. For each contaminant, the contaminant concentration in supply air is:

$$\rho_{csa} = \rho_{cma} \cdot (1 - \varepsilon_{sa}) \quad \text{Equation 4-17}$$

Where:

ρ_{csa} = Contaminant concentration in supply air of the air supply system [mg/m^3]

ε_{sa} = Efficiency of supply air filter [dimensionless]

4.2.4.4.3. Air system outdoor air flow rate requirement

The total air flow rate for all the zones severed by the air supply system is calculated in EnergyPlus based on zone heat and moisture balance. The amount of outdoor airflow rate is however based on the indoor air quality requirement following the ventilation rate procedure or IAQ procedure of ASHRAE Standard 62.1. More stringent requirements for IAQ than that set in ASHRAE Standard 62.1 can also be set and its impact on energy efficiency simulated. With the total supply airflow rate determined by the zone heat and moisture balance, its outdoor air fraction is used as a control parameter for satisfying the IAQ requirement.

4.2.4.4.4. Determine outdoor air fraction based on prescribed ventilation rates (i.e., the ventilation rate procedure in ASHRAE Standard 62.1)

ASHREAE 62.1-2010 (ASHRAE, 2010b) introduces the calculation method to determine the outdoor air flow rate, which is adopted by the enhanced CHAMPS-Multizone model in this study.

- **Zone Calculations**

The design outdoor airflow required in the breathing zone of the occupiable space or spaces in a zone, i.e., the breathing zone outdoor airflow (V_{bz}), shall be determined in accordance with Equation 4-18.

$$V_{bz} = R_p \cdot P_z + R_a \cdot A_z \qquad \text{Equation 4-18}$$

Where:

Vbz = Breathing zone outdoor airflow rate [m3/s]

A_z = zone floor area: the net occupiable floor area of the zone [m^2]

Pz = zone population: the largest number of people expected to occupy the zone during typical usage.

R_p = outdoor airflow rate required per person [$m^3/s \cdot person$]

R_a = outdoor airflow rate required per unit area [$m^3/s \cdot m^2$]

The design zone outdoor airflow (Voz), i.e., the outdoor airflow that must be provided to the zone by the supply air distribution system, shall be determined in accordance with Equation 4-19.

$$Voz = Vbz/Ez \qquad \text{Equation 4-19}$$

Where:

Voz = design zone outdoor airflow [m^3/s]

Ez = zone air distribution effectiveness [dimensionless], which can be determined using Table 4-6.

Table 4-6 Zone air distribution effectiveness (ASHRAE, 2010b)

Air Distribution Configuration	E_z
Ceiling supply of cool air.	1.0
Ceiling supply of warm air and floor return.	1.0
Ceiling supply of warm air 15°F (8°C) or more above space temperature and ceiling return.	0.8
Ceiling supply of warm air less than 15°F (8°C) above space temperature and ceiling return provided that the 150 fpm (0.8 m/s) supply air jet reaches to within 4.5 ft (1.4 m) of floor level. ***Note:*** For lower velocity supply air, E_z = 0.8.	1.0
Floor supply of cool air and ceiling return provided that the 150 fpm (0.8 m/s) supply jet reaches 4.5 ft (1.4 m) or more above the floor. ***Note:*** Most underfloor air distribution systems comply with this proviso.	1.0
Floor supply of cool air and ceiling return, provided low-velocity displacement ventilation achieves unidirectional flow and thermal stratification.	1.2
Floor supply of warm air and floor return.	1.0
Floor supply of warm air and ceiling return.	0.7
Makeup supply drawn in on the opposite side of the room from the exhaust and/or return.	0.8
Makeup supply drawn in near to the exhaust and/or return location.	0.5

1. "Cool air" is air cooler than space temperature.
2. "Warm air" is air warmer than space temperature.
3. "Ceiling" includes any point above the *breathing zone.*
4. "Floor" includes any point below the *breathing zone.*
5. As an alternative to using the above values, E_z may be regarded as equal to air change effectiveness determined in accordance with ANSI/ASHRAE Standard 129[16] for all air distribution configurations except unidirectional flow.

- **Single-Zone Systems**

When one air handler supplies a mixture of outdoor air and recirculated air to only one zone, the outdoor air intake flow (Vot) shall be determined in accordance with Equation 4-20.

$$V_{ot} = V_{oz} \quad \text{Equation 4-20}$$

Where:

V_{ot} = outdoor air intake flow [m^3/s]

- **100% Outdoor Air Systems**

When one air handler supplies only outdoor air to one or more zones, the outdoor air intake flow (Vot) shall be determined in accordance with Equation 4-21.

$$Vot = \sum_{i=1}^{N} Voz,i \qquad \text{Equation 4-21}$$

Where:

Voz,i = design i-th zone outdoor airflow [m^3/s]

N = number of zones

- **Multiple-Zone Recirculating Systems**

For non 100% outdoor air multi-zone systems, the system outdoor air flow shall be determined in accordance with Equation 4-22.

$$Vot = Vou/Ev \qquad \text{Equation 4-22}$$

Where:

V_{ou} = The design uncorrected outdoor air intake [m^3/s]

E_v = System ventilation efficiency [dimensionless]

$$Vou = \sum_{i=1}^{N}(Rp \cdot Pz) + \sum_{i=1}^{N}(Ra \cdot Az) \qquad \text{Equation 4-23}$$

The system ventilation efficiency (Ev) is equal to the lowest calculated value of the zone ventilation efficiency Evz. The zone ventilation efficiency Evz, i.e., the efficiency with which a system distributes outdoor air from the intake to an individual breathing zone, shall be calculated using Equation 4-24 or Equation 4-27.

Single Supply Systems case:

$$Evz = 1 + Xs - Zd \qquad \text{Equation 4-24}$$

Where:

Evz = zone ventilation efficiency [dimensionless]

X_s = Average Outdoor Air Fraction [dimensionless]. At the primary air handler, the fraction of outdoor air intake flow in the system primary airflow.

Zd = Discharge Outdoor Air Fraction [dimensionless]. The outdoor air fraction required in air discharged to the zone.

$$X_s = V_{ou}/V_{ps} \qquad \text{Equation 4-25}$$

Where:

V_{ps} = System Primary Airflow [m^3/s]. The total primary airflow supplied to all *zones* served by the system from the air handling unit at which the outdoor air intake is located.

$$Z_d = V_{oz}/V_{dz}$$ Equation 4-26

Where:

V_{dz} = Zone Discharge Airflow [m^3/s]. The expected discharge (supply) airflow to the zone that includes primary airflow and locally recirculated airflow.

Equation 4-24 shall be used for "single supply" systems, where all the ventilation air is a mixture of outdoor air and recirculated air from a single location, e.g., Reheat, Single-Duct VAV, Single-Fan Dual-Duct, and Multizone.

General Case:

$$Evz = (Fa + Xs \cdot Fb - Zd \cdot Fc)/Fa$$ Equation 4-27

Where:

Fa = Fraction of supply air to the zone from sources outside the zone.

Fb = Fraction of supply air to the zone from fully mixed primary air.

Fc = Fraction of outdoor air to the *zone* from sources outside the zone.

$$F_a = E_p + (1 - E_p) \cdot E_r$$ Equation 4-28

$$Fb = Ep$$ Equation 4-29

$$Fc = 1 - (1 - Ez) \cdot (1 - Er) \cdot (1 - Ep)$$ Equation 4-30

Where:

E_p = Primary air fraction to the *zone* [dimensionless]

E_r = The zone secondary recirculation fraction.

$$E_p = V_{pz}/V_{dz} \qquad \text{Equation 4-31}$$

Where:

V_{pz} = Zone Primary Airflow [m^3/s]. The primary airflow supplied to the *zone* from the air-handling unit at which the outdoor air intake is located. It includes outdoor intake air and recirculated air from that air handling unit but does not include air transferred or air recirculated to the zone by other means.

Equation 4-27 shall be used for systems that provide all or part of their ventilation by recirculating air from other zones without directly mixing it with outdoor air, e.g., dual-fan dual duct, fan-powered mixing box, and transfer fans for conference rooms.

The system ventilation efficiency shall be calculated using.

$$E_v = min\ (E_{vz}) \qquad \text{Equation 4-32}$$

4.2.4.4.5. Determine outdoor air fraction based on IAQ procedure

The IAQ Procedure determines the outdoor airflow rate (i.e., the ventilation rate) based on the target contaminant concentration limits. The procedure of determining the ventilation rate to dilute the indoor contaminants is similar to the procedure of determining the supply air flow rate (or supply air temperature) to control the zone temperature. EnergyPlus (US DOE, 2012b) uses the Predictive System Energy Balance method to calculate the air system output required to maintain the desired zone air temperature. A similar method is adopted to calculate the supply air contaminant concentrations required to control the zone contaminate concentrations below the given limits.

Using Euler Method, the derivative term in the left of Equation 4-6 may be express as:

$$\frac{\partial \rho_c^t}{\partial t} = \frac{(\rho_c^t - \rho_c^{t-\delta t})}{\delta t} + O(\delta t)$$ Equation 4-33

The zone pollutant governing equation (Equation 4-6) updated at the current time step using the Euler Method may be expressed as follows:

$$V\frac{\left(\rho_c^t - \rho_c^{t-\delta t}\right)}{\delta t} = \sum_{i=1}^{n} \dot{m}c_i(\rho_c^t) + \sum_{i=1}^{N_{cc}} S_{cc,i}(\rho_c^t) + \sum_{i=1}^{N_{ds}} S_{ds,i}(\rho_c^t) + \sum_{i=1}^{N_{bl}} S_{bl,i}(\rho_c^t) + \dot{m}c_{sa}(\rho_c^t)$$ Equation 4-34

For the pollutant concentration prediction case, the contaminant mass flow rate from supply air (Equation 4-10) needs to be predicted. The predictive method assumes the zone pollutant concentration will reach the limits and thus determines the contaminant mass flow rate from supply air using the contaminant limit. Equation 4-35 and Equation 4-36 shows the predicted contaminant mass flow rate from supply air.

Equation 4-35

$$\dot{m}c_{sa,load}(\rho_{c,limit}) = \frac{\dot{m}_{sa}}{\rho_a} \cdot [\rho_{csa,r} \cdot (1 - \varepsilon_Z) - \rho_{c,limit}]$$

$$\dot{m}c_{sa,load}(\rho_{c,limit}) = V\frac{(\rho_{c,limit} - \rho_c^{t-\delta t})}{\delta t} - \sum_{i=1}^{n} \dot{m}c_i(\rho_{c,limit})$$

Equation 4-36

$$- \sum_{i=1}^{N_{cc}} S_{cc,i}(\rho_{c,limit}) - \sum_{i=1}^{N_{ds}} S_{ds,i}(\rho_{c,limit}) - \sum_{i=1}^{N_{bl}} S_{bl,i}(\rho_{c,limit})$$

Where:

$\dot{m}c_{sa,load}$ = the predicted contaminant mass flow rate from supply air [mg/s]

$\rho_{c,limit}$ = the pollutant concentration limit [mg/m^3]

$\rho_{csa,r}$ = the required supply air contaminant concentration from the zone [mg/m^3]

Based on Equation 4-35 and Equation 4-36, the required supply air pollutant concentration from a zone can be determined as follows:

$$\rho_{csa,r} = \left\{ \left[V \frac{\left(\rho_{c,limit} - \rho_c^{t-\delta t}\right)}{\delta t} - \sum_{i=1}^{n} \dot{m}c_i\left(\rho_{c,limit}\right) - \sum_{i=1}^{N_{cc}} S_{cc,i}\left(\rho_{c,limit}\right) - \sum_{i=1}^{N_{ds}} S_{ds,i}\left(\rho_{c,limit}\right) - \sum_{i=1}^{N_{bl}} S_{bl,i}\left(\rho_{c,limit}\right) \right] \cdot \frac{\rho_a}{\dot{m}_{sa}} + \rho_{c,limit} \right\} \cdot \frac{1}{(1-\varepsilon_z)}$$ Equation 4-37

In order to satisfy all the zones, the required supply air pollutant concentration of the air supply system should be the minimum value among all the requirements from the zones.

$$\rho_{csa,sr} = \min_{1 \le i \le N_z} \left(\rho_{csa,r,i}\right)$$ Equation 4-38

Where:

$\rho_{csa,sr}$ = Required supply air pollutant concentration of the air supply system [mg/m^3]

$\rho_{csa,r,i}$ = Required supply air pollutant concentration from zone i [mg/m^3]

Based on the equations in Section 4.2.4.4.2, the supply air pollutant concentration can be expressed as follows:

$$\rho_{csa} = \left[\varphi \cdot \rho_{coa} \cdot (1-\varepsilon_{oa}) + \frac{\sum_{k=1}^{n}\left(\frac{\dot{m}_{rak}}{\rho_{ak}} \cdot \rho_{ck}\right)}{\sum_{k=1}^{n}\left(\frac{\dot{m}_{rak}}{\rho_{ak}}\right)} \cdot (1-\varepsilon_{ca})(1-\varphi) \right] \cdot (1-\varepsilon_{sa})$$ Equation 4-39

Apply Equation 4-38 to Equation 4-39, and solve the equation to obtain the required outdoor air fraction.

$$\varphi_{sr} = \frac{\dfrac{\rho_{csa,sr}}{(1-\varepsilon_{sa})} - \dfrac{\sum_{k=1}^{n}\left(\dfrac{\dot{m}_{rak}}{\rho_{ak}}\cdot \rho_{ck}\right)}{\sum_{k=1}^{n}\left(\dfrac{\dot{m}_{rak}}{\rho_{ak}}\right)}\cdot(1-\varepsilon_{ca})}{\rho_{coa}\cdot(1-\varepsilon_{oa}) - \dfrac{\sum_{k=1}^{n}\left(\dfrac{\dot{m}_{rak}}{\rho_{ak}}\cdot \rho_{ck}\right)}{\sum_{k=1}^{n}\left(\dfrac{\dot{m}_{rak}}{\rho_{ak}}\right)}\cdot(1-\varepsilon_{ca})} \qquad \text{Equation 4-40}$$

Equation 4-40 uses the zone return air conditions from previous time step to calculate the ventilation rate requirement of the current time step. As the range of the outdoor air fraction is 0 to 1, the outdoor air fraction now can be expressed as follows:

$$\varphi = 0 \qquad when\ \varphi_{sr} \le 0 \qquad \text{Equation 4-41}$$

$$\varphi = \varphi_{sr} \qquad when\ 0 < \varphi_{sr} < 1 \qquad \text{Equation 4-42}$$

$$\varphi = 1 \qquad when\ \varphi_{sr} \ge 1 \qquad \text{Equation 4-43}$$

4.2.5. Development of a new HVAC template type in EnergyPlus

One of the goals for the present project is to use the Syracuse CoE building to demonstrate VDS capabilities. The Syracuse CoE building has a central ground source heat pump with a backup central plant with chillers and boilers. The ground source heat pump provides space heating and cooling as a main source, while a central plant works as backup, when the ground source heat pump could not provide enough space heating or cooling. However, the ground source heat pump templates are not available in EnergyPlus HVAC templates. This section shows the development of adding the ground source heat pump templates by revising the ExpandObjects program. The single story 3-zone building as introduced in section 4.3 is used as an example to demonstrate the modification in sections 4.2.5.5 and 4.2.5.6.

4.2.5.1. Revise ExpandObjects program

The ExpandObjects program is a preprocessor that is currently used with the HVACTemplate objects (US DOE, 2012a). The preprocessor reads an idf file and generates an expanded.idf file (usually with the extension .expidf). The original idf file contains objects that will be read by the preprocessor and those that are ignored by the preprocessor. The objects read can be either commented out or left as is. The objects created by the preprocessor in the expanded.idf file should require no further preprocessing. The preprocessor does not read the EnergyPlus Data Dictionary file (Energy+.IDD) and does limited validation. Most of the object values that are created are "passed" through from input objects. This allows EnergyPlus to provide most of the validation. If errors are found, error messages are passed to the EnergyPlus program using the Output:Preprocessor object. These errors will be shown in the usual EnergyPlus error file. When used with EP-Launch, the expanded.idf file is renamed to the original file name with the extension expidf.

The system type of Variable air volume systems with boilers and water-cooled chillers, an object related to towers is used as a base to make a new system template type as ground source heat pump with a backup central plant. Modifications were done in three templates: chiller, boiler and tower.

4.2.5.2. HVACTemplate:Plant:Chiller

A new chiller type is added as WaterToWaterHeatPump. When this type is entered, the preprocessor program was revised to recognize this chiller type is a cooling coil of a ground source heat pump. Then a new field is added to allow users to input the water flow rate, since the ground source heat pump may not enable autosize. Figure 4-25 shows a typical object input for the revised HVACTemplate:Plant:Chiller. Any modification and addition is highlighted in red.

```
HVACTemplate:Plant:Chiller,
  WTW Cooling,              !- Name
  WaterToWaterHeatPump,     !- Chiller Type
  45000,                    !- Capacity {W}
  3.2,                      !- Nominal COP {W/W}
  WaterCooled,              !- Condenser Type
  1,                        !- Priority
  1.0,                      !- Sizing Factor
  0.0,                      !-Minimum Part Load Ratio
  1.0 ,                     !-Maximum Part Load Ratio
  1.0,                      !-Optimum Part Load Ratio
  0.25,                     !-Minimum Unloading Ratio
  5.0,                      !-Leaving Chilled Water Lower Temperature Limit
  0.003;                    !- Side Flow Rate
```

Figure 4-25 Typical object input for the revised HVACTemplate:Plant:Chiller

It should be pointed out that the priority should be set to 1, so that this coil will be a main space cooling source, while a real chiller will be used as a backup. Therefore, the second object is needed with a real chiller with priority set to 2.

4.2.5.3. HVACTemplate:Plant:Boiler

A new boiler type is added as WaterToWaterHeatPump. When this type was entered, the program is revised to recognize that this boiler type is a heating coil of a ground source heat pump. Following this, a new field is added to allow users to input the water flow rate, since the ground source heat pump could not perform autosize at the current stage. Figure 4-26 shows a typical object input for the revised HVACTemplate:Plant:Boiler. Any modification and addition is highlighted in red.

```
HVACTemplate:Plant:Boiler,
   WTW Heating,                  !- Name
   WaterToWaterHeatPump,         !- Boiler Type
   45000,                        !- Capacity {W}
   3.5,                          !- Efficiency
   ,                             !- Fuel Type
   1,                            !- Priority
   1.0,                          !- Sizing Factor
   0.0,                          !-Minimum Part Load Ratio
   1.1,                          !-Maximum Part Load Ratio
   1.0,                          !-Optimum Part Load Ratio
   100,                          !-Water Outlet Upper Temperature Limit
   0.003;                        !- Side Flow Rate
```

Figure 4-26 Typical object input for the revised HVACTemplate:Plant:Boiler

It should be pointed out that the priority should be set to 1, so that this coil will be a main space heating source, while a real boiler will be used as a backup. Therefore, the second object is needed with a real boiler with priority set as 2.

4.2.5.4. HVACTemplate:Plant:Tower

A new tower type is added as GroundHeatExchanger. When this type is entered, the program is revised to recognize that this tower type is a vertical ground heat exchanger for a ground source heat pump. A new field is added to allow users to input the water flow rate, since the vertical ground heat exchanger could not perform autosize. Figure 4-27 shows a typical object input for the revised HVACTemplate:Plant:Tower. Any modification and addition is highlighted in red.

```
HVACTemplate:Plant:Tower,
  VerticalGroudHeatExchanger, !- Name
  GroundHeatExchanger,         !- Tower Type
  autosize,                    !- High Speed Nominal Capacity {W}
  autosize,                    !- High Speed Fan Power {W}
  autosize,                    !- Low Speed Nominal Capacity {W}
  autosize,                    !- Low Speed Fan Power {W}
  autosize,                    !- Free Convection Capacity {W}
  1,                           !- Priority
  1.0,                         !- Sizing Factor
  0.003;                       !- Maximum Flow Rate {m3/s}
```

Figure 4-27 Typical object input for the revised HVACTemplate:Plant:Tower

It should be pointed out that the priority should be set to 1, so that this ground heat exchanger will provide a main heat exchanger for a ground source heat pump, while a real tower in a condenser loop will be used as a backup. Therefore, the second object is needed with a tower with priority set as 2.

4.2.5.5. Baseline system

The baseline system is a variable air volume system with a boiler and a water-cooled chiller, and an object related to a tower. Each conditioned zone has a terminal unit with a reheat water heating coil. The terminal type is AirTerminal:SingleDuct:VAV:Reheat. An air handling unit has an outdoor air system, a main water cooling coil, and a main water heating coil. The supply fan type is variable air volume. The following diagrams show component-based system configurations. These figures also show node connections, which are automatically generated by the preprocessor program.

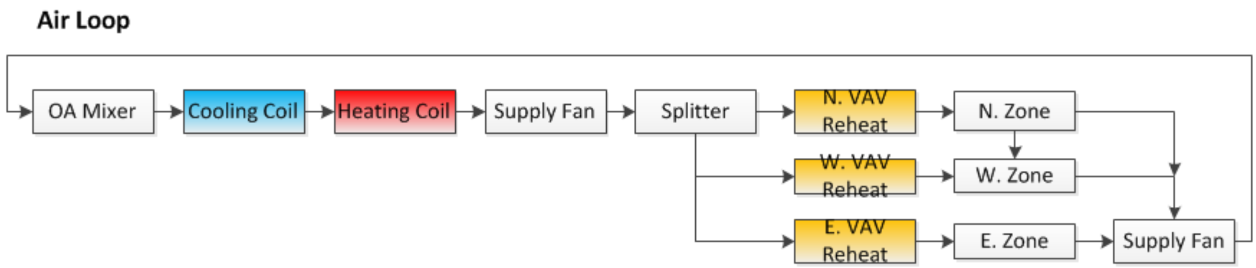


Figure 4-28 Air system loop diagram

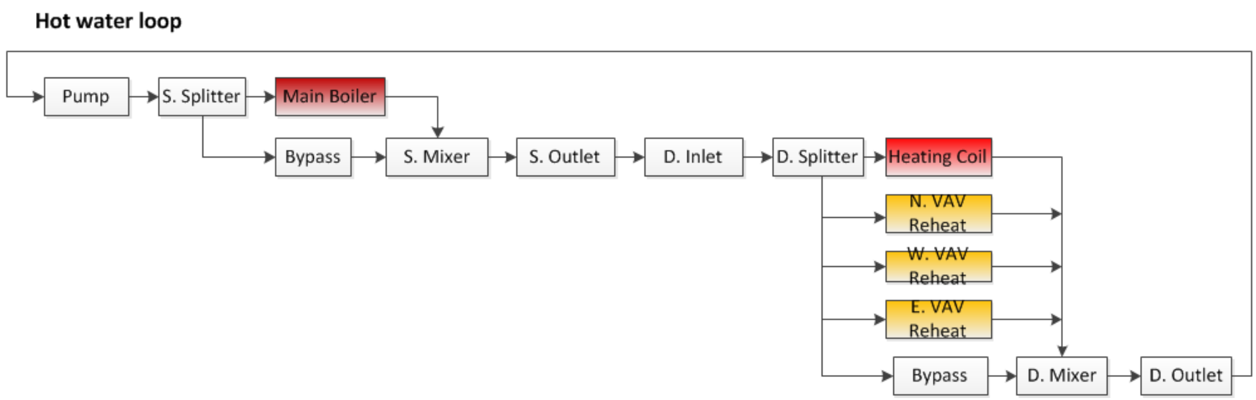


Figure 4-29 Hot water loop diagram

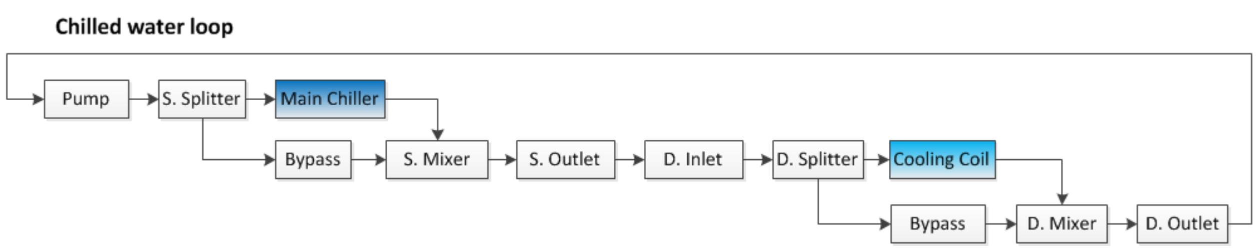


Figure 4-30 Chilled water loop diagram

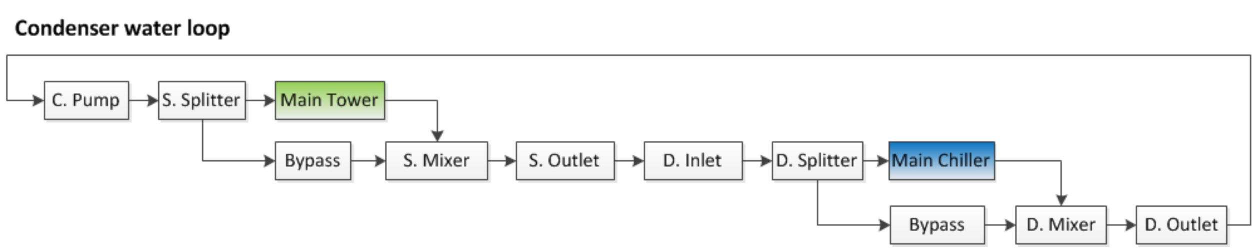


Figure 4-31 Condenser water loop diagram

Since the system is a baseline system, the current preprocessor program has capabilities to generate required EnergyPlus inputs using existing HVAC templates.

4.2.5.6. Ground source heat pump with a central backup plant with a chiller and boiler

The revised preprocessor program is able to pre-process these templates to generate regular EnergyPlus inputs for a ground source heat pump with a central backup plant. The air system loop configurations remain the same. The other three loops (chiller water loop, hot water loop and condenser loop) are revised to make the program accept ground source heat pump inputs. The following diagrams show component-based system configurations. These figures also show node connections, which are automatically generated by the preprocessor program.

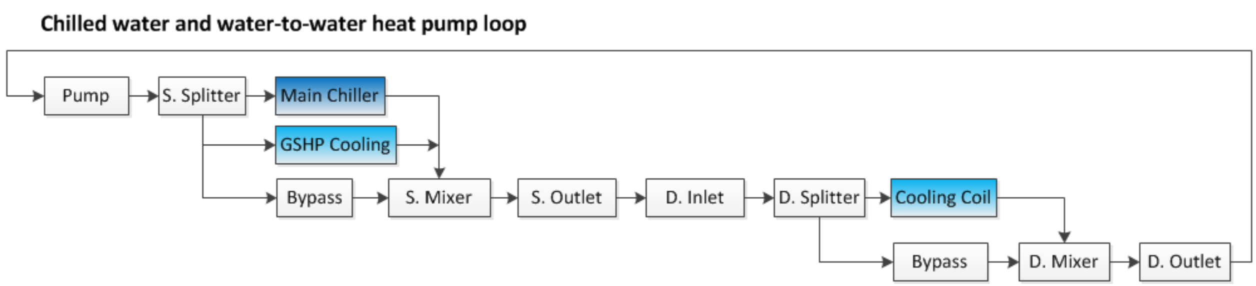


Figure 4-32 Chilled water loop and water-to-water heat pump loop diagram

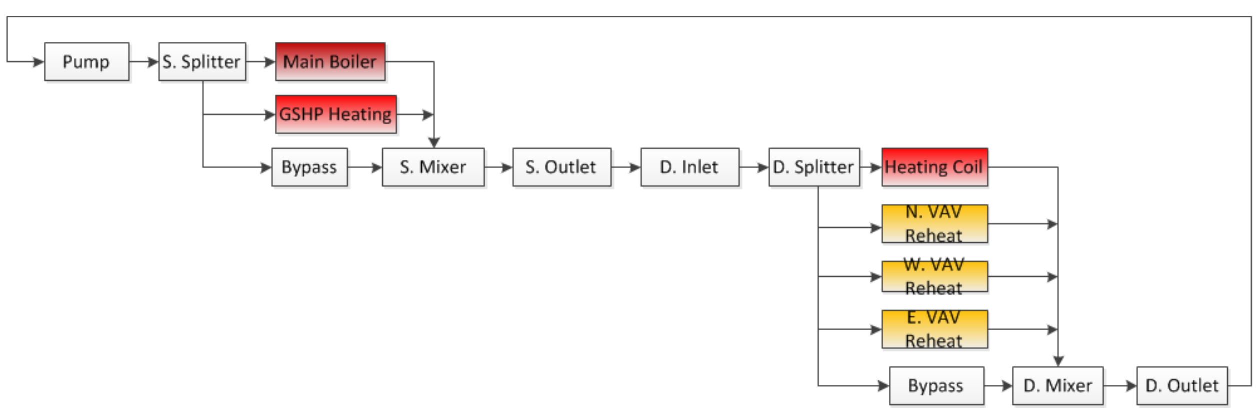


Figure 4-33 Hot water loop and water-to-water heat pump loop diagram

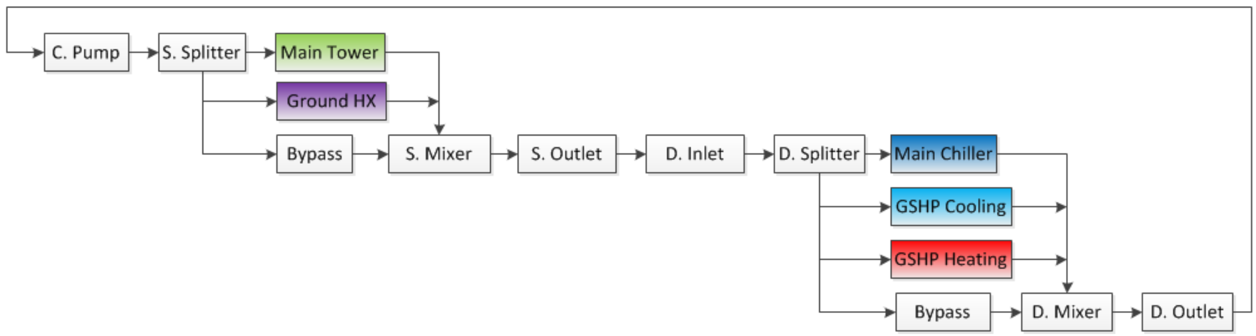


Figure 4-34 Condenser water loop and ground heat exchanger loop diagram

4.3. Testing and verification

In this section, a single story 3-zone building is used to test and verify the simulation models discussed in the previous sections. The simulation models include the EnergyPlus only simulation and the CHAMPS-WholeBuilding Co-Simulation.

Figure 4-35 shows the schematic of the 3-zone building. It has a flat roof with no plenum. The floor to ceiling height is 3.05m. The building is located in Syracuse, New York. Figure 4-36 shows the 3-D geometry view of the 3-zone building in VDS result quadrant. The climate, zoning, enclosure, and HVAC system information is set to the same as the VDS reference building for Syracuse condition, which is introduced in Section 5.5.1. For daylighting control, the daylighting reference points are set to the middle of the zones with a height of 0.8m. The daylighting control setpoint is 400 lux. The lights are controlled continuously.

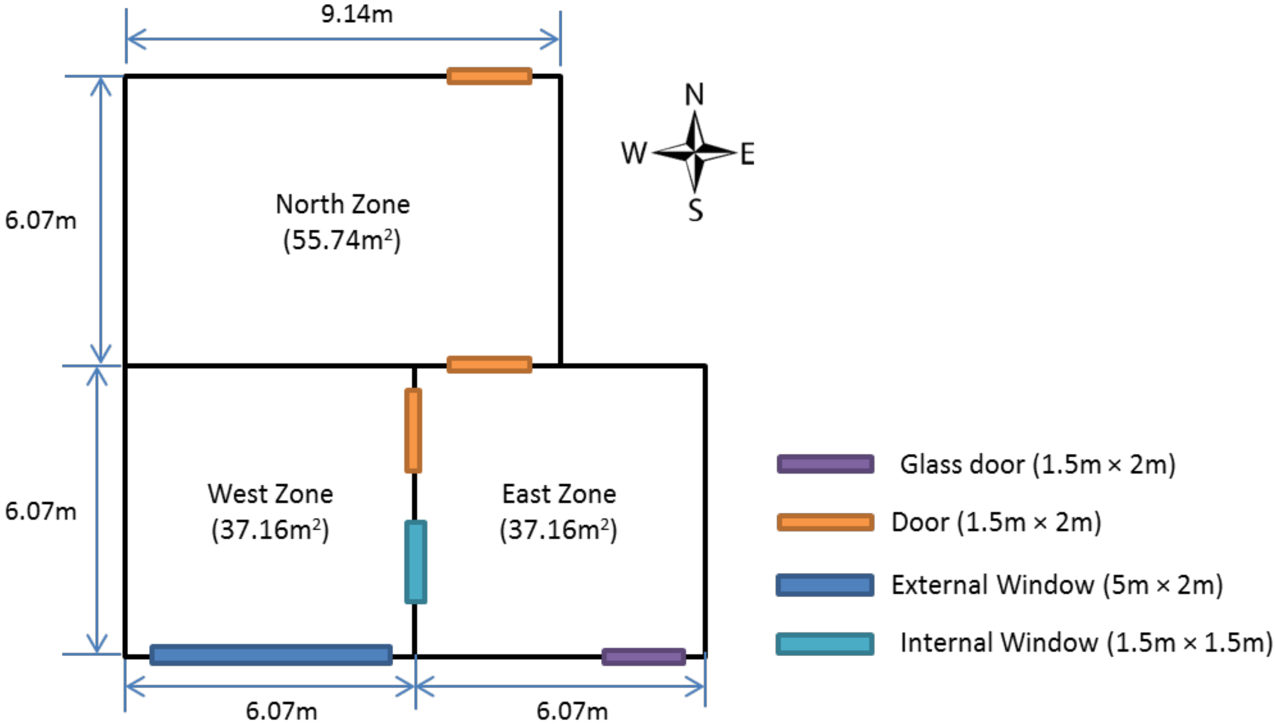


Figure 4-35 Schematic of the 3-zone office building

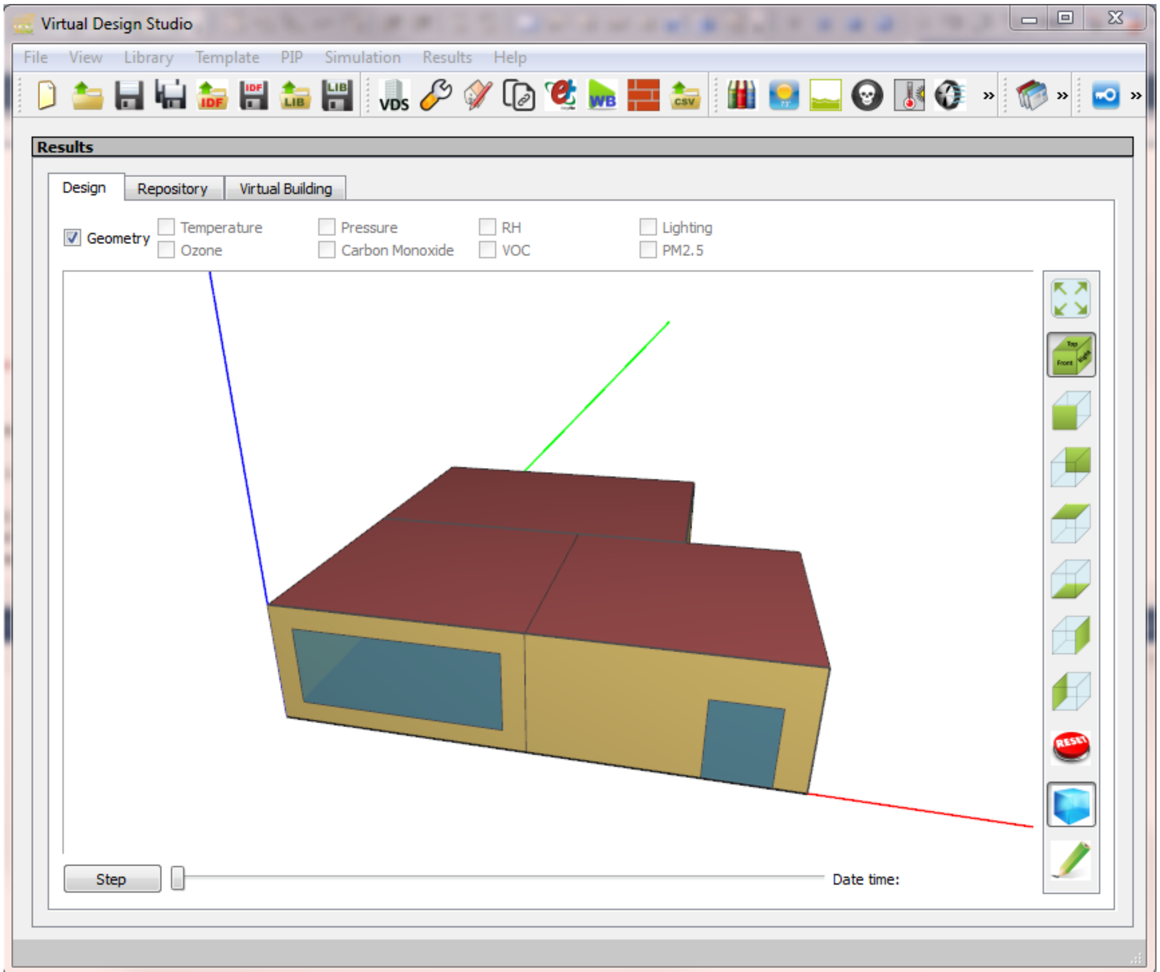


Figure 4-36 3-D geometry view of the 3-zone building in VDS result quadrant

4.3.1. EnergyPlus only simulation

The 3-zone building is simulated using the EnergyPlus only simulation. The whole year simulation is performed and the simulation results are presented in the following sections.

4.3.1.1. Energy consumption

The energy consumption by end use is one of the major results from the EnergyPlus only simulation. Figure 4-37 and Figure 4-38 show the monthly and annual energy consumption by end use. The 3-zone building totally consumes 147 kWh/m^2.year of electricity and 311 kWh/m^2.year of natural gas.

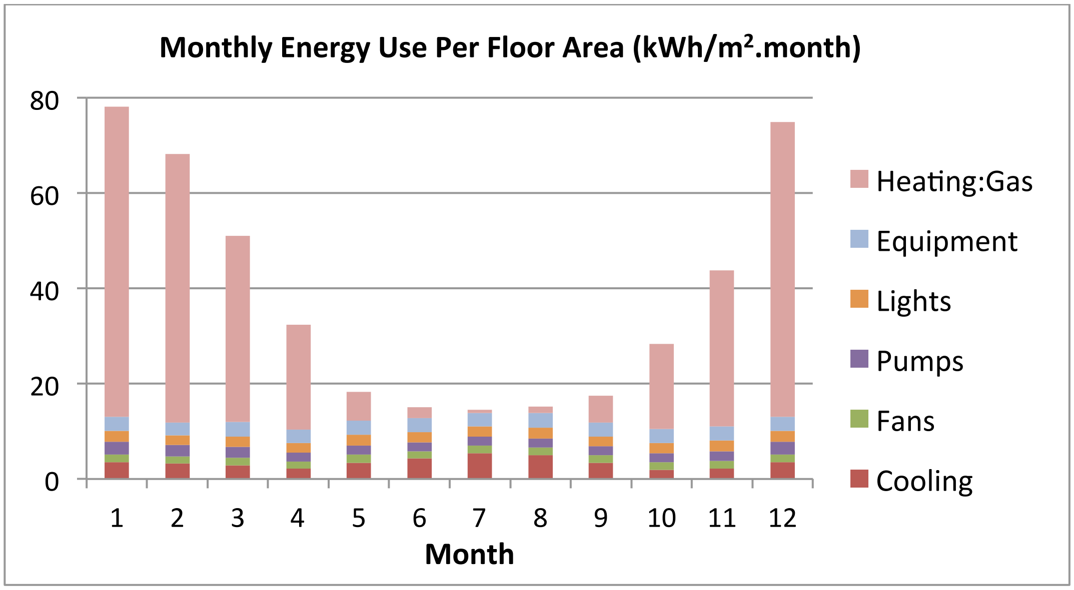


Figure 4-37 Monthly energy use per floor area

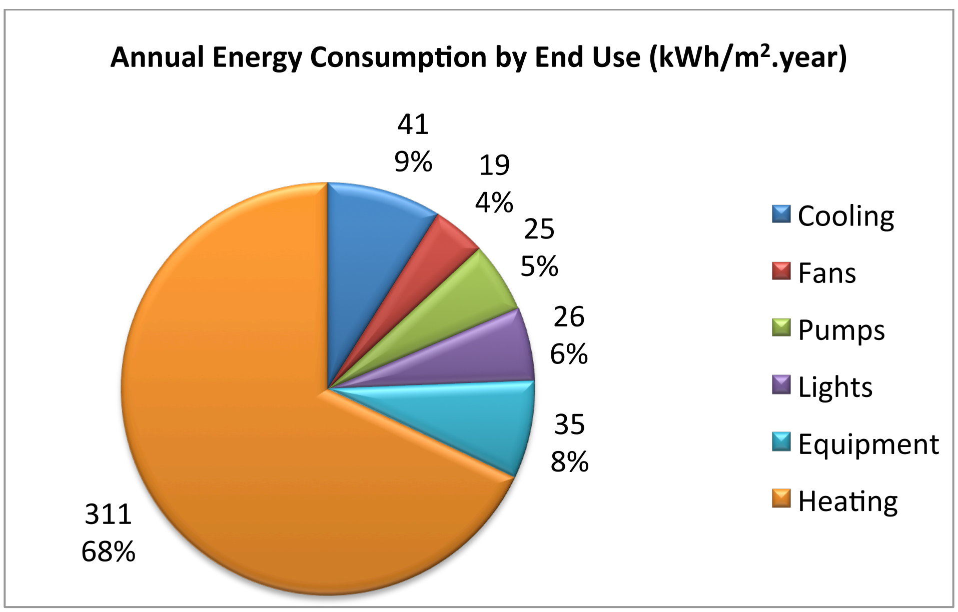


Figure 4-38 Annual energy consumption by end use

4.3.1.2. Energy cost

For commercial buildings in New York, the price of electricity in June, 2013 was 15.93 cent/kWh (US EIA, 2013c), while the average price of natural gas in 2011 was 0.932 cent/ft^3 (US EIA, 2013a). The energy density of natural gas is 38.7 MJ/m^3 (Envestra Limited, 2013). Figure 4-39 and Figure 4-40 show the monthly and annual energy cost by end use. The 3-zone building costs 34.4 \$/m^2.year.

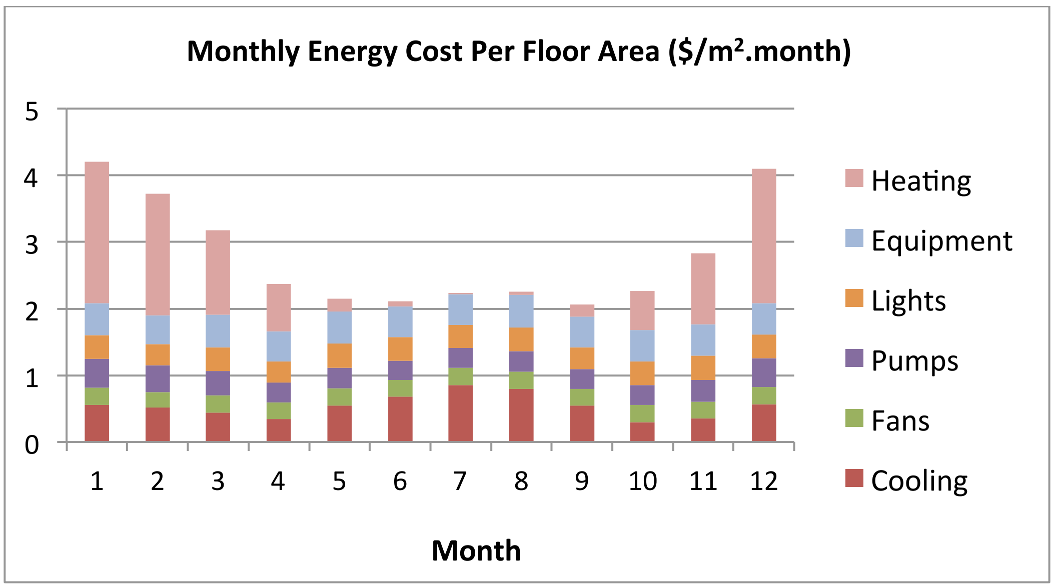


Figure 4-39 Monthly energy cost per floor area

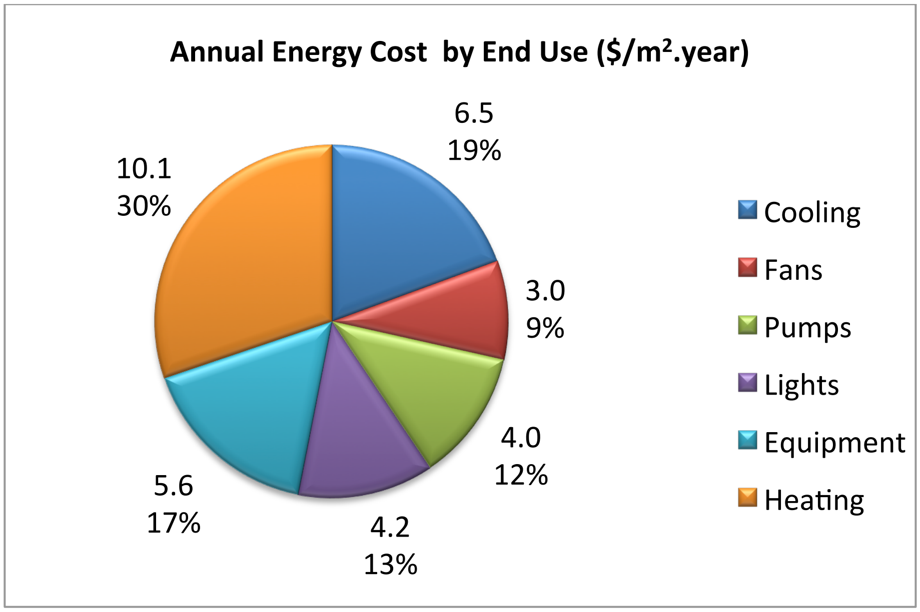


Figure 4-40 Annual energy cost by end use

4.3.1.3. Temperature and RH

The temperature and RH conditions for the three zones are almost the same, as their thermostat settings are the same. So only the dry-bulb temperature and RH conditions of West Zone are presented here. In order to show the results clearly, the hourly dry-bulb temperature and RH conditions of the first Wednesday of every two months are presented (Figure 4-41 and Figure 4-42). The dry-bulb temperature is controlled between 21 and 24°C from 6am to 10pm, and between 15.6 and 26.7 °C for the rest of the day. The RH is not controlled. The average RH is 11.1 % in January and 56.6 % in July. The VDS provides the capability to show the dry-bulb temperature and RH distribution of all the zones at a given time step. Figure 4-43 and Figure 4-44 show the dry-bulb temperature and RH distribution of the three zones at 12pm on July 5th.

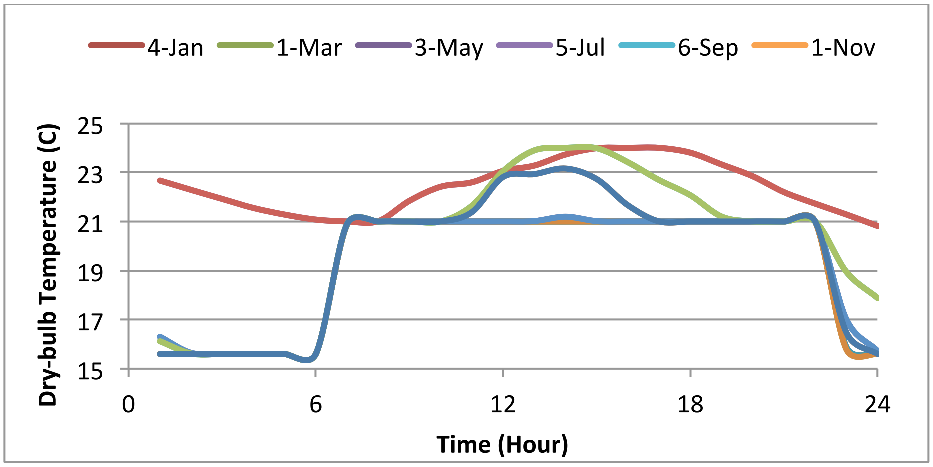


Figure 4-41 Hourly Dry-bulb temperature of West Zone for the selected days

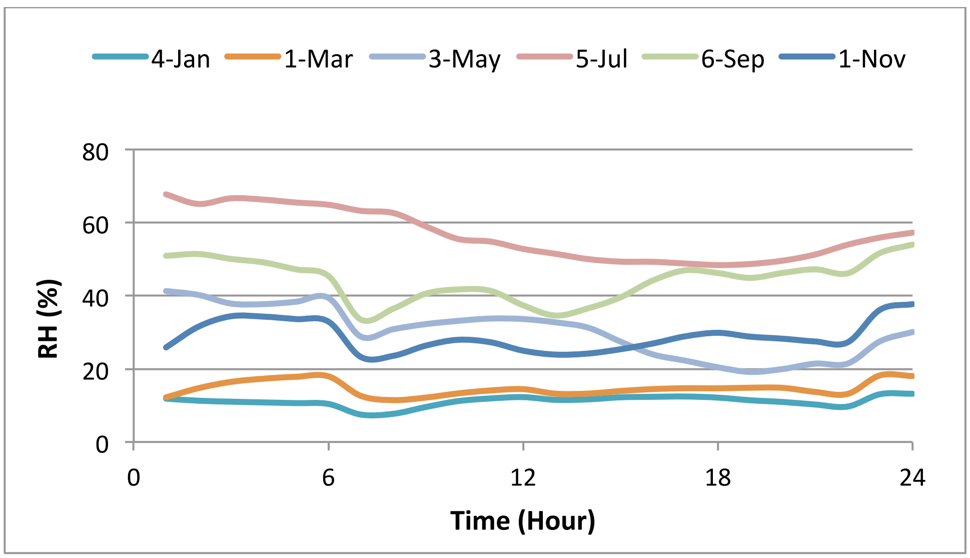


Figure 4-42 Hourly RH of West Zone for the selected days

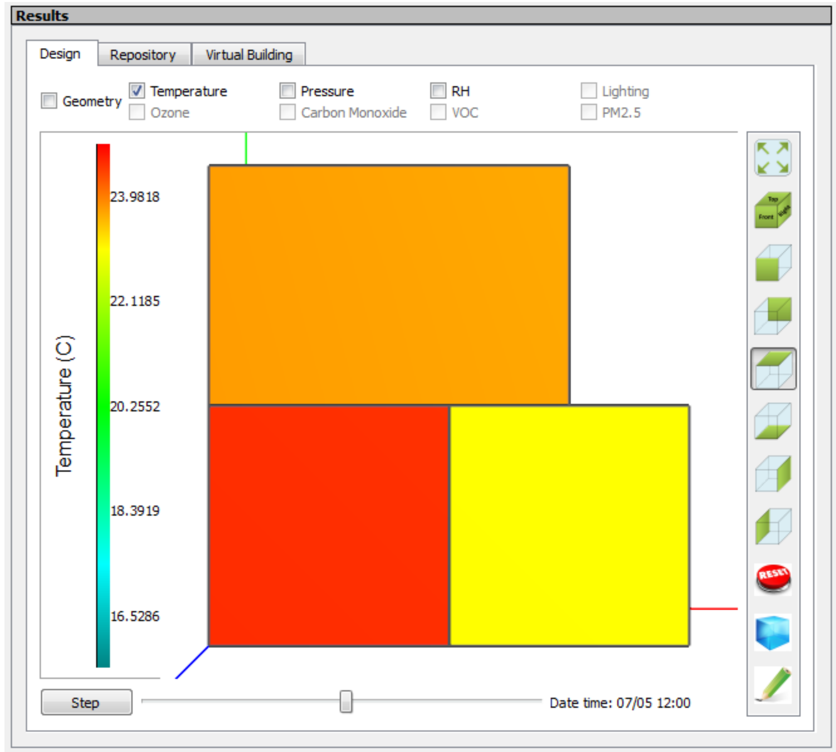


Figure 4-43 Dry-bulb temperature distribution at 12pm on July 5th

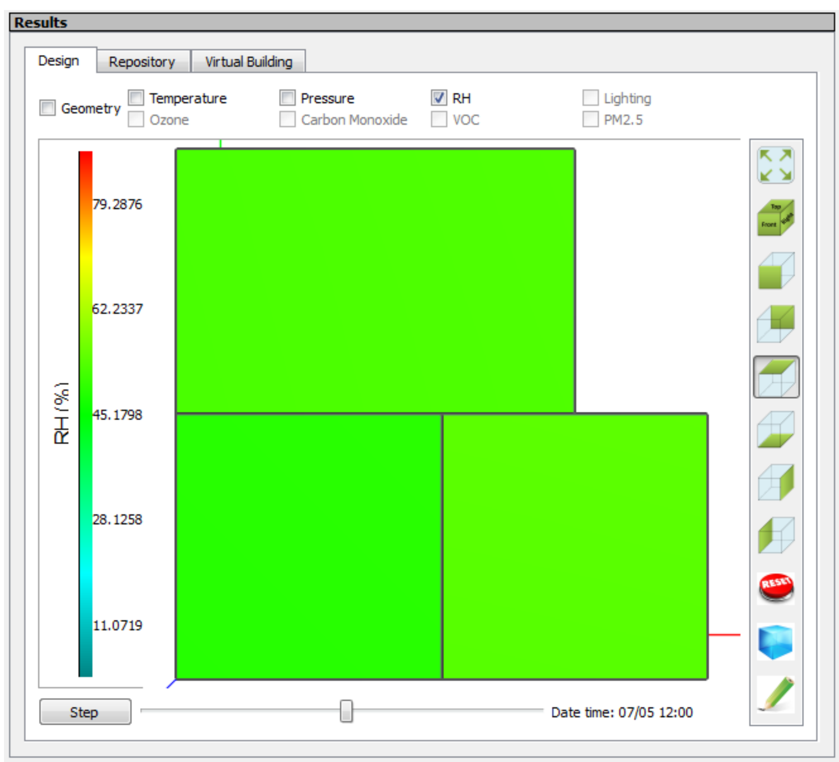


Figure 4-44 RH distribution at 12pm on July 5th

4.3.1.4. PPM and PPV for thermal comfort

The metabolic rate, clothing insulation, air temperature, radiant temperature, air speed, and humidity are used to calculate the Predicated Mean Vote (PMV) and Predicated Percentage of Dissatisfied (PPD). The clothing insulation of 1 clo, metabolic rate of 78.45 W/m^2 with skin surface area of $1.8m^2$, and air speed of 0.137 m/s are used, while the air temperature, radiant temperature and humidity are simulated by EnergyPlus at every time step. Figure 4-45 and Figure 4-46 show the hourly calculated PMV and PPD of West zone for the selected days.

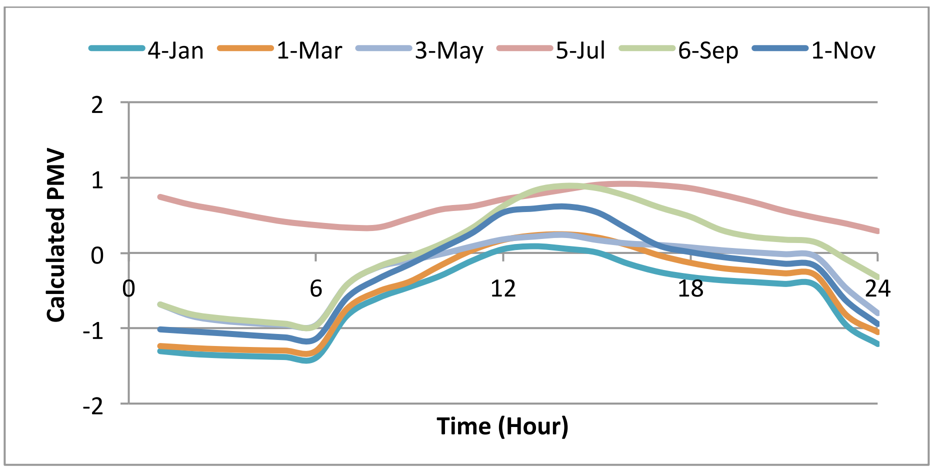


Figure 4-45 Hourly PMV of West Zone for the selected days

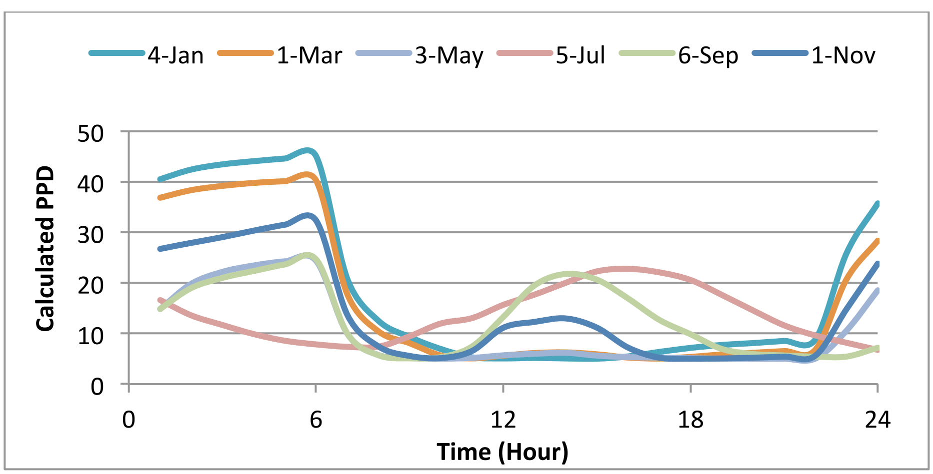


Figure 4-46 Hourly PPD of West Zone for the selected days

4.3.1.5. Air pressure

The airflow network model is included in the EnergyPlus only simulation. The model simulates the zone air total pressure related to the outdoor barometric pressure. Figure 4-47, Figure 4-48 and Figure 4-49 show the hourly relative air pressure of the three zones for the sleeted days.

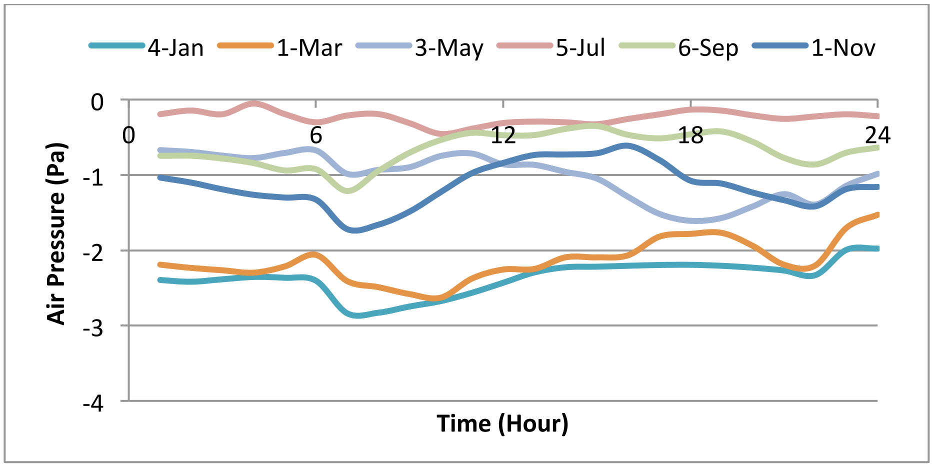


Figure 4-47 Hourly relative air pressure of West Zone for the selected days

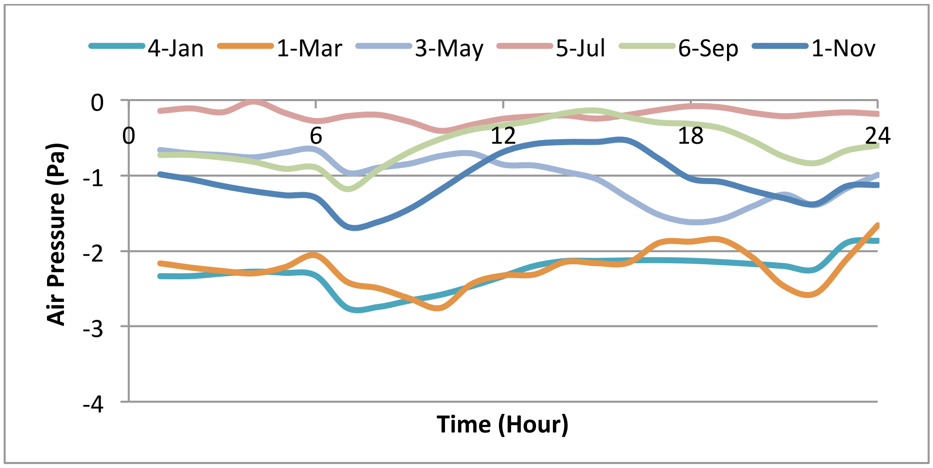


Figure 4-48 Hourly relative air pressure of East Zone for the selected days

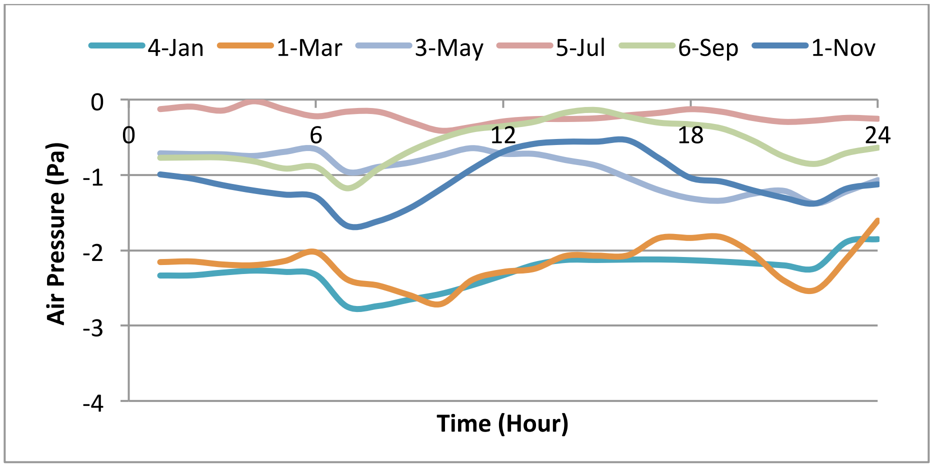


Figure 4-49 Hourly relative air pressure of North Zone for the selected days

4.3.1.6. Illuminance for Daylighting

The illuminance levels of the zones are simulated and used for the daylighting control. Figure 4-50, Figure 4-51, and Figure 4-52 shoe the illumination map at 9 am, 12pm, and 3pm on Sep. 21st.

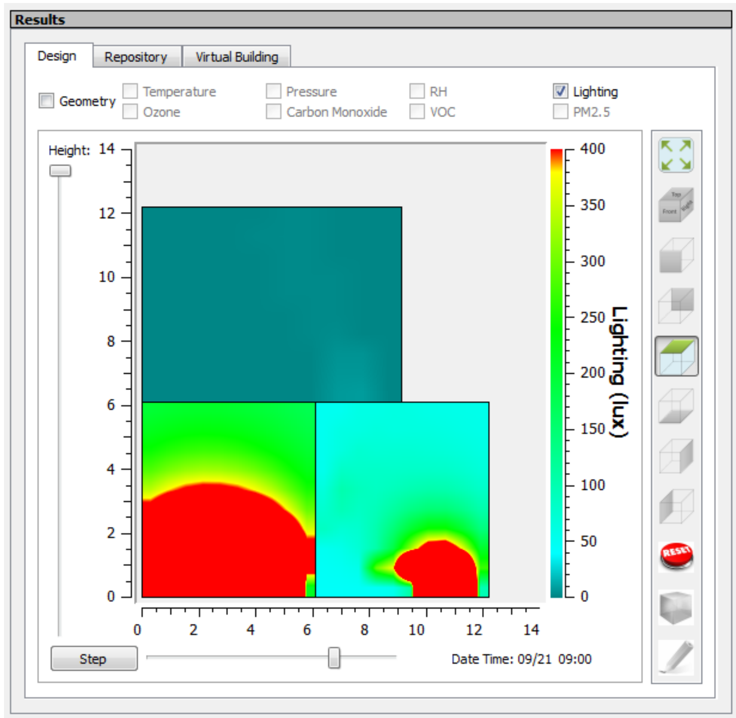


Figure 4-50 Daylighting distribution at 9am on Sep. 21st

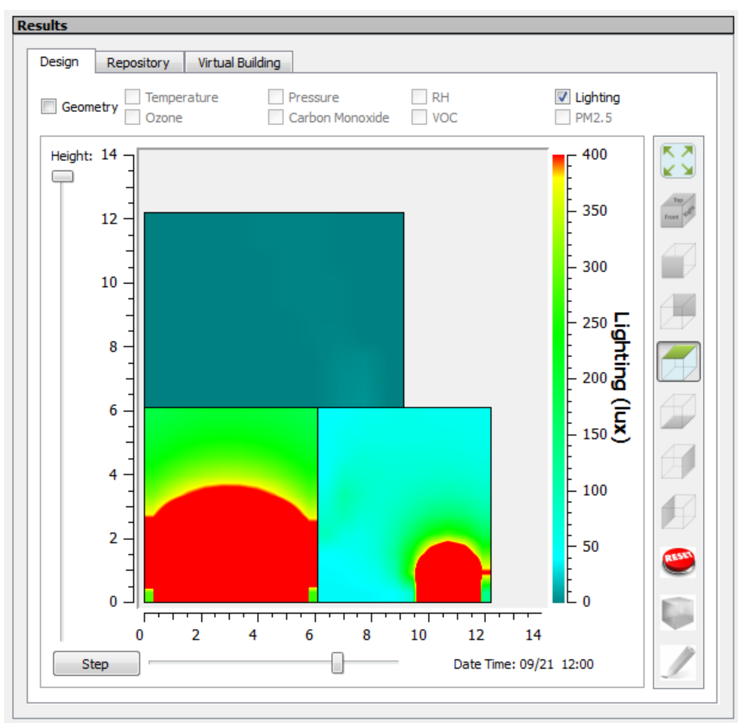


Figure 4-51 Daylighting distribution at 12pm on Sep. 21st

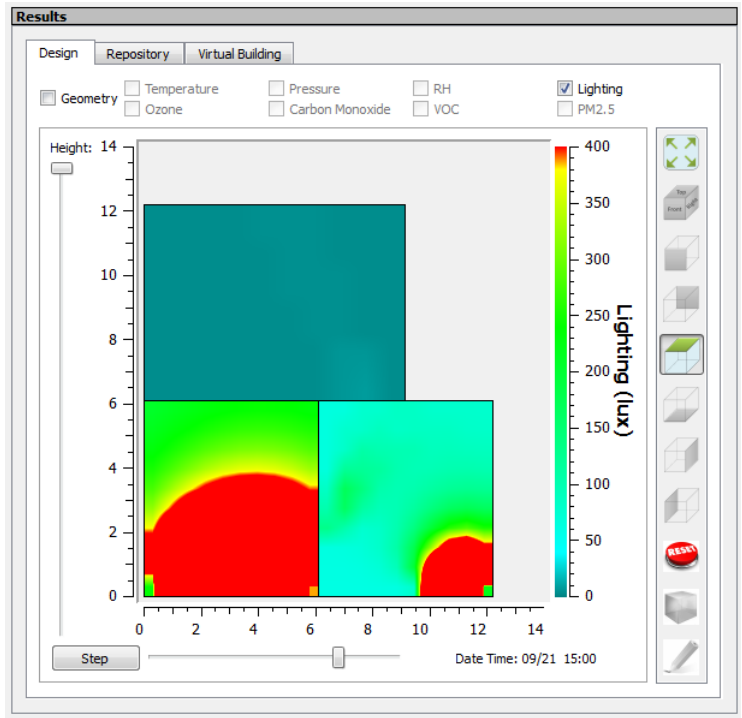


Figure 4-52 Daylighting distribution at 3pm on Sep. 21st

4.3.2. CHAMPS-WholeBuilding co-simulation

In additional to the EnergyPlus only simulation, the CHAMPS-WholeBuilding co-simulation predicts the indoor contaminant concentrations based on the contaminant balance model. Figure 4-53 shows the carbon monoxide distribution at 12pm on July 5th.

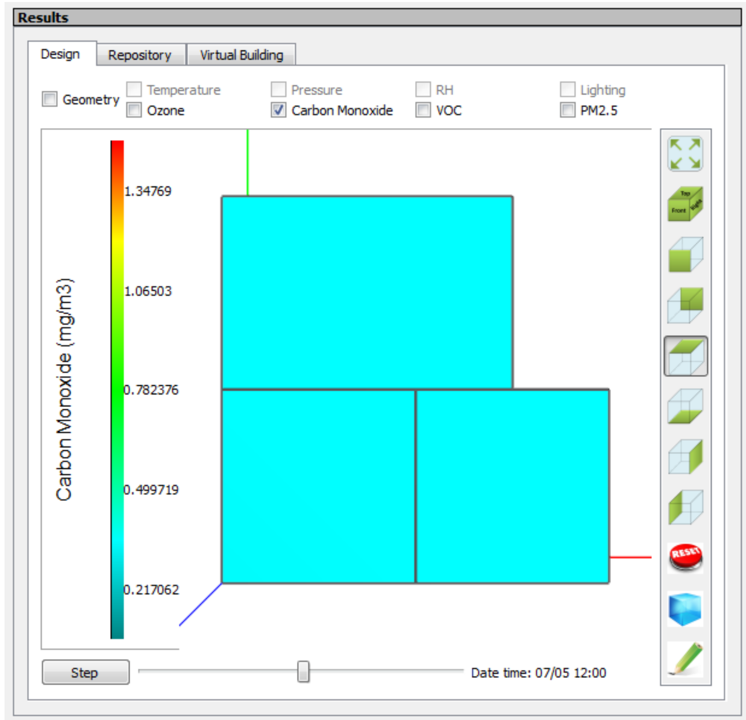


Figure 4-53 Carbon monoxide distribution at 12pm on July 5th

There are no ozone sink or source in the West Zone. The system supply air filter efficiency for ozone is 5%. Figure 4-54 shows the hourly ozone concentration of West Zone. The concentration ranges from 0 to 0.076 ppm with an average of 0.026 ppm.

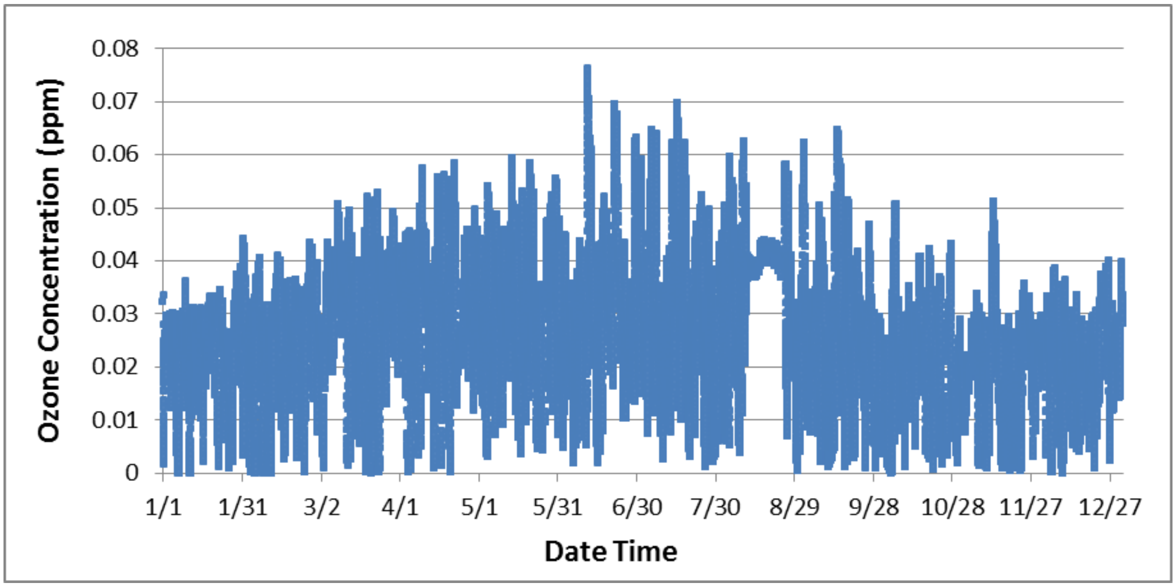


Figure 4-54 West Zone ozone hourly concentration

There are no carbon monoxide sink or source in the West Zone. There is no filter for carbon monoxide. Figure 4-55 shows the hourly carbon monoxide concentration of West Zone. The concentration ranges from 37.3 to 725 ppb with an average of 123 ppb.

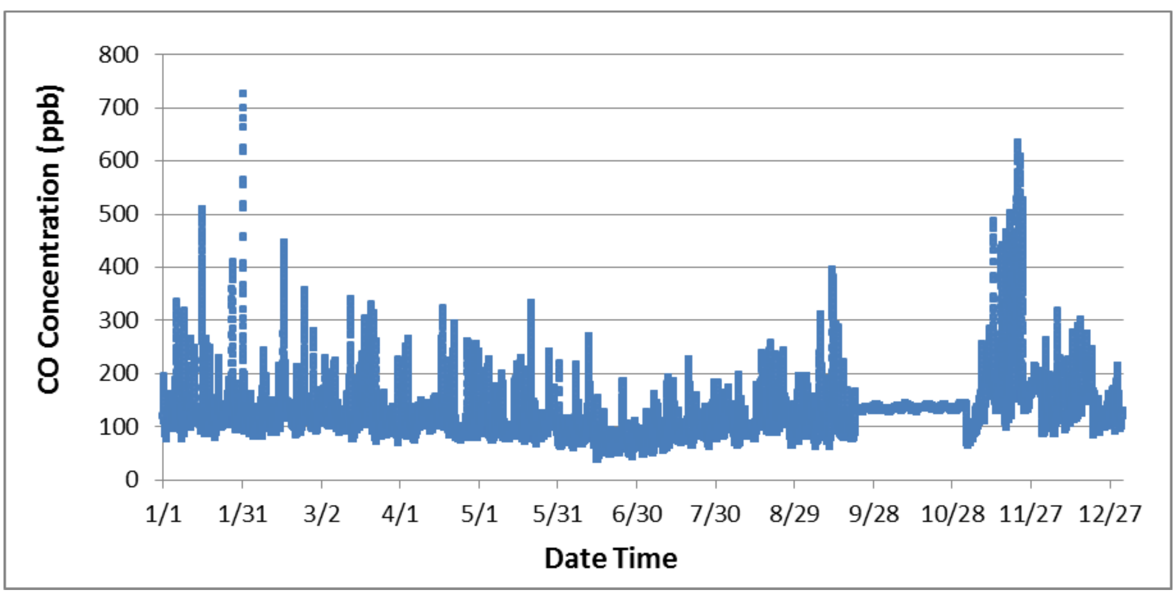


Figure 4-55 West Zone carbon monoxide hourly concentration

There are no PM2.5 sink or source in the West Zone. The system supply air filter efficiency for PM2.5 is 25%. Figure 4-56 shows the hourly PM2.5 concentration of West Zone. The concentration ranges from 0 to 25.3µg/m^3 with an average of 5.1µg/m^3.

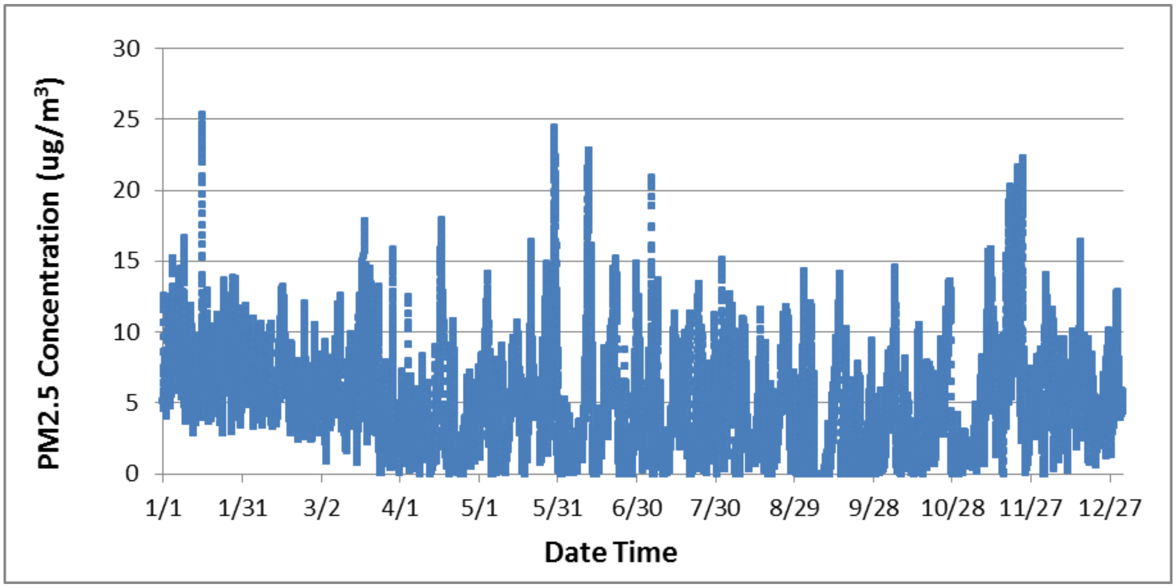


Figure 4-56 West Zone PM2.5 hourly concentration

There is a VOC source of 0.5 mg/m^2.h in the West Zone. There is not filter for. Figure 4-57 shows the hourly VOC concentration of West Zone. The concentration ranges from 0.03 to 0.40 mg/m^3 with an average of 0.13mg/m^3.

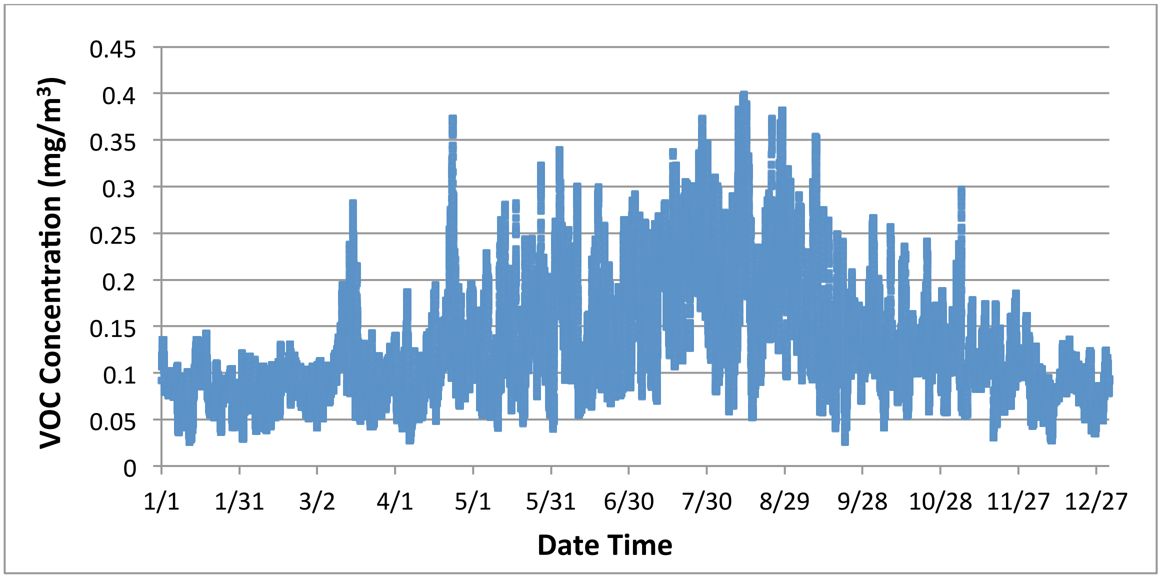


Figure 4-57 West Zone VOC hourly concentration

4.4. Conclusions

First, an integrated simulation environment for energy efficiency and IEQ analysis which enables the simulations of combined heat, air, moisture, pollutant transport and daylighting for whole building has been developed.

Second, EnergyPlus and an enhanced CHAMPS-Multizone model have been integrated for the whole building simulation by using BCVTB for data exchange during run time.

Third, a new template system allows VDS to simulate the ground source heat pump system configurations by revising the current preprocessor program: ExpandObjects has been developed. The program revision provides the capability to develop new templates for future VDS enhancement.

The simulation environment has been tested and verified by using a simple 3-zone building. It will be further tested by using a more complex building, Syracuse COE Headquarters building in Chapter 5.

Chapter 5. Method and Procedure for Performance Evaluation

As reviewed in Section 2.4, there are several performance assessment systems developed to support the design of high performance buildings, including LEED, ASHRAE 189.1, BERRAM, DGNB, and WBDG. These performance assessment systems organize the design strategies into multiple performance aspects (Table 2-3). The designers need to accomplish the design strategies to meet the requirements for the high performance building design. These design strategies have a positive influence on the design, construction and management of buildings.

Some systems like ASHRSE 189.1 and WBDG did not provide a scoring system. On the other hand, some systems like LEED and BREEAM provide a straightforward scoring system to evaluate the building performance by assigning credits directly to the design strategies. When the designers accomplish the requirements for some design strategies in the building design process, LEED and BREEM assign the credits associated with those design strategies to the building. Based on the total credits that the building achieves, LEED and BREEAM determine the rating/certification level of the building (Table 5-1). This straightforward scoring system is transparent, flexible, easy to understand, and is supported by evidence-based science and research (BREEAM, 2012a).

Table 5-1 BREEAM (BRE Global Ltd, 2008) and LEED (USGBC, 2009) rating benchmarks

BREEAM	**Rating**	UNCLASSIFIED	PASS	GOOD	VERY GOOD	EXCELLENT	OUTSTANDING
	Score	<30	≥30	≥45	≥55	≥70	≥85
LEED	**Certification**	Uncertified	Certified	Silver	Gold	Platinum	N/A
	Points	<40	40-49	50-59	60-79	≥80	N/A

There are, however, some limitations of the scoring system that LEED and BREEAM used. First, the design strategies with same amount of credits/points may have different impacts on the building performance. For example, LEED (USGBC, 2009) assigns 5 credits when a new building saves 20% of energy cost compared with the baseline building defined by ASHRAE 90.1 (ASHRAE, 2010c) Appendix G. The same amount of credits is assigned when the energy produced by the on-site renewable systems is 5% of the building's annual energy cost (USGBC, 2009). The two strategies both have 5 credits; however, their impacts on energy performance can be very different. Second, some design strategies may have the impacts on multiple building performance aspects. For example, LEED organizes the "Increased Ventilation" in IEQ aspect (USGBC, 2009), but it can also have negative or positive impact on the "Energy and Atmosphere" aspect depending on climate conditions. Third, the same design strategies may have different impacts on the building performance for difference building conditions. The "Increased Ventilation" strategy may have different impacts on the building performance when the buildings are located in different climate zones. Last and not least, the interaction or inter-dependencies of different strategies are not explicitly considered in the rating system, though the "innovation" credits in the LEED could potentially be used to account for this.

In summary, the scoring system that LEED and BREEAM system used can provide a rough estimation of the building performance, and guide the designers to achieve high performance building design. However, their credits are based on the design strategies instead of the impacts of the design strategies on the building performance. The scoring system mixes the design strategies with the performance criteria. This chapter focuses on the development of a performance evaluation model that has the following functions:

- The model should be able to evaluate all five aspects of building performance, including Site Sustainability, Water Efficiency, Energy and Atmosphere, Materials and Resources, and IEQ.
- The model should be able to evaluate the building performance from early design assessment stages to final detailed design stages.
- The model should be able to evaluate the impacts of both quantitative design parameters and qualitative green building design strategies on the building performance.

This chapter first introduces the overall framework of the VDS performance evaluation model. It then shows the scope of current implementation and discusses the results. A method of modeling the reference building for performance evaluation is developed based on "US DOE Commercial Reference Building Models of the National Building Stock (NREL, 2011)" and "Airflow and Indoor Air Quality Models of DOE Reference Commercial Buildings (Ng, Musser, Persily, & Emmerich, 2012)". A minimum set of design criteria collectively defined by ASHRAE 90.1-2010 (ASHRAE, 2010c), and 62.1-2010 (ASHRAE, 2010b) and 55-2010 (ASHRAE, 2010a) are also considered in defining the reference building. By computing the percentage improvement between the proposed design and the reference building for each performance index, the quantitative evaluation model estimates relative performance of the proposed building. The performance indices can be used to calculate the performance of the sub-performance aspects, and the performance of the sub-performance aspects can be further aggregated to assess the performance aspects, and then the overall building performance. This provides the quantitative evaluation of the proposed building at various design stages.

5.1. Overall framework of VDS performance evaluation model

5.1.1. Classification and organization of performance aspects

Based on the review of existing performance assessment systems, Figure 5-1 shows the systematic classification and hierarchical representation of green building performance aspects considered by VDS, including five performance aspects and their sub-performance aspects. Table 2-3 shows how the VDS performance aspects relate to the existing high performance and green building standards. A brief description of each performance aspect is provided in the following sections.

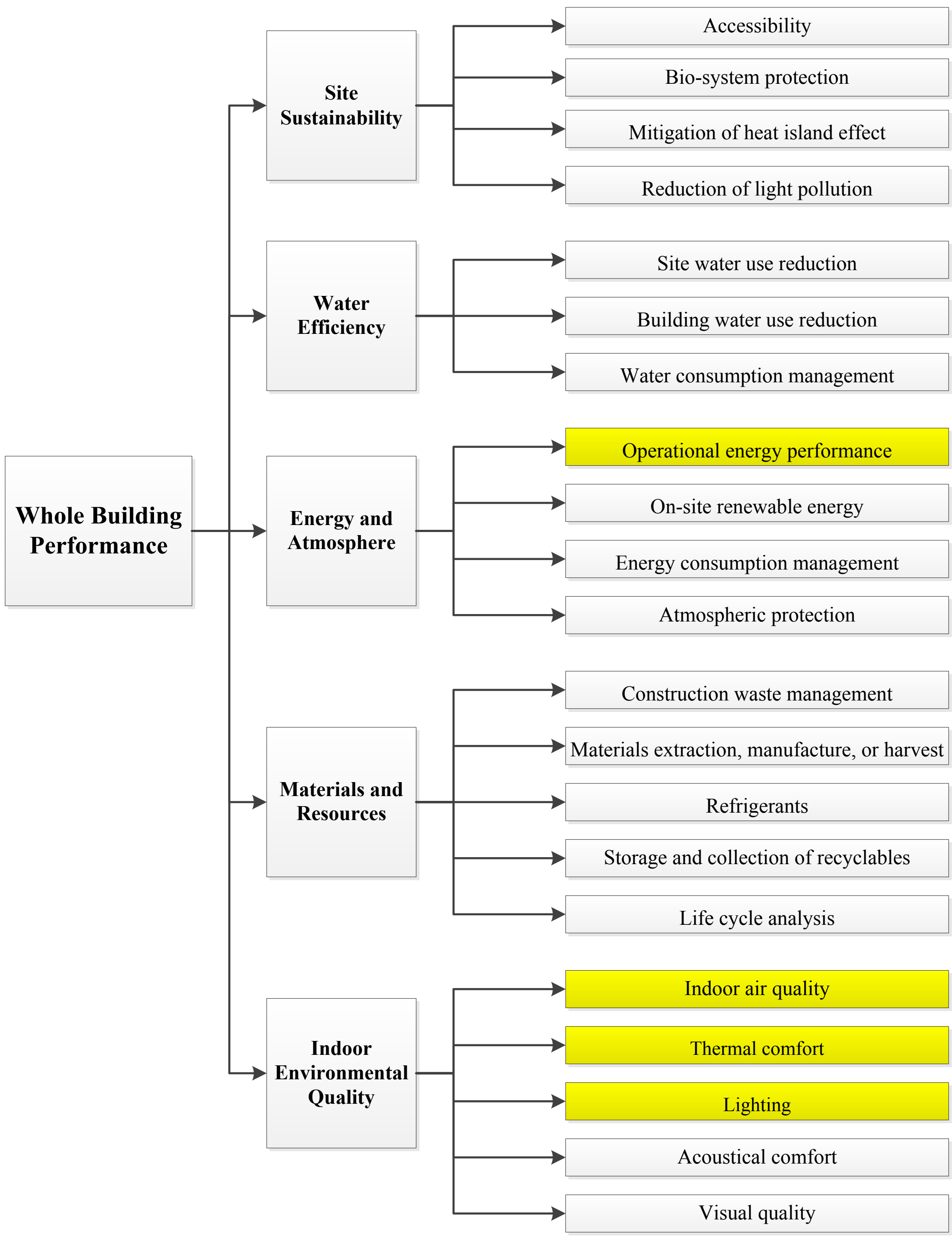


Figure 5-1: Systematic classification and hierarchical representation of green building performance aspects (highlighted sub-performance aspects have been implemented in the current VDS)

5.1.1.1. Site Sustainability

Site sustainability performance aspect measures the performance of the proposed building in terms of its site selection and development (including accessibility associated with transportation, existing and maintained vegetation and bio-diversity, planting sustainable landscapes, providing water management), protecting surrounding habitats, reducing heat island effect, and prevention of excessive light pollution. This performance aspect is categorized into three sub-performance aspects namely accessibility and ecosystems protection, mitigation of heat island effect, and reduction of light pollution.

5.1.1.2. Water Efficiency

Investigations related to water efficiency performance aspects measure the predicted performance of the proposed building in terms of the buildings site water use reduction, building water use reduction, and strategies used for monitoring building water consumption and water efficient landscaping practices incorporated in the building design. This performance aspect is categorized into three sub-performance aspects namely site water use reduction, building water use reduction, and water consumption management.

5.1.1.3. Energy and Atmosphere

Energy and atmosphere performance aspect measures the predicted performance of the proposed building in terms of its operational energy use i.e. energy generation / conservation and minimized consumption for space heating, cooling and ventilating, lighting, service water heating and other "active" operational equipment. The performance of the building in relation to energy generated from renewable energy sources, strategies for tracking energy consumption and buildings impact on the atmosphere in terms of carbon and Chlorofluorocarbon (CFC) emissions is evaluated. This performance aspect is categorized into four sub-performance aspects namely, operational energy performance, on-site renewable energy, energy consumption management, and atmospheric protection.

5.1.1.4. Materials and Resources

Materials and resources performance aspect measures the predicted performance of the proposed building in terms of the sustainability of the buildings materials and the embodied energy respectively, refrigerants, and waste reduction practices as well as building life cycle impact. This performance aspect is categorized into five sub-performance aspects namely, construction waste management, "materials extraction, manufacture or harvest", refrigerants, storage and collection of recyclables, and Life cycle analysis.

5.1.1.5. Indoor Environmental Quality

Indoor environmental quality aspect measures the predicted performance of the proposed building in terms of improved ventilation and managing indoor contaminants, occupant's thermal comfort and acoustical comfort, day-lighting and visual quality. This performance aspect is categorized into five sub-performance aspects namely, indoor air quality, thermal comfort, day-lighting, acoustical comfort, and visual quality.

5.1.2. Relative performance indexing

We propose to use a relative performance indexing system in which the performance at every level of the hierarchical representation of the building performance is quantified by its percent of improvement over a "reference case" at the corresponding level. The reference level can be defined by the minimum standards (which can be the local or state building code requirements, minimum requirements set by professional societies such as ASHRAE), or the average or median performance case for the similar climate and cultural conditions. Details on the reference case definition will be discussed in a later section (see section 5.3).

5.1.3. Performance evaluation method and procedure for each sub-performance aspect

The following procedure is used to evaluate the performance of a sub-performance aspect.

Step 1: Define a reference building which satisfies all the minimum requirements related to all the sub-performance aspects.

> The current implementation focuses on Operational Energy Performance, Indoor Air Quality, Thermal Comfort, and Daylighting sub-performance aspects; therefore, ASHRAE standard 90.1-2010, 62.1-2010 and 55-2010 are considered in the definition of reference building.

Step 2: Define the absolute performance parameter for the sub-performance aspect. The value of the performance parameter must be measurable.

> For example, the performance index for Operational Energy Performance is annual energy cost.

Step 2: Calculate the values of the performance index for both the proposed building (PI_{pb}) and the reference building (PI_{rb}).

> For example, for "Operational Energy Performance", the annual energy cost of both the proposed building and the reference building need to be calculated by considering both

quantitative design parameters and qualitative green building design strategies. The detailed calculation methods for the performance parameters implemented in current research are introduced in Section 5.4.

Step 4: Compare the calculation results to determine the relative performance of the sub-performance aspect. When the performance index is a positive indicator such as energy saving or percent of people satisfied, Equation 5-1 should be applied; if the index is a negative indicator such as energy cost or percent of dissatisfied people, Equation 5-2 should be used.

$$RP_{sp} = \frac{PI_{pb} - PI_{rb}}{PI_{rb}} \qquad \text{Equation 5-1}$$

$$RP_{sp} = \frac{PI_{rb} - PI_{pb}}{PI_{rb}} \qquad \text{Equation 5-2}$$

Where:

RP_{sp} = Relative performance of the sub-performance aspect (percentage improvement compared with the reference building)

PI_{rb} = Performance index of the reference building

PI_{pb} = Performance index of the proposed building

5.1.4. Performance aggregation method

When the relative performances of the sub-performance aspects are calculated, the relative performance of each performance aspect can be obtained by aggregating its sub-performance aspects (Equation 5-3).

$$RP_p = \sum(\omega_{spi} \times RP_{spi}) \quad \text{Equation 5-3}$$

Where:

RP_p: Relative performance of the performance aspect.

ω_{spi}: Weighting factor for i-th sub-performance aspect

RP_{spi}: Relative performance of i-th sub-performance aspect

When the relative performances of the performance aspects are calculated, the relative performance of whole building performance can be obtained by aggregating all the performance aspects (Equation 5-4).

$$RP_{wb} = \sum(\omega_{pi} \times RP_{pi}) \quad \text{Equation 5-4}$$

Where:

RP_{wb}: Relative performance of the whole building

ω_{pi}: Weighting factor for i-th performance aspect

RP_{pi}: Relative performance of i-th performance aspect

As shown in Equation 5-3 and Equation 5-4, any direct summation would require proper weighting factors, which are difficult (if not impossible) to determine due to the comparability among different performance aspects or sub-performance aspects and their dependency on specific project emphases. Further studies of the proper weighting factors are required. For the purpose of the VDS evaluation framework development in the current project, we propose to set the default weighting factors to be 1, while allow users to change according to specific project needs. Setting uniform weighting factors would mean that the relative performance improvement for each performance aspect is given the same recognition in its importance. Such a premise is not unacceptable in the absence of proper justification of assigning more weight to one aspect than another, especially when the performance aspects and sub-aspects are grouped in such a way that each has similar importance among their "peers" at the same hierarchical level. Using the VDS performance framework as example (Figure 5-1), Site Sustainability, Water Efficiency, Energy and Atmosphere, Materials and Resources, and IEQ would have the same priority in design. IEQ's sub-aspects (namely IAQ, thermal comfort, lighting, acoustic, and visual quality) would also have the same importance in design. The total relative improvement of a building's performance is the summation of the relative improvement in all aspects. The maximum possible improvement of a building's performance over a reference case then depends on the number of performance aspects classified and the definition of the reference case.

5.2. Scope of current implementation

For "Energy and Atmosphere" aspect, the total building energy consumption is considered, which is related to the "Operational energy performance" of the "Energy and Atmosphere" performance aspect.

Within the scope of the current VDS development, IAQ, thermal comfort and lighting aspects of the IEQ are considered as they are closely coupled with energy consumption. Acoustic and visual aspects of IEQ have not been included, though it should be considered in the design process.

Therefore, the current implementation aims to evaluate four sub-performance aspects, including “Operational energy performance”, “Indoor air quality”, “Thermal comfort”, and “Lighting” (Figure 5-1). Here after, these four sub-performance aspects are referred as Energy and IEQ aspects.

5.3. VDS reference building definition for energy and IEQ performance evaluation

As introduced in section 5.1, the performance evaluation model calculates the relative performance for each sub-performance aspects, which requires a reference building to compare with. The current implementation focuses on Energy and IEQ performance aspects; therefore, ASHRAE standard 90.1-2010, 62.1-2010 and 55-2010 are considered as the minimum standards in the definition of reference building. This section first introduces the established minimum standards (ASHRAE 90.1-2010, 62.1-2010 and 55-2010), and how they can be used to define the VDS reference building specifically. It then compares the ASHRAE 90.1 baseline building and the NREL reference building. After the comparison, the NREL reference building is adopted as the foundation to develop the VDS reference building. Moreover, additional definition of the indoor air quality conditions for the reference building is presented. Finally, the VDS reference building is introduced.

5.3.1. Building codes and standards for the VDS reference building

Building energy codes and standards establish the minimum level of energy efficiency for residential and commercial buildings. They improve efficiency by mandating performance, achievable through careful construction and proper selection of building components, including insulation for both opaque elements and fenestration, SHGC (Solar Heat Gain Coefficient) for fenestration, HVAC equipment, and lighting power density and controls.

ANSI/ASHRAE Standard 90.1-2010 (ASHRAE, 2010c)**:** Energy Standard for Buildings except Low-Rise Residential Buildings (Table 5-2), is published to provide minimum requirements for the energy-efficient design of new and renovated or retrofitted buildings. ASHRAE 90.1 has become the basis for building codes, and the standard for building design and construction throughout the United States. It has been recommended by DOE as the minimum energy standard to be met by all states in the U.S. It is written in a code intended language as minimum requirements, and hence does not necessarily provide exemplary or state-of-the-art design guidance.

ASHRAE 90.1-2010 is used to determine the requirements for building envelope systems, HVAC systems, and lighting power density for the VDS reference building. Building envelope requirements (Section 5.5.1.4) include: "insulation (maximum U-value and minimum R-value) for roof, ceiling/floor, external wall, internal partition, opaque door, and ground floor construction", and "maximum U-value and SHGC value for window and skylight". The requirements for HVAC systems include: HVAC system type, and the efficiencies of the HVAC equipment (Section 5.5.1.5). Requirements for the lighting power density are introduced in Section 9 of the standard.

ANSI/ASHRAE Standard 62.1-2010 (ASHRAE, 2010b)**:** Ventilation for Acceptable Indoor Air Quality (Table 5-3). The purpose of this standard is to specify minimum ventilation rates and other measures intended to provide indoor air quality that is acceptable to human occupants and that minimizes adverse health effects.

ASHRAE 62.1 is used to determine the ventilation rate, indoor air contaminant concentration limits, and occupant density for the VDS reference building. The detailed information is introduced in Section 5.5.1.3.

ANSI/ASHRAE Standard 55-2010 (ASHRAE, 2010a)**:** Thermal Environmental Conditions for Human Occupancy (Table 5-4). The purpose of this standard is to specify the combinations of indoor thermal environmental factors and personal factors that will produce thermal environmental conditions acceptable to a majority of the occupants within the space.

ASHRAE 55 is used to determine the metabolic rates of the occupants and the thermal comfort conditions in the VDS reference building as shown in Section 0 and Section 5.3.4.5.3.

The above standards are used in the VDS to establish the reference building for evaluating how much the various green building design strategies proposed in the design process would improve the building's Energy and IEQ performance.

Table 5-2: Summary of ANSI/ASHRAE 90.1-2010 (ASHRAE, 2010c)

Purpose The purpose of this standard is to provide minimum requirements for the energy-efficient design of buildings except low-rise residential buildings.		
Scope Requirements for the design and construction of: • new buildings and their systems • new portions of buildings and their systems • new systems and equipment in existing buildings Applicable to spaces: • heated by a heating system whose output capacity is greater than or equal to 3.4 Btu/h·ft2 or • cooled by a cooling system whose sensible output capacity is greater than or equal to 5 Btu/h·ft2		
Focus Area	**Key Performance Criteria**	**Relevant Sections**
Building Envelope	• Minimum rated R-values of insulation for different climatic zones. • Maximum U-factor, C-factor, or F-factor for the entire assembly. • Fenestration and door performance.(U-factor, SHGC, Visible light transmittance) • Air leakage performance and building envelope sealing.	Section 5.1 – 5.8

	• Insulation installation and protection.	
Heating, Ventilating and Air Conditioning	• Mechanical equipment efficiency • Controls • HVAC system construction and insulation • System balancing • Economizers • Simultaneous heating and cooling limitation • Air system design and control • Hydronic system design and control • Heat rejection equipment • Energy recovery • Exhaust hoods • Radiant heating systems • Hot gas bypass limitation	Section 6.1 – 6.7
Service Water Heating	• Sizing of systems • Equipment efficiency • Service hot water piping insulation • System controls • Pools • Heat traps • Space heating and water heating • Service water heating equipment	Sections 7.1 – 7.8
Power	• Voltage drop	Sections 8.1- 8.7
Lighting	• Lighting controls • Tandem wiring • Exit signs • Installed interior lighting power • Luminaire wattage • Exterior building grounds lighting • Interior Lighting Power Allowance • Exterior Lighting Power Allowance	Sections 9.1- 9.6
Other Equipment	• Motor efficiency	Sections 10.1-10.4

Table 5-3: Summary of ANSI/ASHRAE 62.1-2010 (ASHRAE, 2010b)

Purpose The purpose of this standard is to specify minimum ventilation rates and other measures intended to provide indoor air quality that is acceptable to human occupants and that minimizes adverse health effects.
Scope • Applies to all spaces intended for human occupancy except those within single family houses, multi family structures of three stories or fewer above grade. • Defines requirements for ventilation and air cleaning system design, installation, commissioning, operation and maintenance. • Additional requirements for industrial, laboratory, health care and other spaces may be dictated by workplace and other standards as well as by process occurring within the space. • It does not prescribe specific ventilation rate for spaces that contain smoking.

Focus Area	Key Performance Criteria	Relevant Sections
Outdoor Air Quality	• Regional air quality • Local air quality • Documentation	Section 4.1 – 4.3
Systems and Equipment	• Natural ventilation (location and size of openings, control and accessibility) • Ventilation air distribution • Exhaust duct location • Ventilation system controls • Airstream surfaces (resistance to mold growth and erosion) • Outdoor air intake location • Local capture of contaminants • Combustion air • Particulate matter removal • Dehumidification system performance • Finned tube coils and heat exchanger performance • Humidifier system and water spray system performance • Access for inspection cleaning and maintenance • Re-designation	Section 5.1 – 5.18
Procedures	• Ventilation rate procedure • IAQ procedure	Sections 6.1 – 6.4
Construction and Systems Start-Up	• Air duct system construction • Ventilation system start-up	Sections 7.1- 7.2
Operations and Maintenance	• Ventilation system operations • Ventilation system maintenance	Sections 8.1- 8.4

Table 5-4: Summary of ANSI/ASHRAE 55-2010 (ASHRAE, 2010a)

Purpose The purpose of this standard is to specify the combinations of indoor thermal environmental factors and personal factors that will produce thermal environmental conditions acceptable to a majority of the occupants within the space		
Scope • The environmental factors addressed include temperature, thermal radiation, humidity, and air speed • The personal factors include activity and clothing • All the criteria in this standard should be applied together since human comfort is the result of the interaction of all factors. • Applicable for altitudes up to 10,000 ft. • It does not address non-thermal environmental factors such as air quality, acoustics, illumination or other physical, chemical and biological contaminants which will affect human comfort.		
Focus Area	**Key Performance Criteria**	**Relevant Sections**
General Requirements	• Identifying specific space considered and the occupants of that space • Activity and clothing of occupants.	Section 4

Condition that Provide Thermal Comfort	• Methods for determining acceptable thermal conditions in occupied space o Graphical Method for Typical Indoor Application o Computer Model for General Indoor Application o ASHRAE thermal sensation scale/ PMV-PPD index • Acceptable thermal environmental conditions o Operative temperature o Humidity limits o Elevated air speed o Local thermal discomfort o Temperature variation with time • Optional method for determining acceptable thermal conditions in naturally conditioned spaces	Section 5.1 – 5.4
Evaluation of the thermal Environment	• Measuring device criteria • Measurement positions • Measurement periods • Measuring Conditions • Mechanical Equipment Operating Conditions • Validating the Thermal Environment	Sections 7.1 – 7.6

5.3.2. ASHRAE 90.1 baseline building vs. NREL reference building

Appendix G of ASHRAE 90.1 (ASHRAE, 2010c) defined a baseline building for rating the energy efficiency of building designs that exceed the requirements of ASHRAE 90.1. The baseline building may be useful for evaluating the performance of all proposed designs, including alterations and additions to existing buildings, except designs with no mechanical systems. It is adopted by LEED (USGBC, 2009) to evaluate the "Optimize Energy Performance". The performance of the proposed building is compared with the baseline building performance. The proposed building achieves the LEED credits based on the percentage of the improvement over the baseline building. Here after, this baseline building is called the ASHRAE 90.1 baseline building.

NREL (NREL, 2011) also detailed the development of standard or reference energy buildings for the most common commercial buildings to serve as starting points for energy efficiency research. The models represented realistic typical building characteristics and construction practices. Fifteen commercial building types and one multifamily residential building were determined by consensus between DOE, the NREL, Pacific Northwest National Laboratory, and LBNL, and represent approximately two-thirds of the commercial building stock. The reference buildings provided a common starting point to measure the progress of DOE energy efficiency goals for commercial buildings. The models of the reference buildings are used for DOE commercial buildings research to assess new technologies; optimize designs; analyze advanced controls; develop energy codes and standards; and to conduct lighting, daylighting, ventilation, and indoor air quality studies. The input parameters for the building models came from several sources. Some were determined from ASHRAE Standard 90.1-2004, 62.1-2004, and 62-1999 for new construction and Standard 90.1-1989 for post-1980 construction; others were determined from studies of data and standard practices. Here after, this reference building is called the NREL reference building.

The major difference between ASHRAE 90.1 baseline building and the NREL reference building is in the specification of the form and massing of the building. ASHRAE 90.1 baseline building uses the same geometry as the proposed building, while the NREL reference building pre-specifies the form to be the defined typical for a given building type. The ASHRAE 90.1 baseline building can be used to evaluate the percentage improvement resulting from the internal configuration, external enclosure design, and HVAC system design. However, it cannot be used to evaluate the percentage improvement due to form and massing design, as the geometry of the baseline building and the proposed building is the same. However, the form and massing design has significant impact towards achieving high performance building. As VDS is designed to evaluate the impacts of all design factors (including form and massing) on building performance. The NREL reference building is a more suitable starting point to evaluate the impacts of all the design strategies on the energy efficiency. The ASHRAE 90.1 baseline building could be used as second reference point after the form and massing has been defined, but then the interdependence between the "form and massing" and other design factors could not be evaluated. Therefore, the NREL reference building is adopted as the foundation of the VDS reference building, which will be further detailed in Section 5.3.4.

5.3.3. Additional definition of indoor air quality conditions for the reference building

As introduced in Section 4.1, there are two ventilation control procedures considered in this project, which are Ventilation Rate Procedure and IAQ Procedure. Both the ASHRAE 90.1 baseline building and the NREL reference building use Ventilation Rate Procedure to control the indoor air quality. In order to apply the IAQ procedure, additional inputs for outdoor contaminant concentration conditions, indoor contaminant sources, and air purification equipment efficiencies need to be considered.

Ng et al. (2012) modeled the airflow and IAQ using CONTAM (NIST, 2013) based on the NREL reference building to perform the indoor air quality analysis. The airflow and IAQ models specified the outdoor contaminant concentration conditions, the indoor contaminant source, and air purification equipment efficiencies. The method of specifying the information is used to determine the atmosphere pollution, pollutant source and sink, and HVAC filter efficiencies in VDS reference building as shown in Sections 5.3.4. Hereafter, the model is called NIST IAQ model.

5.3.4. Specification of the VDS reference building

Table 5-5 Data sources for the design parameters in each group of the VDS reference building

Category	Group	Data sources
	Building type	Proposed design
Climate	Climate zone	Proposed design
	Heating and cooling design conditions	Proposed design
	Detailed climate conditions	Proposed design
	Atmosphere pollution	Proposed design
Site	Site location	Proposed design
	Building position	Proposed design
	Landscape and surrounding environment	Proposed design
Form		Proposed design and NREL reference building
Zoning	Program type	NREL reference building
	IEQ requirements	ASHRAE 62.1 and 55 and NREL reference building
	Occupancy	ASHRAE 62.1 and 55 and NREL reference building
	Lighting	ASHRAE 90.1 and NREL reference building
	Equipment	NREL reference building
	Pollutant source and sink	NIST IAQ model
	Initial pollution conditions	NIST IAQ model
Enclosure	Roof	ASHRAE 90.1 and NREL reference building
	Façade	ASHRAE 90.1 and NREL reference building
	Internal Assembly	ASHRAE 90.1 and NREL reference building
	Foundation and Basement	ASHRAE 90.1 and NREL reference building
HVAC	System type	ASHRAE 90.1
	Space conditioning	ASHRAE 90.1, and NIST IAQ model
	Air handling system	ASHRAE 90.1, and NIST IAQ model
	Water supply system	ASHRAE 90.1

Current VDS simulation considers the site and climate, form and massing, internal configuration, external enclosure, and HVAC systems in the Energy and IEQ simulation and analysis. The VDS reference building needs to contain all the information about the design parameters in those design factors, which are organized into 6 categories in VDS input quadrant: Climate, Site, Form, Zoning, Enclosure, and HVAC. The data sources used to model the VDS reference building include: ASHRAE 90.1-2010, ASHRAE 62.1-2010, ASHRAE 55-2010, NREL reference building, NIST IAQ model, and the information from the proposed design. Table 5-5 shows the data sources for the design parameters in each group of the VDS reference building.

5.3.4.1. Building type, climate, and site

Office buildings were divided into small, medium, and large, based on the number of floors (small is defined as single story, medium as two to four stories, and large more than four stories) (NREL, 2011). The current research focuses on the medium and large office buildings. The building type, climate, and site information of the VDS reference building is the same as the proposed building.

5.3.4.2. Form

The form of the medium and large office buildings of the NREL reference buildings "were developed from analysis of Commercial Building Energy Consumption Survey (CBECS) (US EIA, 2005) and Time-Saver Standards for Building Types (DeChiara & Crosbie, 2001) and from experience with the building types" (NREL, 2011). Based on the NREL reference building for small, medium, and large office building, the specification of the form and massing for the VDS reference building is shown as follows.

The shape of the VDS reference building for small, medium, and large office buildings is rectangular block (Figure 5-2). The floor area of each story is the same as the average floor area of the proposed building. The number of floors is the same as the proposed building. Each story is divided into five zones, four perimeter zones and one core zone. The depth of the perimeter zone is 4.57m (15ft). Table 5-6 shows the VDS reference building form parameters. Aspect ratio is defined as the length in the east-west direction divided by the width in the north-south direction.

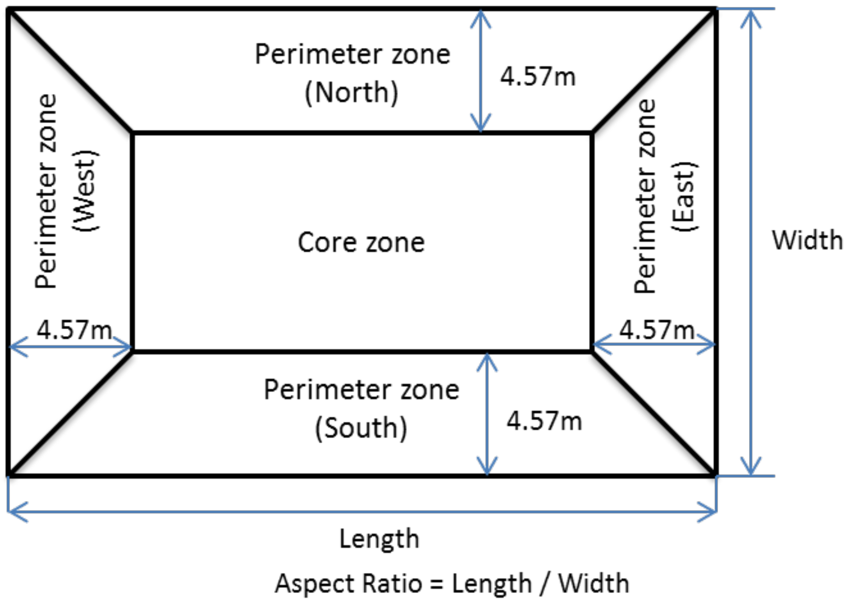


Figure 5-2 Floor plan of the VDS reference building for office buildings

Table 5-6 VDS reference building form parameters

Building Type	Small Office	Medium Office	Large Office
Floor Area	Proposed design	Proposed design	Proposed design
Aspect Ratio	1.5	1.5	1.5
No. of Floors	1	Proposed design	Proposed design
Floor-Floor Height (m)	3.05	3.96	3.96
Floor-to-ceiling height (m)	3.05	2.74	2.74
Glazing Fraction	0.21	0.33	0.38

Figure 5-3 shows the relationship between the width of the core zone and the total floor area of the story in the VDS reference building for office. It should be pointed out that the method introduced in this section may not be applicable for the buildings with “small average floor area”. In this study, the “small average floor area” is defined as the average floor area less than 300 m^2 where the width in north-south direction of the core zone is less than 5 m.

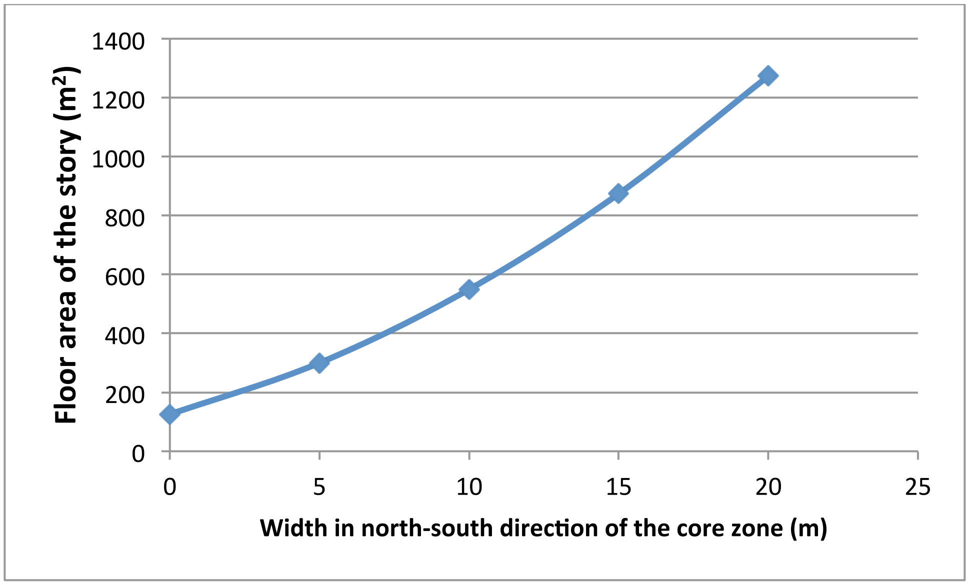


Figure 5-3 Relationship between the width of the core zone and the total floor area of the story

5.3.4.3. Zoning

5.3.4.3.1. Program type

The original geometry characterization of the reference models was developed by LBNL to capture the average energy consumption patterns and intensities of a specific building sector. The reference models were not intended to create realistic looking "typical" buildings (Huang, Akbari, Rainer, & Ritshard, 1991). Each story of the reference building for office buildings was divided into five zones, and all the zones are considered as office space. It should be point out that a detailed office building may include corridors, storage rooms, conference rooms, reception, lobby, atria, restrooms, and others. Huang el al. (1991) calibrated the 5-zone model by comparing with the detailed building with 26 zones. The results showed that the 5-zone model avoided the extraneous detail in the 26-zone building description, while still capturing the diversity in energy use intensities between different areas due to their differing comfort criteria and HVAC system configurations. Therefore, the program types in the VDS reference building for office buildings are all "Office".

5.3.4.3.2. IEQ requirements

The IEQ requirements include thermal comfort, outdoor ventilation rate, and daylighting control. For thermal comfort, the thermostats of all zones are set to the same as the NREL reference building. The Ventilation Rate procedure is used in the VDS reference building to control the IAQ. The outdoor air requirements for the space are from ASHRAE 62.1-2010. There is not daylighting control in the VDS reference building, meaning that the same artificial lighting density requirements will be applied regardless of the availability of day-lighting for any given zone.

5.3.4.3.3. Occupancy

The occupancy densities for the VDS reference building models were taken from the maximum occupancy densities in ASHRAE 62.1-2010. The metabolic rates for the typical tasks are from ASHRAE 55-2010. The occupancy schedules are from NREL reference building.

5.3.4.3.4. Lighting

The lighting power densities for the VDS reference building models were set to the lighting power densities using the building area method in ASHRAE Standard 90.1-2010, defined as Watt per unit floor surface area. The lighting schedules listed in the NREL reference building are adopted for VDS reference building.

5.3.4.3.5. Equipment

Determining the plug or process load intensity is difficult because available measured data are scarce (NREL, 2011). The plug or process load intensities in the VDS reference buildings are set to the same as the NREL reference buildings.

5.3.4.4. Enclosure

The building envelope requirements for each climate zone were determined from ASHRAE 90.1-2010. For the VDS reference building, the constructions need to be defined, including roof construction, ceiling/floor construction, external wall construction, window construction, internal partition construction, and ground floor construction.

ASHRAE 90.1-2010 defines three primary roof types, three ceiling/floor types, four wall (external wall) types, four window types, and two slab-on-grade floor (ground floor) types. There are not requirements for the internal partition in ASHRAE 90.1-2010. The NREL reference building provided the recommendations for the roof, wall, and ground floor construction by building type based on the analysis of the CBECS data. In this study, the ceiling floor construction types are determined based on the external wall type; while the window construction type are considered as fixed window with metal framing. Table 5-7 shows the recommended construction types for medium and large office building.

The constructions and materials used in VDS reference buildings are based on the NREL reference building for new constructions, and are modified to meet the building envelope requirements in ASHRAE 90.1-2010.

Table 5-7 Recommended constructions for medium and large office building

Envelope component	Construction Types	
	Medium Office	**Large office**
Roof	Insulation entirely above deck	Insulation entirely above deck
Ceiling/Floor	Steel-Joist	Mass
External Wall	Steel frame	Mass
Window	Metal framing (fixed window)	Metal framing (fixed window)
Ground floor	Unheated	Unheated
Internal partition	No insulation requirement	No insulation requirement

5.3.4.5. HVAC

The baseline HVAC systems defined in ASHRAE 90.1-2010 are used in the VDS reference building. The system type is determined based on the building type and the available energy sources. The equipment sizing for the VDS reference building models is determined from design day simulations by EnergyPlus with a sizing safety factor of 1.2. The equipment efficiencies for fans, pumps, chillers, and boilers are determined from ASHRAE 90.1-2010. The equipment efficiencies for filters are determined from NIST IAQ model. Section 5.5.1 provides a complete definition of the reference building for the Syracuse CoE building as a case study.

5.4. Performance evaluation for Energy and IEQ aspect

5.4.1. Performance indicator for each sub-performance aspect

As introduced in Section 5.1.3, in order to calculate the performance for each sub-performance aspect, the performance index of the sub-performance aspect and the calculation method for the performance index needs to be defined. This section introduces the performance indices for the four sub-performance aspects as discussed in Section 5.2. The sub-performance aspects considered in current implementation are Operational Energy Performance, Indoor Air

Quality, Thermal Comfort, and Daylighting. The definition and calculation of the performance indices of these four sub-performance aspects are introduced in the following sections.

The current VDS implementation focuses on the evaluation of the impacts of the quantitative design parameters on the building performance. There is an ongoing study of this performance evaluation model which will expand the capability to evaluate the impacts of the qualitative design strategies on the building performance.

5.4.1.1. Operational Energy Performance aspect

In consistence with LEED 2009, the "Operational Energy Performance" aspect evaluates the operational energy performance of the buildings to reduce the environmental and economic impacts associated with excessive energy use. It can be achieved by reducing the system loads and/or improving the equipment efficiencies.

There are several performance indicators that are related to "Operational Energy Performance", such as Energy Consumption, CO_2 Emission, and Energy Cost. The Energy Consumption and CO_2 emission indicators can be used to evaluate the environmental impacts of the building; while the Energy Cost indicator can be used to evaluate the economic impacts of the building. The Energy Consumption and CO_2 Emission indicators do not distinguish the difference of the energy sources. The Energy Cost indicator aggregates the different energy sources consumed by the buildings based on their prices. In this study, the annual energy cost is used as the performance indicator for the "Operational Energy Performance" aspect.

The VDS simulation models predict the energy consumption of the building by end use, including heating, cooling, fans, pumps, lights, and equipment. The energy cost can be obtained based on the amount of energy consumed and the price of the energy.

5.4.1.2. Indoor Air Quality aspect

In consistence with LEED 2009, the intent of "Indoor Air Quality" aspect is to improve indoor air quality (IAQ) and promote occupant comfort, well-being and productivity. It can be achieved by providing additional outdoor air ventilation, installing air purification equipment, or reducing the sources of the contaminants that are odorous, irritating and/ or harmful to the comfort and well-being of installers and occupants.

5.4.1.2.1. Definition of the performance index

As introduced in Chapter 4, the whole building performance simulation models predict the pollutant concentrations in each zone at each simulation time step based on the airflow network model and pollutant balance model. The U.S. Environmental Protection Agency (EPA) (US EPA, 1999) presented the method to report the outdoor air quality using the Air Quality Index (AQI). As introduced in Section 5.4.1.2.2, the US EPA AQI is calculated based on the outdoor air pollutant concentration data. The EPA AQI was adopted or modified by several researches to evaluate the outdoor air quality. Kumar and Goyal (Kumar & Goyal, 2013) presented the forecasting of US EPA AQI in Delhi using neural network based on principal component analysis. Golge et.al (Golge, Yenilmez, & Aksoy, 2013) presented an air-water quality index by the aggregation of US EPA AQI and a water quality index to evaluate air and water pollutions levels. Dimitriou et.al (Dimitriou, Paschalidou, & Kassomenos, 2013) presented the assessment of the air quality with regards to its effects on human health at 14 monitoring stations in 8 European Union countries through two different two different AQI methodologies. One of the AQI methodologies was a modification of the US EPA AQI.

The US EPA AQI was developed based on the impacts of the exposure to the contaminants on the human health. It should be able to be used for indoor contaminants as well. Therefore, in this study, the US EPA AQI is adopted to evaluate the indoor air quality in each zone at each time step. The AQIs in every zone at every time step are further aggregated to calculate the whole building air quality index (WBAQI). The calculation method for US EPA AQI and the aggregation method are introduced in the following section. The WBAQI is used as the performance index for the "Indoor Air Quality" aspect. It is understood that the WBAQI defined per the EPA AQI is only limited to the indoor pollution due to outdoor sources. A more complete WBAQI should include pollutants from indoor sources and secondary pollutants due to indoor and surface chemistry (e.g., O3 initiated reaction products). The approach used in defining the AQI for outdoor pollutants, however, can be extended to include indoor pollutants as to shown in the AQI definition for formaldehyde in the following section.

5.4.1.2.2. Calculation of the performance index

5.4.1.2.2.1. Calculation of AQI

The AQI of ozone, PM 2.5, carbon monoxide, or formaldehyde can be calculated by using the pollutant concentration data, linear interpolation equation (Equation 5-5), and the breakpoints information in Table 5-8. The Equation 5-5 is referred from US EPA report (US EPA, 1999). The pollutant concentrations are time-average values with the time given in Table 5-8. Figure 5-4 shows the relationship between the calculated AQI values with the air quality categories. When single containment is considered, the calculated AQI values of the single containment are used; when multiple contaminants are considered, the aggregated AQI values for multiple contaminants are used.

$$I_p = \frac{I_{Hi} - I_{Lo}}{BP_{Hi} - BP_{Lo}}(C_p - BP_{Lo}) + I_{Lo}$$ Equation 5-5

Where:

I_p: The index of pollutant p

C_p: The rounded concentration of pollutant p

BP_{Hi}: The breakpoint that is greater than or equal to C_p

BP_{Lo}: The breakpoint that is less than or equal to C_p

I_{Hi}: The AQI value corresponding to BP_{Hi}

I_{Lo}: The AQI value corresponding to BP_{Lo}

Table 5-8 Breakpoints for the AQI

Breakpoint					AQI value
Ozone (ppm) 8-hour	Ozone (ppm) 1-hour	PM2.5 (µg/m3) 24-hour	CO(ppm) 8-hour	Formaldehyde (ppb) 8-hour	
0.06	-	15	4	13.5	50
0.08	0.12	40	9	27.0	100
0.10	0.16	65	12	41.8	150
0.12	0.2	150	15	56.5	200
0.37	0.4	250	30	76.7	300
-	0.5	350	40	78.9	400
-	0.6	500	50	81	500

Air Quality Index (AQI) Values	Levels of Health Concern	Colors
When the AQI is in this range:	*...air quality conditions are:*	*...as symbolized by this color:*
0 to 50	Good	Green
51 to 100	Moderate	Yellow
101 to 150	Unhealthy for Sensitive Groups	Orange
151 to 200	Unhealthy	Red
201 to 300	Very Unhealthy	Purple
301 to 500	Hazardous	Maroon

Figure 5-4 Relationship between the AQI value and air quality categories

Table 5-9 Relationship between the time exposure concentration level and the AQI values

Exposure time	Carbon monoxide concentrations level	Formaldehyde concentration level	AQI values
8 hours	9 ppm	27 ppb	100
1 hour	25 ppm	76 ppb	266
30 minutes	50 ppm	81 ppb	500

1The breakpoints for ozone 8-hour, ozone 1-hour, PM2.5, and carbon monoxide in Table 5-8 are adopted from the US EPA report (US EPA, 1999). The breakpoints for formaldehyde are proposed based on the comparison of ASHRAE Standard 62.1-2010 (ASHRAE, 2010b) requirements and the US EPA report (US EPA, 1999), whereas a lower limit of the two documents was adopted, Table 5-9). Table 5-9 shows the concentration limits of carbon monoxide and formaldehyde based on the exposure time suggested by ASHRAE Standard 62.1-2010. It also listed the AQI values based on the carbon monoxide concentration level. The same

AQI values are used by the formaldehyde at the given concentration level. A linear interpolation is used to determine the other breakpoints for formaldehyde. The final results of the breakpoints for formaldehyde are shown in Table 5-8.

For ozone, both 1-hour and 8-hour AQI values need to be calculated. For multiple pollutants, we use the highest AQI value as the AQI value of the zone at the time step (Equation 5-6) to represent the worst case scenario, as recommended by EPA in the outdoor air quality assessment.

$$I_{zt} = \max(I_p) \quad \text{Equation 5-6}$$

Where:

I_{zt}: The AQI value of the zone at each time step

I_p: The index of pollutant p.

5.4.1.2.2.2. Aggregation of the AQI

As shown above, the AQI value of each zone at each time step is determined based on the pollutant concentration data of the zone from both current time step and the previous time steps. The data are used to calculate the 1-hour average, 8-hour average, and 24-hour average contaminant concentrations.

The aggregation method introduced in this section aims to obtain a whole building air quality index value to determine the indoor air quality performance of the design. The AQI values at a given time step of all the zones are aggregated through the space domain by using the number of people in each zone at that time step. This method calculates the overall exposure for the occupants, and takes into account the effect of occupancy pattern. In this method, the zones with large number of people have higher impacts then the zones with small number of people (Equation 5-7).

$$I_{WB} = \frac{\sum_{t=T_s}^{T_e}\left[\sum_{z=1}^{N_z}(I_{zt} * \text{People}_{zt})\right] * \Delta t}{\sum_{t=T_s}^{T_e}\left[\sum_{z=1}^{N_z}(\text{People}_{zt})\right] * (T_e - T_s)} \quad \text{.....................Equation 5-7}$$

Where

I_{WB}:	The WBAQI value
I_{zt}:	The AQI value of zone z at time t
$People_{zt}$:	The number of people in zone z at time t
z:	The zone index
t:	The time
N_z:	The number of zones
Δt:	The time step
T_s:	The simulation start time
T_e:	The simulation end time

5.4.1.3. Thermal Comfort aspect

The intent of "Thermal Comfort" aspect is to provide a comfortable thermal environment that promotes occupant productivity and well-being.

5.4.1.3.1. Definition of the performance index

The most notable models have been developed by P.O. Fanger (the Fanger Comfort Model), the J.B. Pierce Foundation (the Pierce Two-Node Model), and researchers at Kansas State University (the KSU Two-Node Model) (US DOE, 2012b). "Fanger's Comfort model was the first one developed. It was published first in 1967 (Fanger, 1967) and then in1970 (Fanger, 1970), and helped set the stage for the other two models. The mathematical model developed by P.O. Fanger is probably the most well-known of the three models and is the easiest to use because it has been put in both chart and graph form. (US DOE, 2012b)" The Fanger's Comfort model was used for the ISO Standard 7730. The ISO Standard 7730 was then used by ASHRAE 55-2010 (ASHRAE, 2010a) to calculate the PMV (Predicated Mean Vote) and PPD (Predicated Percentage of Dissatisfied) values.

The PMV is an index that predicts the mean value of the votes of a large group of persons on the seven-point thermal sensation scale. The PMV model uses heat balance principles to relate the six key factors for thermal comfort to the average response of people on the seven-point thermal sensation scale (ASHRAE, 2010a). The key factors include: metabolic rate, clothing insulation, air temperature, radiant temperature, air speed, and humidity. The PPD is an index calculated based on the PMV value to determine the percentage of people who are dissatisfied.

In this study, the PPD is adopted to evaluate the thermal comfort in each zone at each time step. The PPD values in every zone at every time step are further aggregated to calculate the whole building thermal comfort index (WBTCI), which is used as the performance index for the "Thermal Comfort" aspect.

The Fanger's Comfort model is included in EnergyPlus to calculate the PMV and PPD values for each zone at each time step. The calculation method of PMV and PPD can be found from EnergyPlus Engineering Reference (US DOE, 2012b). The same aggregation method as introduced in Section 5.4.1.2.2.2 is used.

5.4.1.4. Daylighting aspect

The intent of "Daylighting" aspect is to provide building occupants with a connection between indoor space and the outdoors through the introduction of daylight and views into the regularly occupied areas of the building (USGBC, 2009).

5.4.1.4.1. Definition of the performance index

In order to achieve the "IEQ Credit 8.1: Daylight and Views – Daylight" in the LEED system, the criteria via simulation are demonstrated through computer simulations that 75% or more of all regularly occupied spaces areas achieve daylight illuminance levels of a minimum of 25 footcandles (fc) and a maximum of 500 fc in a clear sky condition on September 21 at 9am and 3pm. Areas with illuminance levels below or above the range do not comply. However, designs that incorporate view-preserving automated shades for glare control may demonstrate compliance for only the minimum 25 fc illuminance level. (USGBC, 2009)

The WBDG (WBDG, 2013) presented the general principles and commitments for daylighting for federal high performance and sustainable buildings design. The general principles and commitments is to achieve a minimum of daylight factor of 2 percent (excluding all direct sunlight penetration) in 75 percent of all space occupied for critical visual tasks. Provide automatic dimming controls or accessible manual lighting controls, and appropriate glare control.

In order to give building users sufficient access to daylight, the BREEAM (BRE Global Ltd, 2010) required the following demonstrates compliance:

1. At least 80% of net lettable office floor area is adequately daylight as follows:

    a. An average daylight factor of 2% or more.

PLUS either (b) **OR** (c **AND** d) below

    b. A uniformity ratio of at least 0.4 or a minimum point daylight factor of at least 0.8% (spaces with glazed roofs, such as atria, must achieve a uniformity ratio of at least 0.7 or a minimum point daylight factor of at least 1.4%).

OR

    c. A view of sky from desk height (0.7m) is achieved.

AND

    d. The room depth criterion $\frac{d}{w} + \frac{d}{H_w} < \frac{2}{(1-R_B)}$ is satisfied.

    Where:

d: The room depth

w: The room width

H_w: The window head height from floor level

R_B: Average reflectance of surfaces in the rear half of the room.

2. The provision of daylight has been designed in accordance with the guidance in CIBSE Lighting Guide 10 Daylighting and window design, BS8206 Part 2 and the BRE Site Layout Guide.

By comparing the three systems mentioned above, they all require a minimum daylight illuminance levels or daylight factors for more than certain percentage of floor area. Moreover, they all consider the glare control. LEED requires a maximum daylight illuminance levels when the design does not incorporate view-preserving automated shades for glare control. Based on the review, a daylight performance index (DPI) is defined as the percentage of all regularly occupied floor areas that meets the daylight requirements. The daylight requirements are: 1) the spaces need to achieve daylight illuminance levels of a minimum of 25fc (269 lux); and 2) if the design does not incorporate view-preserving automated shades for glare control, the space's daylight illuminance does not exceed a maximum of 500 fc (5382 lux). The DPI already aggregates the space domain using the regularly occupied floor area as the reference, and hence is scalable from individual zones to whole buildings by using the occupied floor area of corresponding zones as the weights for calculating the weighted average for the whole building. The DPIs at every time step are further aggregated to calculate the whole building daylight performance index (WBDPI).

The calculation method for DPI and the aggregation method are introduced in Section 5.4.1.4.2. The WBDPI is used as the performance index for the "Daylighting" aspect.

5.4.1.4.2. Calculation of the performance index

Figure 5-5 shows the procedures for calculating the whole building daylight performance index. The calculation methods of the whole building daylight performance index are introduced step by step as follows:

Step 1: the mesh for each zone is performed to generate the grids for daylighting simulation. The minimum scale is set to 0.1 m as default and the maximum scale is set to 0.5 m as default. VDS provides the capability for users to specify the minimum and maximum scales.

Step 2: EnergyPlus (US DOE, 2012b) is used to simulate the illuminance level for each grid point at each hour.

Step 3: Calculate the DPI for each hour. First, check whether the illuminance level of the grid at the hour meets the daylight requirements. If yes, the area of the grid is added to the complied area. After all the grids are checked, the DPI of the hour can be calculated (Equation 5-11).

$DPI_t = \frac{CA_t}{TOA}$………………..Equation 5-8

Where

DPI_t: The daylight performance index of time t

CA_t: The complied area of time t

TOA: The total occupied area

Step 4: Calculate the whole building daylight performance index. After all the DPIs are calculated, they are further aggregated to obtain the whole building daylight performance index.

$$WBDPI = \frac{\sum_{t=1}^{N_t}(DPI_t)}{N_t} \text{.....................Equation 5-9}$$

Where:

$WBDPI$: The whole building daylight performance index

DPI_t: The daylight performance index at time index t

N_t: The number of hours aggregated

t: The time index

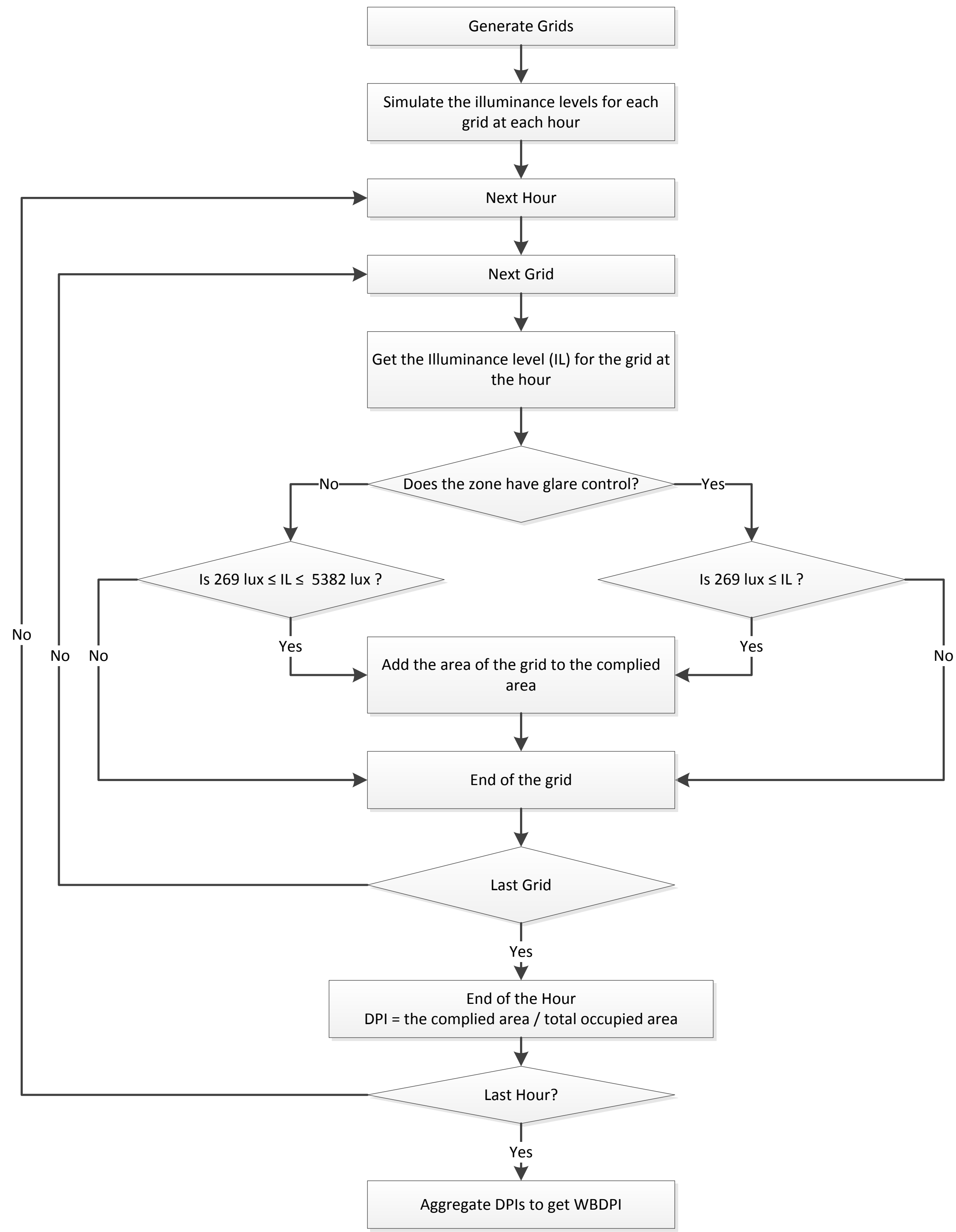


Figure 5-5 Procedures for calculating the whole building daylight performance index (WBDPI)

5.4.2. Determine the potential and contributions of the design factors on the performance improvement

Section 5.4.1 introduces the method to evaluate the performance improvement over the reference building when all the quantitative design parameters are considered at the same time. This section presents the methodology to determine the potential and contribution of each design factor on the performance improvement.

As shown in Figure 3-1, there are eight design factors and their interdependencies considered in VDS. The current VDS implementation focuses on five design factors, which are Site & Climate, Form & Massing, Internal Configuration, External Enclosure, and Environmental Systems. In the following discussion, we assume that site & climate have already been defined so that we will use the remaining four factors to illustrate the approach. The performance evaluation can be made for three purposes:

1) Comparison between the proposed design and reference building by simulations for two base cases: the reference building and the proposed design (case 0 and case 1 in Table 5-10).

Table 5-10 Base simulation cases

	Form & Massing	Internal Configuration	External Enclosure	HVAC systems
Case 0	Reference Building	Reference Building	Reference Building	Reference Building
Case 1	Proposed Building	Proposed Building	Proposed Building	Proposed Building

2) Estimation of the contributions from individual design factors by comparing the proposed building (case 1) with the cases (cases 2, 3, 4, and 5 in Table 5-11) where a particular design factor remains unchanged from the reference case. We call this approach "backward stepping" for estimating the performance contribution of an individual factor.

The approach estimates what if a particular strategy related to that factor is not adopted, and hence the estimated contribution of the factor to the proposed design.

Table 5-11 Backward simulation cases

	Form & Massing	Internal Configuration	External Enclosure	HVAC systems
Case 2	Reference Building	Proposed Building	Proposed Building	Proposed Building
Case 3	Proposed Building	Reference Building	Proposed Building	Proposed Building
Case 4	Proposed Building	Proposed Building	Reference Building	Proposed Building
Case 5	Proposed Building	Proposed Building	Proposed Building	Reference Building

In the comparison of the performance indices between cases 2, 3, 4 and 5 versus case 1 to determine the contributions from each design factor, when the performance index is a positive indicator (i.e., the higher the better), Equation 5-10 should be applied; if the index is a negative indicator, Equation 5-11 should be used.

$$RPC_f = \frac{PI_{pb} - PI_f}{PI_{rb}}$$ Equation 5-10

$$RPC_f = \frac{PI_f - PI_{pb}}{PI_{rb}}$$ Equation 5-11

Where:

RPC_f = Relative performance contribution of design factor “f”

PI_f = Performance index of the case with design factor “f” remains unchanged from the reference case.

PI_{rb} = Performance index of the reference building

PI_{pb} = Performance index of the proposed building

3) Estimate the potential of individual design factors. This is done through "foreword stepping" to assess the merit of a particular design factor when considering different design options. In this process, one design factor is deviated from the reference case to analyze its potential impact on the performance (Case 6, 7, 8 & 9 in Table 5-12) in comparison with the reference case (Case 0).

Table 5-12 Forewords simulation cases

Case	Form & Massing	Internal Configuration	External Enclosure	HVAC systems
Case 6	Proposed Building	Reference Building	Reference Building	Reference Building
Case 7	Reference Building	Proposed Building	Reference Building	Reference Building
Case 8	Reference Building	Reference Building	Proposed Building	Reference Building
Case 9	Reference Building	Reference Building	Reference Building	Proposed Building

In the comparison of the performance indices between cases 6, 7, 8 and 9 versus case 0 to determine the potential of each design factor, when the performance index is a positive indicator, Equation 5-12 should be applied; if the index is a negative indicator, Equation 5-13 should be used.

$$RPP_f = \frac{PI_f - PI_{rb}}{PI_{rb}}$$ Equation 5-12

$$RPP_f = \frac{PI_{rb} - PI_f}{PI_{rb}}$$ Equation 5-13

Where:

RPP_f = Relative performance potential of design factor "f".

PI_f = Performance index of the case with design factor "f" remains unchanged from the reference case.

PI_{rb} = Performance index of the reference building

PI_{pb} = Performance index of the proposed building

5.5. Testing and verification

The Syracuse CoE headquarters building, here after called COE building, is used as the case building to demonstrate the VDS performance evaluation model.

5.5.1.VDS reference building for the case building

The case building is a five-story large office building with a total floor area of 6277 m^2 located in Syracuse, New York in Cold and Humid (6A) climate zone. Table 5-13 shows the site information of the case building. The building type, climate, and site information of the VDS reference building are the same as the case building.

Table 5-13 Site information of the case building

Latitude (°)	43.05
Longitude (°)	-76.14
Elevation (m)	125
Time Zone	-5
Ground Reflectance	0.2
Terrain	City

5.5.1.1.Climate

5.5.1.1.1.Heating and cooling design conditions

The information of the design day conditions is obtained from EnergyPlus weather data (US DOE, 2013c). Table 5-14 shows the Syracuse summer and winter design day conditions. Figure 5-6 shows the Syracuse monthly ground temperature.

Table 5-14 Syracuse summer and winter design conditions

	Summer Design Condition	Winter Design Condition
Date	Jul. 21st	Jan. 21st
Maximum Dry-bulb temperature (℃)	31.6	-19.3
Daily dry-bulb temperature range (℃)	10.8	0
Wet-bulb temperature at maximum dry-bulb temperature (℃)	22.8	-19.3
Air pressure (Pa)	99832	99832
Wind Speed (m/s)	4.4	3
Wind direction (degree)	260	90
Has Rain?	No	No
Has Snow?	No	No
Use Daylight Savings?	No	No
Solar Model	ASHRAE Tau model	ASHRAE Clear Sky Model
Sky cleanness	0	1.0

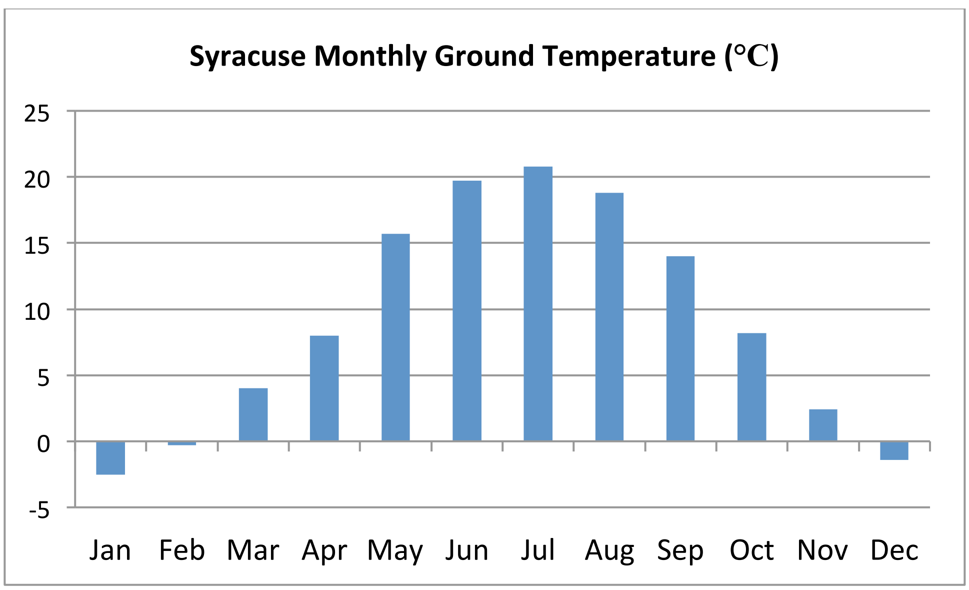


Figure 5-6 Syracuse monthly ground temperature

5.5.1.1.2.Detailed climate conditions

VDS uses EPW format weather file for the detailed climate conditions. The EPW weather file for Syracuse can be obtained from EnergyPlus weather data (US DOE, 2013c). For this study, the "Syracuse-Hancock Intl AP 725190 (TMY3)" file is used.

5.5.1.1.3.Atmosphere pollution

For indoor air quality analysis, VDS mainly considers six contaminants, including ozone, PM2.5, formaldehyde, TVOC, carbon dioxide, and carbon monoxide. Ozone and PM2.5 represent effect of outdoor pollutant sources; formaldehyde and TVOC that of indoor material emissions, CO2 as surrogate of indoor occupant-related emissions, and CO of combustion-related source. The New York Stage Department of Environmental Conservation (NYSDEC) air quality monitoring website (NYSDEC, 2013) allows a real-time view into the ambient air quality database of the NYSDEC. The contaminants measured by NYSDEC include ozone, PM2.5, and carbon monoxide.

For TVOC, the same assumption as the NIST IAQ model (Ng, Musser, Persily, & Emmerich, 2012) is made. The outdoor concentration of TVOC was assumed to be zero.

For ozone monitor locations, the nearest location to the case building is East Syracuse monitor station (longitude: -76.07°, latitude: 43.06°). For outdoor ozone concentration, the 2012 hourly data (Figure 5-7) in East Syracuse from NYSDEC (NYSDEC, 2013) are used. The ozone concentration varies from 0 ppm to 0.084 ppm with an average of 0.029 ppm.

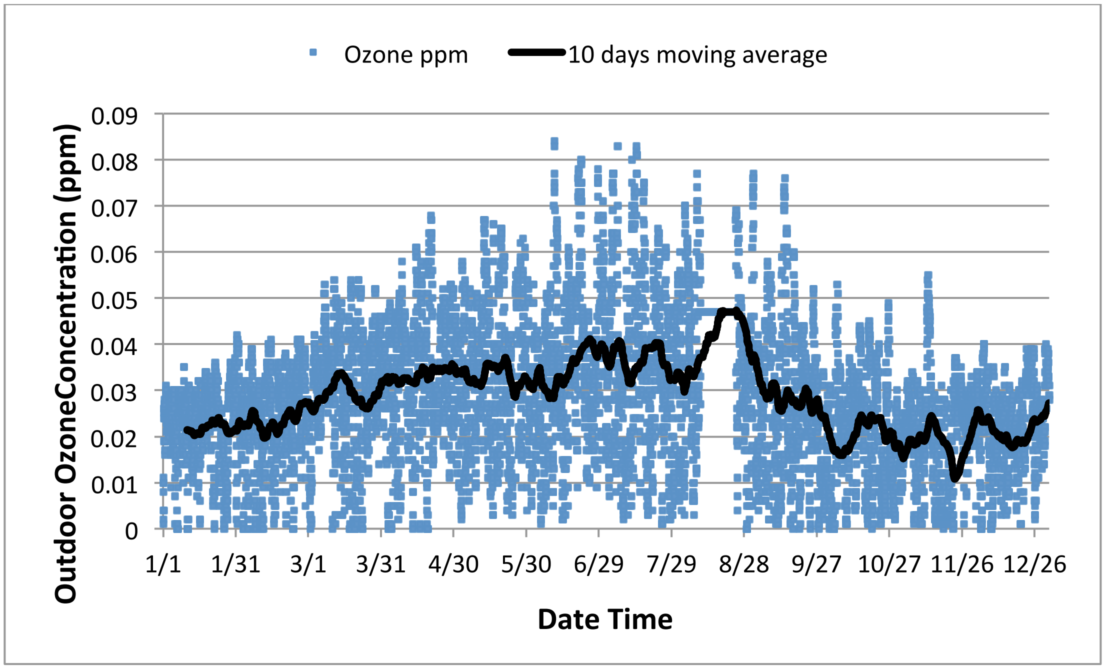


Figure 5-7 Hourly outdoor ozone concentration in East Syracuse, 2012

For PM2.5 monitor locations, the nearest location to the case building is Rochester monitor station (longitude: -77.61°, latitude: 43.16°). For outdoor PM2.5 concentration, the 2012 hourly data (Figure 5-7) in Rochester from NYSDEC (NYSDEC, 2013) are used. The PM2.5 concentration varies from 0 to 48.2 $\mu g/m^3$ with an average of $6.80\mu g/m^3$.

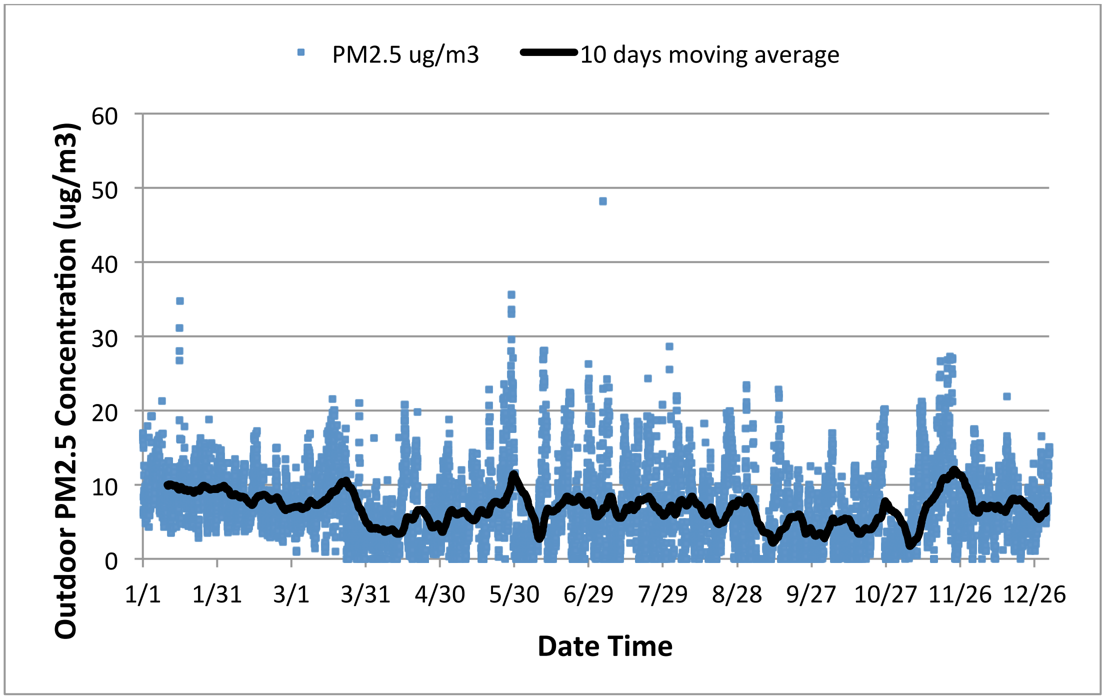


Figure 5-8 Hourly outdoor PM2.5 concentration in Rochester, 2012

For carbon monoxide monitor locations, the nearest location to the case building is Rochester monitor station (longitude: -77.61°, latitude: 43.16°). For outdoor carbon monoxide concentration, the 2012 hourly data (Figure 5-7) in Rochester from NYSDEC (NYSDEC, 2013) are used. The carbon monoxide concentration varies from 63.18 ppb to 1288.02 ppb with an average of 210.18 ppb. These data are used for the purpose of VDS illustration, realizing that actual monitored data on site should be used, especially considering the close proximity between the building and the inter-state freeways.

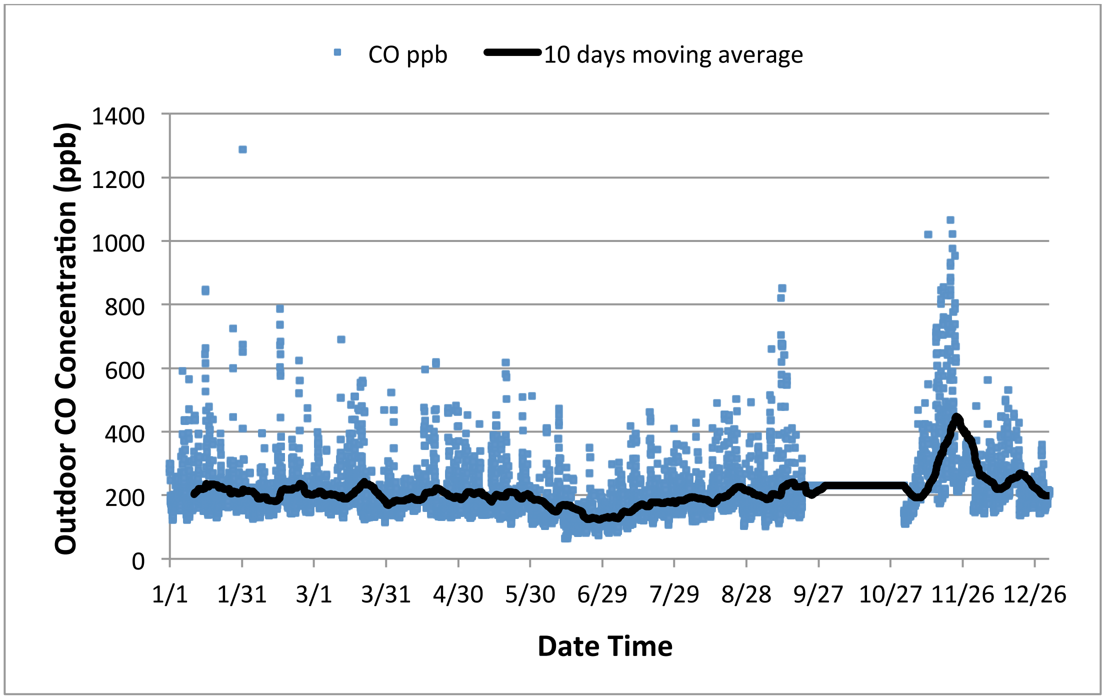


Figure 5-9 Hourly outdoor carbon monoxide concentration in Rochester, 2012

5.5.1.2.Form

Based on the method mentioned in Section 5.3.4.2, the geometry of the reference building is created based on the number of floors and the floor area information of the case building (Table 5-15). Figure 5-10 and Figure 5-11 show the south and north view of the case building. Figure 5-12 and Figure 5-13 show the shape and zoning of the VDS reference building.

Table 5-15 Floor space of COE proposed building and COE reference building

Parameters		COE proposed building	COE reference building
No. of floors		5	5
Floor area (m2)	1st	1880	1255.4
	2nd	2255	1255.4
	3rd	665	1255.4
	4th	732	1255.4
	5th	745	1255.4
	Average	1255.4	1255.4

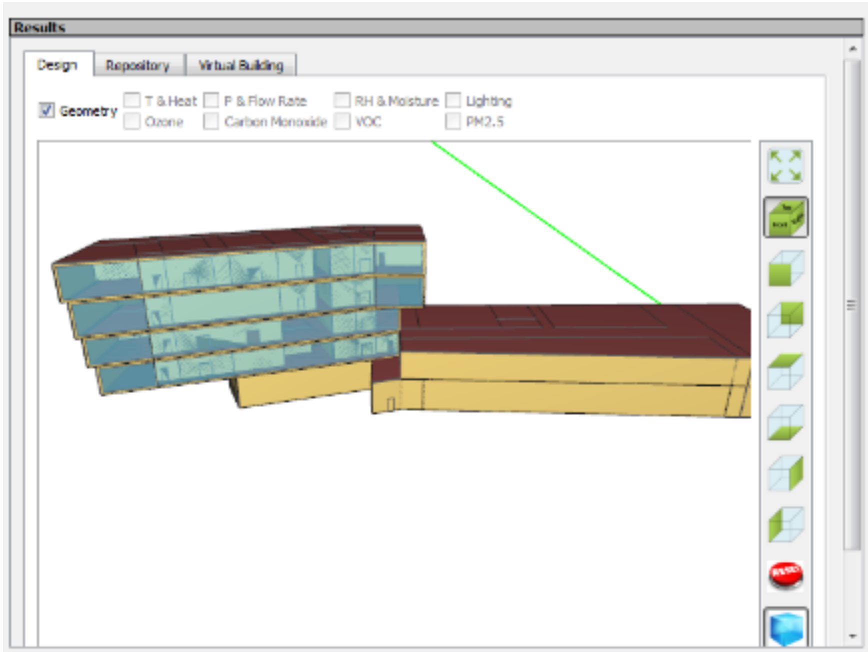


Figure 5-10 South view of the case building

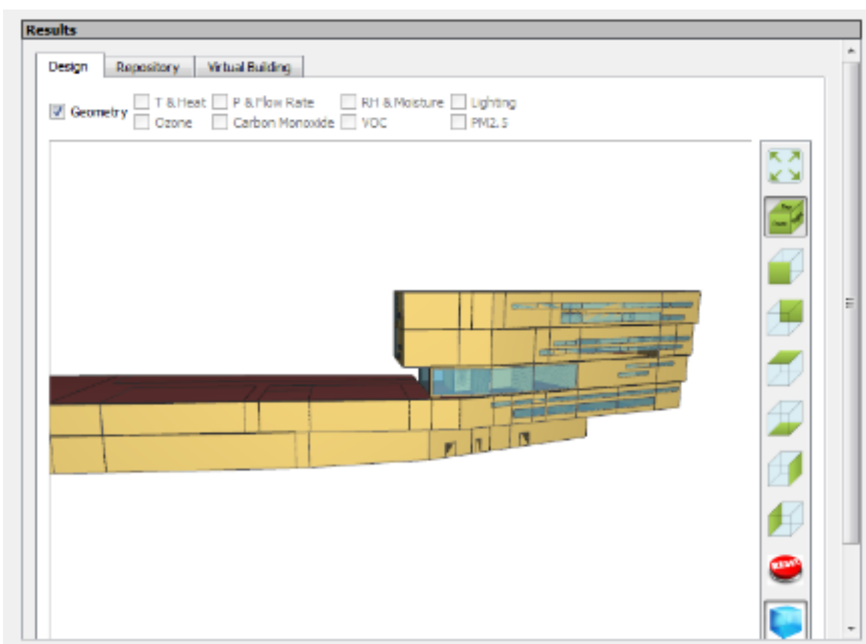


Figure 5-11 North view of the case building

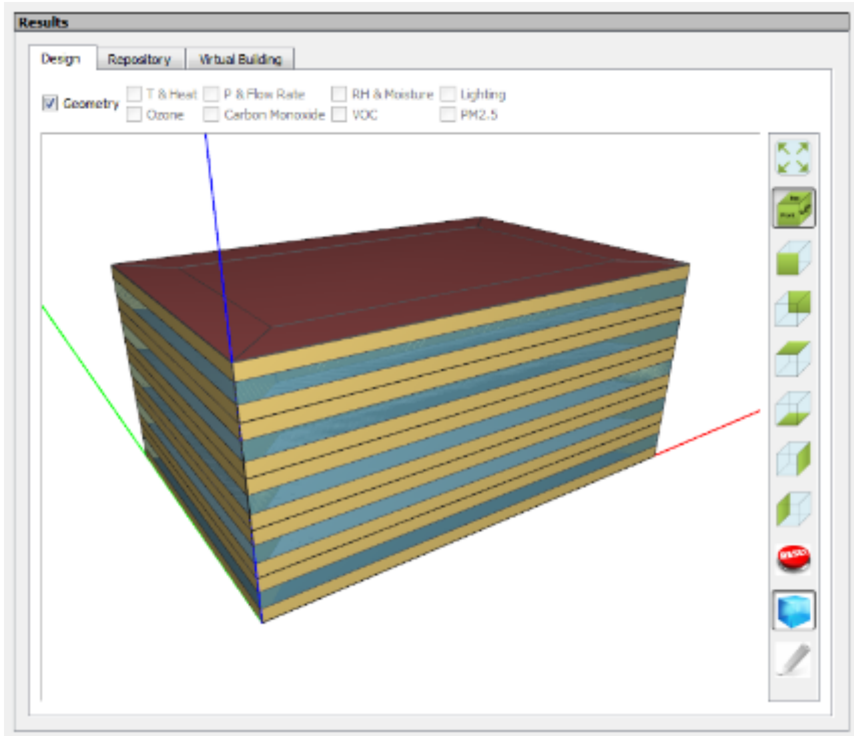


Figure 5-12 Shape of the VDS reference building

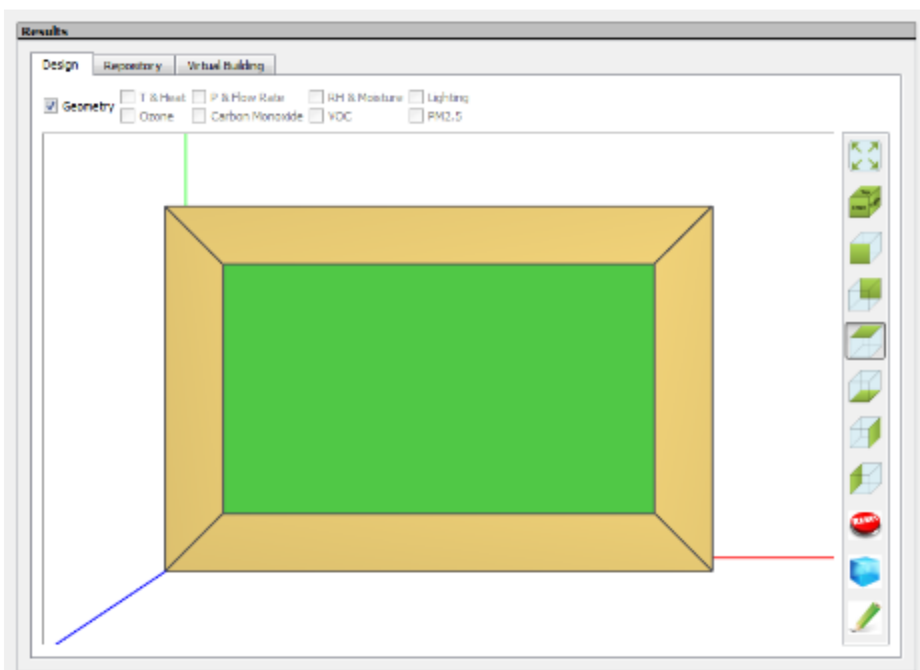


Figure 5-13 Thermal zoning of the VDS reference building

5.5.1.3.Zoning

As discussed in Section 5.3.4.3.1, the thermal zones in the VDS reference building are all "Office".

5.5.1.3.1.IEQ requirements

The IEQ requirements in VDS include thermal comfort, outdoor ventilation rate, and daylighting control. For thermal comfort, Table 5-16 shows the heating and cooling setpoint for all the day types. For outdoor ventilation rate, the people outdoor air rate R_p is 5 $cfm/person$ and the area outdoor air rate R_a is 0.06 cfm/ft^2. With the default occupancy rates for office (200ft^2/person), the total outdoor air rate is 0.085cfm/ft^2.

Table 5-16 Heating and cooling setpoint for all the day types

<table>
<tr><td colspan="2">Start– End (Hour)</td><td>0-6</td><td>6-18</td><td>18-22</td><td>22-24</td></tr>
<tr><td rowspan="4">Heating Setpoint (°C)</td><td>Winter Design Day</td><td>21</td><td>21</td><td>21</td><td>21</td></tr>
<tr><td>Weekdays</td><td>15.6</td><td>21</td><td>21</td><td>15.6</td></tr>
<tr><td>Saturday</td><td>15.6</td><td>21</td><td>15.6</td><td>15.6</td></tr>
<tr><td>Sunday & Summer design day</td><td>15.6</td><td>15.6</td><td>15.6</td><td>15.6</td></tr>
<tr><td rowspan="3">Cooling Setpoint (°C)</td><td>Weekdays & Summer Design Day</td><td>26.7</td><td>24</td><td>24</td><td>26.7</td></tr>
<tr><td>Saturday</td><td>26.7</td><td>24</td><td>26.7</td><td>26.7</td></tr>
<tr><td>Sunday & Winter Design Day</td><td>26.7</td><td>26.7</td><td>26.7</td><td>26.7</td></tr>
</table>

5.5.1.3.2.Occupancy

The default occupancy rates for office in ASHRAE 62.1-2010 is 200ft2/person. Table 5-17 shows the metabolic rates for office activities (ASHRAE, 2010a). The average metabolic rate of all the office activities is 78.57 W/m2, which is used as the occupancy activity level for the VDS reference buildings. The average adult skin surface area is 1.8 m2 (ASHRAE, 2010a).

Table 5-18 show the occupancy schedules for summer design day, weekdays, and Saturday. It is assumed that there are no people in the office in winter design day and Sunday.

Table 5-17 Metabolic rates for typical office activities (ASHRAE, 2010a)

Office Activities	Metabolic Rate (W/m2)
Reading, seated	55
Writing	60
Typing	65
Filing, seated	70
Filing, standing	80
Walking about	100
Lifting/packing	120

Table 5-18 Occupancy schedules for summer design day, weekdays, and Saturday

Start– End (Hour)	0-6	6-7	7-8	8-12	12-13	13-14	14-17	17-18	18-20	20-22	22-24
Summer design day	0	1	1	1	1	1	1	1	1	1	0.05
Weekdays	0	0.1	0.2	0.95	0.5	0.95	0.95	0.7	0.4	0.1	0.05
Saturday	0	0.1	0.1	0.5	0.5	0.5	0.1	0	0	0	0

5.5.1.3.3.Lighting

The lighting power density of Office in ASHRAE 90.1 is 11 W/m^2. Table 5-19 shows the lighting schedules for weekdays and Saturday. For summer design day, the lighting is all on; while for winter design day, the lighting is all off. For Sunday, the fraction is 0.05 for all the time.

Table 5-19 Lighting schedules for weekdays and Saturday

Start– End (Hour)	0-5	5-6	6-7	7-8	8-14	14-17	17-18	18-20	20-22	22-23	23-24
Weekdays	0.05	0.1	0.1	0.3	0.9	0.9	0.7	0.5	0.3	0.1	0.05
Saturday	0.05	0.05	0.1	0.1	0.5	0.15	0.05	0.05	0.05	0.05	0.05

5.5.1.3.4.Equipment

The equipment power density for office building is adopted from the NREL reference building, which is $0.7W/ft^2$ (7.53W/m^2). The equipment schedules listed in the NREL reference building were adopted for VDS reference building. Table 5-20 shows the equipment schedules for weekdays and Saturday. For summer design day, the equipment is all on; while for winter design day, the equipment is all off. For Sunday, the fraction is 0.3 for all the time.

Table 5-20 Equipment schedule

Start– End (Hour)	0-6	7-8	8-12	12-13	13-14	14-17	17-18	18-20	20-22	23-24
Weekdays	0.4	0.4	0.9	0.8	0.9	0.9	0.8	0.6	0.5	0.4
Saturday	0.3	0.4	0.5	0.5	0.5	0.35	0.3	0.3	0.3	0.3

5.5.1.3.5.Pollutant source and sink

Based on NIST airflow and indoor air quality models for NREL reference buildings (NIST, 2013), the indoor contaminant sources included occupant-generated CO_2 and TVOCs from materials and activities. An area-based TVOC source was defined in all occupied building zones. In occupied zones, a 0.5 mg/m^2•h source was included during system-on hours and reduced by 50% during system-off hours (Persily et al. 2003). Zones that were always unoccupied had no TVOC source. Deposition rates of 0.5 h^{-1} for PM 2.5 (Allen et al. 2003; Howard-Reed et al. 2003; Riley et al. 2002) and 4.0 h^{-1} for ozone (Kunkel et al. 2010; Nazaroff et al. 1993; Weschler 2000; Weschler et al. 1989) were included in every zone. No indoor sources were included for ozone, carbon monoxide or PM 2.5.

The emission rate for the generic TVOC was assumed to be constant at a rate of 0.25 mg/h per m2 of floor area during unoccupied periods and 0.50 mg/h•m2 during occupancy. These values are based on limited field measurements of TVOC emission rates (Levin 1995). Although actual contaminant generation rates may differ significantly for different building types, there is not sufficient data available to justify varying these rates in this study (Persily et al. 2003).

5.5.1.4.Enclosure

The case building is located in Climate Zone 6A. ASHRAE standard 90.1 Table 5.5-6 provides the minimum R-value for the roof, ceiling/floor, external wall, and ground floor (Table 5-21). For window, the maximum U-value is 3.12 W/m^2.k, while the maximum SHGC (Solar Heat Gain Coefficient) is 0.4. The detailed constructions and materials from the NREL reference building for large office in climate zone 6A are used. The thicknesses of the insulation materials are modified to meet the minimum R-value requirements.

Table 5-21 Enclosure insulation requirements (ASHRAE, 2010c)

Component	Minimum R-Value (m^2.k/W)
Roof	3.5
Ceiling/Floor	2.2
External Wall	2.3
Ground floor	1.8

5.5.1.5.HVAC

For large office building, NREL (NREL, 2011) and ASHRAE 90.1 all suggest the boiler for heating, the water cooled chiller for cooling, and the multizone VAV systems for air distribution. This HVAC system can be modeled using the VAV with boilers and water-cooled chillers template in EnergyPlus, which is called VAV with reheat system in VDS.

The reheat coil type is set to hot water, while the minimum air flow fraction is set to constant value (0.3). Based on the NREL reference building, the supply fan motor efficiency is set to 0.93, and the supply fan total efficiency is set to 0.6045. For large office building, the COP of the centrifugal chillers is set to 5.5. The efficiency of the boiler in NREL reference building is set to 0.78.

A constant efficiency filter was placed in the mixed air of all HVAC systems. The filter removed ozone at 5 % efficiency (Bekö et al. 2006) and removed PM 2.5 at 25 % efficiency, corresponding to filters with a Minimum Efficiency Reporting Value (MERV) of 6 as required in ASHRAE Standard 62.1-2010 (ASHRAE 2010a; Kowalski and Bahnfleth 2002). A penetration factor of one was assumed for both ozone (Liu and Nazaroff 2001; Weschler et al. 1989) and PM 2.5 (Allen et al. 2003; Thornburg et al. 2001; Tian et al. 2009), i.e., there was no removal of these contaminants in the exterior leakage paths (NIST, 2013).

5.5.2.Performance evaluation results and analysis

Currently, VDS uses EnergyPlus V7.2 to perform the daylighting simulation. The daylighting simulation model in EnergyPlus V7.2 is only available for rectangular shapes, and therefore cannot be applied to evaluate the daylighting performance of the COE building. This section uses the COE building as the proposed building to demonstrate the evaluation and analysis of the operational energy performance, thermal comfort, and IAQ aspects. The ten simulation cases as introduced in section 5.4.2 are performed to evaluate and analyze the operational energy and thermal comfort performance of the proposed building. For IAQ aspects, as the “100% outdoor air with radiant panel” system are not available in the CHAMPS-WholeBuilding co-simulation, only the cases 0, 5, 6, 7, and 8 are analyzed. In order to evaluate and analyze the operational energy performance, both the energy consumption and energy cost results are presented and analyzed. As introduced in Section 4.3.1.2, the electricity price of 15.93

cent/kWh (US EIA, 2013c) and the natural gas price of 0.932 cent/ft^3 (US EIA, 2013a) are used to calculate the energy cost.

5.5.2.1. Operational energy performance aspect

5.5.2.1.1.Comparisons between the design and reference building

Figure 5-14 shows the annual energy consumption of cases 0 and 1.By compared with the reference building, the proposed building has significant energy savings in equipment, lights, pumps, fans, and cooling. However, the proposed building consumed more nature gas for heating than the reference building. Overall, the proposed building saves 6% energy consumption compared to the reference building.

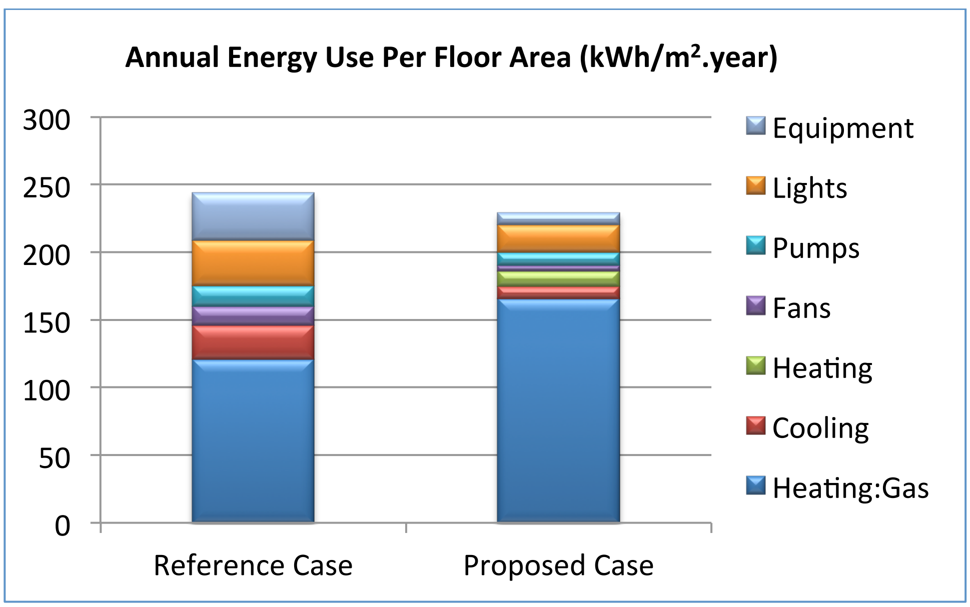


Figure 5-14 Annual energy consumption of cases 0 and 1

For form and massing design factor, the surface to volume ratios of the proposed building and the reference building are 0.503 and 0.166 m^{-1}, respectively. The building is located in the

Cold – Humid climate zone. With much more exterior surfaces, the proposed building consumed 47% more heating energy than the reference building.

For internal configuration design factor, both the power densities and operation hours of the lights and equipment of the proposed building are lower than the reference building. Moreover, the proposed building has daylighting control with illuminance setpoint of 400 lux. As a result, the proposed building saves 58% lights and equipment energy compared to the reference building. It also reduces the cooling load in summer and increases the heating load in winter. The proposed building saves 64% cooling energy compared to the reference building.

Figure 5-15 shows the annual energy cost of the proposed building and the reference building. The proposed building saves 33% energy cost compared to the reference building. Therefore, the related performance index for the operational energy performance aspect is 0.33.

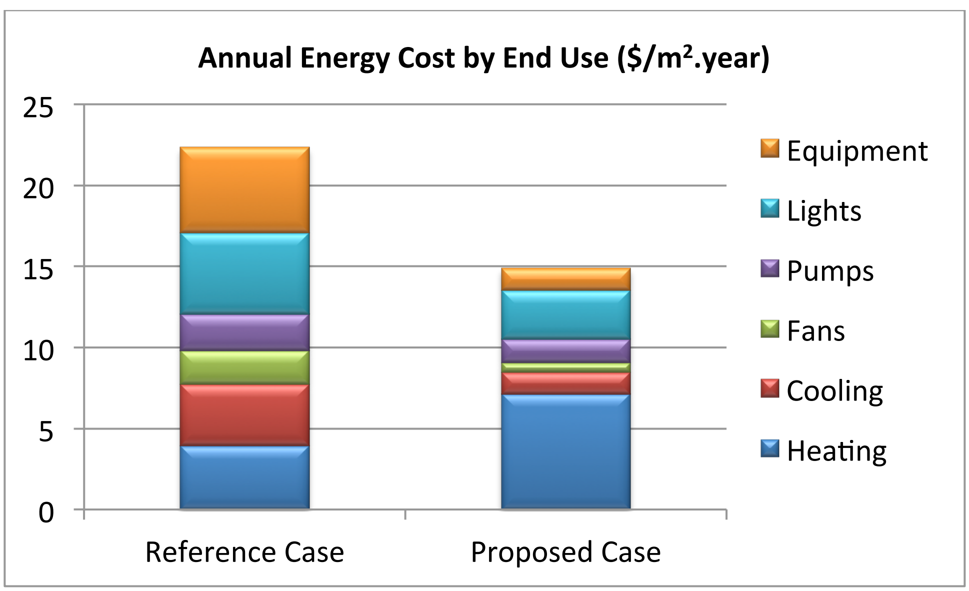


Figure 5-15 Annual energy cost of cases 0 and 1

5.5.2.1.2.Contributions of each design factors to the overall performance

Figure 5-16 shows the annual energy consumption of cases 0, 1, 2, 3, 4, and 5. By comparing case 1 with cases 2, 3, 4, and 5, it can be found that the form and massing factor of the proposed building has a negative impact on the energy consumption, the internal configuration and external enclosure factors have slightly positive impacts, and the HVAC factor has a positive impact.

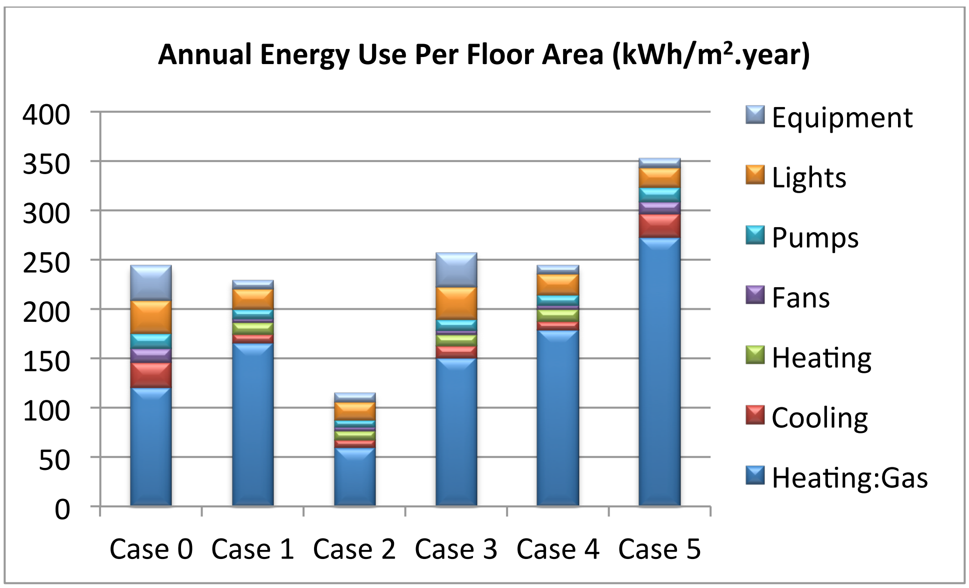


Figure 5-16 Annual energy consumption of cases 0, 1, 2, 3, 4, and 5

The analysis of the "form and massing" and internal configuration factors are presented in the previous section. For external enclosure design factor, the construction R-values and the window properties of the reference building and the proposed building are shown in Table 5-22 and

Table 5-23. Although the properties of the external enclosure components in the proposed building are improved, it does not have a significant impact on the energy consumption.

Table 5-22 Construction R-values of the reference building and proposed building

Component	R-Value (m^2.k/W)	
	Reference building	Proposed building
Roof	3.5	3.9
External Wall	2.3	2.7
Ground floor	1.8	3.8

Table 5-23 Window properties of the reference building and proposed building

Parameter	Window	
	Reference building	Proposed building
SHGC	0.4	0.31
U-value	3.12	1.2

For the HVAC system design factor, the 100% outdoor air with radiant panel system with ground source heat pump system is used in the proposed building, while the VAV with reheat system with water-cooled chiller and boiler system is used in the reference building. The 100% outdoor air with radiant panel system may reduce the amount of air been "over-cooled and reheated" and thus reduce the cooling and heating energy consumption. The ground source heat pump system can improve the energy efficiencies for both heating and cooling systems. By comparing case 1 and case 5, it can be found that the HVAC system of the proposed building has a significant positive impact on the energy consumption.

Figure 5-17 shows the annual energy cost of cases 0, 1, 2, 3, 4, and 5. Table 5-24 shows the related performance contribution of each design factor calculated using Equation 5-11. Both the internal configuration and the HVAC system have significant positive impacts on the energy cost, while the form and massing has a significant negative impact. The impact of the external enclosure is slightly small comparing to the other factors.

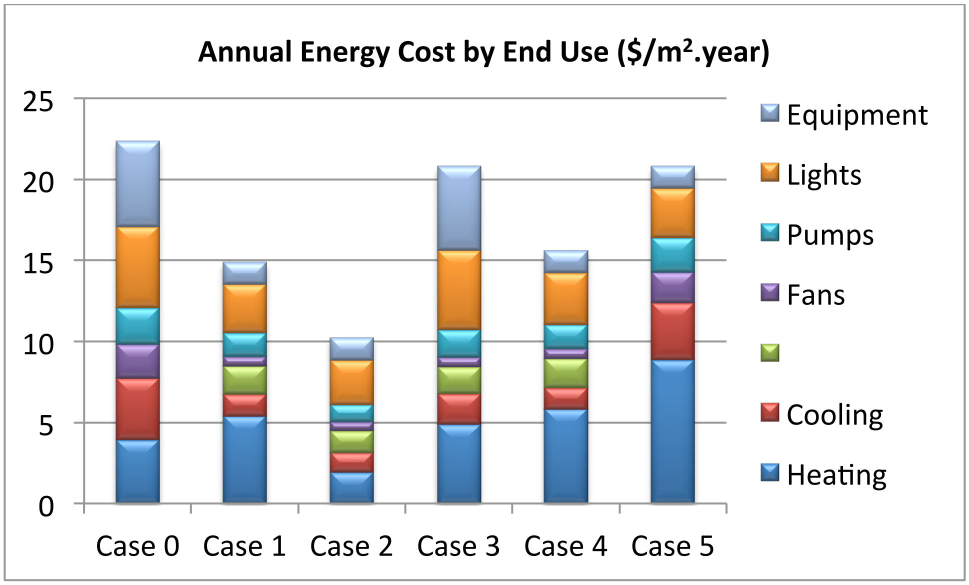


Figure 5-17 Annual energy cost of cases 0, 1, 2, 3, 4, and 5

Table 5-24 Related performance contribution of design factors

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5
Annual Energy Cost ($/m2.year)	22.33	14.88	10.19971	20.82	15.57	20.79
Related performance contribution			-0.21	0.27	0.03	0.27

5.5.2.1.3.Potential improvements over reference building from each design factors

Figure 5-18 shows the annual energy consumption of cases 0, 1, 6, 7, 8, and 9. By comparing case 0 with cases 6, 7, 8 and 9, it can be found that the form and massing factor of the proposed building has a negative impact on the energy consumption, the internal configuration and external enclosure factors have slightly positive impacts, and the HVAC factor has a significant positive impact. The analysis of the impacts of the design factors are introduced in previous sections.

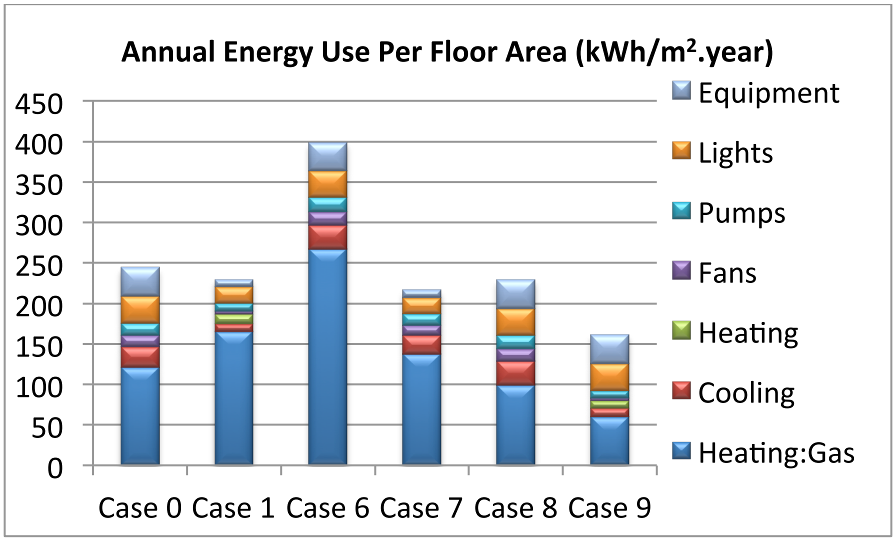


Figure 5-18 Annual energy consumption of cases 0, 1, 6, 7, 8, and 9

Figure 5-19 shows the annual energy cost of cases 0, 1, 6, 7, 8, and 9. Table 5-25 shows the related performance contribution of each design factor calculated using Equation 5-13. Both the internal configuration and the HVAC system have significant positive impacts on the energy cost, while the form and massing has a significant negative impact. The impact of the external enclosure is slightly small comparing to the other factors.

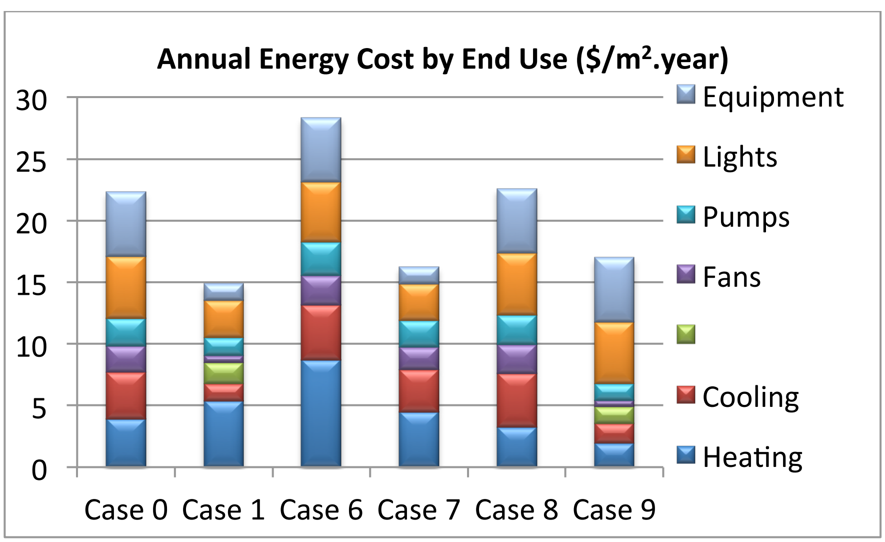


Figure 5-19 Annual energy cost of cases 0, 1, 6, 7, 8, and 9

Table 5-25 Related performance potential of design factors

	Case 0	Case 1	Case 6	Case 7	Case 8	Case 9
Annual Energy Cost ($/m2.year)	22.33	14.88	28.33	16.24	22.59	17.01
Related performance potential			-0.27	0.27	-0.01	0.24

It can be found that the results from both "backward and forward stepping" are similar in this case.

5.5.2.2. Thermal comfort aspect

5.5.2.2.1.Comparisons between the design and the reference building

Figure 5-20 shows the monthly aggregated PPD of cases 0 and 1, and Table 5-26 shows the whole building thermal comfort indices of the two cases. The thermal comfort condition of the proposed building is 32% worse than the reference building. The following section discusses the contribution of each design factors to the overall thermal comfort performance.

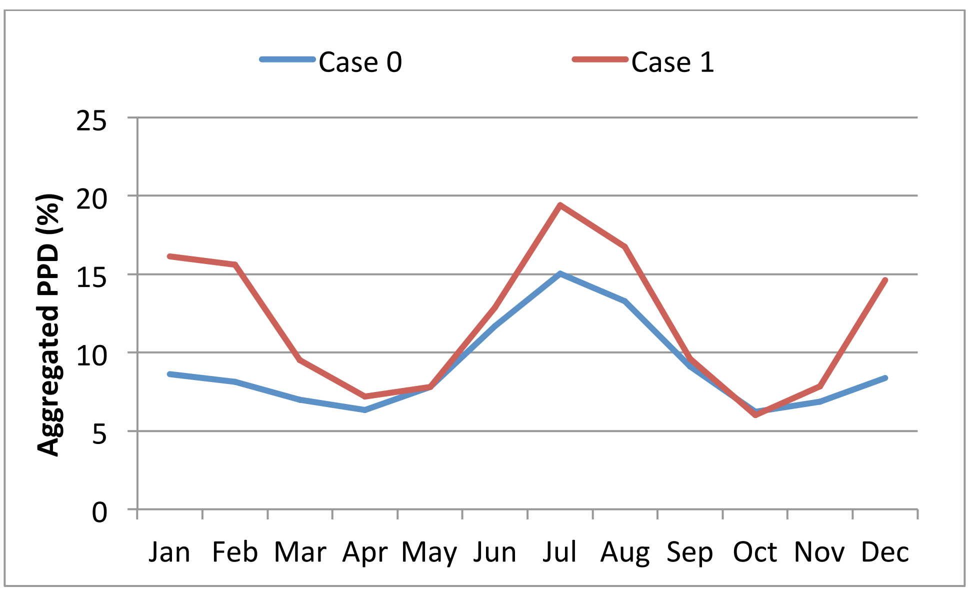


Figure 5-20 Monthly aggregated PPD of cases 0 and 1 `

Table 5-26 Relative performance index of thermal comfort

	Case 0	Case 1	Relative performance index
Whole building thermal comfort index	9.05	11.92	-0.32

5.5.2.2.2.Contributions of each design factors to the overall performance

Figure 5-21 shows the monthly aggregated PPD for cases 0, 1, 2, 3, 4, and 5, and Table 5-27 shows the related performance contribution of each design factor. The results indicate that the HVAC system and "form and massing" are the two main design factors which cause the poor thermal comfort condition of the proposed building comparing to the reference building. The internal configuration design factor has slightly positive impact on the thermal comfort, while the external enclosure design factor has no impacts on the thermal comfort.

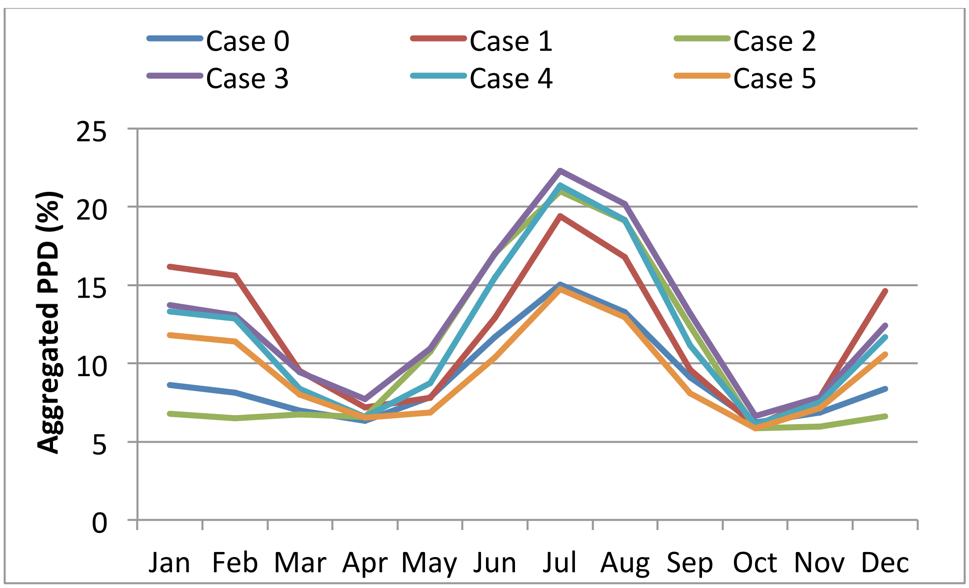


Figure 5-21 Monthly aggregated PPD of cases 0, 1, 2, 3, 4 and 5

Table 5-27 Related performance contribution of design factors

	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5
Whole building thermal comfort index	9.05	11.92	10.49	12.88	11.85	9.51
Related performance contribution			-0.16	0.11	-0.01	-0.27

5.5.2.2.3.Potential improvements over reference building from each design factors

Figure 5-1shows the monthly aggregated PPD for cases 0, 1, 6, 7, 8, and 9, and Table 5-28 shows the related performance potential of each design factor. The similar results as the previous section are found.

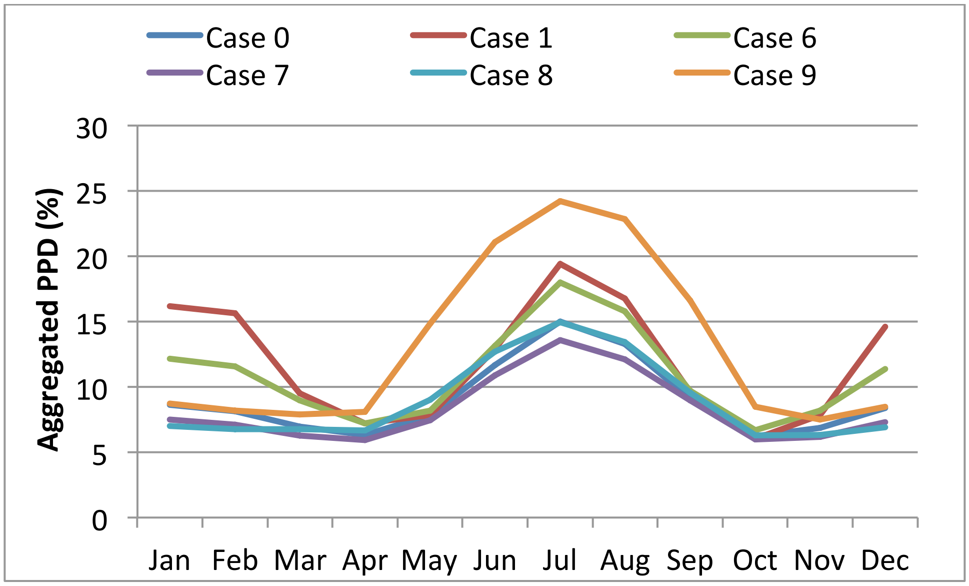


Figure 5-22 Monthly aggregated PPD of cases 0, 1, 6, 7, 8 and 9

Table 5-28 Related performance potential of design factors

	Case 0	Case 1	Case 6	Case 7	Case 8	Case 9
Whole building thermal comfort index	9.05	11.92	10.91	8.28	8.88	13.14
Related performance potential			-0.21	0.08	0.02	-0.45

5.5.2.3.IAQ aspect

Figure 5-23 shows the monthly aggregated AQIs of cases 0, 5, 6, 7, and 8, while Figure 5-24 shows the whole building AQI of those cases. The results show that the monthly aggregated

AQIs for all the five cases range from 15.1 to 29.9 with an average of 23.0. According to the relationship between the AQI and the air quality categories (Figure 5-4), the IAQ of call the cases are considered as “Good”. The major reason of the “Good” air quality is that the zone pollutant sources for the simulated cases are low (Table 5-29).

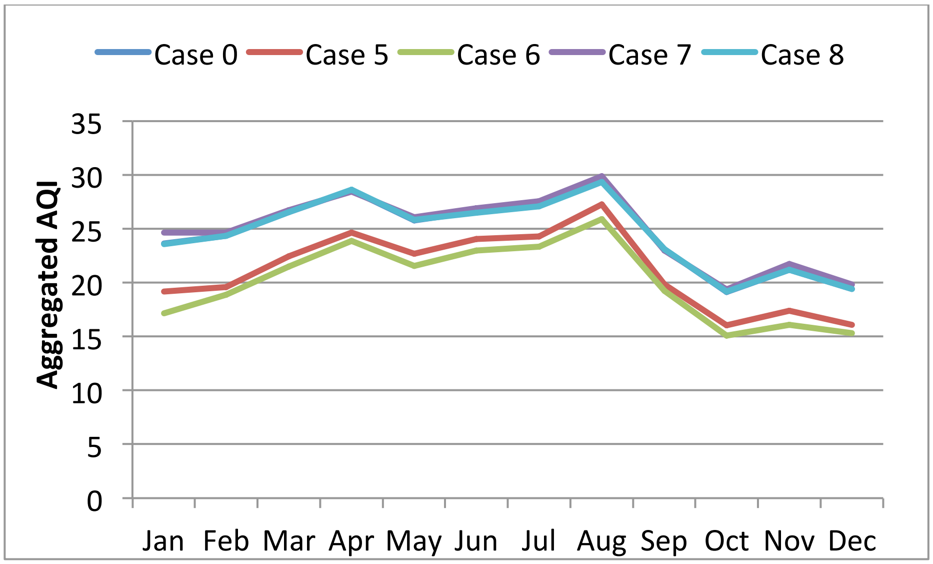


Figure 5-23 Monthly aggregated AQI of cases 0, 5, 6, 7, and 8

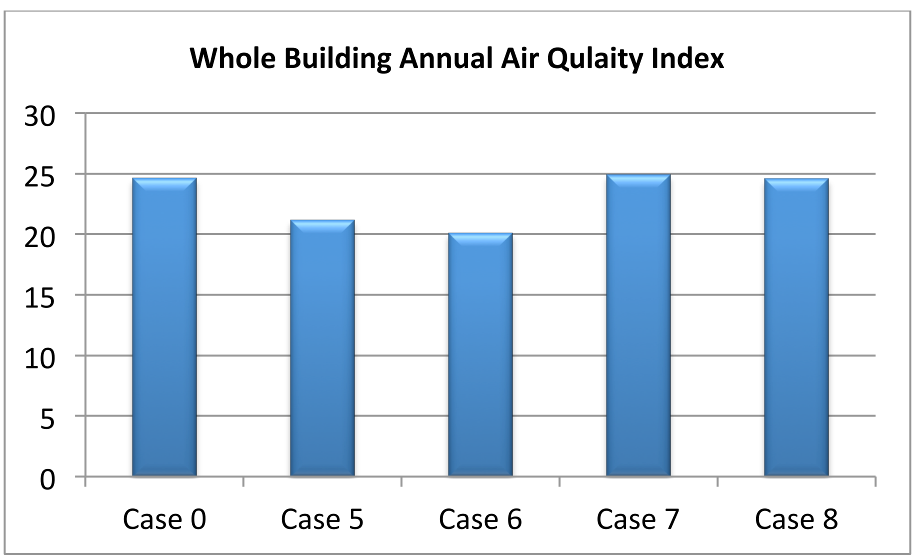


Figure 5-24 Whole building AQI of cases 0, 5, 6, 7, and 8

Table 5-29 Zone pollutant sources for the simulation cases

	Case 0	Case 5	Case 6	Case 7	Case 8
Ozone	0	0	0	0	0
Carbon Monoxide	0	0	0	0	0
PM2.5	0	0	0	0	0
VOC (mg/h.m2)	0.5	0	0.5	0	0.5

5.6. Conclusions

A performance evaluation model has been established for use in the Virtual Design Studio. Specific performance indices have been defined for the operational energy, IAQ, thermal comfort and lighting quality and applied in the framework to illustrate the application of the model. The model enables the estimation of the potential of individual design factors in improving the design from a reference case, and their contributions to the overall performance of the final design. Further investigation is needed to evaluate the effectiveness of the proposed evaluation model in multi-design iterations in achieving an optimal design. Additional works are also necessary to determine the performance indices for other sub-aspects that have not been quantified in the present study.

Chapter 6. Illustration of VDS Application Using a LEED Platinum Building: the Syracuse Center of Excellence (CoE) Headquarters

This chapter intends to illustrate how to achieve a high-performance building design using an optimized design process, simulation models and performance evaluation methodologies introduced in the previous chapters. A LEED Platinum rated, the Syracuse Center of Excellence (CoE) Headquarters building is used as a case study building for this illustration. The purpose of the illustration here is to show how the VDS could assist the design of low energy and high IEQ buildings, demonstrated for particular areas of consideration. Demonstration of VDS application along a real building design process is beyond the scope of the current project, and is planned for future studies.

In this chapter, we first provide an overview of the case building and its green building features categorized according to the design factors and performance aspects defined in VDS. Then, the integrated and coordinated design process is elaborated on by the explanation of a series of inter-connected "tasks", each of which is represented in the form of the established "Input-Process-Output" pattern. We will limit the illustration to major tasks for selected factors at selected design stages, and intend to cover the frequently encountered analyses in performance-based building design. Lastly, selected design options are analyzed for each of the design factors in terms of their impact on the energy and IEQ performance. The performance evaluation model and procedure introduced in Chapter 5 is used to compare the various possible designs with that of the reference building defined for the case building.

6.1. Overview of the case building and its green design features

The LEED Platinum Certified Syracuse CoE Headquarters building is a test bed for environmental and energy technologies and building innovations (Figure 6-1 South façade of Syracuse CoE Headquarters building. It includes an array of green building features that can significantly reduce its energy consumption while providing a high-level of indoor environmental quality. Selected green features of CoE headquarters building (Syracuse Center of Excelence, 2013) are classified systematically according to all VDS design factors and performance aspects mentioned in Table 6-2 CoE green features classified according to the VDS design factors and performance aspects. Some of the features are associated with multiple factors and/or multiple performance aspects, indicating the interdependencies among design factors and their combined effects on the overall building performance, for example: hybrid ventilation, day lighting etc.

Figure 6-1 South façade of Syracuse CoE Headquarters building

Table 6-1 Overview of Syracuse CoE Headquarters building

Cost	$41 million (funded from state and private sources)
Size	55,000 square feet
Location	727 E. Washington Street, Syracuse, NY, 13210. The three-acre site on the corner of Almond and Washington streets is a designated "brownfield", the former site of the LC Smith typewriter factory and Midtown Plaza. (Latitude: N 43° 3.0', Longitude: W 76° 8.5')
Number of Stories	5 Stories (Height75')
LEED Rating	Platinum
Program	Offices; Classrooms; Public spaces; Indoor environmental quality (IEQ), Biomass fuel and other Research Laboratories.

Table 6-2 CoE green features classified according to the VDS design factors and performance aspects

	Site sustainability	Water Efficiency	Energy and atmosphere	Materials and resources	Indoor environmental quality
Site and Climate	• "**Brownfield Remediation -** Environmental contamination associated with previous industrial site uses was remediated, restoring the site for sustained use by future generations." • "**Landscape Design -** Large sloping landforms provide a dynamic reflection of the building, as well as a means for safely encapsulating contaminated soil instead of shipping it to a distant landfill." • **Green Roof** - Plantings on the laboratory roof reduce the heat island effect.	• **Water Tank** - Rain and meltwater are collected from the roof and used to flush toilets, reducing both the consumption of drinkable water and the amount of water that is discharged to the sewer. • "**Storm Water Retention Tank** - The southwest corner of the property features a storm water retention tank to control run-off entering the sewer system." • **Green Roof -** Plantings on the laboratory roof provide rainwater retention.	• **Geothermal Pipes** - Heat exchanged with the ground helps heat the building in the winter and cools it in the summer, saving about 35% of energy compared to traditional systems. • **Easy access by occupants & visitors -** less emission due to transportation. • Wind and thermal buoyancy for natural ventilation.	• **Sustainable Construction Practices -** The construction team diverted 98% of construction waste from going to a landfill.	• **Urban Ecosystem Observatory** - The 150-foot Urban Ecosystem Observatory tower assess Syracuse's urban air quality, air flow, and how outside air affects air quality inside a building.
Form and Massing	• "**Building Shape and Form -** The building is relatively narrow, reducing brownfield site disturbance and excavation."		• "**Building Orientation -** To optimize the building's southern exposure in order to avoid solar energy drain during the colder months, the tower portion of the building is rotated 13-degrees from the urban street grid."		• **"Building Shape and Form -** The building is relatively narrow, with extensive windows providing a high level of occupant comfort with ample natural light and opportunities for views and natural ventilation."

Internal Configuration		• **Restrooms** feature waterless urinals, dual flush low-flow toilets and faucets.	• "**Lighting** - High efficiency compact fluorescent and LED lighting, controlled by a daylight harvesting (auto dimming) system and auto shut-off occupancy sensors, are used throughout the building." • Layout that facilitates different zone temperature settings	• **Restrooms** feature sustainable paper and cleaning products. • "**Furniture** made from recycled materials and FSC wood and wood products. Furniture is also 100% recyclable by the manufacturers upon return." • "**Regenerative Elevator** – The elevator generates electricity on the way down, which can then be used for going back up, used elsewhere in the building, or fed back into the grid."	• "**Open office configuration** allows for maximum daylighting, air circulation, and enhanced views." • **Green Roof** - Plantings on the laboratory roof, made up of six different varieties of sedum, provide a visible connection to nature.
External Enclosure	• Visual quality in the neighborhood (as a piece of urban fabric)	• **Green Roof** - Plantings on the laboratory roof provide rainwater retention.	• "**Insulation** - Solid façades include superior insulation to reduce heating and cooling loads." • **Windows -** The south façade features highly insulated glass with integrated electronically controlled blinds that provide solar heat and glare control. The ceramic white dots on the windows passively reduce glare and solar heat gain. • "**Roof** - The building roof is designed to reflect most of the sunlight, minimizing solar heat gain and reducing the cooling load. The roof is also designed to allow future installation of photovoltaic, building-scale wind turbines, and roof top HVAC units." • **Hybrid ventilation system** - Manual windows are provided to allow for natural ventilation throughout the building.	• "**Insulation** - Interior insulation uses 100% soy-based spray foam. Exterior insulation boards were created from sustainable natural fiber materials.	• "**Vapor Intrusion System** - Ventilation below the foundation prevents underground vapors from entering the building, eliminating a potential source of contaminants in indoor air."

Environmental Systems			• "**Radiant Ceilings** - Most of the heating and cooling in rooms is provided via ceiling panels that are embedded with copper piping that efficiently carries warm or cool water." • **Demand-Controlled Ventilation** - The amount of fresh air delivered to a room varies depending on the number of people who are present, saving energy when rooms are partially occupied. • "**Underfloor Heating** - Hot water is circulated through tubes embedded in the lobby floor to provide efficient heating. • "**Underfloor Ventilation and Raised Flooring** - raised floor system, allowing for even air distribution with lower fan speeds." • **Energy Recovery Ventilator** - exchanges heat and moisture between outgoing and incoming air streams, significantly reducing the amount of energy required to condition incoming air. • **Geothermal Pipes** - Heat exchanged with the ground helps heat the building in the winter and cools it in the summer, saving about 35% of energy compared to traditional systems. • Use high efficiency boilers.	• Use local supplier's manufactured mechanical systems such as: boiler and heat pumps to reduce the embodied energy use.	• "**Underfloor Ventilation and Raised Flooring** - Ventilation is provided close to occupants for improved thermal comfort using a raised floor system, allowing for even air distribution with lower fan speeds. The Tate raised floor system, situated 12 inches above the concrete deck, and also provides convenient wire routing." • **Demand-Controlled Ventilation** - The amount of fresh air delivered to a room varies depending on the number of people who are present, saving energy when rooms are partially occupied.
Energy Systems			• "**Solar Power Prototype** - the building-integrated concentrating photovoltaic system tracks the motion of the sun and uses lenses to concentrate sunlight 500 times, generating both electricity and heat."		
Water Systems		• **Water Tank** - Rain and meltwater are collected from the roof and used to flush toilets, reducing both the consumption of drinkable water and the amount of water			

		that is discharged to the sewer. • "**Storm Water Retention Tank** - The southwest corner of the property features a storm water retention tank to control run-off entering the sewer system." • **Green Roof** - Plantings on the laboratory roof provide rainwater retention.			
Material Use and Embodied Energy				• Recycled materials made furniture, carpet • Exterior insulation boards were created from sustainable natural fiber materials. • Use local supplier's manufactured mechanical systems such as: boiler and heat pumps to reduce the embodied energy use. • "**Structure** - The use of substantial cantilevers in the steel structure on the north, south, and west sides of the building reduce the number of columns, overall steel tonnage, and required footings for the building."	

6.2. Scope and approach

This chapter shows how a multi-disciplinary design team could use VDS to achieve a low energy and high IEQ building design, from conceptual to detailed design stage, while considering the interaction of multi-design factors and their combined effects on the building performance. The illustrations will be limited to the following scope:

- Three design stages including “Assess”, “Define” and “Design”;
- Five design factors including: “Site and climate”, “Form and Massing”, “Internal Configuration”, “External Enclosure”, and “Environmental Systems”.
- Quantitative simulation analyses for energy consumption and IEQ.

Five performance aspects introduced in chapter 5 will be evaluated and the evaluation results will support decision making and further design development. Overall qualitative evaluation will be performed first to illustrate the usage of VDS for systematic consideration of different design factors. Where applicable, the quantitative simulation will be performed with results that are intended to support the decision making process for the building design and component development.

6.3. Design process and definition of tasks

6.3.1. Design process overview

The CoE building is meant to be a showcase and create a test bed for innovations in building integrated environmental and energy systems. Programmed spaces mainly include offices, semi-public spaces for meetings and convention, and laboratories. With these general project objectives and space functionality requirements in mind, the first task for the management team is to set up the design process, determine the required team configuration and develop a work plan including tasks and schedule for the project.

As introduced in section 3.2.1, the coordinated design process, VDS “Magic Cube”, is organized by design teams, design factors and design stages. Two of these three dimensions - design factors and design stages have been defined in the scope section for this illustration. For each new project, designers also need to provide basic building information such as building type, size, location, and required function, and assign tasks to team members according to the project type and procurement. VDS provides a project setup window to input this information (Figure 6-2 VDS project setup window). For the illustration, building type “medium office” is selected for the CoE project. This selection will directly impact a series of default parameter settings for the reference building (baseline building model) as introduced in section 5.3.4. Each of the three teams (management team, architectural design team, and system design team) can be further divided for more specific roles. For example: architectural design team may be further divided to represent architect, landscape architect, and interior designer. The team configuration may vary depending on project type, scale and other requirements. The template offers the opportunities to customize team configuration, but it is not necessary to specify each role for every project.

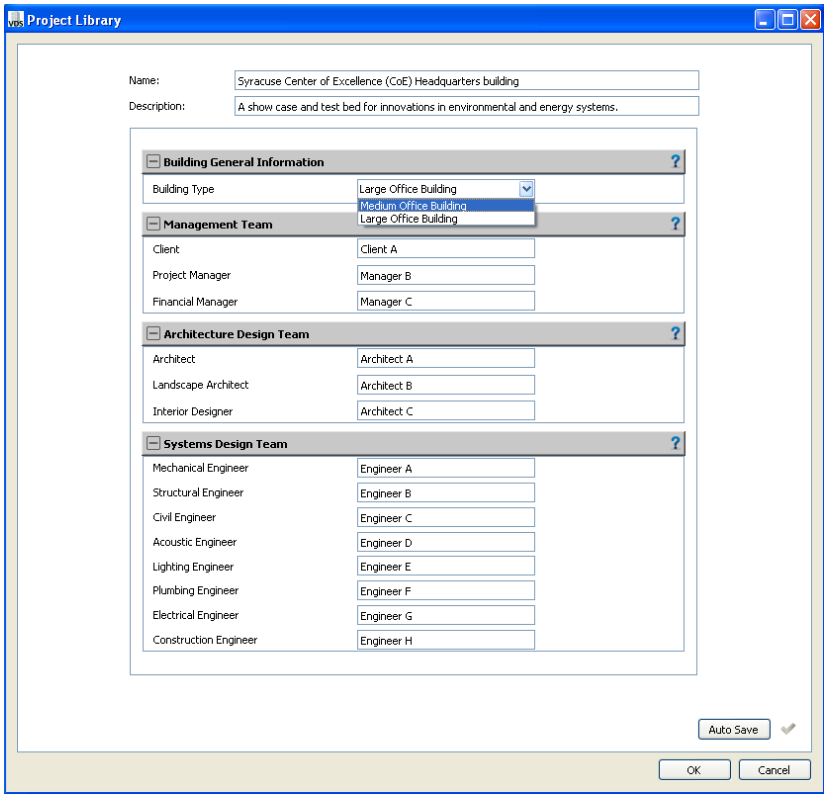


Figure 6-2 VDS project setup window

Once project type and team configurations are specified, it is the next task to set up the building design process in terms of tasks for each design stage. In the VDS context, the management team in consultation with the architectural and systems design teams is presumed to specify all the major tasks that need to be completed at the various design stages according to the various relevant design factors. VDS provides a framework for the task planning, monitoring and coordination throughout the design and systems development.

The scheduled tasks for the hypothetical CoE building design process are presented in a tree view in the VDS “process window” (Figure 6-3). An overarching process diagram that corresponds to all design processes is shown in Figure 6-4 Overarching design process and system interdependencies diagram (to be implemented in the future version of VDS). In addition to the scheduled individual tasks and the process flows (solid lines connecting the tasks), the anticipated team interactions and possible interdependencies between different design factors are also indicated in the process diagram (Figure 6-4). For example, In order to consider the use of natural ventilation to reduce energy consumption, the local wind and air quality conditions in the building site (output of the "Assess Environment" task) will be needed as input for the assessment of "Enclosure Opportunities" and "Environmental Systems Resources".

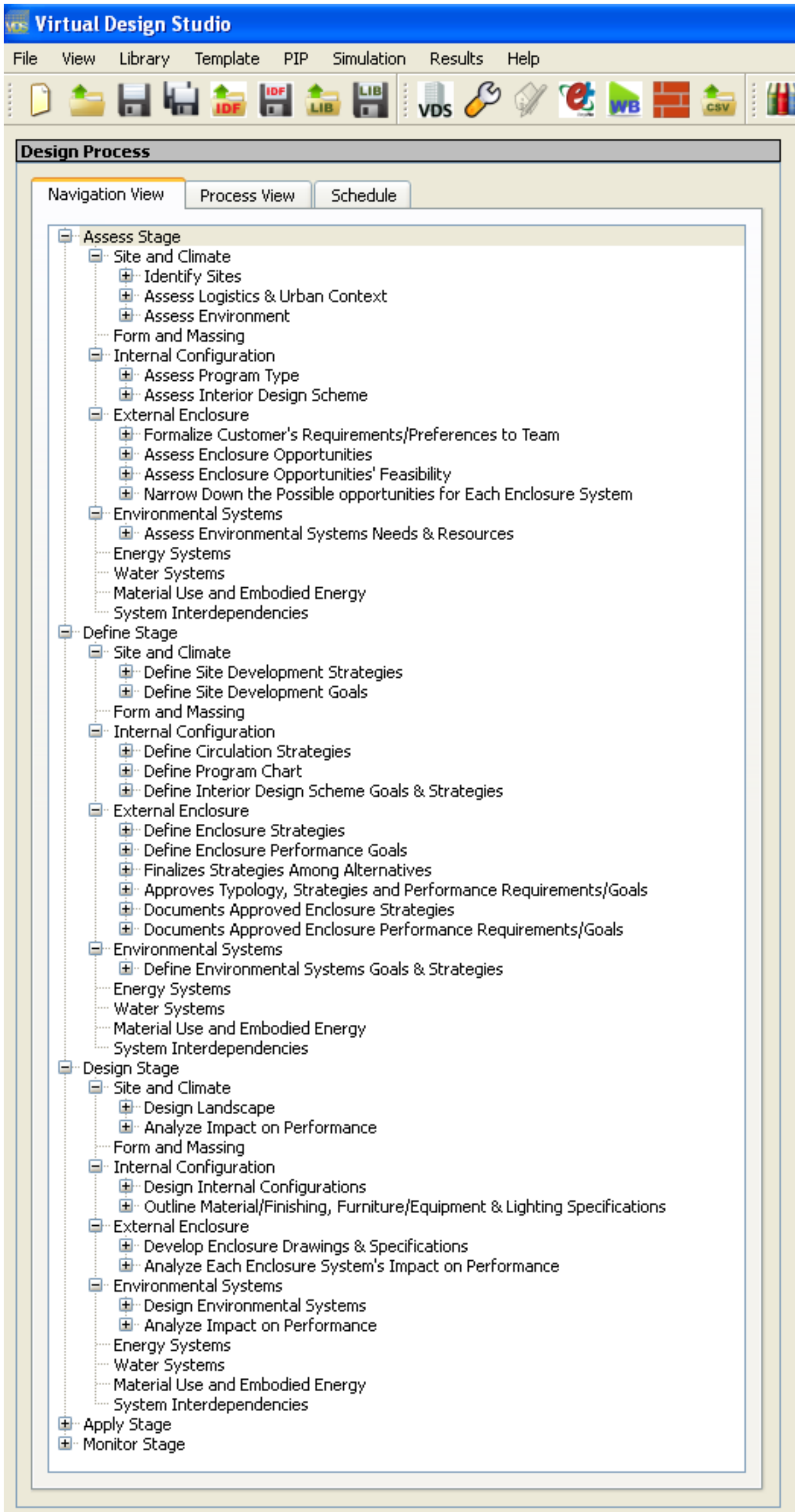


Figure 6-3 Tasks of hypothetical CoE building design process study

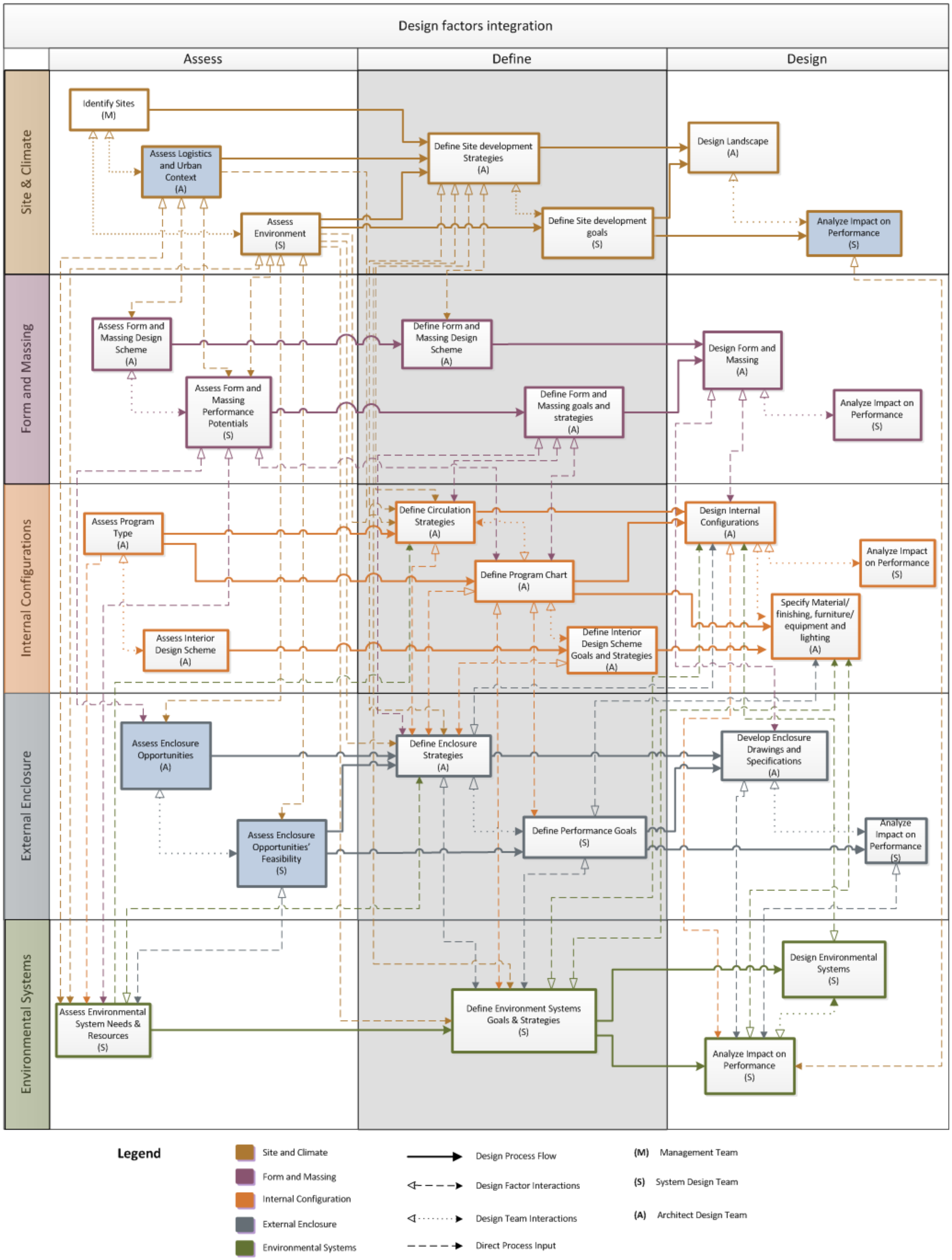


Figure 6-4 Overarching design process and system interdependencies diagram

The design process matrix (Table 6-2 Tasks selected for hypothetical CoE design process illustration shows the selected major tasks that will be discussed in this chapter for the hypothetical design process. In the following subsections, tasks in each cell of the matrix will be discussed regarding task definition, task input and output, and respective interdependencies. The detailed performance evaluation and associated simulation analysis for comparing different design options will be discussed in Section 6.4.

Table 6-2 Tasks selected for hypothetical CoE design process illustration

Design Factor	Assess	Define	Design
Site and Climate	• Identify Sites • Assess Logistics and Urban Context • Assess Environment		
Form and Massing	• Assess Form and Massing Preferences According to Building Typology • Assess Design Alternatives for Site Allocation and Massing Distribution • Assess Form and Massing Performance Potential for the Developed Options		
Internal Configuration		• Define Programmatic Zoning and Circulation Strategies According to Spatial Relationships • Define Program Chart • Define Performance Aspects for Different Room Programs	

		• Define Interior Design Scheme Goals and Strategies	
External Enclosure		• Define Enclosure Strategies • Define Performance Goals	
Environmental Systems			• Design Environmental Systems with Preference Given to Efficient Passive and Hybrid System Solution • Analyze Impact on Whole Building Energy and IEQ Performance
Systems Interdependencies			• System integration (optimize all related components)

6.3.2. Site and climate

Planning sustainable buildings starts with a proper site selection. The location of a building affects a wide range of factors such as: building energy consumption, environmental impacts, indoor environmental quality and renewable energy utilization. The location also impacts the energy consumed by transportation for occupants commuting, and the use/reuse of existing structures and infrastructures (WBDG Sustainable Committee, 2013). Therefore, it is important to address the site selection early on in the project development process. This also applies to the CoE building design case as the site was not determined at the beginning of the project, and two alternative sites were evaluated.

To identify and select the optimal site, conditions and available resources of each candidate site need to be comprehensively analyzed. Therefore, at stage "Assess", for design factor "Site and Climate", three tasks are planned by management team: "Identify (suitable/potential) Sites", "Assess Logistics & Urban Context", and "Assess Environment" (Figure 6-5 Process diagram for "Site and Climate" at "Assess" stage.

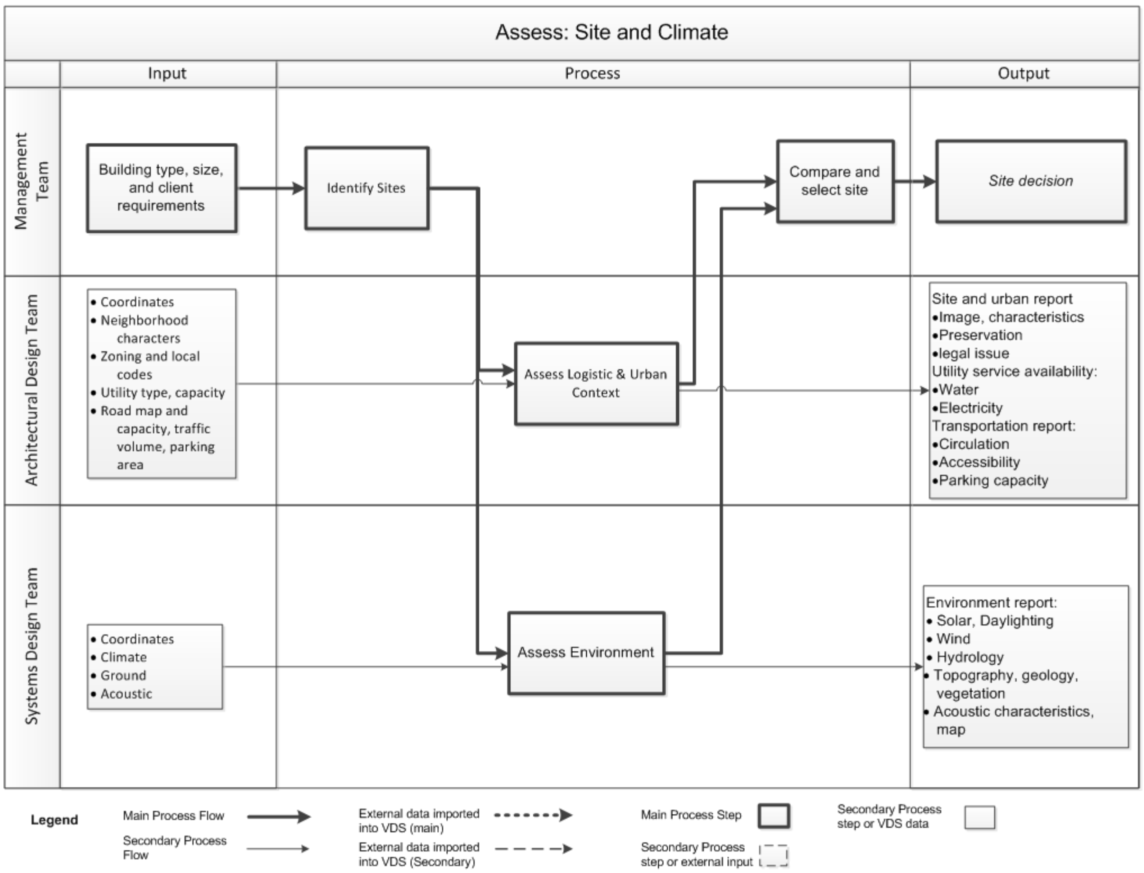


Figure 6-5 Process diagram for "Site and Climate" at "Assess" stage

The CoE design process starts with task "Identify Sites" which is meant to provide the opportunities for all participated team members to understand the site as well as other fundamental project information which may be constrained by site conditions. This task is led by the Management Team including clients and project managers. Candidate site(s) can be identified based on an understanding of the basic project requirements such as input from the following areas: building type, size, functionalities and other project specific requirements. The output of this task -- candidate site(s), then is passed to the other two tasks “Assess Logistics & Urban Context” and “Assess Environment” for in depth analysis. The client of the CoE building intended to build a demonstration building, create a test bed for environmental and energy technologies, and test the integration of building innovations. To meet the intent, two candidate sites were identified (Figure 6-6 Candidate sites of CoE headquarters building). They are located at: corner of 690 & 81 highway, downtown Syracuse (Site A) and south campus of Syracuse University (Site B), respectively.

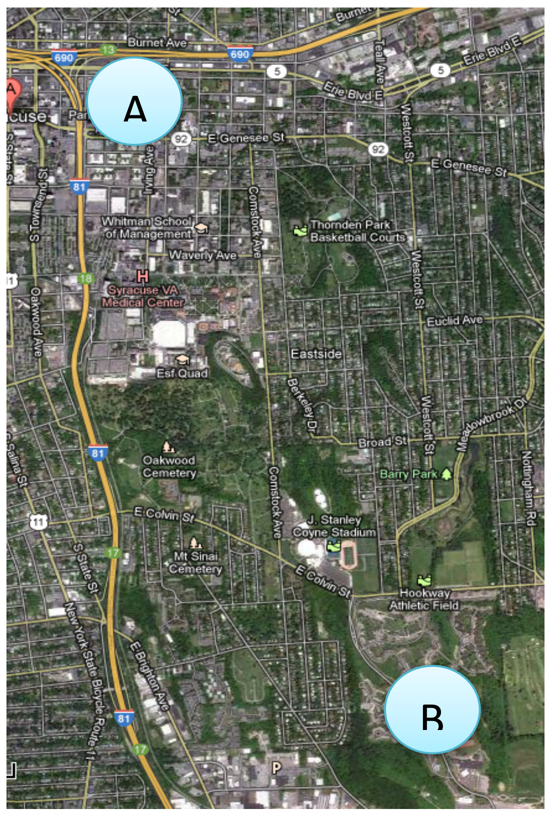


Figure 6-6 Candidate sites of CoE headquarters building

The purpose of task “Assess Logistics & Urban Context” is led by architects who fully explore and understand the logistics and urban context conditions of the candidate sites. Design teams can get to know the site characteristics, required historical preservation and other legal requirements by collecting site location, neighborhood conditions, zoning and local codes as input. Similarly, given the utility type and capacity information, the availabilities of utility services such as water, electricity, gas can be concluded. Reviewing the road map and capacity, traffic pattern and volume can provide information related to site circulation, accessibility and parking capacity. For CoE building project, “Site A” is located at downtown Syracuse while “Site B” is located at south campus of Syracuse University. There are two highways (#81 and #690) passing by site A with convenient local road access while only a few local roads are connected to site B. Another noticing difference between these two candidate sites is: “Site A” is designated “brownfield”, it is the former site of the LC Smith typewriter factory and Midtown Plaza. Site B is a part of the south campus area, a designated industrial park that has not ever been developed. It is a much more quite and secluded site, typical of an “academic environment”, and can be readily accessed via campus bus. The site is nearby a golf course, and has no apparent air pollution and noise issues. Situated on top of a hill, it also has a high elevation than Site A, and has stronger wind.

Besides an urban context and logistical analysis, the system design team will simultaneously perform the task “Assess Environment” which analyzes the environmental conditions for the candidate site(s). Site location, climate, air, ground, and acoustic conditions will be collected as input. The candidate site(s) profile regarding solar, daylight, wind, hydrology, geology, acoustic conditions will be generated. Due to the variety of project and associated goals, analysis performed by architectural and system design teams may partially cover aspects mentioned above. For CoE building, task “Assess Environment” asks the user to input the site and climate conditions for the candidate sites including climate zone, summer design day, winter design day, latitude, longitude, and elevation. The information will be used for many later tasks.

Additional documentation which may help to complete the current task "Assess Environment" can be uploaded to the "Repository" on "Result Window", e.g., sun path, wind rose (Western Regional Climate Center, 2013) (Figure 6-7 Additional documentations uploaded to PIP: sun path, wind rose).

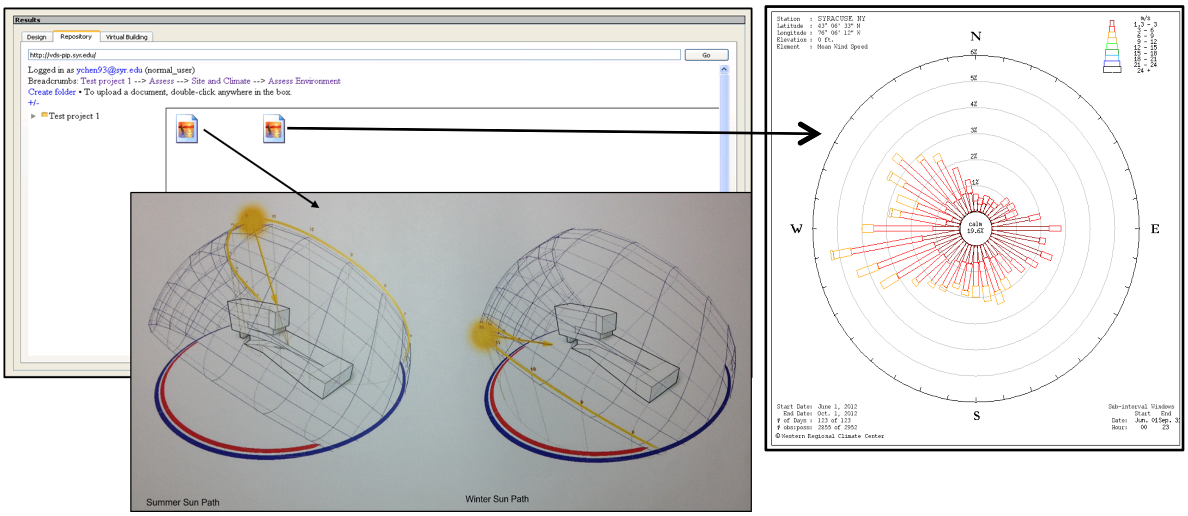


Figure 6-7 Additional documentations uploaded to PIP: sun path, wind rose

Site will be finally selected by comparisons among candidate sites against particular project criteria. Analysis from both architectural and system design teams will perform more detailed analysis to compare the different sites (to be discussed in section 6.4).

6.3.3. Form and massing

Form and massing refer to the shape, orientation and overall configuration of a building. The form placement in relation to its immediate site and neighboring buildings is a crucial aspect of building design (Crisman, 2007). In addition, building form and massing have fundamental impact toward achieving high-performance building because these early stage design decisions impact all design parameters and potential limitations for the later design. For example:

daylighting potential, energy transfer characteristics and overall energy usage of a building (ASHRAE, 2011). The actual choice of building form and massing is a very complex process which may be affected by site constrains, building functionality requirements, project intents and sustainability objectives etc.

At the "Assess" design stage of "form and massing", there are three tasks scheduled to manage the complexity mentioned above: "Assess Form and Massing Preferences according to Building Typology", "Assess Design Alternatives for Site Allocation and Massing Distribution", and "Assess Form and Massing Performance Potential for the Developed Options".

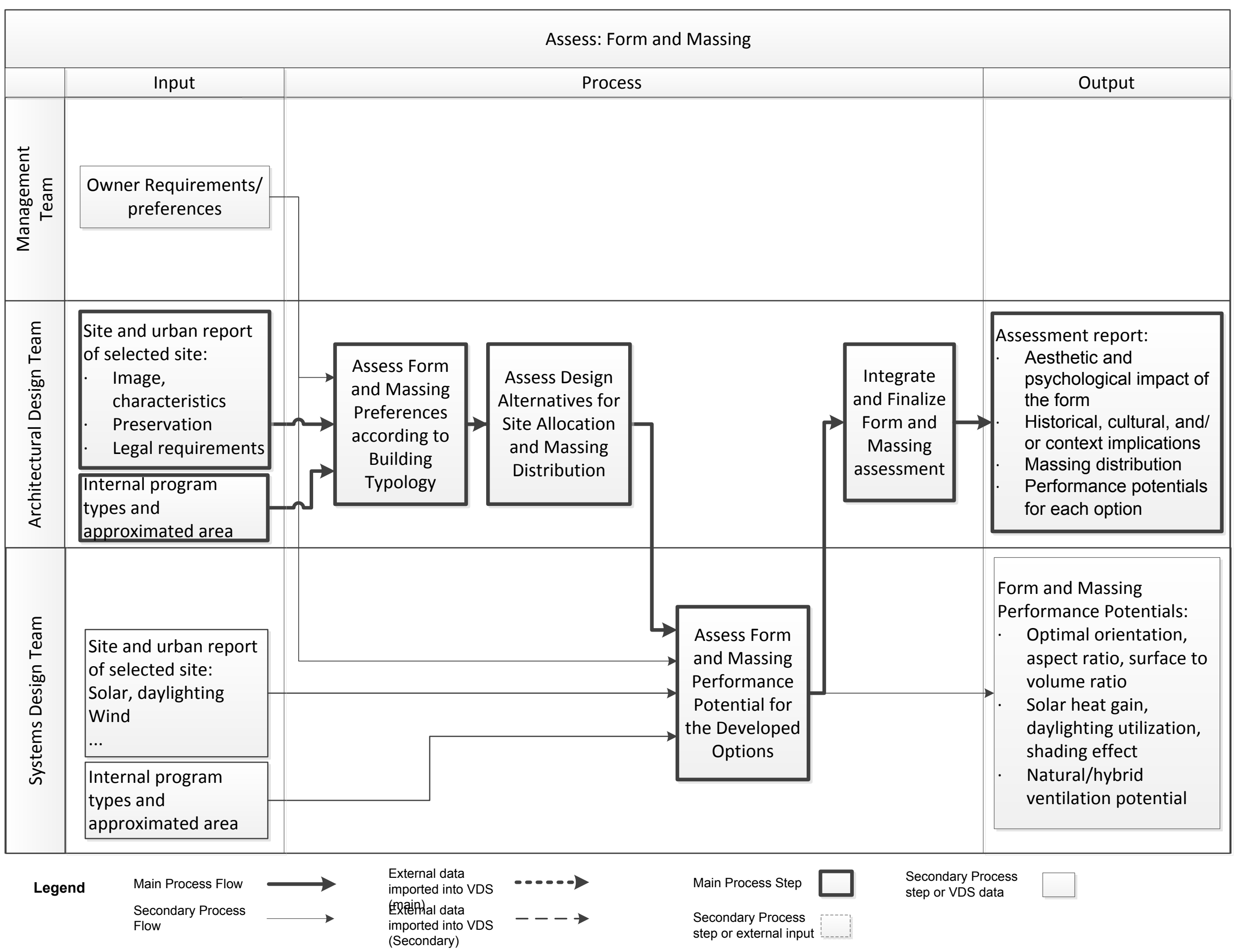


Figure 6-8 Process diagram for "Form and Massing" at "Assess" stage

Task “Assess Form and Massing Preferences According to Building Typology” is led by the Architectural Design Team. This task is meant to answer questions such as: “What should the aesthetic and psychological impact of the form design be? How should form relate to the surroundings? Should the building image be similar to or distinct from its neighbors? Are there historic, cultural, and/or context implications of the given form?” (Edith Cherry, 2009). To answer these questions, the results from task “Assess Logistics and Urban Context” of “Site and Climate” and “Assess Program Type” of “Internal Configuration” are used as the inputs. For example, Site A, located at downtown, was selected because of its visibility and potential impact on the local community in promoting sustainability and technology innovation. There were no specific historical, cultural, and/or context implications. The CoE building was intended to be a showcase and a test bed for environmental and energy technologies and building innovations. Required spaces included offices, classrooms, public spaces, and research laboratories from small scale to large scale.

Architectural Design Team leads the task “Assess Design Alternatives for Site Allocation and Massing Distribution”. In order to meet the form and massing preferences assessed by previous task and project’s sustainable intent, this task tries to use different massing (volumetric) designs to assess the relations of the building with its site, surrounding context, and of the building with its sub-parts (massing elements). Some questions to be answered include: how much of the site area should be occupied by the building and overall development foot print (a tall building with a small footprint or shorter building with a larger footprint)? Should the building be divided into multiple massing elements? How much open space should be provided? The CoE building may be built relatively higher with smaller footprint because: its site is remediated from brownfield, smaller footprint can avoid potential pollutant penetration from soil;

higher building can attract more attentions so the sustainable goal of CoE could be better promoted to the community; a smaller building footprint also means less impact on surrounding environment.

Task “Assess Form and Massing Performance Potential for the Developed Options” is led by the System Design Team. This task intends to explore the opportunities to minimize the building energy demand by integrating passive design potentials in form and massing design. The passive design potentials may include but not limited to:

- Optimize the building orientation, aspect ratio, façade orientation, floor depth, and surface to volume ratio to reduce the building’s energy consumption.

- Consider a suitable cross section for maximum use of day lighting and enhanced natural/hybrid ventilation.

- Consider less perimeter area in massing design because too many jogs and changes in the massing can lead to significant increases in the building perimeter, which means more materials to enclose the building and therefore, larger costs (Building and Construction Authority, 2010). An example is shown in Figure 6-9 Same floor area with varying building perimeters.

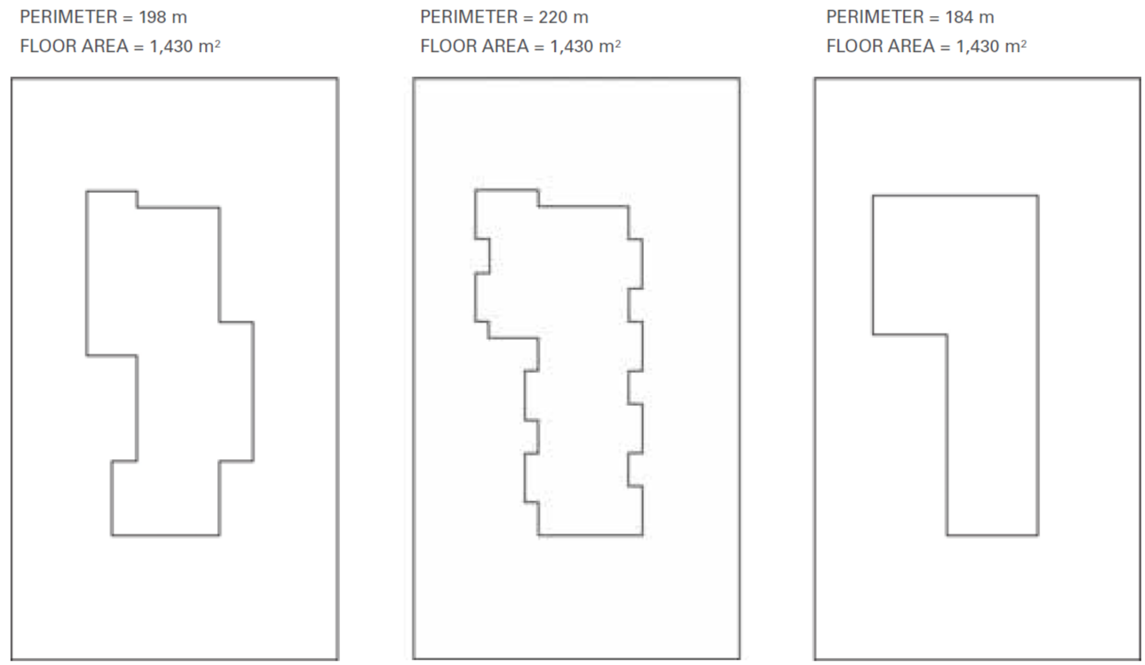


Figure 6-9 Same floor area with varying building perimeters

Major input to this task is the site environmental profile from task "Assess Environment" of "Site and Climate". It includes sun path, prevailing winds, noise and pollutant sources, etc. The CoE building's latitude is N 43° 3.0', longitude is W 76° 8.5'. The sun path and wind rose of Syracuse is shown in Figure 6-7 Additional documentations uploaded to PIP: sun path.

Output of this task provides the preliminary optimal range or recommendations on form and massing related parameters such as: orientation, aspect ratio, surface to volume ratio etc. These related parameters help the later development in next stage and will impact design factors such as "Internal configuration" and "External enclosure" design.

6.3.4. Internal configuration

Internal configuration deals with the programmatic zoning related design aspects as stated in section 3.2.1.3. The Architectural Design Team leads the development of internal configuration design tasks, allocating the interior spaces based on the understanding of the functional needs of the project and associated relationships among the spaces.

At the “Assess” stage, critical project functional information/requirements that may affect “internal configuration” design has been collected, such as: the client’s organizational structure and relationships, space usage and area requirements, space accessibility (regarding security/privacy), activities and associated schedules, necessary equipment, etc. The CoE building is mainly occupied by office staff and researchers. The approximate space areas are (in square feet): laboratory 16000, office 7000, public spaces 4000, mechanical room 2000, classrooms 1000, etc. Common office requirements and accessibilities standards are applied to most of the spaces. The office portion of the building will be operated under regular office hour schedule, while the research labs are expected to be operated under more flexible schedules depending on the research and experimental needs.

At the “Define” stage, tasks for “Internal configuration” are meant to produce the master/general level program chart in order to guide the “Internal configuration” detail design at the “Design” stage. Circulation strategies will be defined by analyzing activity patterns to develop the master/general level program chart. Additional interior design goals and strategies may also be established. Therefore, corresponding tasks “Define Programmatic Zoning and Circulation Strategies According to Spatial Relationships”, “Define Program Chart”, “Define Performance Aspects for Different Room Programs”, and “Define Interior Design Scheme Goals and Strategies” are planned (Figure 6-10 Process diagram for “Internal Configuration” at “Define” stage). Strategies, program chart, performance aspects, and goals defined for “Internal Configuration” from this stage will also have impact on many decisions of other tasks related to different design factors. For example, fenestration design of “External Enclosure” and mechanical systems design of “Environmental Systems”.

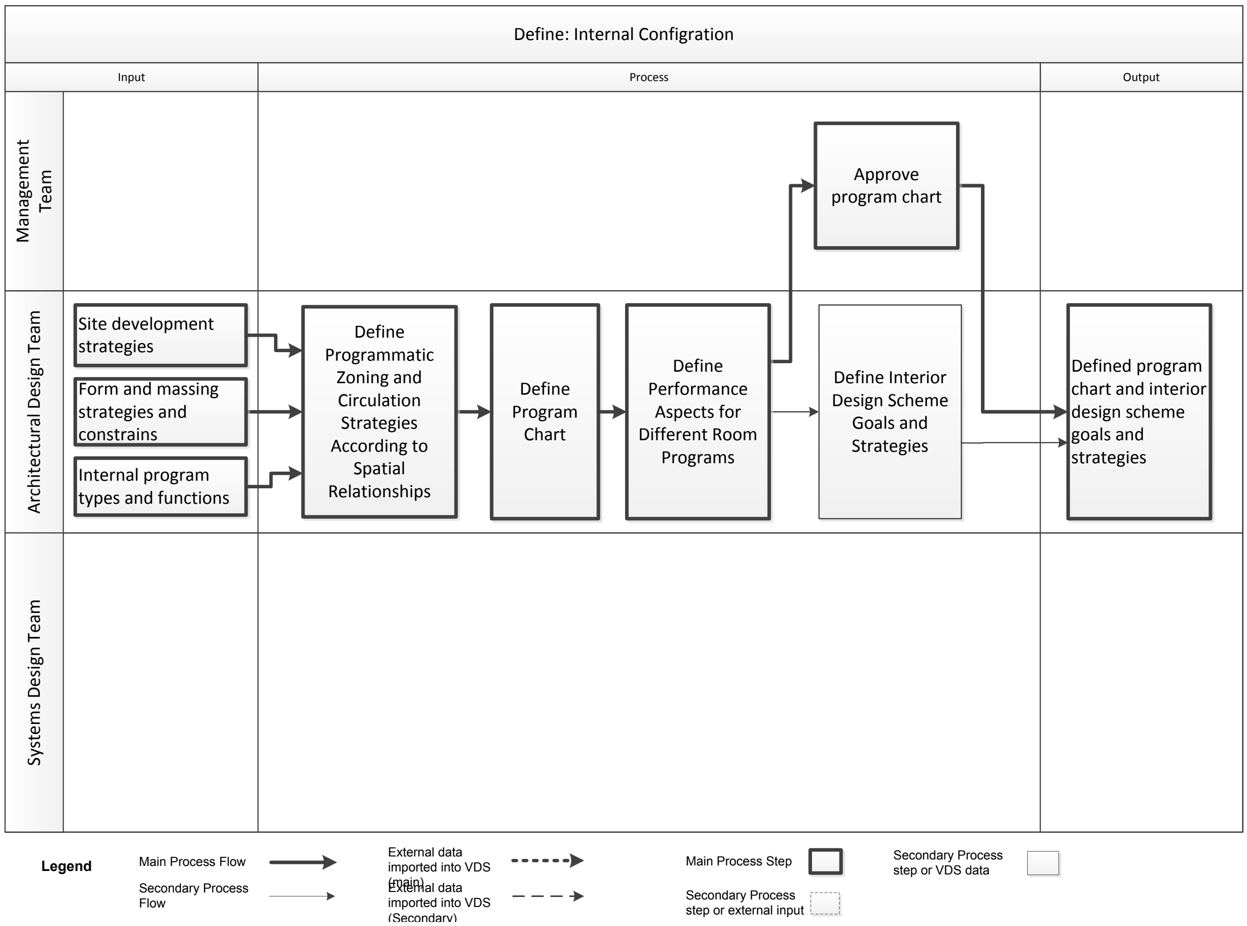


Figure 6-10 Process diagram for “Internal Configuration” at “Define” stage

Task “Define Programmatic Zoning and Circulation Strategies According to Spatial Relationships” intends to identify, consider and define strategies for occupant circulation in the building (i.e., the flow of people). Its outputs will be used in the development of the program chart development in task “Define Program Chart”. It uses the collected functional and other information/requirements from “Assess” stage, examines patterns of activity in facility and considers how those patterns create spatial relationships (WBDG Functional / Operational

Committee, 2013). The CoE building's space requirements include: offices, classrooms, public spaces, and research laboratories from small scale to large scale. To accommodate these functional requirements and allow for good circulation among these spaces, the preliminary building form is divided into two primary masses. The offices and field laboratories that are intended to simulate full-scale office environments for testing of IEQ conditions are allocated in what is labeled the "tower", while the various specialized experimental facilities are to be located in the open spaces under the sloped ramp wing, called the "barn".

Task "Define Program Chart" is meant to develop master/general level program chart(s) to help determine structural and building functional modules that may be more accommodating for furniture and equipment placement. "Bubble diagram" is frequently used during this task. These "bubble diagrams" indicate relationships between spaces with different functionalities to help in deciding where to locate them (Gretchen Addi, 2000). An example is shown in Figure 6-11 "Bubble diagram" example for the CoE building in which bubbles represent the space and lines indicate their relationships. Different offices share similar functions and are more private compare to research laboratories so they are grouped together and located further from the reception area. Research laboratories are allocated more closely to service/support room such as mechanical rooms and storage rooms since researchers will frequently work among these rooms. Class rooms are allocated behind the reception area for public access convenience.

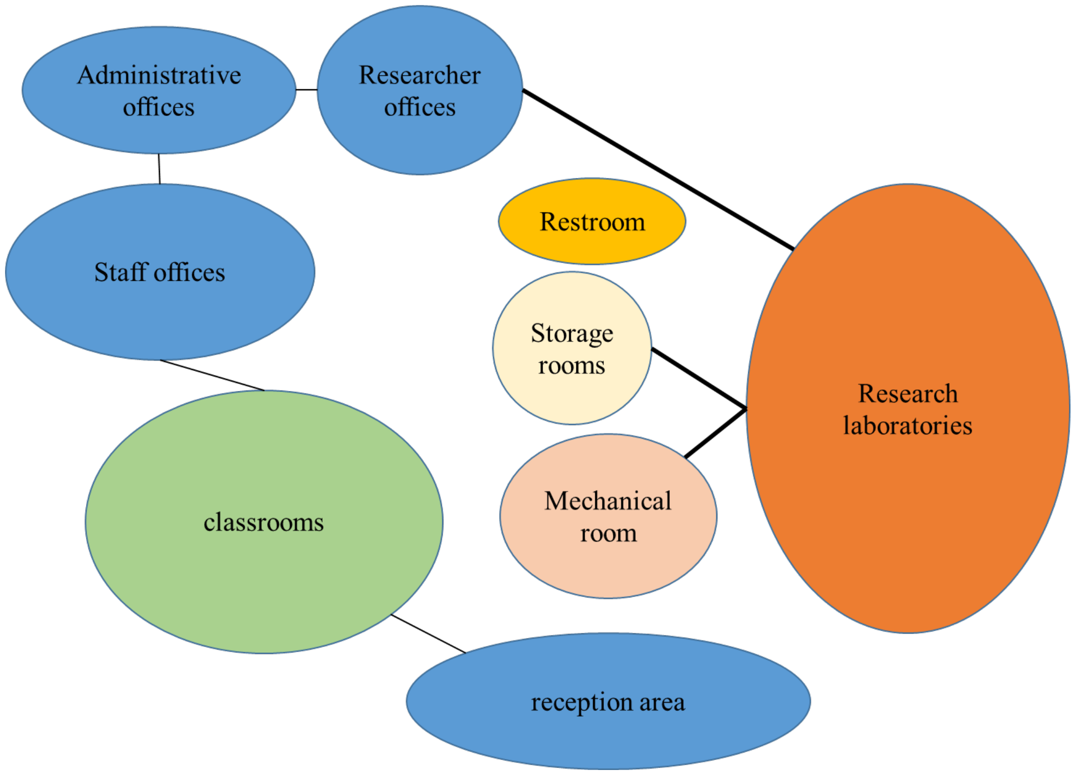


Figure 6-11 "Bubble diagram" example for CoE building

Besides "bubble diagram" methodology, some examples of common categories of internal configuration strategies also need to be considered, including (Edith Cherry, 2009):

- “Centralization and decentralization: What function components are grouped together and which are segregated? For example, in some offices the location for copy machines is centralized, while in others there are copiers for each department.”

- “Flexibility: What types of changes are expected for various functions? Do facilities need to change over a period of a few hours? A few days? A summer recess? Or is an addition really needed?”

- “Flow: What goods, services, and people move through the project? What is needed at each step of the way to accommodate that flow?”

- “Priorities and phasing: What are the most important functions of the project? What could be added later? Are there ongoing existing operations that must be maintained?”

- “Levels of access: Who is allowed where? What security levels are required where?”

For the CoE building, the above mentioned strategies are considered in the task “Define Program Chart”: in terms of “Flexibility” and “Flow” strategies, the specialized laboratory facilities may encounter frequent reconfigurations for different research subjects. The reconfiguration potentially requires high volume of goods, services, and people to move through the building. So it is a good choice to allocate them under the sloped ramp wing which is on the ground floor and separated from the main offices. In terms of “Centralization and decentralization” and “Levels of access” strategies, administrative offices that require more privacy and have close relationships with other rooms such as conference, class and social functional rooms are centralized on the same floor in the tower, shown in Figure 6-12 CoE program and organization .

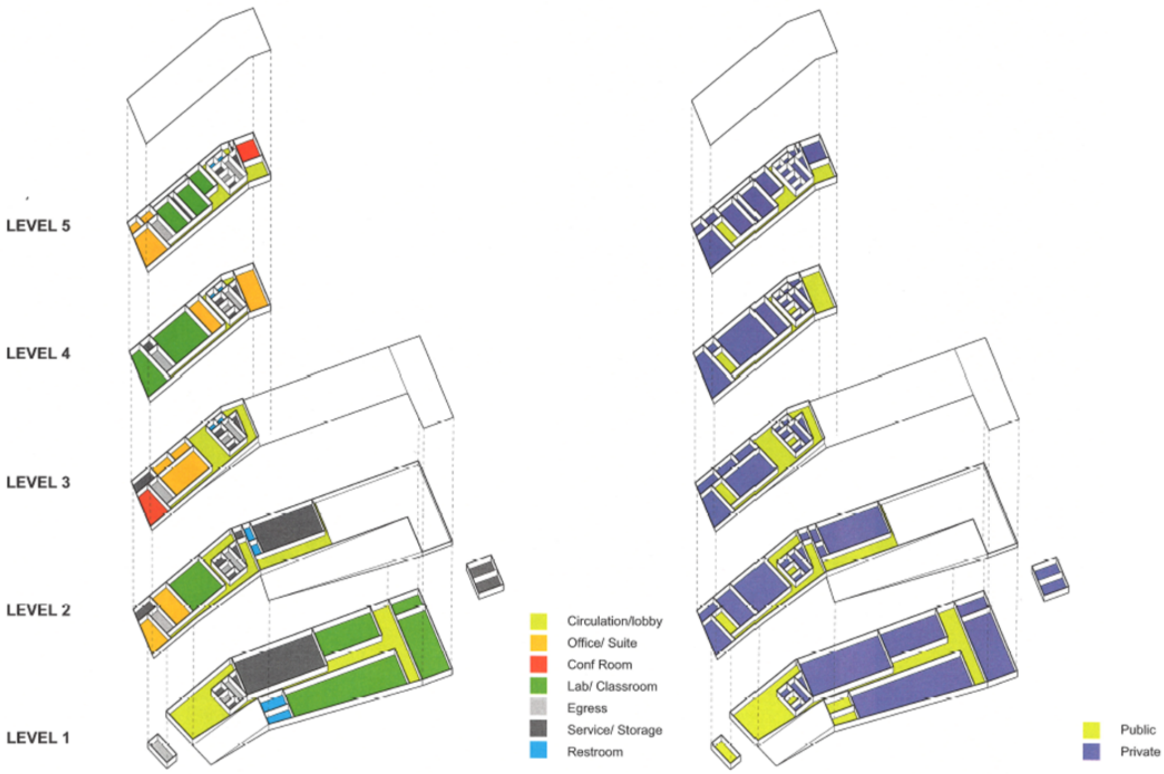


Figure 6-12 CoE program and organization (Augustine, 2011)

Based on the master/general level program chart(s) considering above qualitative strategies, detailed quantitative analysis regarding energy performance may be performed to finally select the master level program chart.

Because there are many different types of rooms in a building, and each type of room has its own performance requirements, task "Define Performance Aspects for Different Room Programs" is scheduled to specify those requirements for each (type) room. For example: in order to meet different environmental conditioning settings of certain experiments, research laboratories in CoE building may require support of separated HVAC system from the central systems, so the laboratories can be controlled individually without interfering the whole building operation.

During or after the development of the master/general level program chart, task "Define Interior Design Scheme Goals and Strategies" may establish the goals and strategies for specifying/selecting interior finishing, furnishings, and equipment in order to design a healthy, comfort, productive, and aesthetical interior environment.

6.3.5. External enclosure

The external enclosure of a building separates the outdoor environment from indoor spaces. It provides the protections of occupants by controlling and balancing external and internal forces. Functions of external enclosure can be grouped into four sub-categories (Straube, 2006): support functions (support structural loadings), control functions (control, regulate and/or moderate mass and energy flow), finish functions (meet visual, esthetic requirements), and distribution functions (distribute services or utilities). Due to the responsibilities for such large amount of functions, external enclosure design has great influence on the whole building performances.

External enclosure typically includes the physical components: roof system(s); façade system(s), including wall system(s) and fenestration; basement and/or foundation system(s); and hybrid system(s) which interact(s) with above system(s). In order to achieve the high-performance enclosure design, not only each of these systems needs to be carefully analyzed, but also the interactions between these components and their combined effects on the performance need to be considered.

Because of not only the function, but also inter-related components integration requirements, at the "Define" stage, it is critical to define the strategies and performance goals for external enclosure design. These strategies and performance goals will heavily influence enclosure potential performance and guide the detail design in the following “Design” stage. The corresponding planed tasks are: “Define Enclosure Strategies” and “Define Performance Goals” (Figure 6-13 Process diagram for “External Enclosure” at “Define” stage). Each of these tasks will be further decomposed for specifying each enclosure components, respectively. Because enclosure interacts with exterior environmental and building interior space conditions, the general input for these tasks are: exterior - assessed urban context and environmental conditions from factor “Site and Climate” and stage “Assess”; interior - programming and space uses information from factor “Internal Configuration” and stage “Define”. The preliminary geometry information from factor “Form and Massing” and stage “Assess” also impose constrains on enclosure design.

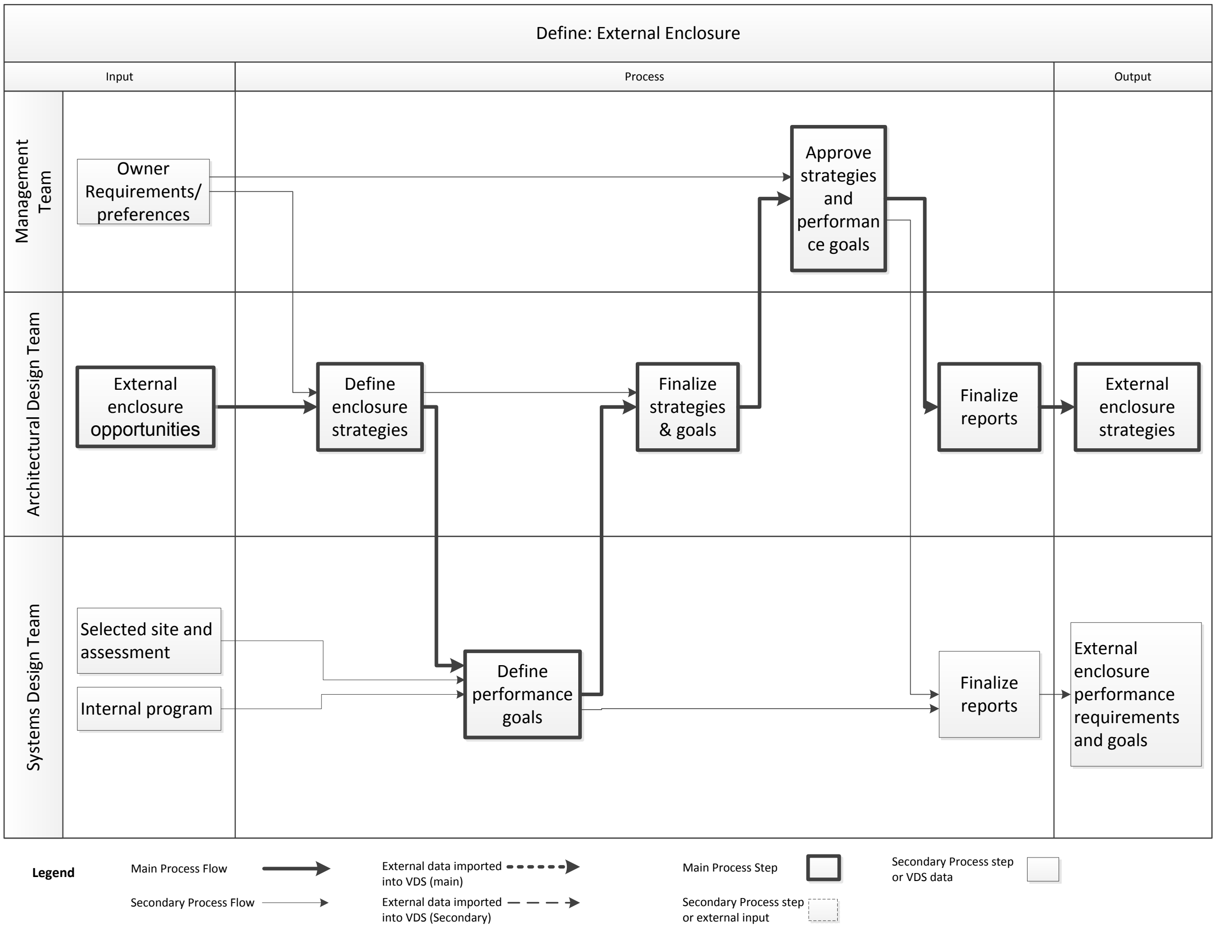


Figure 6-13 Process diagram for "External Enclosure" at "Define" stage

Task "Define Enclosure Strategies" is led by architect design team. It intends to make decisions on typology for each enclosure component (roof, façade, basement/foundation, and hybrid system(s)) and select the strategies which can maximize the utilization of site resources to satisfy all functional requirements as well as promoting sustainability in building design.

For example, the Architectural Design Team may have considered the following strategies in CoE building design:

- For roof system(s), increasing surface reflectivity to reduce the HVAC loading and mitigate the heat island effect, using green roof and storm water collection system to reduce the water runoff as well as water usage demand.

- For Façade system(s), architects may weigh the insulation improvement of wall and window system(s) against the construction and operation cost. They may also adjust window size, select appropriate glazing types, and adding shading devices in order to balancing daylighting potential, glare and solar heat gain. For the basement/foundation system(s), thermal, moisture and pollutant control need to be carefully considered. Especially, CoE project is developed on a brownfield, the ground floor insulation needs to prevent the pollutant intrusion from the contaminated soil.

- For hybrid system(s), operable window(s) need to be integrated if natural ventilation is applied. The Architectural Design Team will closely collaborate with the systems design team along the process to approve the feasibilities of defined strategies for each enclosure component.

Task "Define Performance Goals" is led by System Design Team. In this task, the System Design Team is supposed to provide technical feedback/support for Architectural Design Team's decision on strategies selection. At the same time, system team will define the performance goals for each external enclosure component with focus on control functions, especially the flow of heat, air, moisture and pollutant. Daylight control and utilization, acoustics control, and potential renewable energy generation systems (such as: turbine and photovoltaic systems) which are closely related to enclosure design will be discussed as well. To perform the analysis, required input parameters will be based on actual design and assigned to this task. However, as the actual enclosure and whole building design is not completed at "Define" stage, a considerable amount of input will use reference building settings described in section 5.3.4 to perform the analysis.

When the above two tasks are completed, one or more types of enclosure components would have been identified and selected. The corresponding design strategies and goals for each component would also be defined. All these selections and strategies will be used as input for detailed drawings development for the external enclosure systems at the design stage.

6.3.6. Environmental systems

At "Design" stage, since most of architectural features have been determined (such as: building form and massing, external enclosure, internal space configurations), the design shifted from architectural design to building environmental systems design. As introduced in section 3.2.1.3, factor "Environmental Systems" is primarily responsible for HVAC systems design. For medium size office building, like case building CoE, the major objectives of HVAC systems are to provide and maintain thermal comfort and indoor environmental qualities to its occupants in an energy efficient manner.

At "Design" stage, the System Design Team needs to find appropriate, constructible, controllable, affordable, and maintainable heating, ventilating, air-conditioning, and refrigerating (HVAC&R) solutions (Charles E. Gulledge III, 2010). In the meantime, these solutions must be integrated and coordinated with parallel design factors like Internal Configuration and External Enclosure etc. In order to design HAVC systems, as well as integrate the design with other closely related design factors, there are two tasks "Design Environmental Systems" and "Analyze Impact on Performance" scheduled (Figure 6-14 Process diagram for "Environmental

Systems" at "Design" stage). The first task is to design the HAVC systems, and the second to evaluate the whole building performance of various HAVC system design options.

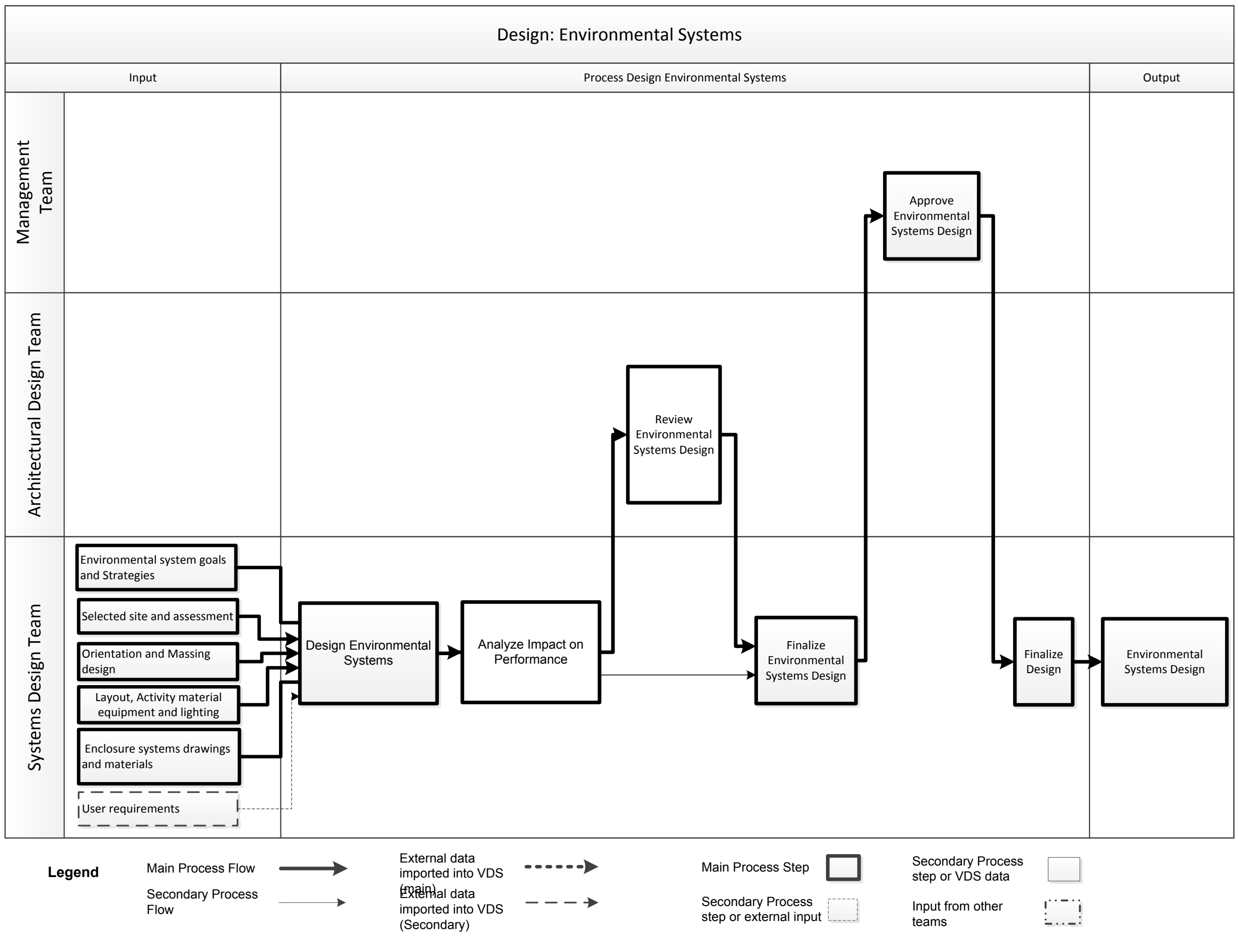


Figure 6-14 Process diagram for "Environmental Systems" at "Design" stage

Major activities (subtasks) involved in task "Design Environmental Systems with Preference Given to Efficient Passive and Hybrid System Solution" include: finalize heating and cooling load requirements, identify system type and specification, finalize HVAC design and HVAC system drawings. The input, process, output information for each of the activities is as follows:

- Finalize heating and cooling load requirements: calculate detailed zone by zone heating and cooling load based on climate condition, actual building construction, zoning, activity and schedule as well as required indoor thermal conditions. For CoE building, all offices need to be fully conditioned, but some large scale laboratories' which are likely to not be fully occupied may only need partial conditioning. The determined load requirements is then used for the final equipment selection and sizing.

- Identify system type and specification: select equipment type and sizing, review of mechanical room requirements, air distribution system space requirements such as supply and return plenums, ducts, and terminals. For the CoE building, central plant heating and cooling services are not applicable. Moreover, the sustainability intents of CoE building strongly recommend high efficiency systems.

- Design HVAC system drawings: develop final drawings outlining HVAC design, layout drawings locating mechanical rooms risers, and primary services routes, reflected ceiling plans, final duct layouts, production of larger scale detailed drawings, co-ordination of all HVAC drawings with, structure and architecture.

- And finalize HVAC design: based on review from the Architectural Design Team, finalize HVAC systems design. This includes finalizing HVAC system, mechanical room as well as duct layout design.

Task "Analyze Impact on Whole Building Energy and IEQ Performance" closely collaborates with task "Design Environmental Systems" to verify the HVAC design alternatives' impact on whole building energy and IEQ performance. It represents the integrated and coordinated design process concept of VDS. In this task, with variation of HVAC design alternatives for the proposed building will be modeled and simulated. Simulation uses the case building climate conditions, geometries, envelope structures, internal zoning, presumed operation schedules etc. Results generated from this task provide information for optimizing the design of the HVAC system.

6.3.7. Design integration/optimization: systems interdependencies

A high-performance building design can be only achieved when not only each individual design factor (or building system) is appropriately designed, but also all design factors are integrated and coordinated concurrently throughout the design process.

To reduce the energy consumption while maintaining high-level indoor environmental quality, passive design strategies are frequently considered. One of the passive design strategies is to take the advantage of renewable resource – solar. There are two aspects associated with solar related design that can be integrated into the whole building design: light (daylight) and heat (solar radiation). Both of these two aspects need to be evaluated from the beginning of the design process among multiple design factors.

As shown in Figure 6-15 Interdependent design factors of solar related design, we use solar related design as an example to illustrate the interdependencies among design factors and how design impacts on different performance aspects. In order to use solar resources, conditions such as sun path, angle, solar intensity, surrounding buildings context which may block the sun light need to be evaluated in factor “Site and Climate”. Building surface to volume ratio, aspect ratio, orientations of roofs and façades which directly determine incident of sunlight and heat transfer through the enclosure require coordination among “Form and Massing”, “External enclosure”, and “Internal Configuration”. In factor “Internal Configuration”, zoning (especially perimeter zoning) needs to simultaneously accommodate thermal comfort and lighting requirements for occupancies, which can be strongly affected by light and heat associated with sun light. The designed indoor space immediately impacts "Indoor Environmental Qualities" such as thermal comfort, visual qualities. It also impacts the "Energy and Atmosphere" because of the artificial lighting load required to supplement natural lighting. In factor "External Enclosure", the effects of fenestration size, glazing type, U-value, solar heat gain coefficient, visible transmittance, related shading devices, and other opaque wall assemblies' U-value and thermal mass on the space load and IEQ need to be considered. In factor "Environmental Systems", given the above architectural design, HVAC systems will be designed according to heating and cooling loads determined by the combined effect of building form, enclosure and internal zoning. The operational energy consumption of the designed HVAC systems directly impacts the "Energy and Atmosphere" as it is a major portion of total building energy consumption.

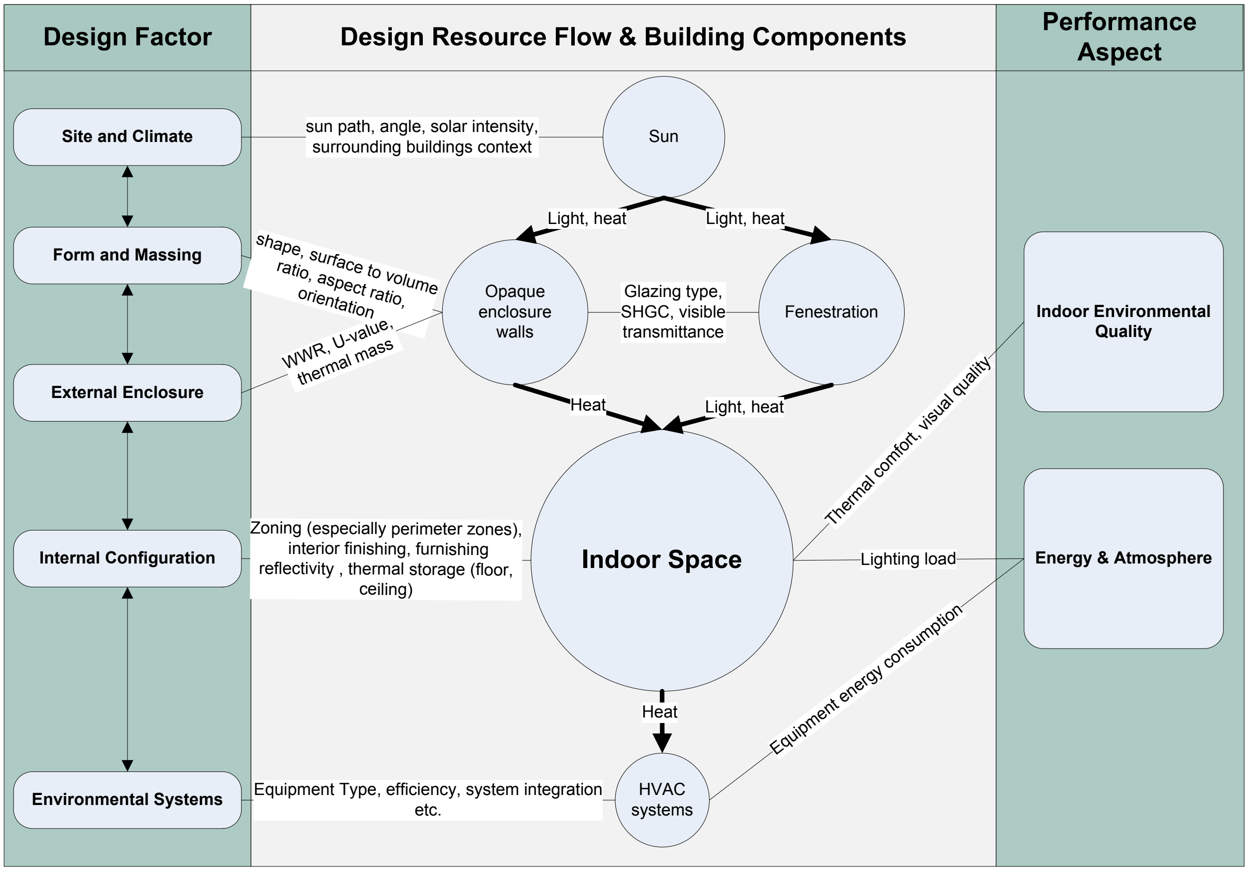


Figure 6-15 Interdependent design factors of solar related design

However, to concurrently integrate and coordinate both aspects of solar related design are very complex, not only because of each of them influences the design/decisions of multiple design factors, but also these influenced design factors may compete or even conflict with each other. For instance: reducing the enclosure exposure (building form with small surface to volume ratio) of the building form can reduce the heating/cooling load because less chance of thermal exchange. However, it may also cause increasing of lighting energy consumption because of less of sunlight exposure, artificial light need to be provided to compensate lighting requirements.

In VDS, beside individual design factors which map to the certain aspects (parts) of the physical building components, factor “System Interdependencies” is proposed to deal with overall building (system) efficiencies related to individual design factors (subsystems) and their coordination, integration, and operation. Each factor has a task named "Impact on performance" to analyze how design variations of that particular factor can improve performance of itself, as well as contribution of performance improvement at whole building level.

6.4. Design analysis and performance evaluation

6.4.1. Site and climate

As elaborated in section 6.3.2, tasks "Assess Logistics & Urban Context" and "Assess Environment" comprehensively analyzed site and climate conditions for two candidate sites for CoE building. The selection from these two candidate sites mainly impact on performance aspects "site sustainability", "Energy and Atmosphere", "indoor environmental quality". Detailed comparisons between these two candidate sites are listed in Table 6-3 Candidate sites performance aspect

Table 6-3 Candidate sites performance aspect

	Site sustainability	**Energy and Atmosphere**	**IEQ**
Site A (Downtown Syracuse)	**Pros:** • Downtown area offers good accessibility to a variety of services and community. • Nearby highway also improve the public exposure which can enhance the visibility of	**Pros:** • Low elevation of site A provides more opportunities for ground heat sour pump (GSHP) utilization (For example: less drilling depth, less total pipe length).	**Pros:** **Cons:** • Contamination associated with previous industrial site uses may pollute indoor environment. • Ambient air pollution level is higher due to

	the sustainability activities of CoE. • Remediate the brownfield which can restore the site for sustained use by future generations. **Cons:** • Limited use of ground due to toxic soil content	**Cons:** • Limited opportunity for natural ventilation due to less wind and more ambient air contamination. • Less potential for power generation by wind	the traffic. • Ambient noise level is higher due to the traffic.
Site B (South campus of Syracuse University)	**Pros:** • Convenient access for faculty and students • No contamination from the ground **Cons:** • Not as accessible to the public as Site A.	**Pros:** • More natural ventilation due to better air quality and higher wind speed • Potential for wind power generation **Cons:** • Less likely to use ground water source due to higher elevation	**Pros:** • Ambient air pollutant level is lower. • Ambient noise level is lower. **Cons:**

There are pros and cons from both candidate sites in terms of potential impacts on the sustainability goals. At the end, site A nearby downtown Syracuse was selected, largely due to the strong emphasis on the needs to better facilitate community engagement and collaboration between academia and industrials as well as its visibility as a symbol of research and technology transfer for sustainable/green building development for the region, state and beyond.

6.4.2. Form and massing

Many opportunities exist for the task “Assess Form and Massing Performance Potentials” at the “Assess” stage. In this illustration, we focus on two form and massing related parameters: aspect ratio and orientation which have significant impact on building energy performance, for instance: solar heat gain, daylighting potential, natural ventilation.

Since no building has been designed yet at the “Assess” stage, VDS uses the reference building model (defined in section 5.3.4) to analyze the energy performance. The detail settings for the design factor are listed in Table 6-4.

Table 6-4 Aspect ratio and orientation analysis settings at “Assess” stage

	Assess Stage	
Site and Climate	• Syracuse climate condition, include ; • No surrounding buildings 	
Form and massing	**Aspect ratio** **Orientation**	**Recommended values need to be evaluated**
Internal Configuration	5 (office) zones on each floor (use reference building model defined in section 5.3.4); Lighting is controlled by step dimming and the indoor luminance level is controlled at 500 lux.	
External Enclosure	Walls system: light weight construction assembly; Windows system: double glazing; with equal 20% window to wall ratio for	

	four facades.
Environmental Systems	HVAC systems are not designed and we continue to use purchased (district) heating and cooling for simple analysis.

In the analysis, maintaining the building model total floor area at approximated the design area 3700 m^2, we conducted one year building energy performance simulation with varied aspect ratio from 1:1 to 5:1 Table 6-5 Building model aspect ratio and corresponding dimension and also varied the building model's orientation from 0° to 180° with a 30° increment Figure 6-16). We compared the energy consumptions among the different settings and recommended optimal value (or range) for aspect ratio and orientation of the case building.

Table 6-5 Building model aspect ratio and corresponding dimension

Aspect Ratio (L:W)	Length (m)	Width (m)
1:1	27.2	27.2
2:1	38.5	19.2
3:1	47.1	15.7
4:1	54.4	13.6
5:1	60.8	12.2

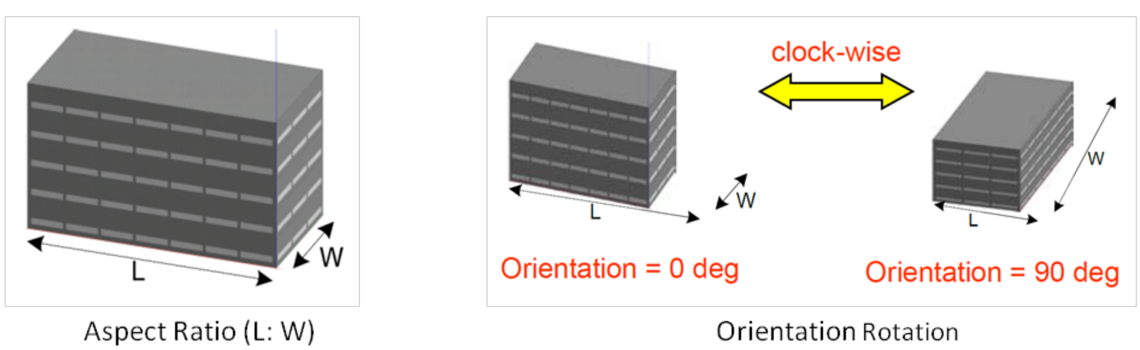


Figure 6-16 Building form and rotated orientation

The building energy performance results are given in Figure 6-17 Building performance results for form, massing and orientation The three axes in the figure are: building's aspect ratio (L:W); building's orientation where 0° means building is oriented as L represents its length of South and North sides and W represents its width of West and East side; building energy for lighting, cooling, heating, and total energy use.

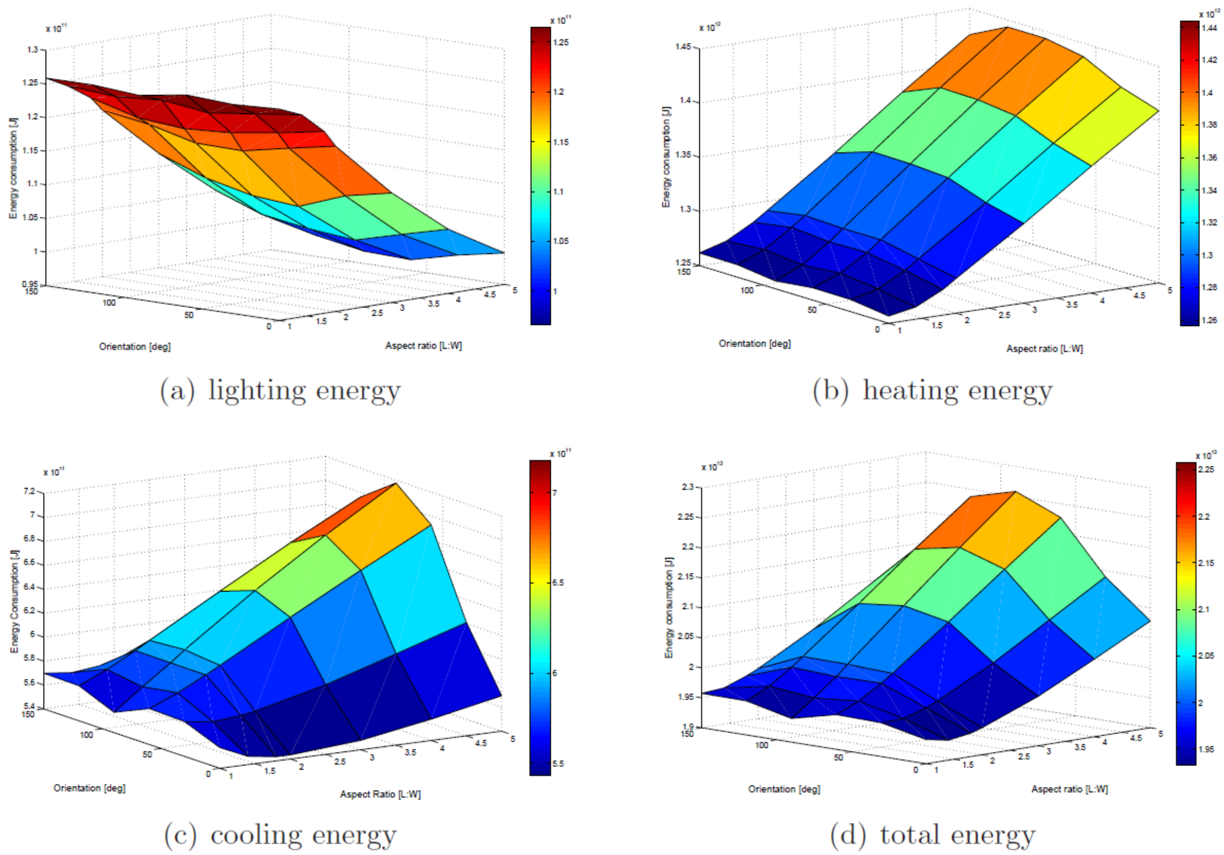


Figure 6-17 Building performance results for form, massing and orientation (Wei Feng, 2012)

It is shown in the results that the case building's lighting energy keeps decreasing with the increase of aspect ratio under certain orientation. Take building's orientation at 0° for example. The increase of building's aspect ratio from 1:1 to higher value will increase case building's surface areas. The South facade's area will also increase with the increase of aspect ratio and thus allow more daylight to come into the building, which decreases the needs of artificial lighting. The increase of building aspect ratio also results in the decrease of building width W and thus allowing daylight to penetrate "deeper" inside the building from South side. The lighting energy does not change much with the building orientation.

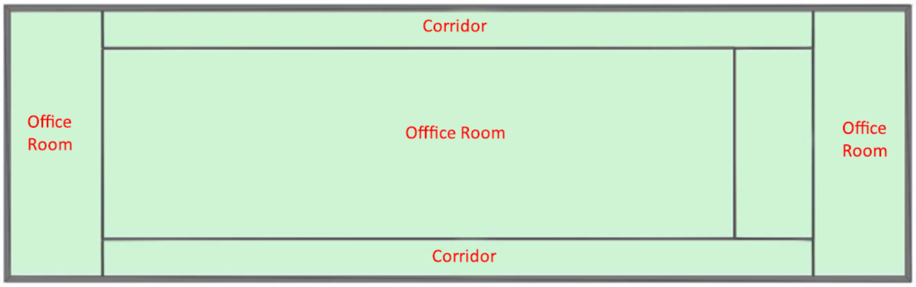
The heating energy consumption exhibits a different behavior compared with lighting energy consumption. Increase of building's aspect ratio leads to the increase of building heating energy consumption because of the increase in exposed surface areas that leads to more heat loss through the building envelope.

Cooling energy is very sensitive to building's orientation especially when building is stretched in high aspect ratio. When building is oriented at 90° and its aspect ratio is over 3 (which means building has its long side L facing West and East and has its short side W facing South and North direction), the cooling energy consumption increases dramatically. This is not only because of the increase of building surface area, but also the West-East facing facades can introduce significant amount of solar radiation and hence thermal load in summer time and thus requires more cooling energy. Although when building's orientation is 0° (building is in South-North direction), the cooling energy also increase with respect to aspect ratio increase mainly because of building surface area increase, the magnitude of cooling energy demand is much less than 90° orientation case. In this case, it is found that the minimum cooling energy usage happen at aspect ratio value between 2 and 3.

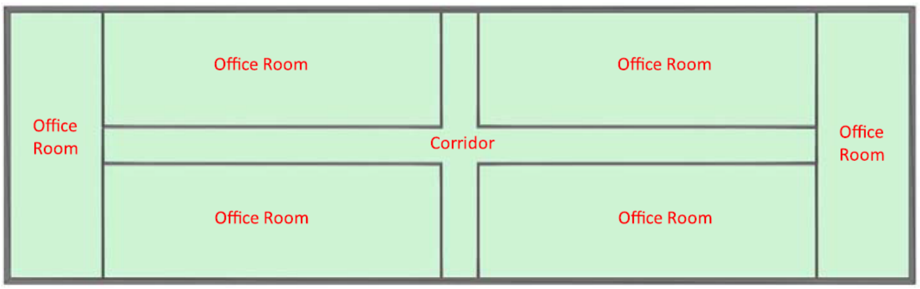
The simulation results revealed the energy performance trends regarding lighting, heating, cooling, and total energy consumption under different building aspect ratios and orientations. It recommends the aspect ratio between 2 to 3 with the long side façade facing south/north for the actual design. However, the final form and massing design need to carefully consider many other related parameters and criteria and integrate all of them in a well balanced way. The final CoE building form and massing design considered the combined effects of solar heat gain, daylighting, hybrid ventilation, and functional requirement, and configured the building with two major masses, a office tower and a lab wing, and rotated the tower portion of the building 13° from the East-West orientation (the orientation of the urban street grid).

6.4.3. Internal configuration

Internal configuration heavily impacts the building performances in "Energy and atmosphere" and "Indoor environmental quality". Take interior programming as an example, allocate the office spaces along the perimeter area or centralize all of them in the middle of the floor plan may achieve very different daylighting potential, natural ventilation potential, space conditioning configurations. Therefore, two internal configuration (zoning) strategies are evaluated when Task "Define Program Chart" is performed. The first one, which is also called "external circulation design", is to put corridors close to building envelope and office rooms in the middle of the floor. And the second "internal circulation design" is to have corridors in the middle of the floor but have offices and conference rooms close to building envelope. The two zoning strategies are illustrated in Figure 6-18 .



(a) External Circulation Design



(b) Internal Circulation Design

Figure 6-18 External & Internal circulation design

The impacts of exterior and interior zoning designs on "Energy and atmosphere" and "Indoor environmental quality" are listed in Table 6-6 Performance comparisons of exterior and interior zoning.

Table 6-6 Performance comparisons of exterior and interior zoning

	Energy and atmosphere	**Indoor environmental quality**
Exterior circulation	**Pros:** • Can use corridor as the buffer zone to reduce heating/cooling load. **Cons:** • Less opportunities of integrating passive design to reduce the energy consumption, such as: daylighting, natural ventilation	**Pros:** • Less noise interference from outside (also depends on façade treatment). **Cons:** • Reduce the daylighting potential and visual quality of the perimeter zones.

Interior circulation	**Pros:** • Higher chance to use daylighting which can save lighting energy. • Higher chance to use natural ventilation which can reduce heating/cooling load. **Cons:** • Depends on façade build up, perimeter zones may increase the heating/cooling load due to the heat transfer through building enclosure.	**Pros:** • Better visual quality for perimeter zones (if corridor is not fully glazed). • Higher chance to use natural ventilation which can improve the indoor air quality. **Cons:** • Depends on façade build up, more complex HAVC system design and operation may be required to maintain perimeter zones' thermal comfort. • Require more carful glare control for perimeter zones. • Require more carful noise control for perimeter zones.

Furthermore, the interior partition material type is also related to the program design. Two partition materials are considered. The first one is traditional gypsum wall board partition and the second one is to use glass wall to create transparent partition which is often seen in modern interior space design. Compared with traditional gypsum wall board partition, it is estimated that the glass wall has potentials to distribute daylights into rooms and thus reduce lighting energy demand. However, the possibilities of energy savings need to be verified through performance simulations. The four internal configuration cases simulated are:

- Exterior circulation with opaque partition;
- Exterior circulation with window partition;
- Interior circulation with opaque partition; and

- Interior circulation with window partition.

The whole building's energy performance is simulated. The simulation cases are built by applying the known building shape and orientation, climate conditions, listed in section 6.4.1 and 6.4.2. Well insulated enclosure opaque walls with U-value 0.23 and low-E windows are used. The third floor's results are shown in Figure 6-19 Energy simulation results of exterior and interior circulation design. It can be found from the simulation results that the cases with glass partition wall exhibit lower lighting energy consumption and therefore total energy consumption. That is because the glass partitions allow daylight, mainly entering from the building's South facade curtain wall, to penetrate through corridors and office rooms and diffuse to cover more floor areas compared with opaque partition wall.

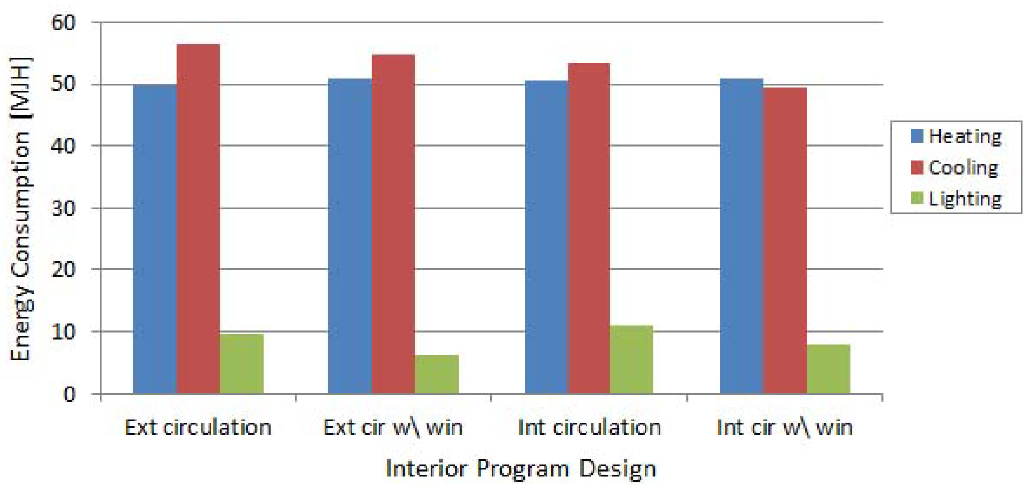


Figure 6-19 Energy simulation results of exterior and interior circulation design

However, the result does not give strong preference on which interior design strategy is better for building's energy performance. The total energy for interior circulation design and exterior circulation design demonstrate similar energy performance with glass partition wall. The main reason of this result is because the change of corridor and room space configuration does not pose significant change on building's whole cooling and heating load. The well insulated enclosure mitigates the energy loss through the enclosure, so even more zone surfaces of internal circulation design are directly connected to the outside environment, the effect on energy performance is not significant. So the Architectural Design Team will more focus on other performance aspect such as "Indoor environmental quality" and actual functionality requirements to make their decisions regarding the internal configuration.

6.4.4. External enclosure

As mentioned in section 6.3.5, external enclosure is an interface between the interior and the exterior environments, so its design relates to a broad scope of design strategies/parameters not only from enclosure design itself but also from many other design factors such as form and massing, internal configuration, and environmental systems. Because of this, external enclosure design will affect a wide range of performance aspects. In this section, two roof systems design strategies are evaluated; performance of different façade designs are analyzed for opaque building envelope (usually refers to wall systems) and fenestration systems (usually refers to window systems) and the relationship between them – window to wall ratio (WWR).

In task "Define Enclosure Strategies", the architect design team may consider a conventional roof systems, more sustainable roof strategies like white/cool roof or other sustainable roof types like green roof in order to improve the performance. The comparisons among them are listed in Table 6-7 Performance comparisons of roof strategies with focus on more roof design related aspect: "Site Sustainability", "Water Efficiency", "Energy and Atmosphere" (Green roof, 2013), (Reflective surfaces, 2013).

Table 6-7 Performance comparisons of roof strategies

	Site Sustainability	Water Efficiency	Energy and Atmosphere
White/cool roof	**Pros:** • Help in mitigating the heat island effect. • Offsetting of the warming impact of greenhouse gas emissions. **Cons:** • Increase the air conditioning demands and energy usage of nearby buildings because of reflected solar radiation form white roof.	N/A	**Pros:** • Reduce cooling load. • Reduce air pollution and greenhouse gas emissions. **Cons:** • May increase heating load as white/cool roof reflects solar which would help warm the building.
Green roof (Intensive)	**Pros:** • Help in mitigating the heat island effect. • Create natural habitat. • Help filtering air pollutants.	**Pros:** • Reduce storm water runoff. • Reduce site water usage **Cons:** • Increase weight of roof and hence required building structure. • Increase waterproofing systems complexity. • Require more maintenance.	**Pros:** • Reduce cooling load. • Reduce heating load. • Improved thermal comfort in buildings that do not have air conditioning.

There are two main issues with white roof application: reflected solar radiation from white roof may cause energy use increase or glare issues for surrounding buildings; solar heat gain needs to be balanced between heating and cooling demand as higher heat gain is desirable in winter, but not in summer. Because there are only a few buildings around the site of the CoE building, most of them are lower than the tower mass of CoE building, so white roof can be applied to it without causing energy use increase or glare issues for surrounding buildings. In addition, most of the building roofs are covered by snow for a long period of time during the winter in Syracuse, so there is no solar heat gain balancing question of white roof application in Syracuse. White roof can be used on top of office tower of CoE building to minimize the solar heat gain and reducing the cooling load.

The green roof technology can be applied to the sloped ramp wing because it can mitigate the heat island effect; provide better visual comfort for occupants in office rooms; help filtering the air pollutants coming from the nearby highway; reduce the storm water runoff; and reduce both heating and cooling load (Figure 6-20 White roof and green roof defined for CoE building).

In addition to the benefit of applying white and green roof systems, both the tower and lab wing portion of the building could also incorporate skylight and rainwater collection systems to further improve the sustainability.

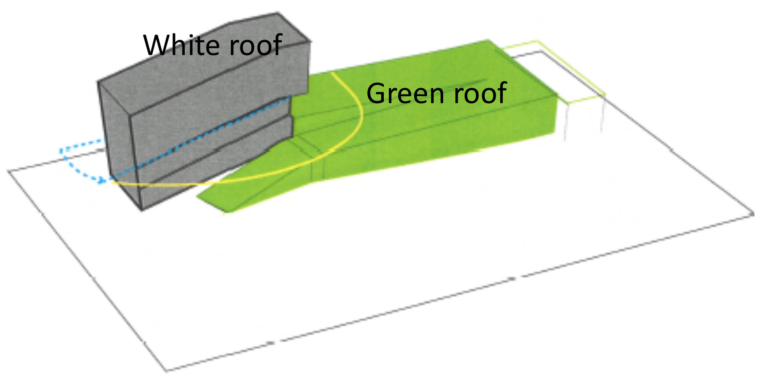


Figure 6-20 White roof and green roof defined for CoE building (Augustine, 2011)

In task "Define Enclosure Strategies", the architect design team considers strategies for facade systems. The analysis can be mainly divided into two parts: the opaque building envelope (wall systems) and fenestration systems (window systems). The following analysis focuses on the energy performances for each of them.

The majority of opaque building envelope is made up of exterior walls through which built environments interact with outdoor environment. The design of exterior walls will affect building heat, moisture, and airflow exchange with outdoor environment and therefore significantly influence building's energy, moisture and indoor air quality performance. ASHRAE defines the prescriptive building envelope in terms of its maximum U value or minimum R value in accordance with the climate zone where the building is located. The lower U value can buffer the heat transfer between indoor and outdoor environment and thus reduce the cooling or heating energy consumption. A series of typical wall assemblies are simulated in this section to understand their impact on building energy consumption, including: light, medium, and heavy weight constructions. Their cross sectional views are shown in Figure 6-21 Cross sectional views of wall assemblies, U values and detail structure descriptions are in Table 6-8 U-value and description of analyzed wall assemblies

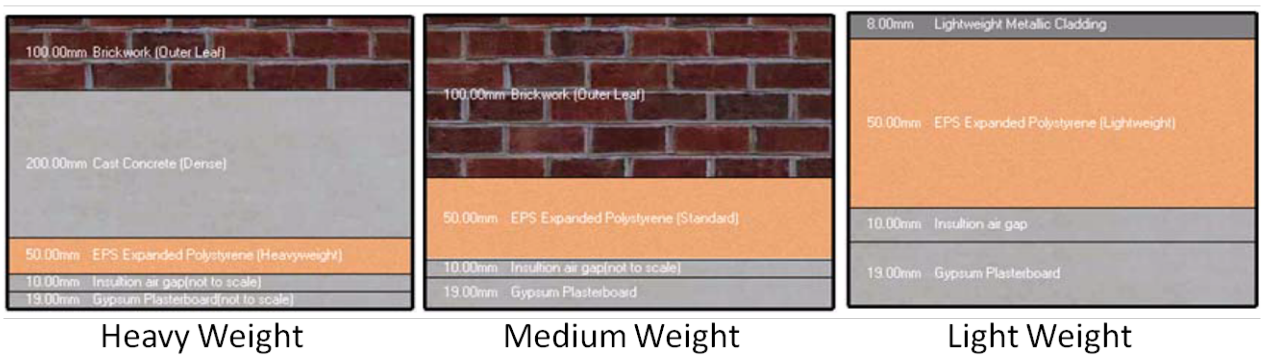


Figure 6-21 Cross sectional views of wall assemblies

Table 6-8 U-value and description of analyzed wall assemblies

Type	**U value (W/ $m^2 \cdot K$)**	**Descriptions**
Heavy Weight	0.47	Composed of brick, cast concrete, insulation material, air gap and gypsum wall board.
Medium Weight	0.56	Composed of brick, insulation material, air gap and gypsum wall board.
Light Weight	0.65	Composed of exterior cladding, insulation material, air gap and gypsum wall board.

To quantify different wall assemblies and their impact on building energy performance, three types of wall assemblies are applied to the building model by keeping the designed shape and using Central NY climate condition. Window to wall ratio is set as 20% equally applied to each facade and double pane window is selected for the simulation model. Simple ideal HVAV system is configured and only input heating and cooling energy is calculated to quantify building's performance. The one year building heating and cooling energy consumption under different wall assembly configuration is given in

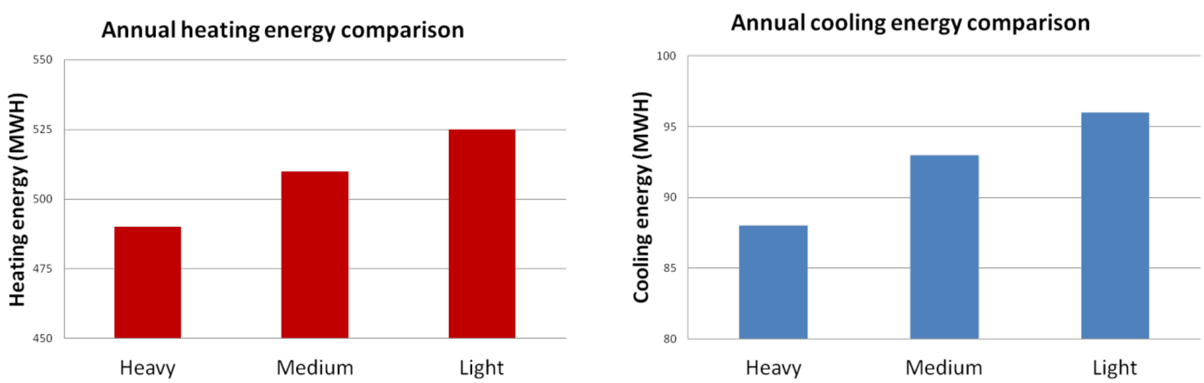
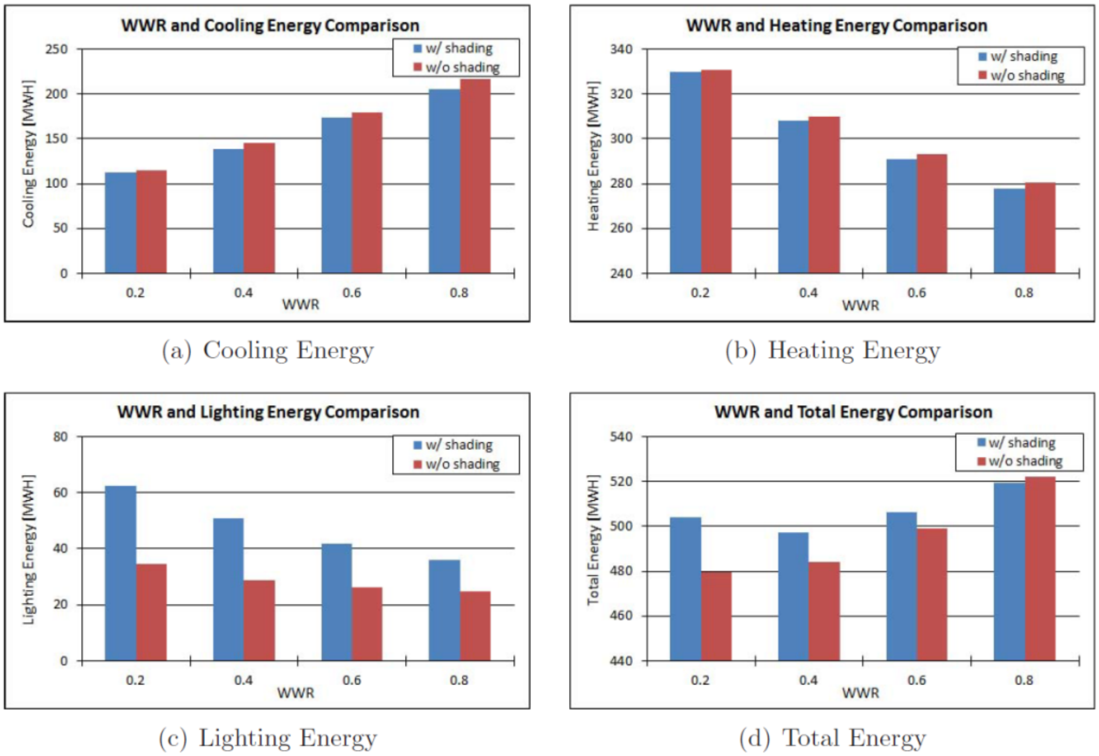


Figure 6-22 Heating and cooling energy comparison of wall assemblies (Wei Feng, 2012)

It is found that building model's heating and cooling energy consumption is directly related to the wall assembly U value. The higher U value of building wall assembly will give higher energy demands case building has in cooling and heating. The simulation revealed the heating and cooling energy consumption trend against the U value variation. The final decision on wall assemblies design for CoE building should be balanced between the energy performance and construction cost.

Fenestration systems, different from opaque building envelope, can more dynamically influence building performance because of its capacity to introduce solar radiation and daylight into buildings. Moreover, fenestration systems have relatively higher U value compared with opaque envelope which makes fenestration systems more vulnerable to outdoor climate changes. Therefore, the window to wall ratio (WWR, defined as ratio of total window area to the total building envelope area) becomes a very important design parameter not only it determines windows' influence on building performance but also constrains opaque building envelope's impacts on whole building energy performance.

At define stage, it is quite important to select the optimal WWR value for each façade that facing different directions. The shading factor which is closely related to window system designs also need to be considered. To answer this question, the case building's South, North, West and East facades WWR designs are simulated. Simulations use reference building settings as introduced in section 5.3.4 with parameters adjusted according to previous analysis: use Central New York Climate conditions; aspect ratio is 3.0; opaque wall with U value 0.23; "Low-E" window is selected; idea HVAC system is used. All cases are simulated under "without shading" and "with shading" conditions which can represent effects of shading devices that may be integrated in the window system design. "With shading" scenarios, window blinds are controlled to turn on during summer season (May 1st – Oct. 31st) to block solar radiation passing through windows, and turn off during winter season (Nov. 1st – Apr. 30th) to allow radiation energy come into building and reduce building's heating energy demands. The results are given in Figure 6-23 South facade WWR and building energy comparison to Figure 6-26 East facade WWR and building energy comparison (Wei Feng, 2012).

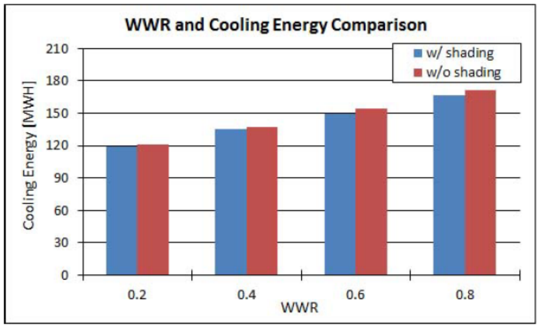


(a) Cooling Energy (b) Heating Energy

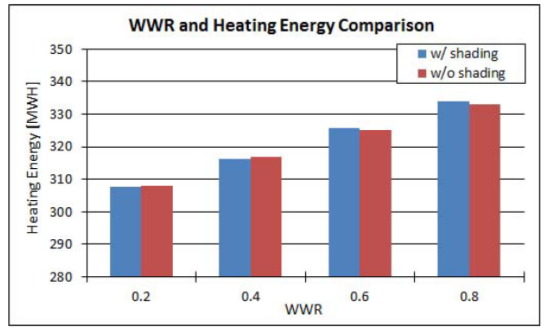
(c) Lighting Energy (d) Total Energy

Figure 6-23 South facade WWR and building energy comparison

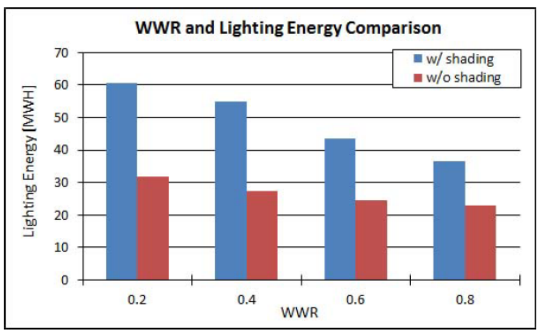
Figure 6-23 South facade WWR and building energy comparison shows the design of South facade WWR and building's energy performance. The building's cooling energy increases with the increase of WWR value on the South facade. However, with shading control, it can reduce certain amount of building's cooling energy demand by reflecting solar ray and blocking radiation energy. For heating energy, WWR plays a positive role in reducing heating demands by making use of solar energy. Higher WWR value on the South facade also utilizes daylight and decreases lighting energy consumption. Overall, the building's total energy performance at high WWR value is very close to that at low WWR value. Thus, from building performance point of view, to have relative high WWR value is acceptable for energy consideration. Moreover, to have large window area at building's Southside can enhance building's visibility viewed from both inside and outside of building as well as building's aesthetic value. The simulation results also suggest that window blind or screen shading is recommended in summer season. Shading device should be turned off during the day in winter time to increase building's solar heat gain.



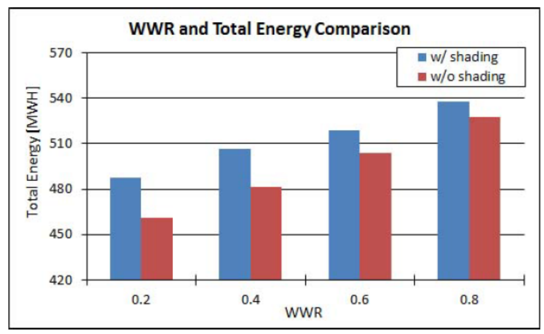
(a) Cooling Energy



(b) Heating Energy



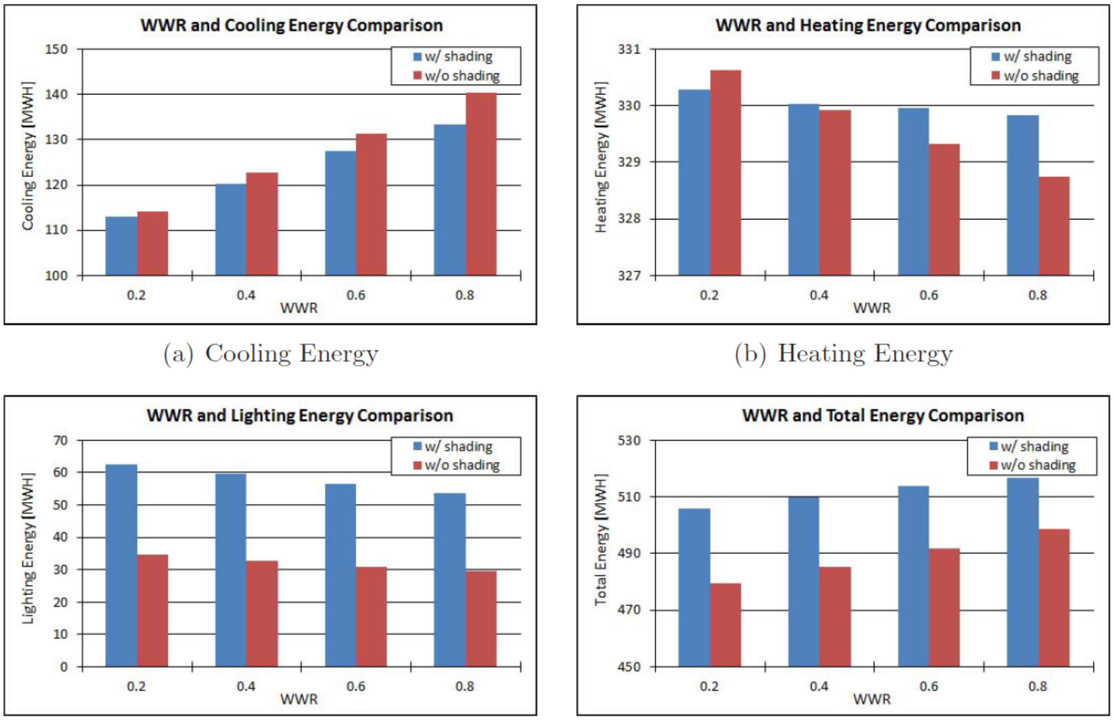
(c) Lighting Energy



(d) Total Energy

Figure 6-24 North facade WWR and building energy comparison

To have high WWR value at building's North facade will increase building's heating and cooling energy even though it is good for daylight. Since CoE building is located at relative high North latitude, large window area cannot bring extra radiation energy into building but, on the other hand, makes the building more sensitive to window conduction heat gain/loss. So, according to simulation results, it is generally not recommended to have large window area in the North facade.

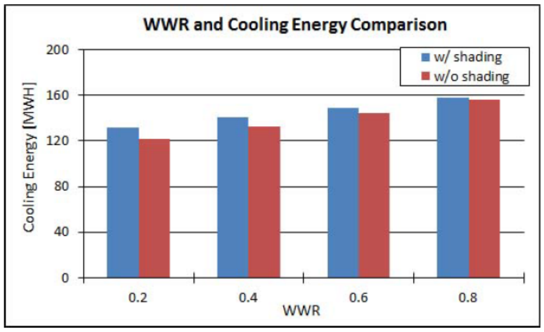


(a) Cooling Energy (b) Heating Energy

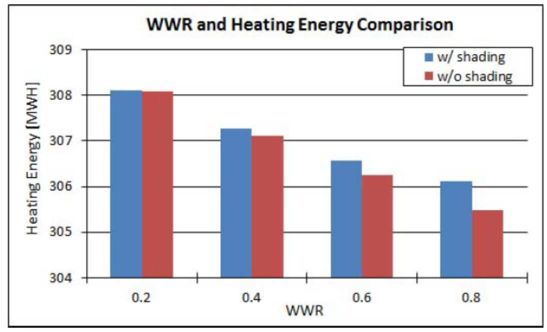
(c) Lighting Energy (d) Total Energy

Figure 6-25 West facade WWR and building energy comparison

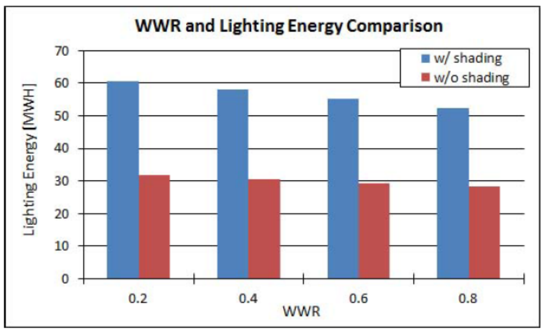
Large window area on the West side is generally not a good practice because of large cooling energy demands. Large WWR has relatively small effects in reducing artificial lighting energy because the existing building shape gives small West facade area and it is very difficult for daylight to penetrate the building from its West side. WWR influence cooling and heating energy in the similar way as demonstrated in South facade case.



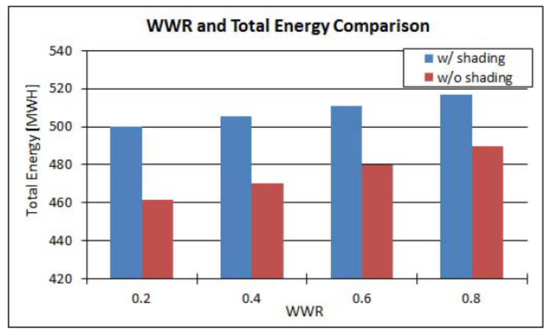
(a) Cooling Energy



(b) Heating Energy



(c) Lighting Energy



(d) Total Energy

Figure 6-26 East facade WWR and building energy comparison

On the East facade, large WWR value is acceptable according to energy simulation results. And the results pattern is very similar as West facade WWR design case.

The enclosure strategies finally will be determined with the support from above analysis. At the same time, architect design team also parallel integrates other sustainable strategies for external enclosure designs to improve the whole building performance, for example, natural ventilation, daylighting etc.

6.4.5. Environmental systems

At "Design" stage, since most of architectural features have been determined, the design emphasis is shifted from architectural design to building service systems design. As introduced in section 6.3.6, one critical subtask of “Design Environmental Systems” is to identify system type and specification.

For medium size office building, like our case, the major role of HVAC systems is to maintain building’s thermal comfort and indoor environmental qualities. Two parts of HVAC are considered here, the first part is also called as “Water Loop” which are HVAC systems central plants, including equipment like chillers, heat pumps, boilers etc. which generate heating and cooling water for terminal equipments needs. Auxiliary equipments like pumps, cooling tower etc. are also included in this part. The terminal parts of water loop system refer to cooling, heating coils, radiant panels, reheat coils and so on. The second part is called as ”air loop” system which, most of time, distributes the heating and cooling energy to condition room space of the building as well as provides necessary fresh air for ventilation and indoor air quality needs. The design of primary system and secondary system is performed separately in following section, and the final design of the whole building HVAC system can be an integration of those two systems. Besides active systems/equipments designed for each loop mentioned above, passive design strategies may also be considered for them in order to take advantages of available natural resources. For instance, “air loop” may incorporate hybrid/natural ventilation, “water loop” may incorporate ground source heat pump (GSHP).

6.4.5.1. Air system design

The air system can have various forms in HVAC design. For our case building design, three types of air systems are considered. The first two are most common applications in office buildings: variable air volume (VAV) system, constant air volume (CVA) system. The third considered type is dedicated outdoor air with radiant panel system. The advantages of applying radiant panel system compared with other two systems are:

- The use of radiant heat exchange between panels and occupants can significant reduce the amount of energy used for ventilation to balance building heat load. Because radiant panel use water as heat exchanging media which has much higher specific heat value than air. This greatly reduces the supply air volume required (typically by 60-80%) which leads to reduced fan power requirements and associated energy savings.
- The control and operation of radiant panel system can achieve better energy saving compared with traditional VAV or fan coil unit (FCU) systems.
- Since radiant panel system removes or supply heat to the space via radiant heat exchange, the total supply air to each space can be significantly reduced to the level of required outdoor air supply. The need of outdoor air (OA) is achieved by applying dedicated outdoor air (DOA) system. The DOA in combination with radiant can produce effective energy saving as well as good indoor environmental qualities.

To finally select the air system type, building performance is simulated to quantify three design alternatives: VAV system with air handling unit (AHU) of mixed OA box, FCU with AHU of mixed OA box, and radiant panel system with DOA AHU.

For VAV and FCU system, the room dry-bulb temperature is our control target. The indoor temperature is controlled at 21 ° C for heating and 24 ° C for cooling. The AHU fan size is determined by building's ventilation needs. 25% OA is applied to the OA mixing box. And the size of cooling and heating coil in the AHU is determined by building's cooling and heating load under the supply air control temperature of 13 ° C for heating and cooling. The rest of heating and cooling energy is delivered by terminal VAV box to meet room control conditions. Also each terminal VAV box and FCU is sized automatically to meet each room's heating or cooling load.

For radiant panel system, room operative temperature is our control object. The radiant panel is operated with water coil 100% open when the room operative temperature is lower than 21 ° C for heating, and higher than 24 ° C for cooling. Control dead band exists between 22-23 ° C. Radiant panel is operated in proportional ramp control between 21-22 ° C for heating and 23-24 ° C for cooling. The dedicated outdoor air system is applied with enthalpy recovery wheel and 100% OA supply air. The fan size is determined by case building's OA ventilation needs. For energy recovery, an enthalpy recovery wheel is normally operated at sensible effectiveness of 60% and latent effectiveness of 50% with pressure drop of 175 Pa. Since both supply air and exhaust air pass through the enthalpy recovery wheel, an overall 350 Pa pressure drop is applied to the enthalpy recovery wheel.

For all three systems, the water loops are identical by using chillers and cooling towers for cooling and boilers for heating. The chiller COP value of 5.2 and boiler efficiency of 80% are assumed. All other pumps, cooling tower sizes are calculated automatically. All systems are operated under the similar schedules. HVAC system is turned on at 6:00am in the morning and turned off at 10:00pm. The occupancy, infiltration, lighting control patterns are kept the same. The simulated results are shown in Figure 6-27 Air system design alternative comparison (Wei Feng, 2012).

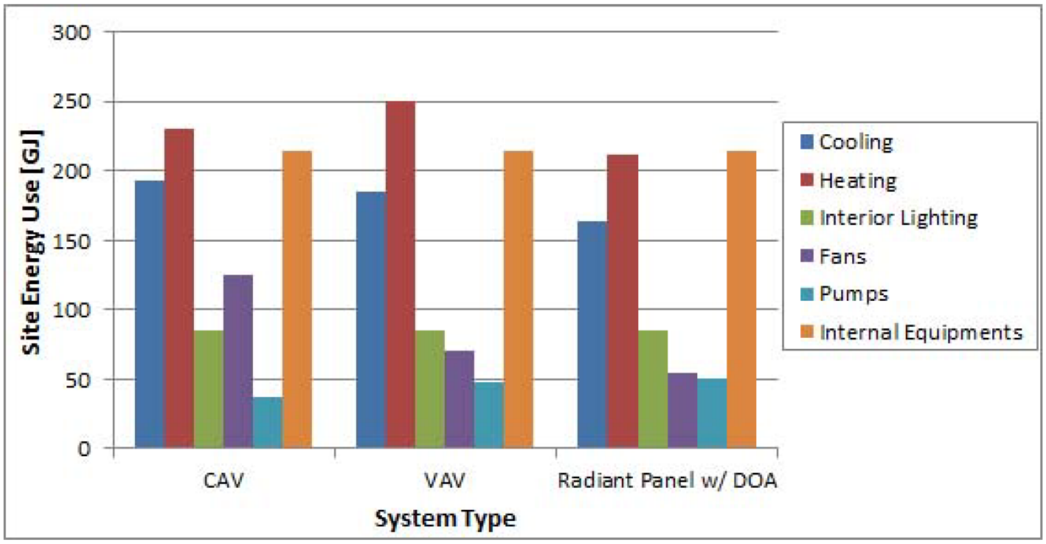


Figure 6-27 Air system design alternative comparison

It is found that FCU system, compared with VAV system, exhibits more fan energy consumptions. VAV system has slightly higher heating energy consumption, because of the use of reheat coil at VAV box terminal side. However, the amount is not very significant. The variable frequency drive (VFD) used to control AHU's fan can produce about 20-30% fan energy saving compared with FCU system without VFD control. Radiant panel system with DOA exhibits the best energy performance among all three systems. The energy savings of radiant panel and DOA system mainly come from the operative temperature control which allows broader band of room dry-bulb temperature and fan energy savings by using smaller size AHU fan.

For building total energy performance, the radiant panel and DOA system shows site energy use of 780.02 GJ, VAV system 851.95 GJ and FCU system 887 GJ. The potential saving of applying radiant panel and DOA system is about 10% compared with VAV system. Because of the energy efficiency advantage, radiant panel with dedicated outdoor air system are selected as the terminal side heating and cooling system, and air system.

6.4.5.2. Water system design

Once the terminal and air system is decided, the design tasks shift to central plant systems. The main purpose of plant systems is to generate heating and cooling water used by air and terminal systems. The central plant system is also where energy like electricity and natural gas get converted to water source based energy. Performance of several heating and cooling system design alternatives will be compared.

First of all, the design of the heating system is studied. Most traditional heating system uses boiler as central plant equipment. The boiled hot water is circulated by a heating water pump to the heating coils and terminal equipment for conditioning the whole building. For traditional office building boilers, an efficiency curve, with maximum value of 83% of its combustion efficiency at 50% boiler part load and minimum 79% efficiency at 15% part load, is often used for energy performance modeling. This configuration is also adopted for our traditional heating plant system design (Matthew Leach, 2010).

The traditional design of cooling plant system consists of chilled water (CHW) system and condensing water (CW) system. Chillers are the main equipment in CHW loop, which absorbs heat from its evaporator and dump heat through its condenser. Four typical chillers can be found in the market according to its different compressor types, reciprocating compression, scroll compression, screw-driven and centrifugal compression. Their coefficients-of-performance (COPs) are typically 4.0 or more.

The heating and cooling water pumps are designed that each has 40 ft (12.2 m) of water head and variable speed pump motors with efficiencies of 87.5% and 90.0% for heating and chilled water loops. Pump part load ratio (PLR) curves are cubic to accurately account for reduced power consumption at low PLRs.

Besides traditional system design, an alternative design strategy is to use GSHP to replace chillers and boilers for both cooling and heating. The potential advantages of GSHP system:

- GSHP system can operate for both heating and cooling mode, which instead of using chiller and boiler for two systems, reduce the complexity of system and initial equipment investment.
- GSHP system can make use of relative constant ground water temperature and operate at relatively higher COP compared with other HP system.

To compare GSHP with traditional chiller-boiler water system configuration and their corresponding building energy performance, a GSHP water loop model is built to connect with air system, and terminal radiant panel. To meet with building's cooling and heating load with certain safety factor, seven GSHPs are designed with equal heating and cooling capacity of 73 KW. The source (ground) water has heat extraction capacity of 50 KW under heating mode, and heat rejection capacity of 90.8 KW for cooling. The heating system has designed supply water flow rate of 0.0221 m^3/s and cooling system design supply water flow rate $0.0157 m^3/s$.

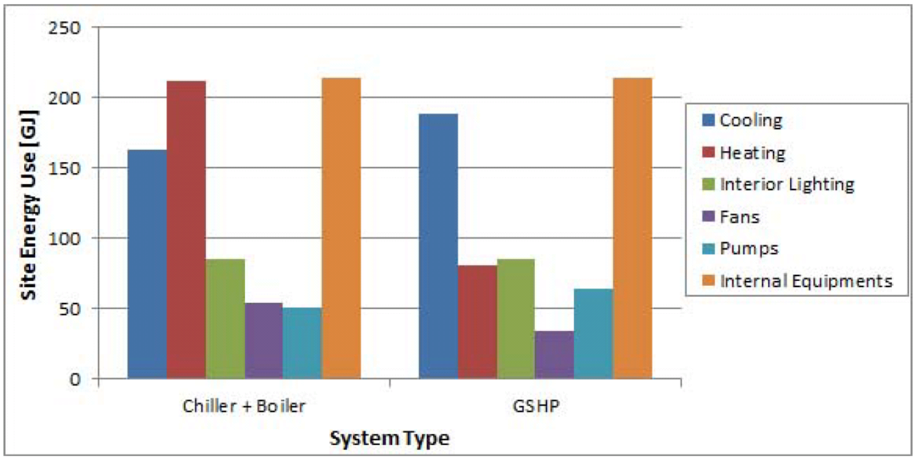


Figure 6-28 Water system design alternative performance comparison

The case building energy performance simulation result is given in Figure 6-28 Water system design alternative performance comparison (Wei Feng, 2012), with GSHP and chiller-boiler plant system. It is found that GSHP has higher cooling energy consumption compared with centrifugal chiller plant system. This is mainly because most centrifugal chiller can reach slightly higher COP value compared with GSHP. The GSHP machine we design for our case building has min COP value of 4.15. And the actual performance COP is related to ground water temperature. GSHP system also requires more pumping energy to circulate ground side water, especially under heating mode when compared with boiler system. However, in cooling mode, since condenser water is cooled by ground soil instead of cooling towers, GSHP system does not use cooling tower energy. Another performance difference comes from heating energy. Most heating water is supplied by GSHP (about 80%) and the rest of it comes from boilers and the COP value of our GSHP during heating mode is around 3.6. So, compared with boiler's COP of 0.8, this makes GSHP can save significant amount of heating energy. The total site energy of GSHP system is 668 GJ, while the boiler and chiller system is 780 GJ. After comparing GSHP and boiler-chiller systems' energy performance, the GSHP design is chosen for our water loop system.

In summary, the above analysis shows that total energy consumption of DOA system with radiant panel system is significantly less than VAV and CAV systems. The CAV system is the least energy efficient among the three air systems evaluated. It also shows that total energy consumption of GSHP system is less than traditional boiler and chiller only system. The following three design cases are selected to evaluate their potential improvement over the reference building as defined in section 5.4.2, reflecting the various options in air and water system selection in HVAC system design:

- **Case 1**: CoE building model with VAV and reheat system. (ASHRAE 90.1 baseline HVAC system type)
- **Case 2**: CoE building model with DOA (100% outdoor air) and radiant panel (RP) systems. (represents medium HVAC system design)
- **Case 3**: CoE building model with DOA (100% outdoor air), RP, and GSHP systems (represents advanced HVAC system design)

As shown in Figure 6-29 Annual energy consumption of selected "Environmental Systems" design alternatives, Case 3 has least energy consumption, and Case 1 has the most, as expected from the above analysis on air and water systems for HVAC. Cases 1 and 2 have higher energy consumption than the reference building mainly because their overall building forms are narrower than the reference building. More surfaces are directly exposed to the outside environment in case 1 and 2 so their heating energy consumptions are much higher compare to reference building. Case 1 and 2 has higher energy cost than reference building (Figure 6-30 Annual energy cost of selected “Environmental Systems” design alternatives) despite a lower energy consumption, which is due to the relative small portion of gas heating energy in total energy consumption and the price differences between electricity and gas (electricity price is 0.1593 $/kWh, equivalent gas price is 0.03255$/kWh). The relative performance potentials improvements of three design alternatives are listed in Table 6-9 Relative performance potential improvements of “Environmental Systems”

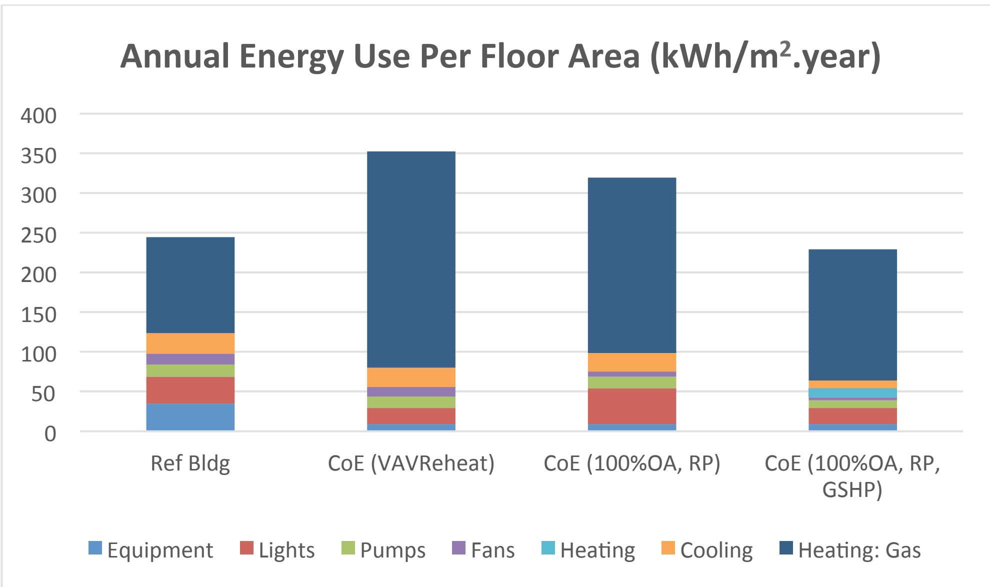


Figure 6-29 Annual energy consumption of selected “Environmental Systems” design alternatives

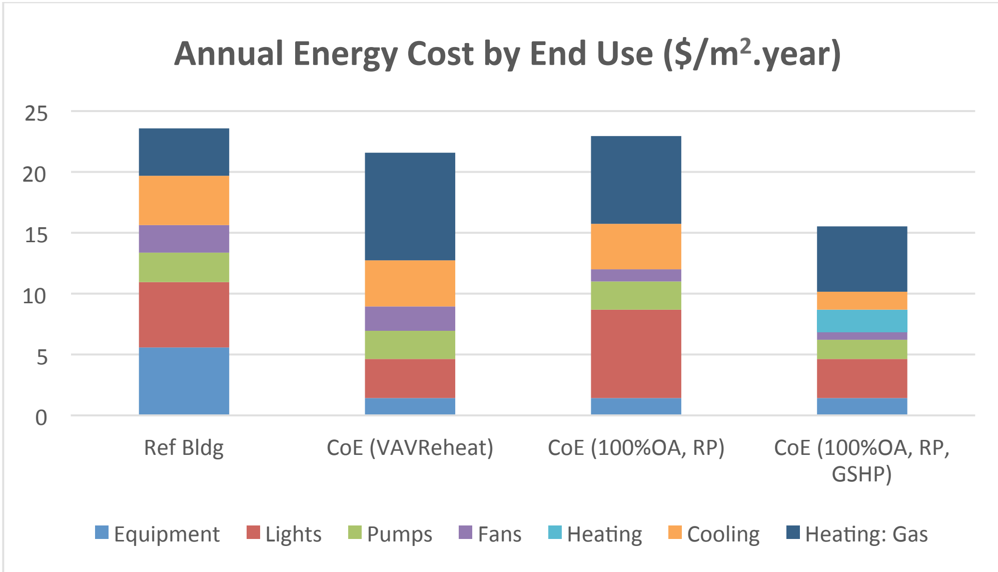


Figure 6-30 Annual energy cost of selected "Environmental Systems" design alternatives

Table 6-9 Relative performance potential improvements of "Environmental Systems"

	Ref Bldg	**Case 1**	**Case 2**	**Case 3**
Annual Total Energy Consumption (kWh/m^2.year)	244.09	352.51	319.48	229.22
Annual Energy Cost ($\$/m^2$.year)	23.60	21.60	22.94	15.53
Relative performance potential improvements	0.00	0.08	0.03	0.34

From Table 6-9 Relative performance potential improvements of "Environmental Systems", we can see that, comparing to reference building, all three design alternatives of "Environmental Systems" can improve relative performance potential. Especially, Case 3 which applies advanced DOA, RP, and GSHP systems demonstrates a significant improvement of 0.34. Design solution 3 (case 3) should be selected according to the relative performance potential.

6.4.6. Systems interdependencies

As discussed in section 6.3.7, design factors are interdependent on each other. For example: site solar conditions, orientation and shape of the building, fenestration size and type, wall assembly thermal mass effect, internal space zoning and lighting design, heating and cooling design are all involved in solar related building design. In order to achieve the high-performance building with low energy consumption, different design factors need to be integrated and concurrently coordinated. In this section, optimization method is applied to select the combination of parameters from all design factors to find the optimal whole building design.

The objectives are defined to minimize building total site energy use and energy cost, respectively. Their definitions are listed in Table 6-10 Optimization objectives

Table 6-10 Optimization objectives

Objective	**Definition**
Site energy use	Building's total annual energy consumption.
Energy cost	Building's annual energy cost by multiplying different types of energy consumption with the energy tariff.

All these optimization objectives share a common simulation scheme which calculates whole building energy site use for each energy type. Once one simulation scheme is calculated in an iteration, the optimization calculation scheme will read simulation results and determine if the results meet with the defined objectives. The optimization scheme will drive the parameters towards the set objectives until the optimization convergence is reached.

The selected design variables from different design factors and their associated ranges are listed in Table 6-11 Design variables and associated range VAV system with chillers and boilers and GSHP with radiant panel HVAC system are applied separately to case building.

Table 6-11 Design variables and associated range

Design Variable	Range
Building aspect ratio	0.2, 5
Orientation	0°, 360°
Envelope color and solar absorptance	0.3, 0.9
South Facade WWR	0, 100%
Window interior blind slat angle	0°, 85°
Internal lighting density	7 W/m^2, 16 W/m^2
Internal lighting illuminance level	300 lux, 600 lux
Indoor temperature setpoint (cooling)	23 °C, 26.5 °C
Indoor temperature setpoint (heating)	18 °C, 23 °C
HVAC system	VAV w/ chillers and boilers, GSHP w/ radiant panel

The optimization uses "Hooke-Jeeves Generalized Pattern Search (GPS) Algorithm" engine in "GenOpt" (GenOpt, 2011). To achieve the best total site energy use and energy cost, the performance of each design factor (sub-system) is traded off with each other so the total energy objectives can reach minimum value. The simulated optimal performance of site energy, and energy cost are summarized in Table 6-12 Building performance optimization results summary - VAV with chiller & boiler for VAV with boiler, and Table 6-13 Building performance optimization results summary – GSHP with radiant panel for GSHP with radiant panel system (Wei Feng, 2012).

Table 6-12 Building performance optimization results summary - VAV with chiller & boiler

		Lighting	Internal Equipment	Cooling	Fan	Pump	Cooling Tower	Heating	Total
VAV, boiler & chiller	Energy (mWh)	20.34	71.01	41.57	13.24	10.48	1.24	35.52	193.42
	Energy Cost	3.67	11.36	6.23	1.98	1.59	0.19	1.36	26.36

	(k USD)								

Table 6-13 Building performance optimization results summary – GSHP with radiant panel

		Lighting	Internal Equipment	GSHP	Fan	Pump	Total
GSHP, radiant panel	Energy (mWh)	21.43	71.01	41.57	7.96	11.41	154.83
	Energy Cost (k USD)	3.43	11.36	6.88	1.27	1.83	24.78

It is found that, under the optimal building performance, the GSHP with radiant panel system can reduce building total thermal energy, but the effect of energy cost is not significant. It is also noticed that, GSHP system can increase pump energy because ground water loop has more resistance and require extra group water pump capacity. The radiant panel with DOA system is effective in reducing fan energy compared with VAV system. The GSHP system, compared with traditional chiller and boiler system, use considerable less amount of energy, since GSHP has COP value around 3.6 for heating which is more efficient than natural gas boiler whose efficiency is around 0.8.

However, when the optimization objective becomes energy cost, the advantage of GSHP is not very obvious. Because the local annual average price is about 10$/GJ for natural gas and 0.16 [$/kWh] for electricity (equivalent electricity price is equal to 44$/GJ). The comparatively cheap natural gas price and expensive electricity price requires the relative COP value of GSHP/boiler larger than 4.4 to make GSHP system cost-effective in building energy efficiency.

Optimized parameters from different design factors are listed in Table 6-14 Building performance optimization parameter (Wei Feng, 2012). Under different optimization objectives, some design parameters tend to be driven to the same optimal results, while some vary based on optimization objectives. The selection of parameters: lighting illuminance level, lighting power density, blind slat angle, window glass transmittance, exterior wall absorptance value, room cooling setpoint and room heating setpoint converge at the same value in different optimization objectives. This is because these parameters either have simple influence on building energy performance, like cooling and heating setpoints, or they don't have strong and complex coupling effects with other parameters. Parameters like building orientation, aspect ratio, South facade WWR have strong coupling effects with other parameters and different energy use types, and their optimization results will vary based on different objectives.

Table 6-14 Building performance optimization parameter for different design factors

	Orien-tation [deg]	Aspect Ratio	South Façade WWR	Lighting Illum-inance [lux]	Lighting Power Density [w/m^2]	Blind Slat Angle [deg]	Win. Glass Transm-ittance	Exterior Wall Absor-ptance	Cooling Setpoint [C]	Heating Setpoint [C]
VAV energy	0	2.8	44%	300	7	85	0.9	0.3	26.5	18
VAV Cost	-3.75	2.9	31%	300	7	85	0.9	0.3	26.5	18
GSHP energy	1.875	2.85	39%	300	7	85	0.9	0.3	26.5	18
GSHP Cost	1.875	2.85	39%	300	7	85	0.9	0.3	26.5	18

The variation is especially big for window WWR value. Under energy optimization, the program selects a large WWR value compared with cost. This is because, thermal energy optimization treats 1J of electricity equal as 1J natural gas. The comparative "cheap" feature of electricity makes the program select large window ratio. In this scenario, cooling is comparatively less important than heating, the benefit of large window area can to make use of solar gain in winter overwhelms the increase of cooling energy use with large window area in summer. However, in cost and primary energy cases, the ratio of electricity to natural gas discussed above is much higher than 1 which makes the program gives more importance to cooling and thus, reduces the window area to decrease cooling energy demand.

In general, optimization results reveal that GSHP system is much more energy efficient than traditional VAV systems with chillers and boilers. However, actual energy cost saving not only depends on amount of energy consumption but also related to different energy types and associated prices. Building orientation, aspect ratio, and WWR have relative higher impact on building energy performances than rest of the perimeters from design factors, such as: window glass transmittance, exterior wall absorptance value, and heating/cooling setpoint.

6.5. Conclusions

As illustrated in a hypothetical design process of a case study building, the VDS framework can be used to assist multidisciplinary teams to define and schedule anticipated design tasks, systematically evaluate potential impacts of individual design factors and their combined effects on energy and IEQ performance of a building. Assessment of green building technologies requires the consideration of multiple design factors and their interdependencies. Further studies are needed to demonstrate the application of the VDS framework in an actual building design process.

Chapter 7. Conclusions and Recommendations

7.1. Summary and conclusions

A software framework, Virtual Design Studio for performance-based design of green building systems, has been established through this research. It has the capabilities of design task planning and coordination, performance simulation, results display and analysis, and performance evaluation. The framework provides a foundation for future research in integrated building system design informed by predicted performances from whole building simulation models. The software is developed using object-oriented design with Model-View-Control (MVC) software architecture. The current implementation includes the three-dimensional "Magic Cube" design process module for design coordination, the data input, persistence, translator modules, the simulation models for energy and IEQ analysis, the performance evaluation model for energy and IEQ performance aspects, and the results processing and visualization module. The software design and implementation of these modules and models are conducted primarily through this research, which is considered as one of the major contributions to the VDS development.

One of the original contributions of this research is to enhance CHAMPS-Multizone and integrate the CHAMPS-Multizone with EnergyPlus for combined energy and IAQ simulation. The integrated simulation environment for energy efficiency and IEQ analysis which enables the simulations of combined heat, air, moisture, pollutant transport and daylighting for whole building has been developed.

Another original contribution of this research is the development of the performance evaluation model to analyze the overall performance of the proposed design, enabling the analysis of the potential of each design factor in performance improvement the contribution of each factor to the overall building performance improvement over a VDS reference building. The VDS reference building is defined based on the NREL reference buildings and ASHRAE 55-2010, 62.1-2010, and 90.1-2010. Specific performance indices have been defined for the operational energy, IAQ, thermal comfort and lighting quality and applied in the framework to illustrate the application of the model.

7.2. Recommendations for future research

While a VDS framework has been developed and demonstrated for energy and IEQ performance evaluation, much remains to be done to enhance and extend its capabilities for integrated building system design. Building upon the VDS framework developed, the following areas are recommended for future research:

1) Determine the performance indices for other sub-aspects that have not been quantified in the present study.
2) Include an optimization module to enable the determination of optimal design variables for the various design factors classified in the VDS.
3) Extend the performance evaluation model to include qualitative analysis of green building design strategies as well as quantitative performance predictions from the building simulation models.
4) Extend the simulation capability to include structural system, energy system, water system, and material usage and embodied energy system.

5) Develop new or use existing site sustainability, water efficiency, and/or material and resources simulation models, and integrate them with the energy and IEQ simulation models to predict all five aspects of building performance.
6) Develop knowledge based expert system for design iteration and optimization with the support of performance simulation.
7) Develop pre-simulated databases for web-based real-time performance predication and evaluation
8) Develop combined dynamic simulation with building monitoring system for building operation optimization and/or fault detection and diagnosis

References

AIA. (2012). *Best Practices And Contract Forms Informaiton*. Retrieved Sep. 2012, from AIA: http://www.aia.org/practicing/business/index.htm

ASHRAE. (2009). *ANSI/ASHREA 189.1, Standard for the Design of High-Performance Green Buildings Except Low-Rise Residential Buildings.* Atlanta: ASHRAE.

ASHRAE. (2010a). *ASHRAE Standard 55-2010: Thermal Environmental Conditions for Human Occupancy.* Atlanta, GA: ASHRAE.

ASHRAE. (2010b). *ASHRAE Standard 62.1-2010: Ventilation for Acceptable Indoor Air Quality.* Atlanta: ASHRAE.

ASHRAE. (2010c). *ASHRAE Standard 90.1-2010 Energy Standard for Buildings Except Low-Rise Residentail Buildings.* Atlanta, GA: ASHRAE.

ASHRAE, A. I. (2011). *Advanced Energy Design Guide for Small to Medium Office Buildings.* ASHRAE.

Augustine, M. M. (2011). *Building analysis report - Syracuse Center of Excellence.*

Autodesk. (2013c). *Autodesk Revit*. Retrieved Sep. 2013, from http://www.autodesk.com/products/autodesk-revit-family/overview

Autodesk. (2013a). *Ecotect Analysis Software Homepage*. Retrieved Jun. 2013, from Autodesk: http://usa.autodesk.com/ecotect-analysis/

Autodesk. (2013b). *Green Building Studio Software Homepage*. Retrieved Jun. 2013, from Autodesk: http://usa.autodesk.com/green-building-studio/

Axley, J. W. (1991). Adsorption Modelling for Building Contaminant Dispersal Analysis. *Indoor Air , 1*, 147-171.

BEESL at Syracuse University. (2013). *CHAMPS in Building Envelope Systems (CHAMPS-BES)*. Retrieved Jul 2013, from BEESL: http://beesl.syr.edu/champs.htm

Bentley. (2013). *AECOsim Energy Simulator*. Retrieved Jun. 2013, from http://www.bentley.com/en-US/

BRE Global Ltd. (2008). *BREEAM Scheme Document SD 5055.* Hertfordshire, WD: BRE Global Ltd.

BREEAM. (2012a). *Building Research Establishment Environmental Assessment Method*. Retrieved Sep. 2012, from http://www.breeam.org

BREEAM. (2012b). *Building Research Establishment Environmental Assessment Method*. Retrieved Sep. 2012, from http://www.breeam.org/ podpage.jsp?id=54/

BREEAM. (2012c). *Building Research Establishment Environmental Assessment Method*. Retrieved Sep. 2012, from http://www.breeam.org/case-studies.jsp/

Brooks, C., Lee, E., Liu, X., Neuendorffer, S., Zhao, Y., & Zheng, H. (2008). *Heterogeneous Concurrent Modeling and Design in Java (Volume 1: Introduction to Ptolemy II).* Berkeley, CA: Electrical Engineering and Computer Sciences, University of California at Berkeley.

Bruse M. & Team. (2012). *ENVI-Met3 Software Homepage*. Retrieved Sep. 2012, from http://www.envi-met.com/

BSSC. (2012). *The Building Seismic Safety Council*. Retrieved Sep. 2012, from http://bssc.nibs.org/index.php/bssc/news/

Building and Construction Authority. (2013). *Building Planning and massing.* Retrieved Jul. 2013, from Building and Construction Authority: www.bca.gov.sg/GreenMark/others/bldgplanningmassing.pdf

Charles E. Gulledge III, D. K. (2010, 07 22). Retrieved 08 19, 2013, from HVAC&R Engineering: http://www.wbdg.org/design/dd_hvaceng.php

Crisman, P. (2007, 03 14). *Form*. Retrieved 08 15, 2013, from http://www.wbdg.org/resources/form.php

Daniels, K. (2003). *Advanced Building Systems: A Technical Guide for Architects and Engineers.* Birkhäuser Architecture.

DeChiara, J., & Crosbie, M. (2001). *Time-Saver Standards for Building Types, 4th ed.* McGraw-Hill Professional.

DesignBuilder Software Ltd. (2013). *DesignBuilder Software Homepage*. Retrieved Jun. 2013

Dimitriou, K., Paschalidou, A., & Kassomenos, P. (2013). Assessing air quality with regards to its effect on human health in the European Union through air quality indices. *Ecological Indicators* , 108-115.

Edith Cherry, J. P. (2009, 09 02). *Architectural Programming*. Retrieved 08 04, 2013, from http://www.wbdg.org/design/dd_archprogramming.php

Ellis, P., & Torcellini, P. (2008). *Energy Design Plug-in: An EnergyPlus Plugin for SketchUp.* Retrieved Jun. 2013, from http://www.nrel.gov/docs/fy08osti/43569.pdf

Envestra Limited. (2013, Sep.). *Natural Gas*. Retrieved Aug. 2013, from http://www.natural-gas.com.au/about/references.html

Feng, W. (2012). *CHAMPS-multizone and virtual building for integrated building systems design and performance evaluation.* Syracuse: Syracuse University.

Feustel , H., & Rayner-Hooson , A. (1990). *Conjunction of Multizone Infiltration Specialists (COMIS) fundamentals.* Berkeley, CA: LBNL.

GenOpt. (2011). Retrieved 09 02, 2013, from http://simulationresearch.lbl.gov/GO/

Golge, M., Yenilmez, F., & Aksoy, A. (2013). Development of pollution indices for the middle section of the Lower Seyhan Basin (Turkey). *Ecological Indicators* , 6-17.

Google. (2013). *SketchUp Software Homepage.* Retrieved Jun. 2013, from http://www.sketchup.com/intl/en/product/index.html

Green roof. (2013, 07 14). Retrieved 08 17, 2013, from Wikipedia: http://en.wikipedia.org/wiki/Green_roof

Gretchen Addi, J. L. (2000). *Architect's Handbook of Professional Practice.*

Harputlugil, G. U., & Hensen, J. (2006). The Relationship Between Building Assessment Systems And Building Performance Simulation. *6th Int. Postgraduate Research Conf.* (pp. 333-343). University of Salford.

HOAI. (2009). *German Professional Architectural Working Stages*. Retrieved Sep. 2012, from HOAI: http://www.hoai.de/online/HOAI_2009/HOAI_2009.php

Huang, J., & Franconi, E. (1999). *Commercial heating and cooling loads component analysis.* Berkeley, CA: LBNL.

Huang, J., Akbari, H., Rainer, L., & Ritshard, R. (1991). *481 Prototypical Commercial Buildings for 20 Urban Market Areas.* Berkeley, CA: LBNL.

IBM. (2013). *How sockets work*. Retrieved Sep. 2013, from http://pic.dhe.ibm.com/infocenter/iseries/v7r1m0/index.jsp?topic=%2Frzab6%2Fhowdosockets.htm

Kim, J.-J. (1998). *Sustainable Architecture Module: Introduction to Sustainable Design.* University of Michigan: National Pollution Preservation Center For Higher Education.

Kumar, A., & Goyal, P. (2013). Forecasting of Air Quality Index in Delhi Using Neural Network Based on Principal Component Analysis. *Pure and Applied Geophysics* , 711-722.

Lawrence Livermore National Laboratory. (2013). *Sundials homepage*. Retrieved Aug. 2013, from Sundials: http://computation.llnl.gov/casc/sundials/description/description.html

LBNL. (2013a). *Building Controls Virtual Test Bed*. Retrieved Jun. 2013, from BCVTB homepage: http://simulationresearch.lbl.gov/bcvtb

LBNL. (2013b). *Building Design Advisor Software Homepage*. Retrieved Jun. 2013, from http://gaia.lbl.gov/BDA/

LBNL. (1993). *DOE-2 Supplement, vERSION 2.1E.* Berkeley, California: LBNL.

LBNL. (2013f). *Ptolemy II*. Retrieved Jul. 2013, from LBNL: http://ptolemy.berkeley.edu/ptolemyII/

LBNL. (2013d). *Radiance Homepage*. Retrieved Jul. 2013, from LBNL: http://radsite.lbl.gov/radiance/

LBNL. (2013e). *Simergy - Graphical User Interface for EnergyPlus.* Retrieved Jun. 2013, from LBNL website: http://simulationresearch.lbl.gov/projects/gui

LBNL. (2013c). *Sundials Description*. Retrieved Jun. 2013, from Sundials: http://computation.llnl.gov/casc/sundials/description/description.html

Matthew Leach, C. L. (2010). *Strategies for 50% Energy Savings in Large Office Buildings.* NREL.

Ng, L., Musser, A., Persily, A., & Emmerich, S. (2012). *Airflow and Indoor Air Quality Models of DOE Reference Commercial Buildings.* Gaithersburg, MD: National Institute of Standards and Technology.

NIBS. (2011). *An Authoritative Source of Innovative Solutions for the Built Environment.* Washington, DC: NIBS.

NIBS. (2013a). *National BIM Standard - United States Version 2*. Retrieved Jul. 2013, from http://www.nationalbimstandard.org/

NIBS. (2013). *National Institute of Building Sciences Homepage*. Retrieved Jun. 2013, from http://www.nibs.org/

NIST. (2013). *Building Life-Cycle Cost (BLCC) Programs*. Retrieved Aug. 2013, from US DOE: http://www1.eere.energy.gov/femp/information/download_blcc.html

NIST. (2013). *CONTAM Multizone Airflow and Contaminant Transport Analysis Software*. Retrieved Jul. 2013, from NIST Multizone Modeling Website: http://www.bfrl.nist.gov/IAQanalysis/CONTAM/

NIST. (2012). *NIST Sustainability Portal*. Retrieved Sep. 2012, from http://www.nist.gov/sustainability-portal.cfm/

NREL. (2013). *OpenStudio Software.* Retrieved Jun. 2013, from http://openstudio.nrel.gov/

NREL. (2011). *U.S. Department of Energy Commercial Reference Building Models of the National Building Stock.* Golden, CO: NREL.

NYSDEC. (2013). *New York State Department of Environmental Conservation*. Retrieved Jul. 2013, from NYSDEC: http://www.dec.ny.gov/airmon/index.php

Parsons Brinckerhoff. (2013). *Sustainability Toolkit*. Retrieved Jun. 2013, from http://pbworld.com/capabilities_projects/sustainable_solutions/pb_sustainability/

Passivhaus. (2012). *Building Cost and Performance Metrics: Richland*. Retrieved Sep. 2012, from http://www.passiv.de/en/index.php/

Persil, A. K., & Emmerich, S. J. (2012). Indoor air quality in sustainable, energy efficient buildings. *HVAC&R Research , 18* (1-2), 4-20.

PHPP. (2012). *International Passive House Association*. Retrieved Sep. 2012, from http://www.passivehouse-international.org/

Pro Oxygen. (2013). *CO2 Now Homepage*. Retrieved Jul. 2013, from CO2 Now: http://co2now.org/

Ratcliff. (2007). *Green Matrix*. Retrieved Sep. 2007, from http://www.greenmatrix.net/

Reflective surfaces. (2013, 08 12). Retrieved 08 18, 2013, from Wikipedia: http://en.wikipedia.org/wiki/Reflective_surfaces_(geoengineering)#cite_note-6

RIBA. (2007). *RIBA Outline Plan of Work*. Retrieved Jun. 2013, from http://www.architecture.com/Files/RIBAProfessionalServices/Practice/Archive/OutlinePlanofWork(revised).pdf

Senescu, R. R., & Haymaker, J. R. (2013). Evaluating and improving the effectiveness and efficiency of design process communication. *Advanced Engineering Informatics , 27* (2), 299-313.

Straube, J. (2006). The building enclosure. *Building Science Digest* .

Syracuse Center of Excelence. (2013). *Syracuse Center of excelence*. Retrieved Jun. 2013, from http://www.syracusecoe.org/coe/whatsnew.html?skuvar=72

Syracuse Center of Excelence. (2013, 09). *Syracuse Center of Excellence Building Features*. Retrieved from http://www.syracusecoe.org/coe/sub1.html?skuvar=17#Overall Building Features

US DOE. (2012c). *Application Guide for EMS.* US DOE.

US DOE. (2013a). *Building Energy Software Tools Directory*. Retrieved Jun. 2013, from DOE: http://apps1.eere.energy.gov/buildings/tools_directory/

US DOE. (2013c). *EnergyPlus Energy Simualtion Software Weather Data*. Retrieved Jul. 2013, from US DOE: http://apps1.eere.energy.gov/buildings/energyplus/weatherdata_about.cfm

US DOE. (2012a). *EnergyPlus Energy Simulation Software Version 7.2*. Retrieved Dec. 2012, from EnergyPlus Homepage: http://apps1.eere.energy.gov/buildings/energyplus/

US DOE. (2012b). *EnergyPlus Engineering Reference.* US DOE.

US DOE. (2013b). *External Interface Application Guide, Version 8.*

US EIA. (2013d). *Annual Enegy Review*. Retrieved Jun. 2013, from EIA Website: http://www.eia.gov/totalenergy/data/annual/index.cfm

US EIA. (2013a). *Average Price of Natural Gas*. Retrieved Aug. 2013, from US EIA: http://www.eia.gov/dnav/ng/ng_pri_rescom_dcu_SNY_a.htm

US EIA. (2005). *Commercial Buildings Energy Consumption Surrvey (CBECS)*. Retrieved Jul. 2013, from http://www.eia.gov/consumption/commercial/

US EIA. (2013b). *Commercial Buildings Energy Consumption Survey (CBECS)*. Retrieved Jul. 2013, from US EIA: http://www.eia.gov/consumption/commercial/data/2003/index.cfm?view=consumption

US EIA. (2013c). *Electric Power Monthly*. Retrieved Aug. 2013, from US EIA: http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_6_a

US EPA. (2013). *AirNow*. Retrieved Jul. 2013, from AirNow: http://www.airnow.gov/index.cfm?action=airnow.main

US EPA. (1999). *Guidelines for the Reporting of Daily Air Quality the Air Quality Index.* North Carolina: US EPA.

US EPA. (1989). *Report to Congress on indoor air quality: Volume 2.* Washington, DC: EPA/400/1-89/001C.

US EPA. (2012). *Sustainability Guidelines*. Retrieved Sep. 2012, from www.epa.gov/gateway/science/sustainable.html

USGBC. (2012). *LEED Certification*. Retrieved Sep. 2012, from http://www.usgbc.org/DisplayPage.aspx?CMSPageID=220/

USGBC. (2009). *LEED 2009 For New Construction and Major Renovations.* Washington, DC: USGBC.

Walton, G. N., & Dols, W. S. (2013). *CONTAM User Guide and Program Documentation.*

WBDG Functional / Operational Committee. (2013, 08 01). *Account for Functional Needs*. Retrieved 08 02, 2013, from http://www.wbdg.org/design/account_spatial.php

WBDG Sustainable Committee. (2013, 08 12). Retrieved 09 02, 2013, from Optimize Site Potential: http://www.wbdg.org/design/site_potential.php

WBDG. (2013). *Whole Building Design Guide*. Retrieved Sep. 2013, from http://www.wbdg.org/

Wei Feng. (2012). *CHAMPS-multizone and virtual building for integrated building systems design and performance evaluation.* Syracuse: Syracuse University.

Welle, B., Haymaker, J., & Rogers, Z. (2011). ThermalOpt: A Methodology for Automated BIM-Based Multidisciplinary Thermal Simulation for Use in Optimization Environments. *Building Simulation , 4* (4), 293-313.

Western Regional Climate Center. (2013, 08 16). *Station Wind Rose*. Retrieved from http://www.wrcc.dri.edu/cgi-bin/wea_windrose.pl?laKSYR

Wetter, M. (2010). Co-simulation of building energy and control systems with the Building Controls Virtual Test Bed. *Journal of Building Performance Simulation , 4* (3), 185-203.

Yan, D., Xia, J., Tang, W., Song, F., Zhang, X., & Jiang, Y. (2008). DeST — An integrated building simulation toolkit Part I: Fundamentals. *Building Simulation , 1* (2), 95-110.

Zhang, J. (2005). Combined heat, air, moisture, and pollutants transport in building environmental systems. *JSME International Journal, Seres B , 48* (2), 1-9.

SYRACUSE UNIVERSITY
BUILDING ENERGY AND ENVIRONMENTAL SYSTEMS LABORATORY (BEESL)
DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING
263 Link Hall, Syracuse University, Syracuse, NY 13244-1240; http://BEESL.Syr.Edu

Virtual Design Studio (VDS) Software Tutorial

Version 1.0

By

Daniel Rice, Yixing Chen, Zhaozhou Meng, Jun Shi, Lixing Gu, Michael Pelken, and Jensen Zhang

Syracuse University

30 Sep 2013

This software tutorial is a living document that will be enhanced and amended with documented revisions to incorporate new ideas, research findings, approaches and applicable technologies deemed appropriate by the development team.

TABLE OF CONTENT

1 Introduction

1.1 About this Document

This tutorial has been structured as follows:
Chapter 1 includes the introduction of VDS, and the organization of this tutorial.
Chapter 2 includes how to begin using VDS; including the required installation environment, prerequisite software, and the steps to install VDS.
Chapter 3 includes information regarding the Graphical User Interface.
Chapter 4 demonstrates the step-by-step procedures to use VDS, including how to customize the project setup, input design parameters, including brief introduction about Library & Template, run simulations, and view both the design results and performance predictions.
Chapter 5 presents details of "Libraries" and "Templates", which helps users input parameters more conveniently.
Appendix A gives detailed examples on how to create geometry for VDS simulation.

1.2 Introduction to VDS

"Virtual Design Studio (VDS)" is a software platform for supporting an integrated, coordinated and optimized design process of very-low energy and high Indoor Environmental Quality (IEQ) buildings.

A 3-D matrix (named "Magic Cube") is used as the fundamental representational and operational structure of VDS to facilitate multi-design teams, multi-design stages and multi-design factors, while considering multiple aspects of the building performance (Figure 1-1 Three-dimensional "Magic Cube" matrix for VDS structure).Within this matrix, all the three areas of consideration are correlated to organize the workflow.

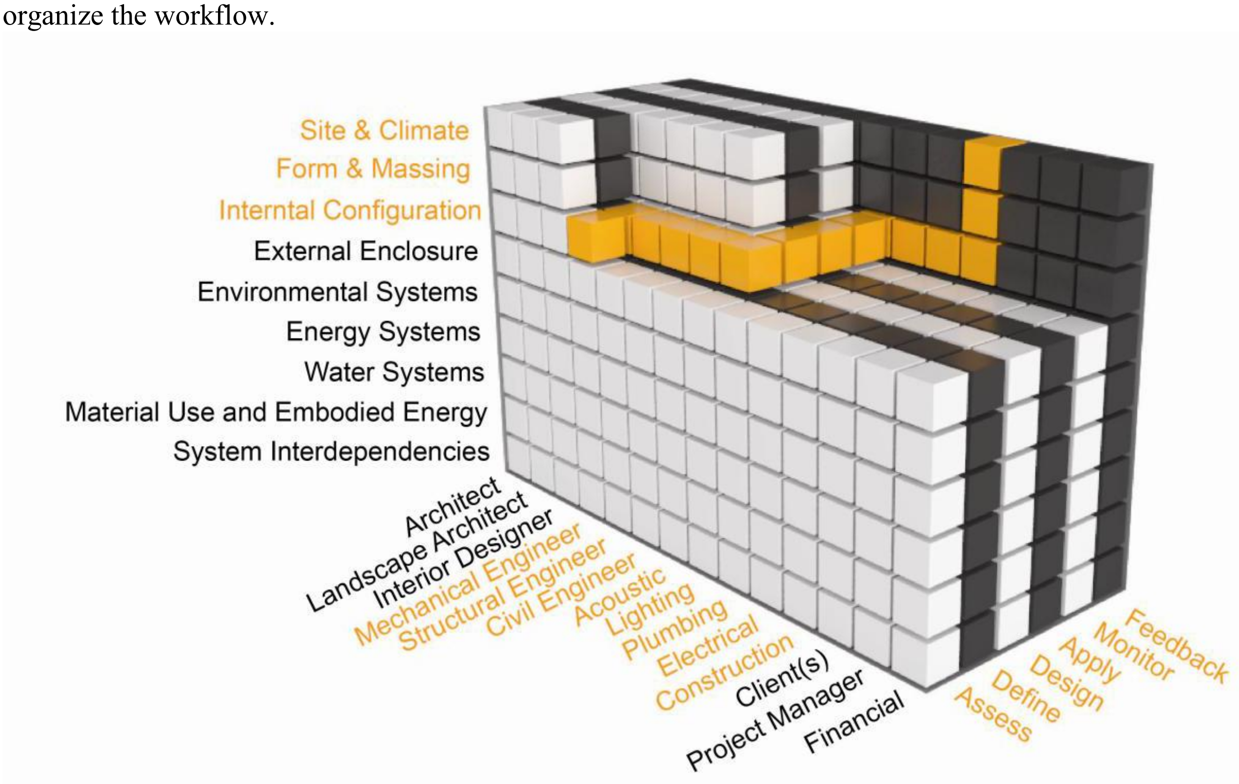


Figure 1-1 Three-dimensional "Magic Cube" matrix for VDS structure

X-axis: Incorporates **Design Teams** from three major areas: (1) architecture, (2) systems design/engineering and (3) project management.

1) Within the category of the architectural design team, a base configuration of architects, interior designers and landscaping architects is initially provided. Properties may be extended or altered, however, to include lighting or acoustics design consultants for example, at any given stage of design.
2) In the category of the systems design team, VDS includes positions of structural, HVAC, Mechanical Electrical Plumbing (MEP) and civil engineers, all specified according to individual project specifications.
3) Finally, in the category of the project management team, specifications are able to be allocated according to client, contract form, project type, and management structure, due to the wide contractual diversity of design practice.

Y-axis: The professional working **stages** can be translated into the five universal performance evaluation and implementation stages used in the established VDS - ADDAM structure. They are as followed:

1) "Assess"---Assess the project's needs, existing conditions, availability of resources and other constrains, and formulate a strategic brief for all areas of consideration (which corresponds to the advisory and negotiation working stages);
2) "Define"---Define the project's performance scope and goals, and propose possible strategies to achieve the performance goals (which corresponds with preliminary design and concept development working stages);
3) "Design"---Design the building and perform required analysis to meet and verify previously defined performance scope and goals. This includes schematic design, final design and detail development working stages;
4) "Apply"---Apply the designed solutions and revisit/verify the defined scope and goals established during construction working stages;
5) "Monitor"---Monitor and commission achieved performance for verification purposes, diagnose design-construction performance discrepancies, and document case study results for possible feedbacks in order to improve the future design of similar buildings.

Z-axis: This axis summarizes important design factors that strongly impact all building system operations. The following design **factors** have been identified as key focus areas for VDS:

1) An appropriate climatic and site specific design response (accessibility, site density, surrounding building mass, regional and local microclimates, site orientation and relationships to solar path and prevailing winds, ground conditions, background noise and air pollution, local renewable resources, bio-diversity, hard and soft landscaping, etc.);
2) The building form, orientation and massing (related to existing site context, proposed surface to volume ratio, orientation related to solar path and prevailing winds, noise and pollutant sources, etc.);
3) The external building enclosure, including roof area as well as the quantity and quality of openings (refers to thermal properties, direct and indirect solar gain, air tightness, day lighting, natural ventilation, etc.);
4) Internal zoning (as it relates to occupant activities, building orientation, massing aspects, exterior conditions, internal plug loads, moisture gains, and indoor pollutant sources, etc.);
5) All environmental control systems (active, passive and hybrid HVAC, mechanical, plumbing and electrical systems etc.);

6) All energy systems (grid management for conservation, consumption and generation; active, passive and hybrid energy and lighting systems, use of local renewable resources, energy storage and distribution solutions, etc.);
7) All water systems (site, supply and waste water management, local water collection and distribution, ground sources, artificial and natural water filtration systems, etc.);
8) Material use and embodied energy, including all phases of a building's life cycle;
9) System interdependencies; addressing overall system efficiencies as they relate to individual subsystems and respective coordination, integrations, and operations throughout the seasons in relation to the building occupancy and operation systems.

During each VDS-ADDAM (Assess, Define, Design, Apply, Monitor) stage, all relevant design factors and their relationships are investigated. Every aspect is evaluated in relation to programmatic needs and performance standards, as well as the impact of the proposed solutions on other areas of design and systems integration. For each given stage and design aspect, and according to the defined project intentions, the relationships between these crucial factors can vary significantly. For a particular area of investigation, all interdependencies can be mapped in future VDS version and understood for one particular planning stage (for instance the Assessment) (Figure 1-2 Interrelationships of design factors during the Assessment Stage). Details of the described VDS components and their operation are presented in 4.2.

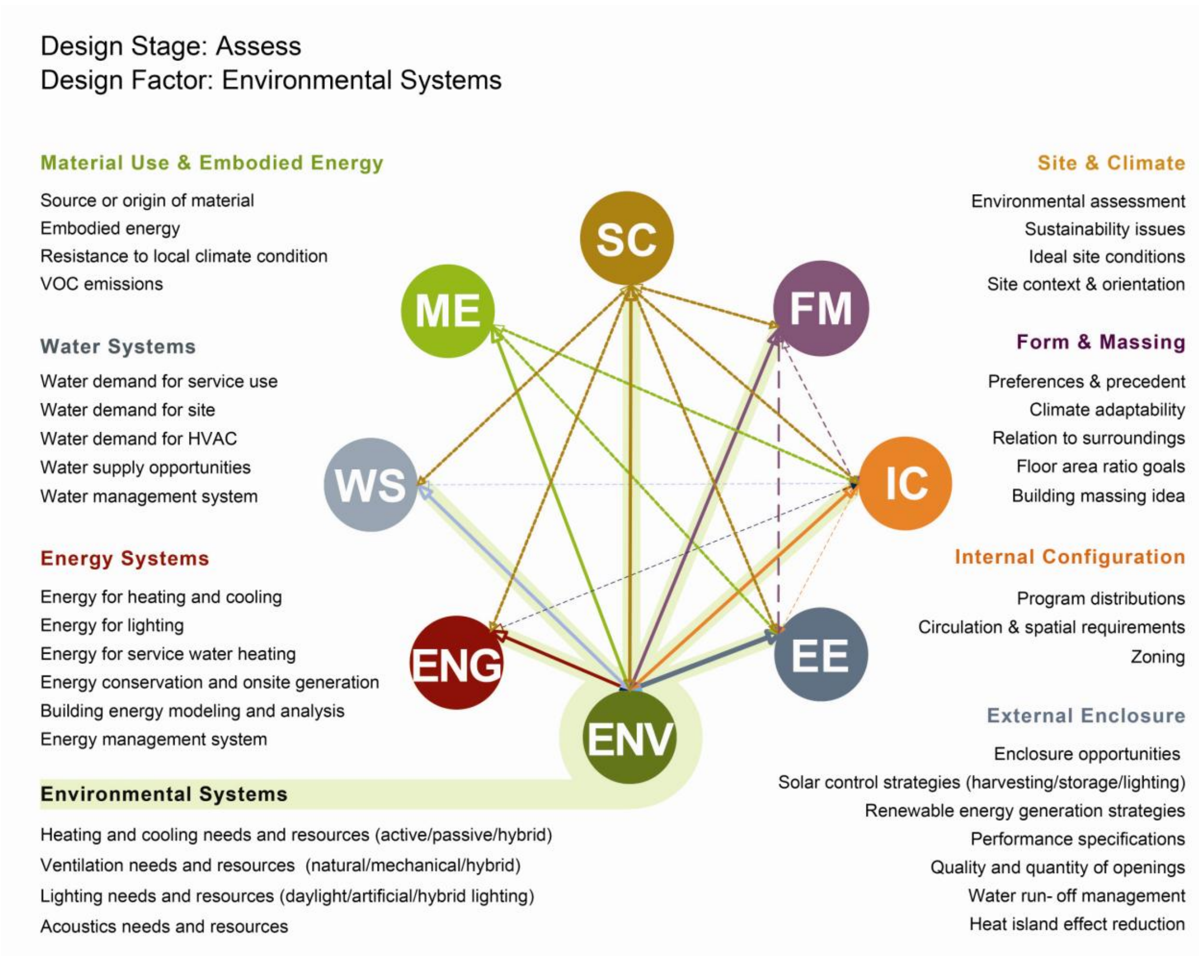


Figure 1-2 Interrelationships of design factors during the Assessment Stage

2 Getting Started

This chapter presents computer requirements for the installation of VDS and then provides information for VDS software installation.

2.1 Requirements

Requirements include two parts: the computer installation environment and required prerequisite software for the support of VDS functions.

2.1.1 Installation Environment

In order to install VDS, the following installation environments are required:

- Operation system: Windows XP, 7 or higher
- Platform: dot net Framework 4.0 or higher

2.1.2 Prerequisite Software

Prerequisite software includes SketchUp+OpenStudio, EnergyPlus, JAVA+BCVTB, CHAMPS BES. Corresponding function and installation details are presented here.

2.1.2.1 SketchUp + OpenStudio

SketchUp8 and OpenStudio Plug-in 1.0.9 are required for geometry modification.

SketchUp 8 is 3D graphical software that can be used by architecture students and architects in addition to other more prolific professional CAD packages to sketch a building for conceptual design and analysis. Download appropriate version of SketchUp 8 from http://www.sketchup.com/intl/en/download/gsu.html

- Install SketchUp 8.
- Choose a folder into which you want to install the program, or simply select the default location which is "C:\Program Files\Google\SketchUp 8" for 32bit system and "C:\Program Files (x86)\Google\SketchUp 8" for a 64bit system. Follow the directions to complete the installation.

OpenStudio plug-in 1.0.9 provides a bridge between SketchUp and EnergyPlus (details in 2.1.2.2), which allows users to quickly create geometry using SketchUp and perform energy simulation using EnergyPlus.

- Get Windows version OpenStudio (1.0.9) from VDS development team (Contact details: Yixing Chen, Syracuse University, ychen93@syr.edu)
- The OpenStudio plug-in will be installed in: (SketchUp Installation Path)\Plugins. By default, for 32bit system, it should be "C:\Program Files\Google\SketchUp 8\Plugins"; while for 64bit system, it should be "C:\Program Files (x86)\Google\SketchUp 8\Plugins" Follow the directions to complete the installation.
- Users are now ready to start modeling. Choose "Plugins>Legacy OpenStudio>Open" to open existing geometry models. SketchUp 8 can convert 2D DXF and 3D CAD models for use in EnergyPlus, details can be found in "Help > OpenStudio User Guide>Tutorials".
- You should see the Legacy OpenStudio Plug-in toolbars. If you don't see them, you can open them via the View > Toolbars submenu.

For documentation, tutorials, and release notes, see the Legacy OpenStudio Plug-in Help within SketchUp. Click the green "?" icon or choose Help > OpenStudio User Guide from the menu. The help files will be displayed in your web browser. The help files can also be found in your local SketchUp plug-in directory under OpenStudio/doc/help.

2.1.2.2 EnergyPlus

EnergyPlus is used to predict energy performance of buildings in VDS. EnergyPlus 7.2 is included in the folder "bin\EnergyPlusV7_2_0_0" ("bin" is an installed folder in VDS).

2.1.2.3 BCVTB+ Java

The Building Controls Virtual Test Bed (BCVTB) is a software environment that allows expert users to couple different simulation programs for distributed simulation (Distributed simulation is used to simulate the interaction of air, heat, etc.).

For example, the BCVTB allows simulating a building and HVAC system in EnergyPlus and the control logic in MATLAB/Simulink, while exchanging data between the software as they simulate. BCVTB is used for Whole Building Energy & IEQ simulation. BCVTB is located in "bin\BCVTB".

Java is required for BCVTB and should be installed in advance.

2.1.2.4 CHAMPS BES

CHAMPS BES is used for analysis and prediction of hydrothermal performance of building enclosures; impact of outdoor climate and pollution on indoor environment; impact of VOC emissions from building materials and indoor furnishings on indoor air quality. CHAMPS-BES is included in VDS in "bin\CHAMPS_BES_2009".

2.2 Installing VDS

This section presents where to obtain the VDS software, how to install it, how to configure each prerequisite software and how to uninstall VDS.

2.2.1 Obtaining VDS

Please contact the development team to obtain the newest version of VDS.
Contact details: Yixing Chen, Syracuse University, ychen93@syr.edu

2.2.2 Installing VDS

Currently, VDS is released as a ZIP format file. Unzip the file to a folder without any space, i.e. "C:\VDS". (More information about WinZip can be found in http://www.winzip.com/downwz.htm.)

2.2.3 Installed Folder

Table 2-1 Folder Location lists the folders installed by the setup program. For each folder, the directory to which it is installed, the name and a brief description are given. The <program> directory is selected when you install the program.

Table 2-1 Folder Locations

Directory	Description
<Program Path>\bin	Required software
<Program Path>\configures	Configuration file
<Program Path>\data	VDS libraries and templates

<Program Path>\Examples	Sample project files
<Program Path>\img	Images in VDS
<Program Path>\lib	Component file for VDS
<Program Path>\Temp	Error Report/Simulation Results/Modified Geometry

2.2.4 Configuration for External Tools

Some external software is required in order to use the relevant functions in VDS as introduced previously. VDS currently utilizes four external programs: SketchUp+OpenStudio, EnergyPlus, CHAMPS BES and Java. When running VDS.exe for the first time, users should configure the path for "SketchUp.exe" and “Java.exe” (Figure 2-1 Configuration of external software). Note: EnergyPlus 7.2, BCVTB & CHAMPS BES are included under “bin” folder in the VDS release so that you don't need to specify their paths. If users intend to change paths for software in future, click “Simulation->Configures” in menu of VDS interface.

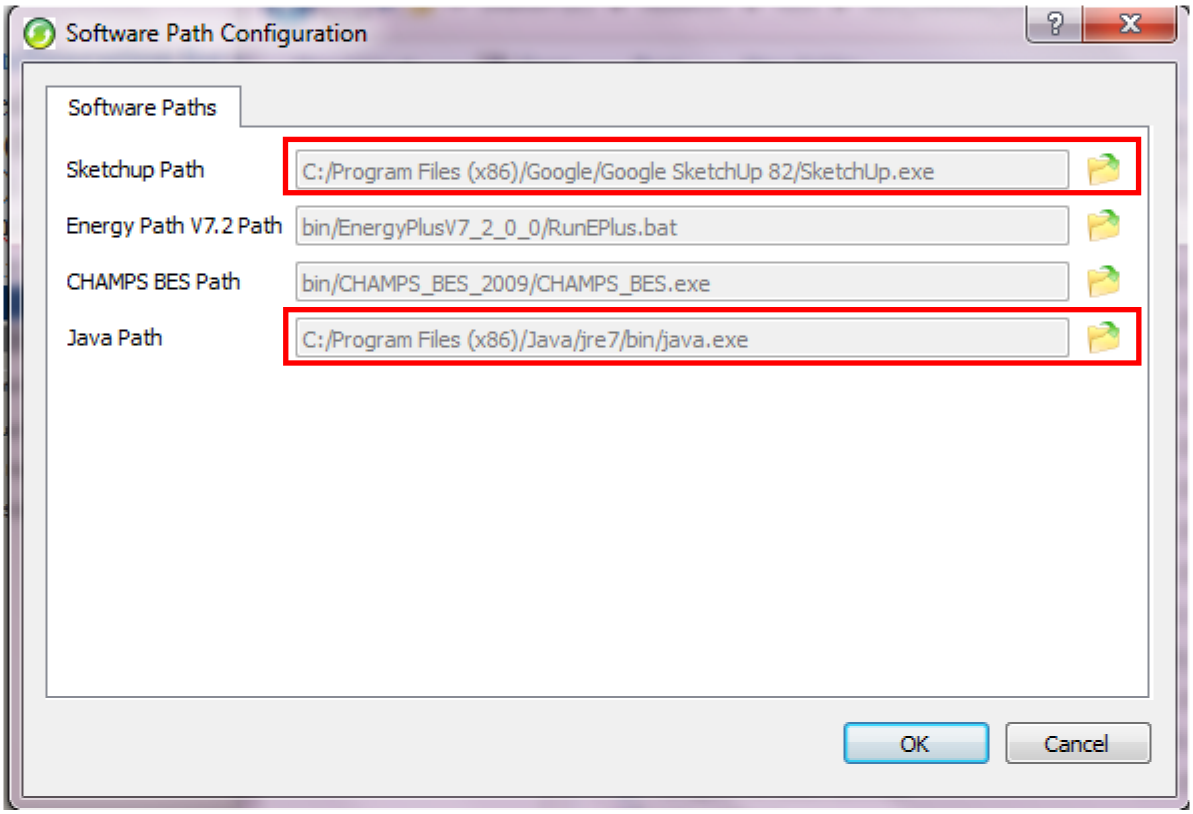


Figure 2-1 Configuration of external software

2.2.5 Uninstalling VDS

Delete all VDS files in the program path.

3 VDS Graphical User Interface (GUI)

This chapter gives details on VDS four-quadrant interface and menu. The user can be familiarized with the layout and tool availability here.

3.1.1 Four-Quadrant Interface

VDS GUI features four basic interactive windows in counter-clockwise organization Design Process, Input, Result and Performance (Figure 3-1 Four quads form (viewer) of VDS graphic user interface (GUI)): The size of each quad can be dynamically adjusted by clicking and dragging the center of GUI. Each quadrant can be maximized to fill the window by double-clicking the bar shown in Figure 3-1. Within each quadrant, tab pages are used to present different categories of information, using a layered-approach. Within each tab's page, further details regarding the information category are presented.

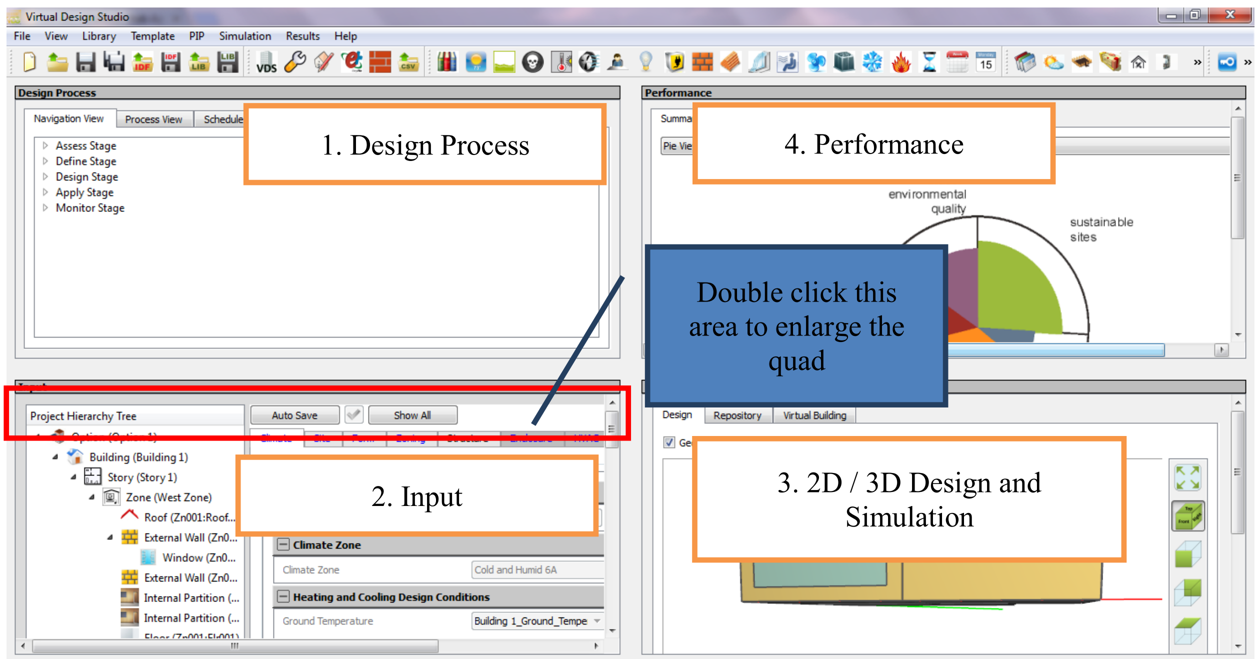


Figure 3-1 Four quads form (viewer) of VDS graphic user interface (GUI)

3.1.1.1 Quadrant 1: Design Process

There are three tabs which are used for the project set up: Navigation tab (Tree view: shows organizational structure of the design process), Process tab (Process view: process flow diagram) and Schedule tab (Gantt chart view: schedule of the design process) as depicted in Figure 3-2.

<u>Navigation Tab</u>

The navigation tree (Figure 3-2) shows the hierarchical structure of the design process, such as the design stages, factors, and associated tasks. Details about teach ta can be found in 4.2.

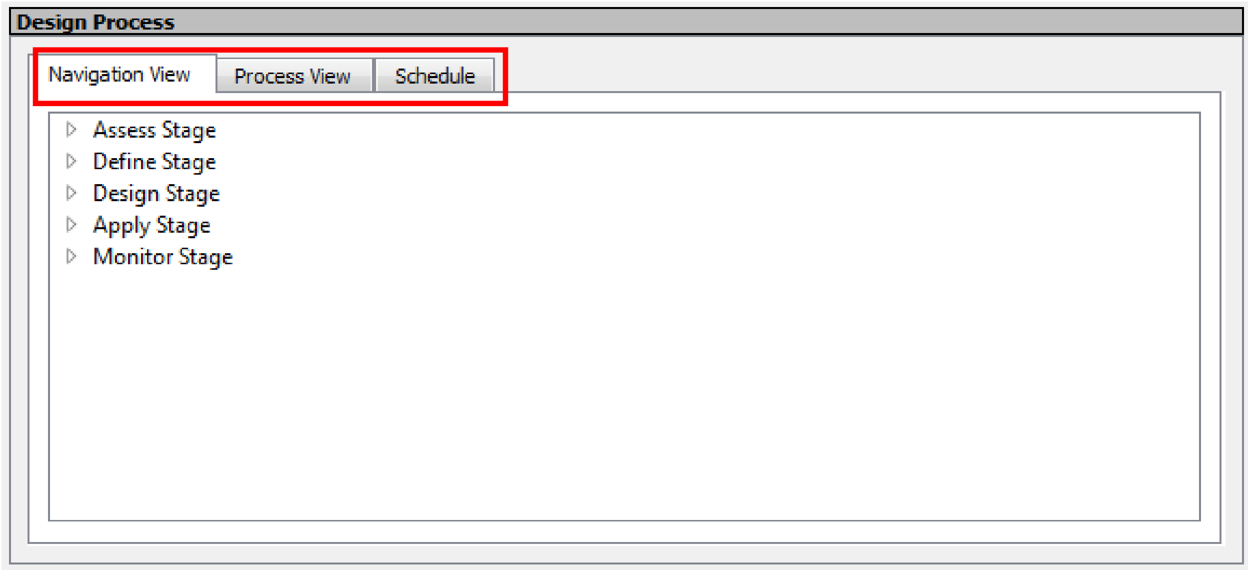


Figure 3-2 Design Process Quadrant

Currently, there are three stages for design processes: (1) assess stage, (2) define stage, and (3) design stage.

Assess Stage (**A**ssess DDAM)
"Assess stage"---Assess the project's needs, existing conditions and availability of resources and other constrains, and formulates a strategic brief for all areas of consideration (which corresponds to the advisory and negotiation working stage). Most importantly, it will specify all performance based considerations and expected standards.

Define" Stage (A **D**efine DAM)
"Define stage"---Defines the project's performance scopes and goals, and propose possible strategies to achieve the performance goals (which correspond to the preliminary design and concept development working stages).

Design Stage (AD **D**esign AM)
"Design stage"---Precedes with the design the building and performs all required analysis steps to meet and verify the previously defined performance scope and goals (which corresponds to schematic design, final design and detail development working stage).

"Apply" and "Monitor" stages are not part of current VDS, but used for Comparison of design / built performance; Creation of project data repository; Case study library / VDS documentation of designed projects.

Process Tab
The Process tab represents the design process in a process flow diagram, so that users can directly view the design process. The starting point for this tab is the "Magic Cube" design matrix as shown in Figure 3-3(not available in the current version):

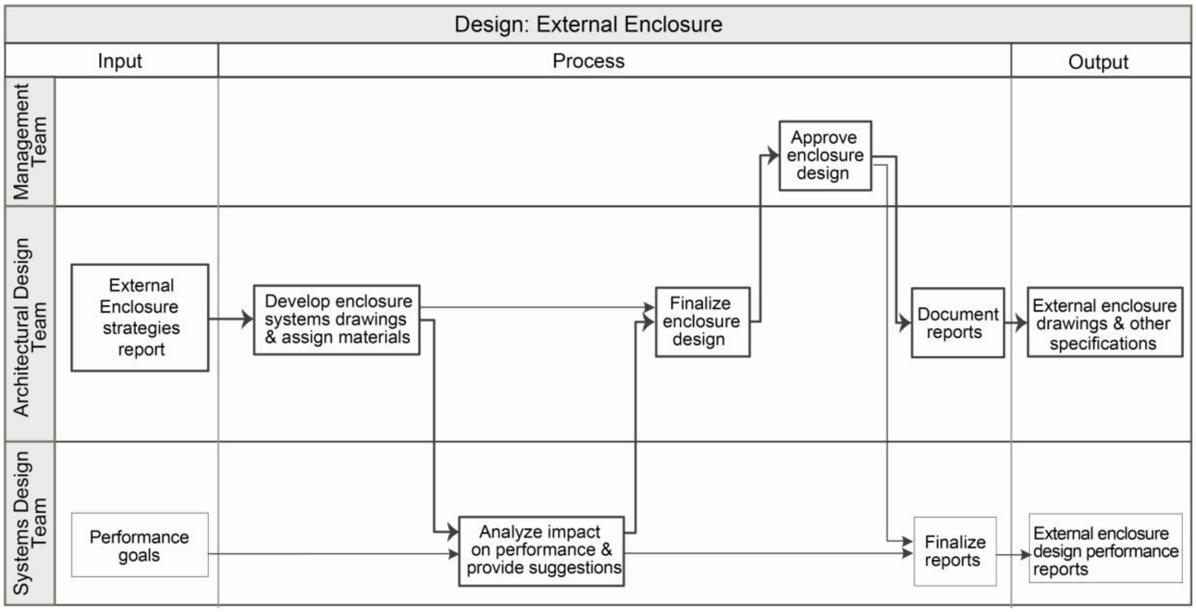


Figure 3-3 Demonstration Process View

Schedule tab

This tab depicts a Gantt chart to illustrate the design process sequence. It is generated based on the design process defined/customized in the Navigation tab (not available in the current version).

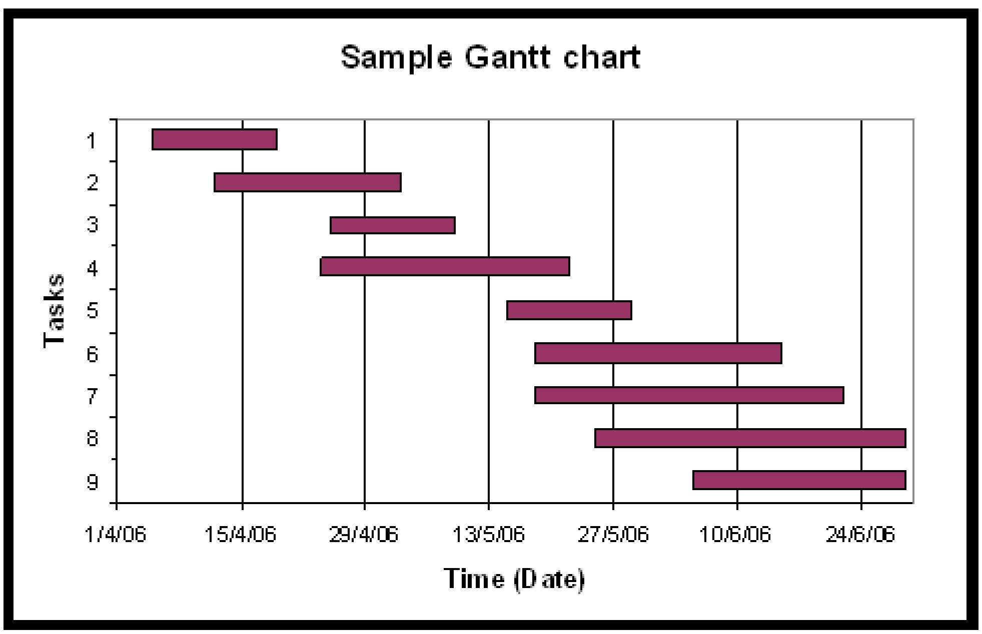


Figure 3-4 Sample of Schedule View in Design Process Window

3.1.1.2 Quadrant 2: Input

The "Input" window presents input design parameters (both quantitative and qualitative) and supporting reference information. Only quantitative information is available at this point. It includes a browsing tree on the left and tab pages on the right (Figure 3-5 Input Quadrant). The tree allows users to focus on a specific level in the building's hierarchical composition. Each tab page represents a category of input parameters of a specific design factor such as Climate, Site, Form, Zoning, Structure, Enclosure, HVAC, Lighting and so on. Details are presented in 4.4.

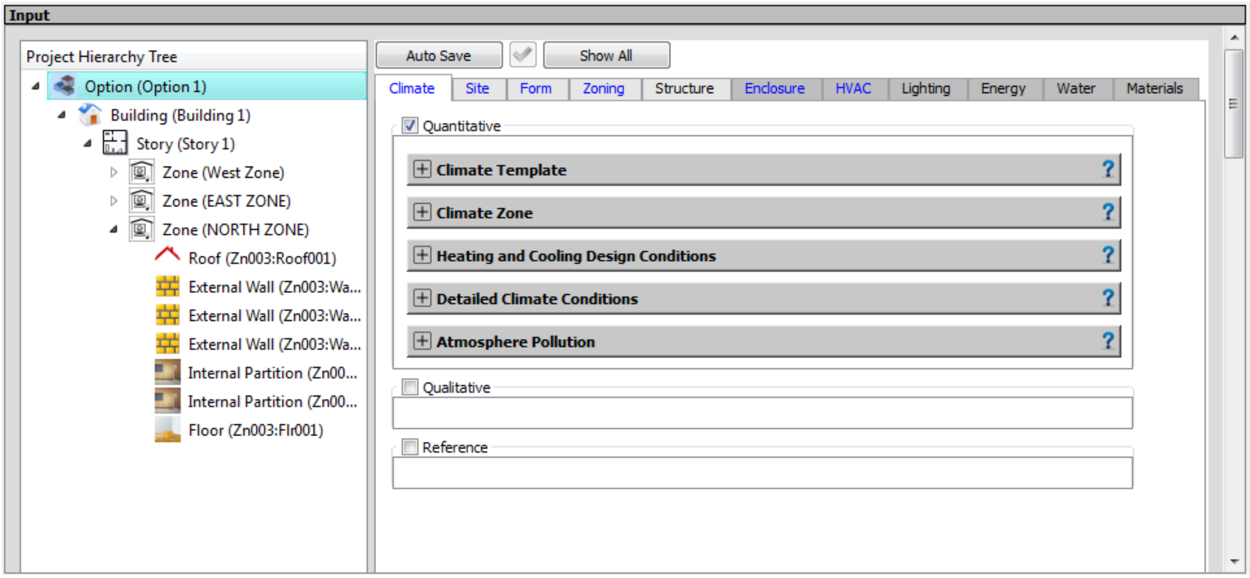


Figure 3-5 Input Quadrant

3.1.1.3 Quadrant 3: 2D / 3D Design and Simulation Result

The "Result" window presents the building's 3D/2D geometry (Figure 3-7), Heat (Figure 3-8), day lighting (Figure 3-9), and pollutants (future version) in the "Design" tab, and a "Repository" tab (Figure 3-10) for document sharing over an internet server through the VDS-PIP. Figure 3-6 shows how to view results in steps, more details are located in 4.6.

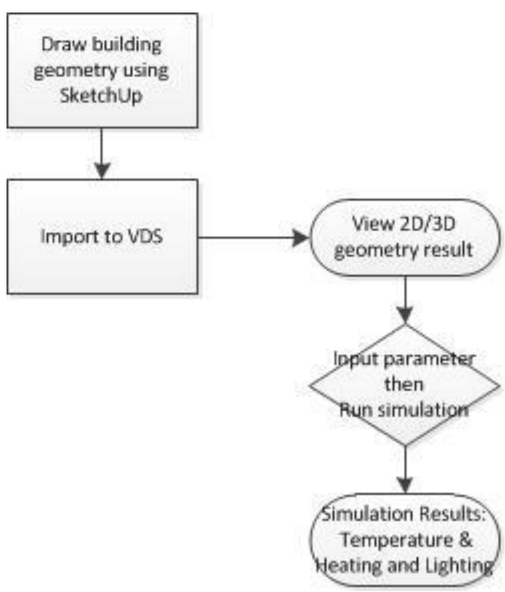


Figure 3-6 How to view results

After importing building's .idf obtained from SketchUp, users can view 3D/2D results in this window directly. On the right of the window, there are several buttons to help users view geometry. More details of buttons can be found in 4.6.1.

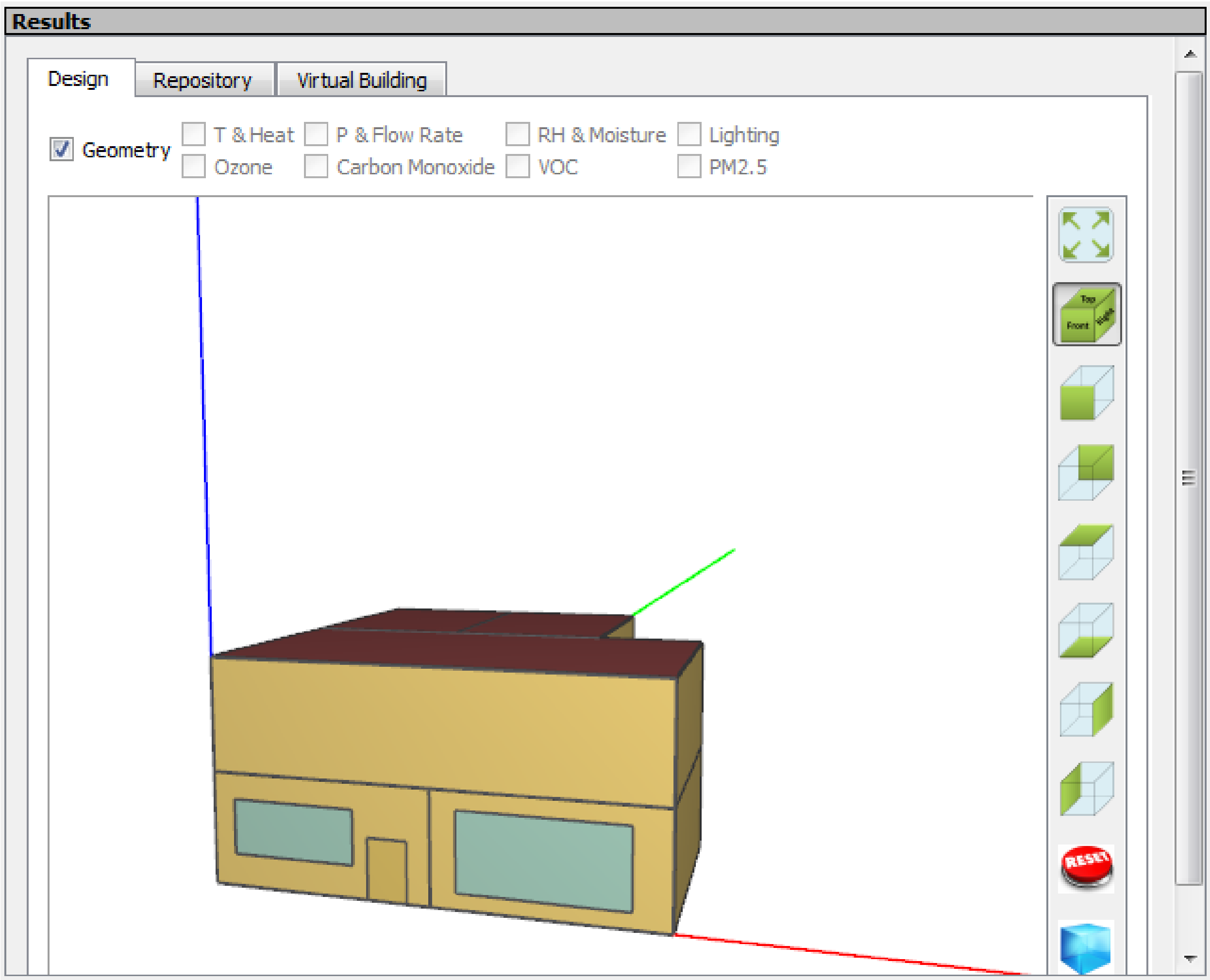


Figure 3-7 The "Design" of a whole building in Result Window

After simulation, results such as "Heat", "Air", "Moisture" "Day-lighting" and "Pollutant" are represented in the forms of contour maps and flux maps with architectural design overlay (as shown in Figure 3-8 and Figure 3-9). More details about how to view current results can be found in 4.6.2.

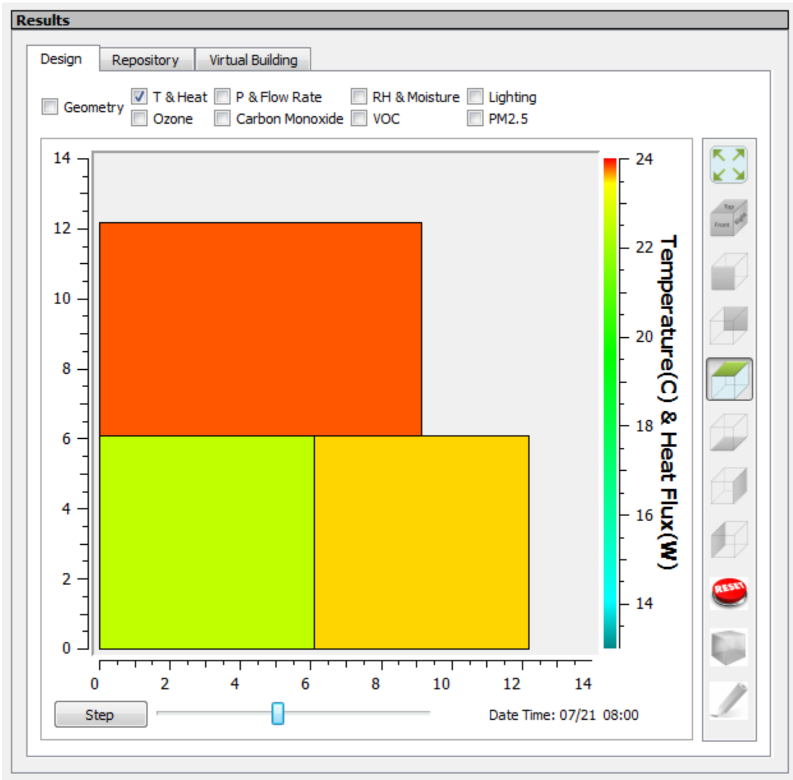


Figure 3-8 Temperature field of the 1st floor building at 8am on Jul. 21st in Result Window

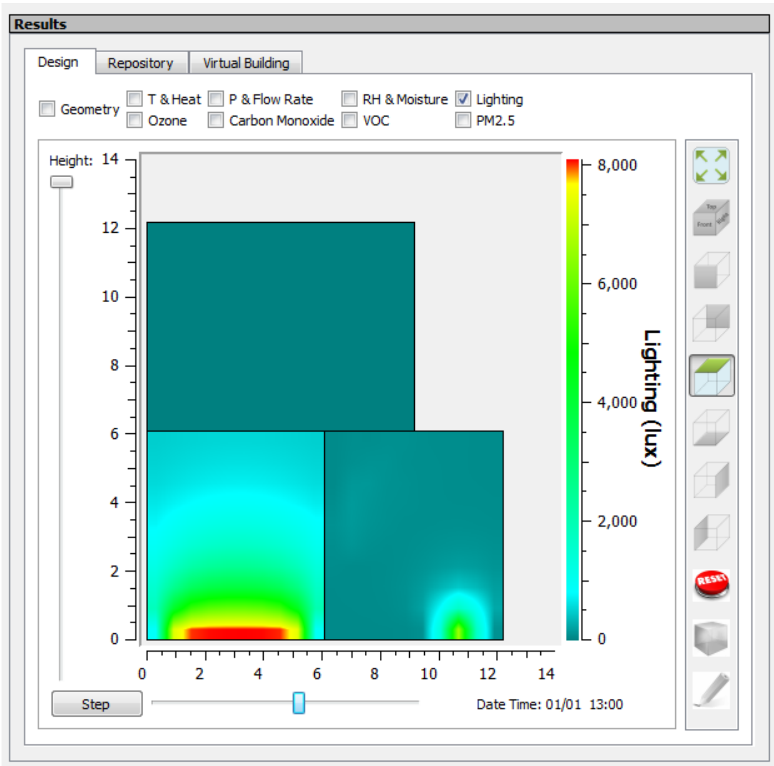


Figure 3-9 Lighting map of the 1st floor building at 1pm on Jan. 1st in Result Window

A **"Repository"** (Figure 3-10 "Repository" tab in "Results") for document sharing over an internet server through the VDS-PIP (Process Integration Platform) is included. A shared framework of project information can enhance a project team's performance by identifying information relationships and data dependencies to provide project teams with the right project data at the right time. The Process Integration Platform (PIP) provides this informational view by graphically representing project information or documents along with associated data dependencies using common web browsing technologies. Further information about PIP is provided in 4.6.3.

The "Repository" button links directly to the VDS-PIP web interface via the web. Here is a project tree on the left and various documents and relationship for task shown on the right. Details about "Result" quadrant are shown in 4.6 "Step 6: View Design Results".

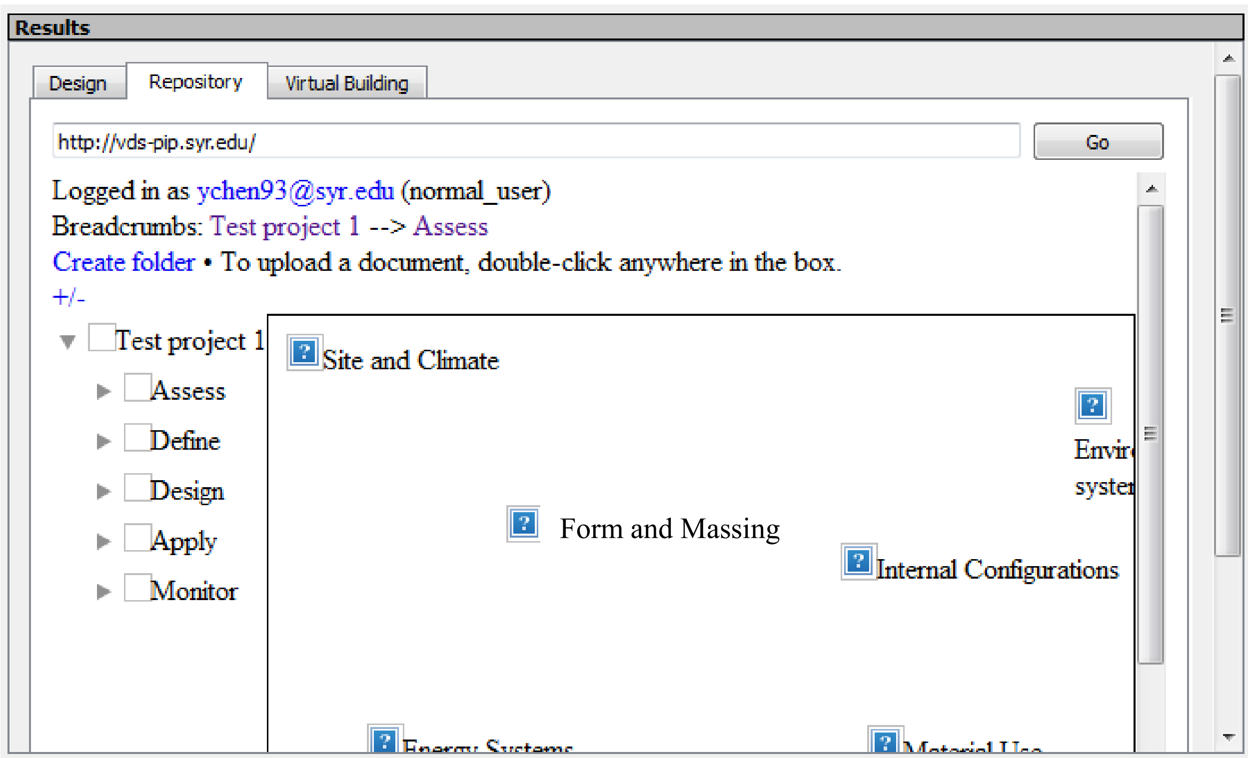


Figure 3-10 "Repository" tab in "Results"

3.1.1.4 Quadrant 4: Performance

"Performance" depicts design efficiencies in the form of a pie chart (Figure 3-11). In response to the established professional performance standards, the VDS platform facilitates simulation processes by offering a range of options for project specific customization of prediction and simulation techniques. All output results are comparable with minimum (e.g., ASHRAE standards 55.1, 62.1 and 90.1) and advanced standards (e.g., BREEAM, LEED, ASHRAE 189.1), before providing valuable input for the next working stage. As part of this evaluation process, the platform will provide a comprehensive overview describing how the current planning state compares to the specified performance goals. The graph is broken down into groups of all relevant performance areas, and indicates the efficiencies related to applicable rating systems. This helps to easily understand where the defined performance criteria have been met, where the performance exceeds the desired performance, or where respective shortcomings have been noted. The window reacts to the task specification in "Design Process" quadrant and "Input" quadrant.

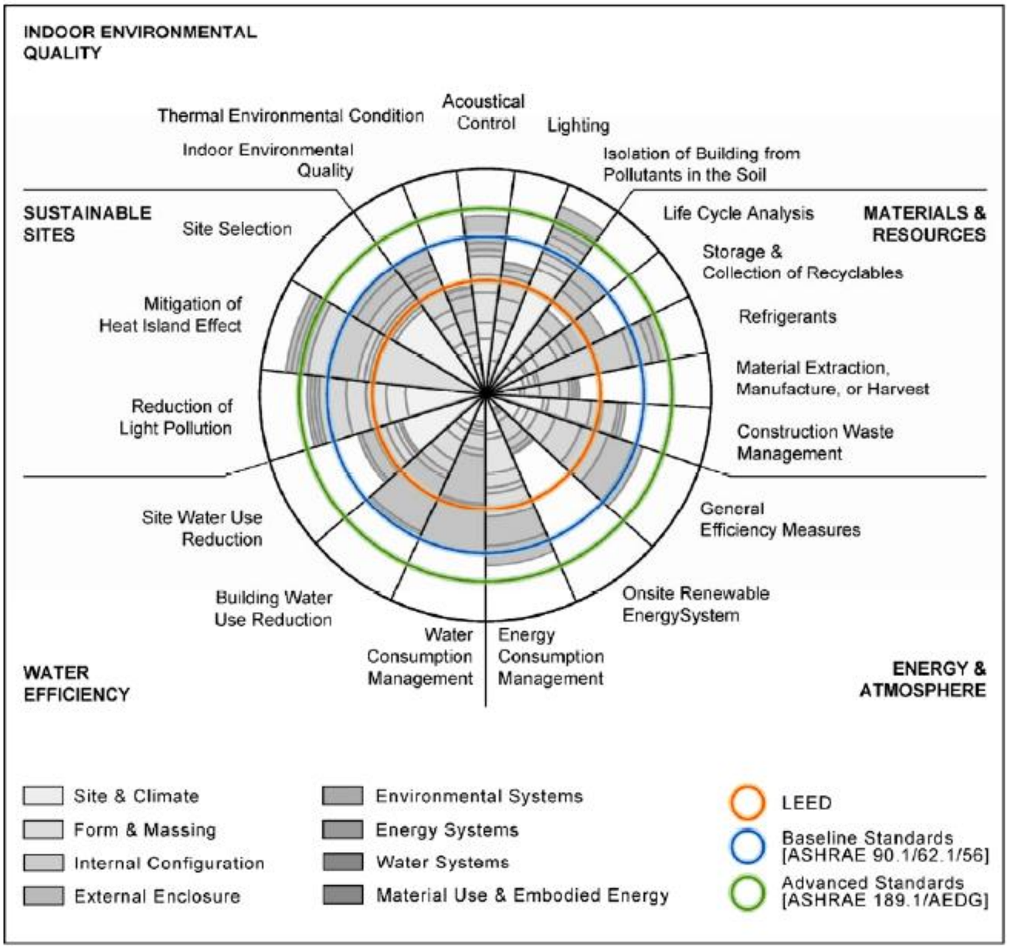


Figure 3-11 Pie chart for a systematic performance comparison

The "Performance" window represents the overall building performance (Figure 3-12), individual aspects like Energy, and cost information (not available in the current version).

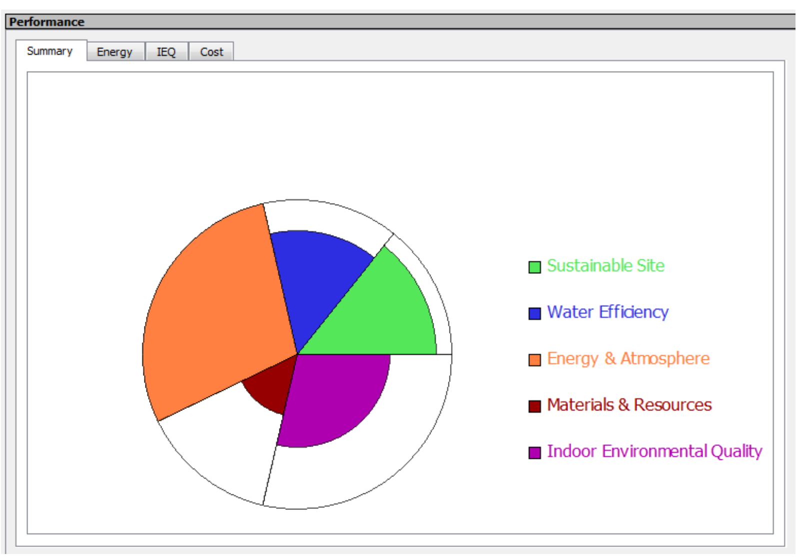


Figure 3-12 Proposed overall building performance summary view

By clicking on an aspect of the building performance in the summary view, the performance subsets of the selected performance aspect will be shown (Figure 3-13).

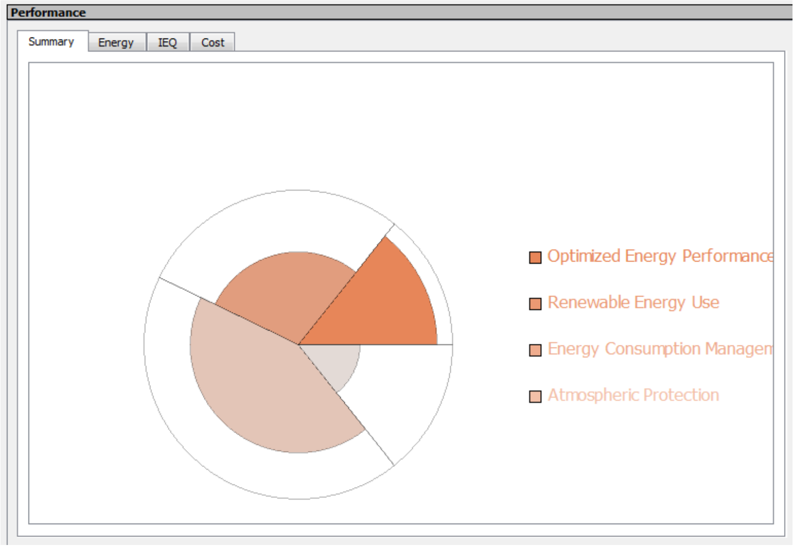


Figure 3-13 Energy & Atmosphere detail

Furthermore, by clicking on a subset, the contributions of each design factor to the improvement of the subset will be shown (Figure 3-14).

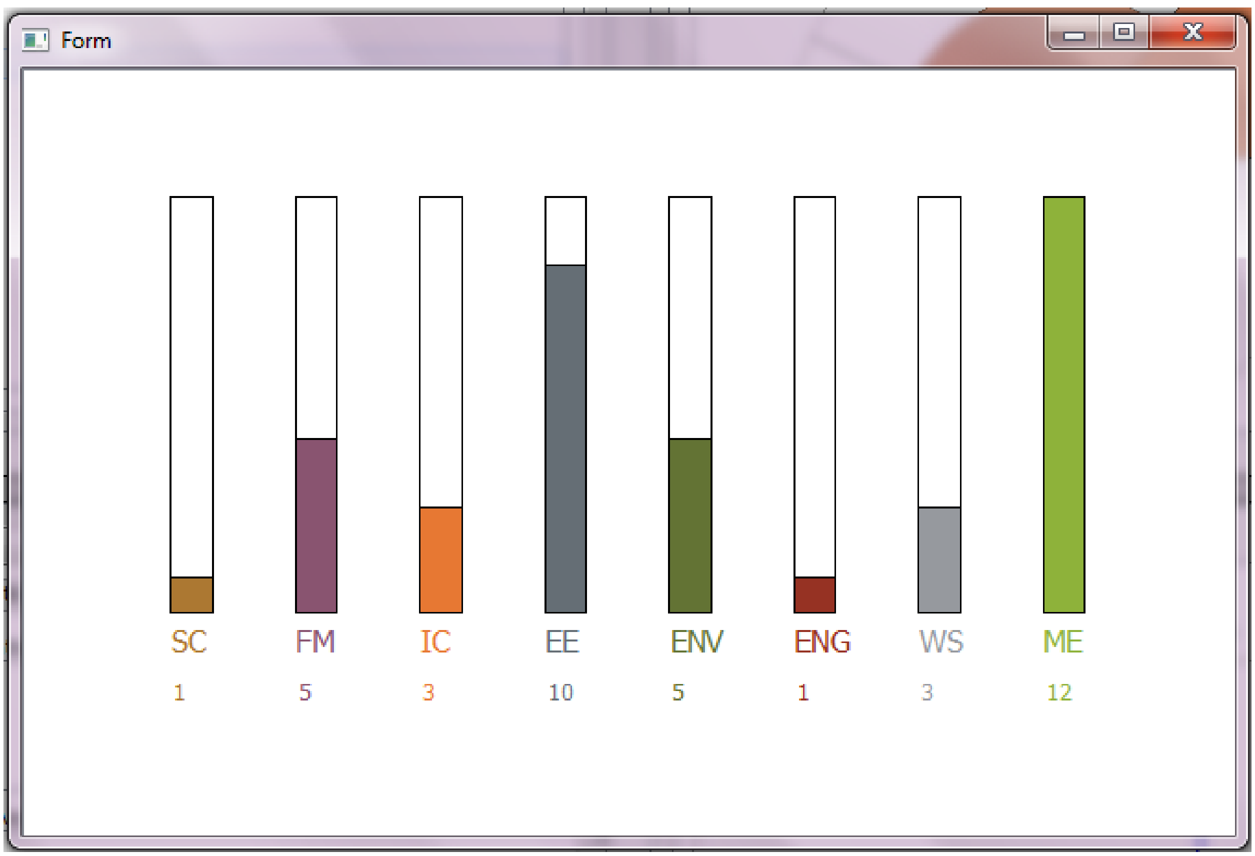


Figure 3-14 Performance relative to reference building by design factor

Finally, by clicking on a design factor, the relationship map of the selected design factor with the other factors will be shown (Figure 3-15). Future program extensions will include the confidence intervals for the predicted performance.

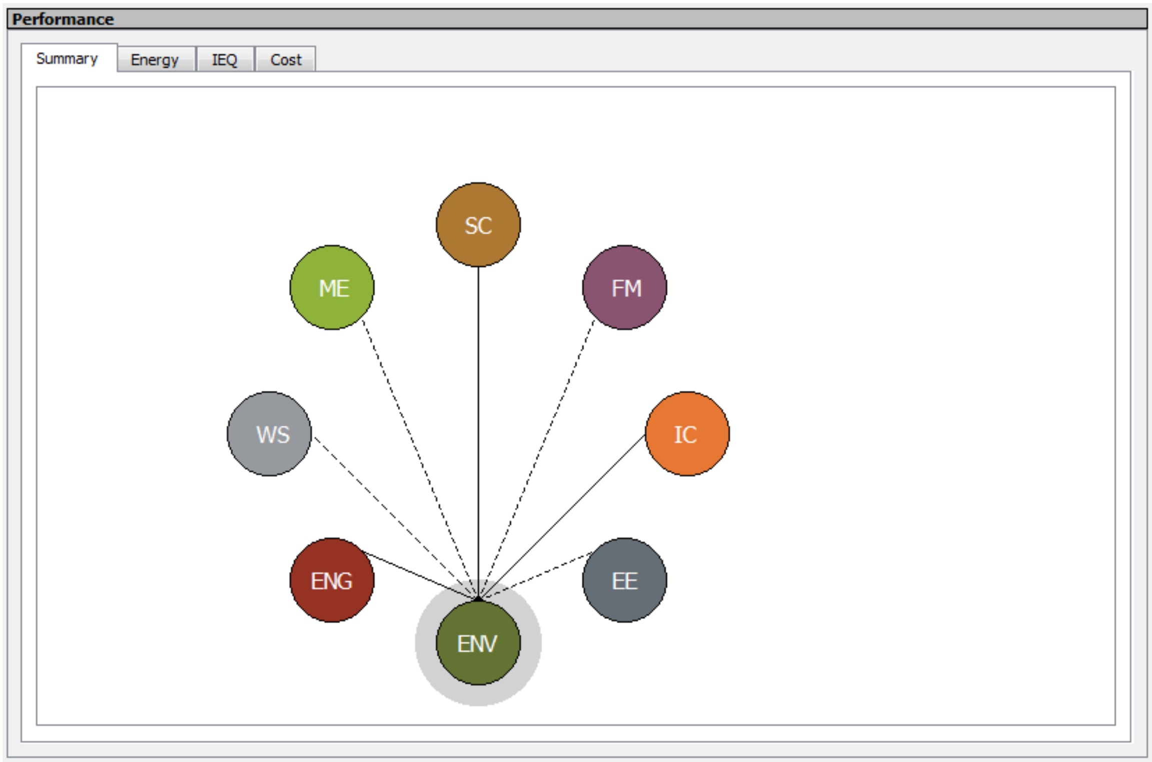


Figure 3-15 Design factor relationship map for a sub-performance aspect

Users can find further information for each quadrant in corresponding steps of VDS procedure in Table 3-1.

Table 3-1 Summary of quadrant

	General Function	Corresponding section in steps
Quadrant 1: Design Process	Organize platform according to magic cube project requirements	4.2
Quadrant 2: Input	Input design parameters and applicable standards	4.4
Quadrant 3: Result	View design and simulation results	4.6
Quadrant 2: Performance	View performance	4.7

3.1.2 Menu and Toolbar

This section gives a quick view for menu and toolbar in VDS.

3.1.2.1 Menu

The menu organization and operation (Figure 3-16) is typical of a Windows program with differences that provide functionality specific to the VDS application.
Table 3-2 illustrates all of functions in Menu.

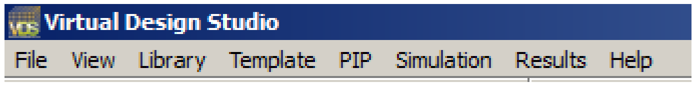
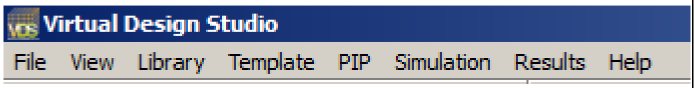
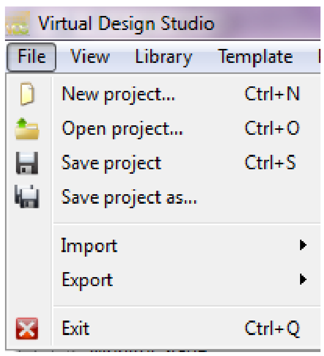
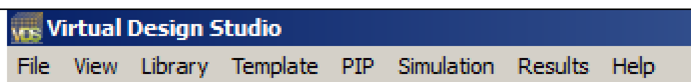
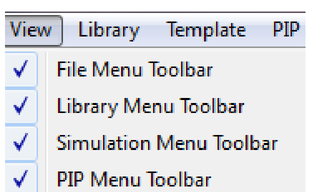
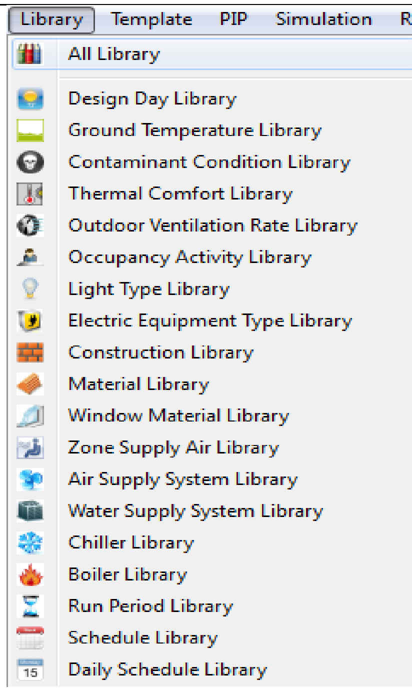
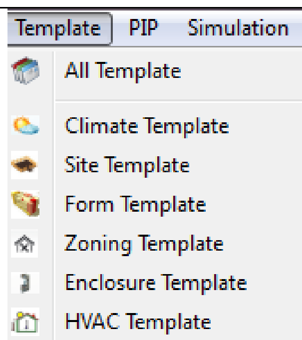
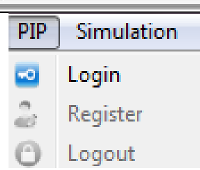
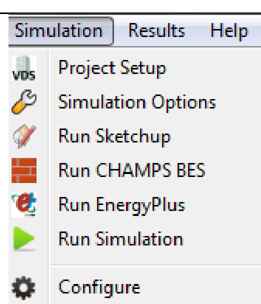


Figure 3-16 Menu

Table 3-2 Menu list

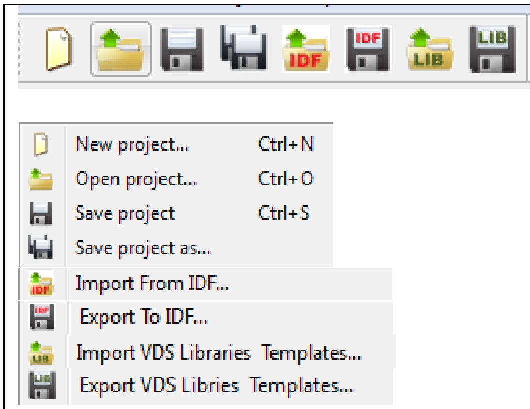
 	File menu: Creating a new project, saving and retrieving created project files. More details in 4.1. Importing and exporting external geometries. More details in 4.3.2. Importing and exporting libraries/templates. More details in 5.1 and 5.2.
 	View Menu: Users can open or close toolbar by ticking corresponding items

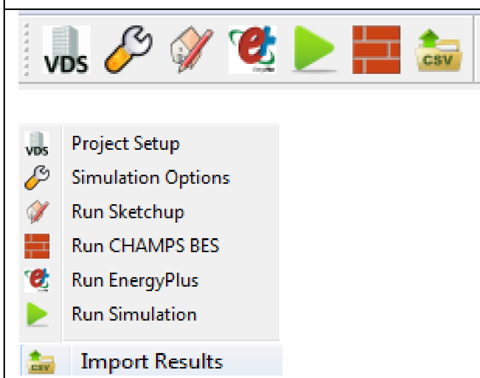
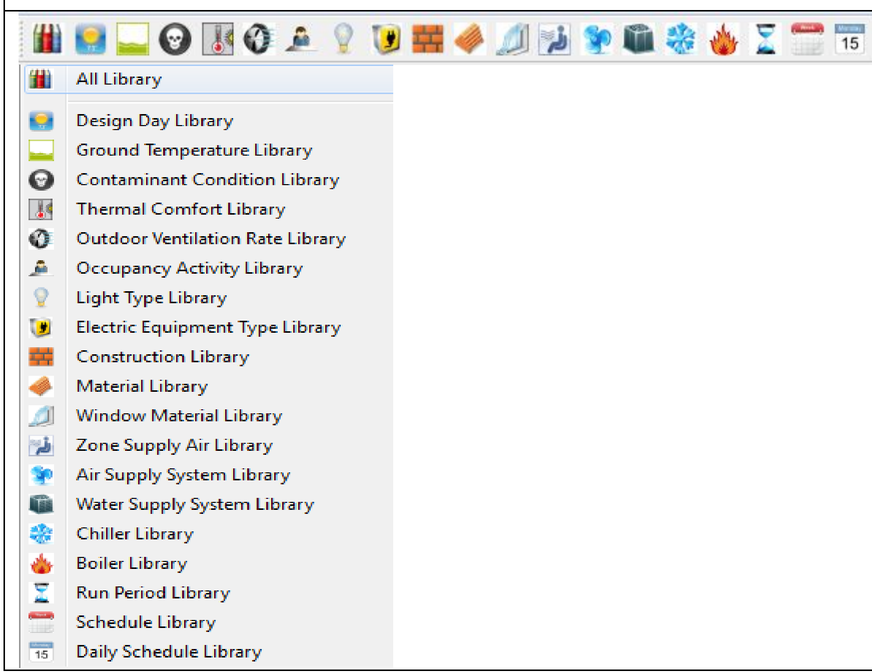
	Library menu: Selecting various libraries, which are required for parameter input Note: How to use libraries is introduced in 4.4.2. Details of libraries are in 5.1
	Template menu: Selecting various templates, which are required for parameter input Note: How to use templates is introduced in 4.4.2. Details of templates are in 5.2
	PIP menu: Accessing the built in Process Integration Platform (PIP). Note: Details about PIP in 4.6.3.
	Simulation menu: Setting up and performing simulations. "Run Sketchup" (Details in 4.3.3) and "Run EnergyPlus" (Details in 4.5.1) are available. "Configure" is to setting software path (Details in 2.2.4).

3.1.2.2 Toolbar

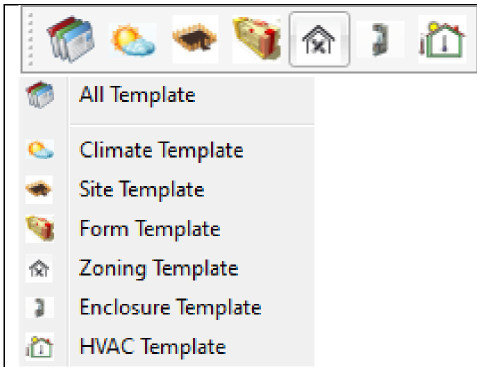
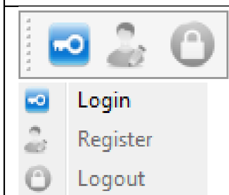
The toolbar provides convenient shortcuts to some of the menu items. A toolbar can be opened or closed by the menu option "View". All functions of the toolbar can be viewed by hover above, Table 3-3 lists all icons function.

Table 3-3: List functions of each icon (from left to right)

<table>
<tr><td>
</td><td>File menu toolbar:
Creating a new project, saving and retrieving created project files. More details in 4.1.

Importing and exporting external geometries. More details in 4.3.2.
Importing and exporting libraries/templates. More details in 5.1 and 5.2.</td></tr>
<tr><td>
</td><td>Simulation menu toolbar:
Selecting simulation engine, more details in 4.5.</td></tr>
<tr><td>
</td><td>Library menu toolbar
Selecting various libraries, which are required for parameter input

Note:
How to use libraries is introduced in 4.4.2.
Details of libraries are in 5.1</td></tr>
</table>

	Template menu: Selecting various templates, which are required for parameter input Note: How to use templates is introduced in 4.4.2. Details of templates are in 5.2
	PIP menu: Note: Accessing the built in Process Integration Platform (PIP). Details about PIP in 4.6.3.

4 Using VDS: Step-by-Step Procedures

This section presents how to use VDS step-by-step. The following flow chart gives an overview of VDS operation (Figure 4-1 VDS example steps).

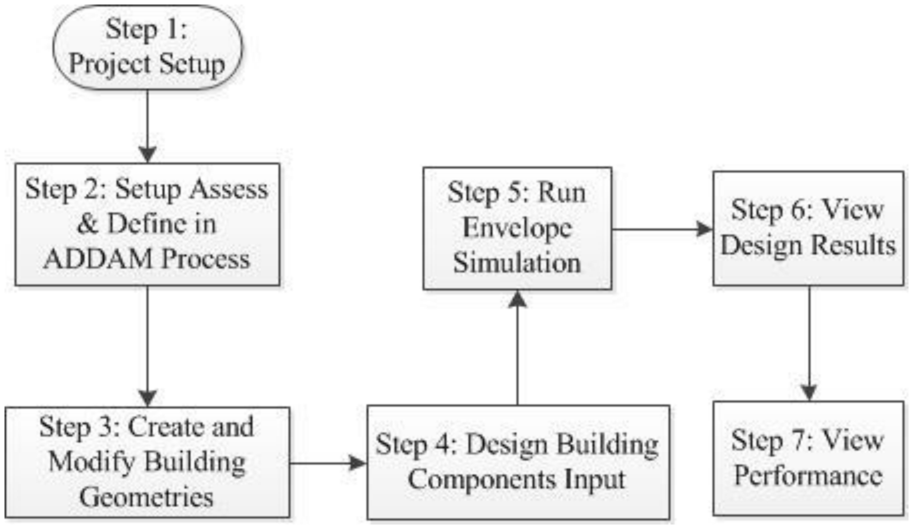


Figure 4-1 VDS example steps for envelop development

4.1 Step 1: Project Setup

If users already have a project file, it can be opened for further editing. Otherwise users can start with a new project.

4.1.1 Creating a New Project

A VDS project is initiated by creating a new project. To do so, click  ("New Project") or choose from File menu, "**File>>New Project**". A pop-out window will appear, as exampled below (Figure 4-2 Pop-up window of saving). You can click "save" current empty project then a new window will pop up (Figure 4-3 Create New Project) to enter project information or click "Ignore" without saving then create a new project.

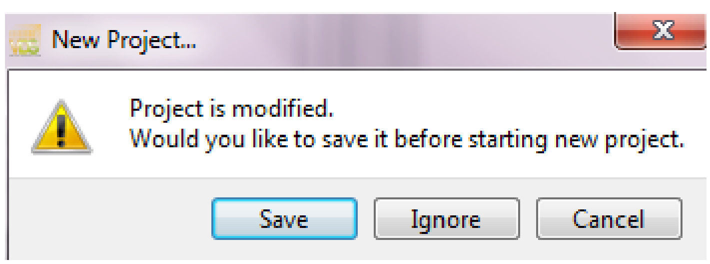


Figure 4-2 Pop-up window of saving

Note: "Ignore" means open a new project without saving, "Cancel" means quitting the dialog box/window.

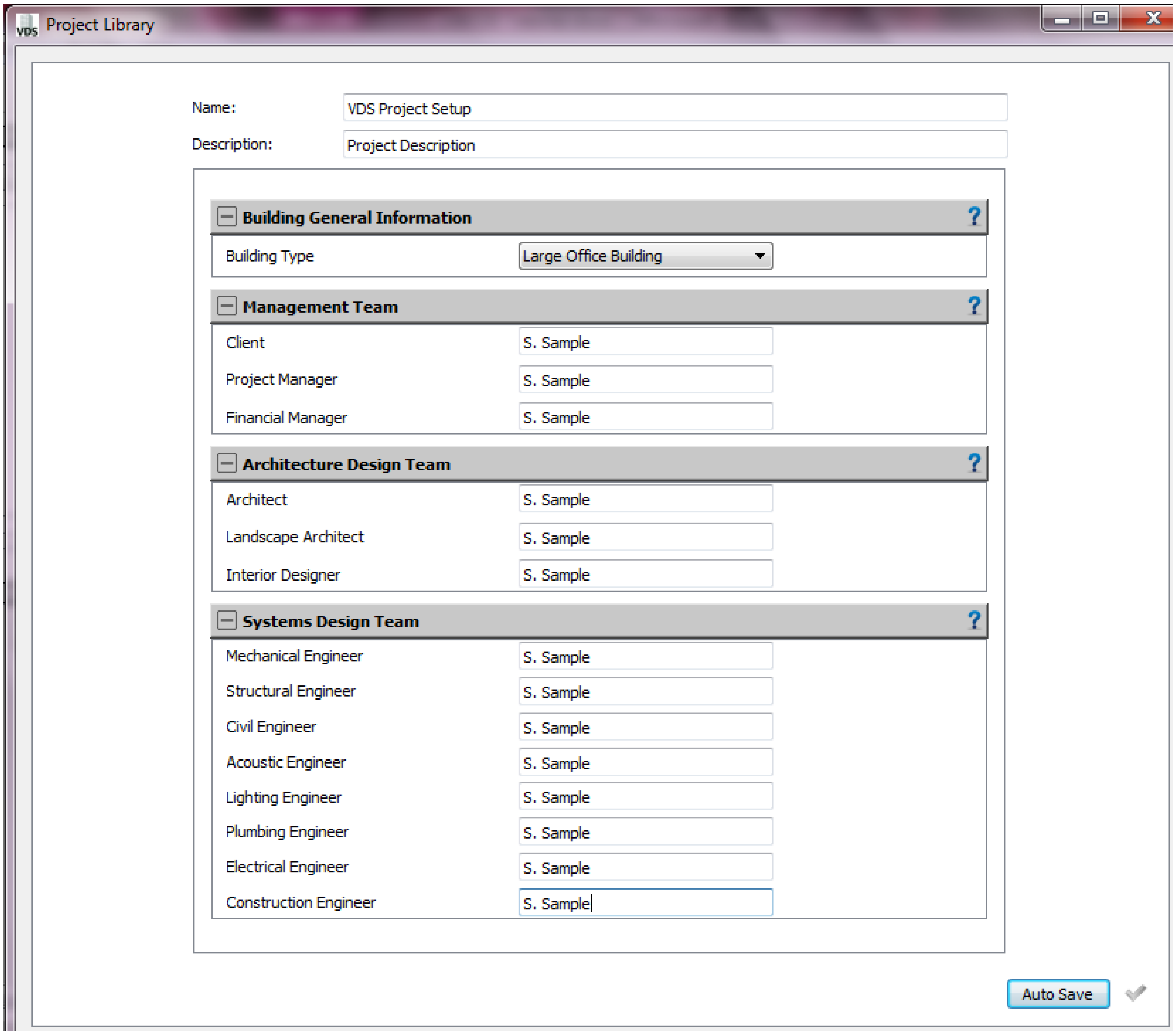
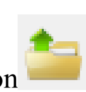


Figure 4-3 Create New Project

For "Name" and "Description", users can specify appropriate information. Select the "Building Type", using the drop-down list, only medium and large office building are available in the current version. Three base team categories based on developer's experience have been identified: (1) architecture, (2) systems design/engineering and (3) project management. In the current VDS, teams are fixed and cannot be modified. Several team members can be typed in each respective item; each needs to be separated by commas or semi-colons.

4.1.2 Open Project

Existing projects can be opened by clicking "Open Project" icon  or choose from "File>>Open Project". It will bring up a pop-up window (Figure 4-4 Pop-up window of open project). Users can save the current project, or click "Ignore" without saving.

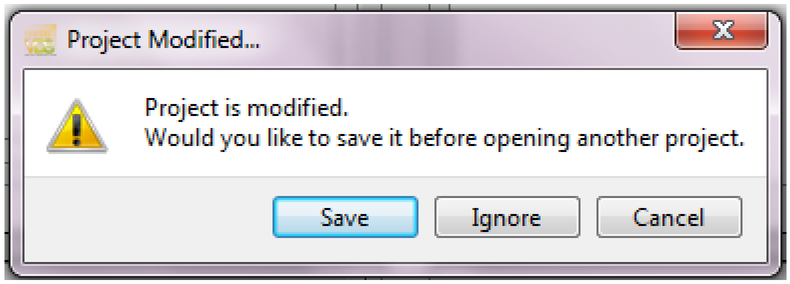
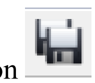


Figure 4-4 Pop-up window of open project

Note: “Ignore” means open a new project without saving, “Cancel” means quitting the dialog box/window.

4.1.3 Save Project

A Project can be saved using “Save” icon  or “Save as” icon  The project will be saved as .xml file (Figure 4-5 Save project).
Note: “Save as” means copy current project and save as another format, but for VDS, project has only .xml format.

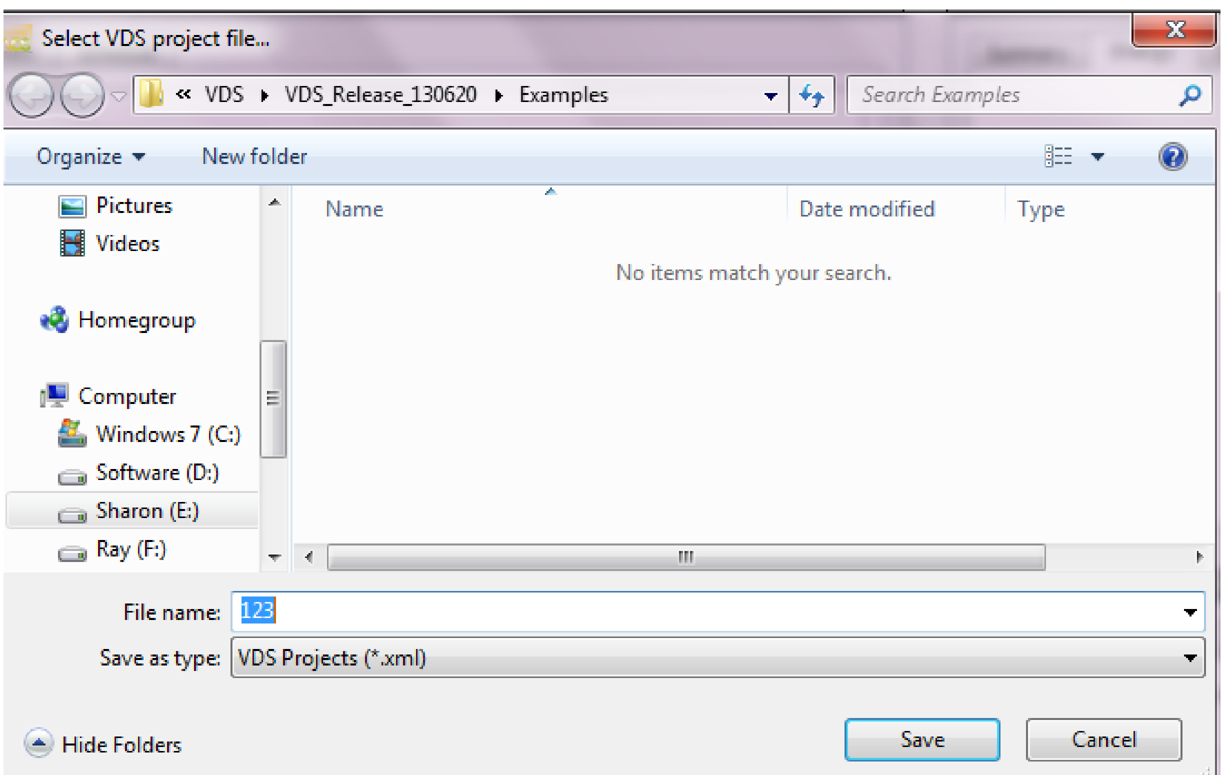


Figure 4-5 Save project

4.2 Step 2: Set Design Process

A 3-D matrix named "Magic Cube" (mentioned in "1 Introduction"), is used as the fundamental structure of VDS to facilitate actors, stages and factors. Figure 1-1 shows a knowledge-based template that represents the complex whole building design process according to actors, stages, and factors. Each cell in the 3-D Cube represents a scheduled task that intends to accomplish certain design work. Related design parameters are assigned to each task to filter the overwhelming design input during the design process. As shown in Figure 4-6, tasks in current version are arranged following "stage", and "Factor". Then, tasks can be hierarchically decomposed from "Root tasks" down to "Tasks/Process Activities".

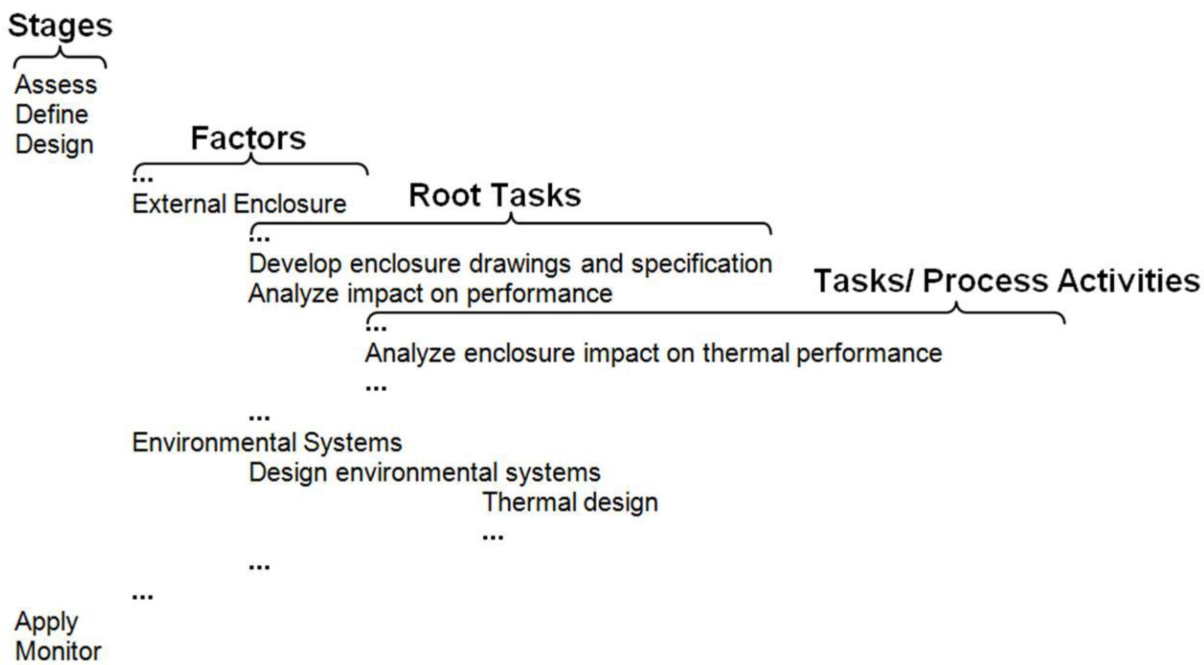


Figure 4-6 Task decomposition

Projects are initially populated with tasks based on an experience-based medium office building design process (default) template (it's fixed and just for demonstration). More design process templates for different project types may be added in future versions of VDS.

This section shows the framework of the design process, because current VDS doesn't support simulations in all stages and root tasks. As shown in 3.1.1.1, there are three tabs in "Design Process". But only "Navigation View" is available now. A navigation tree in "Navigation View" (Figure 4-7) is included to show the hierarchical structure of the design process.

The following descriptions illustrate how to navigate through the design process by clicking tasks under certain stages and factors, and how to use the task/process activity definition window to customize the process based on users' project needs. (Including I-P-O for a task, and interdependencies):

1) Stage
   In the "Navigation View" tab page (Figure 4-7), there are five stages: Assess Stage, Define Stage, Design Stage, Apply Stage and Monitor Stage.

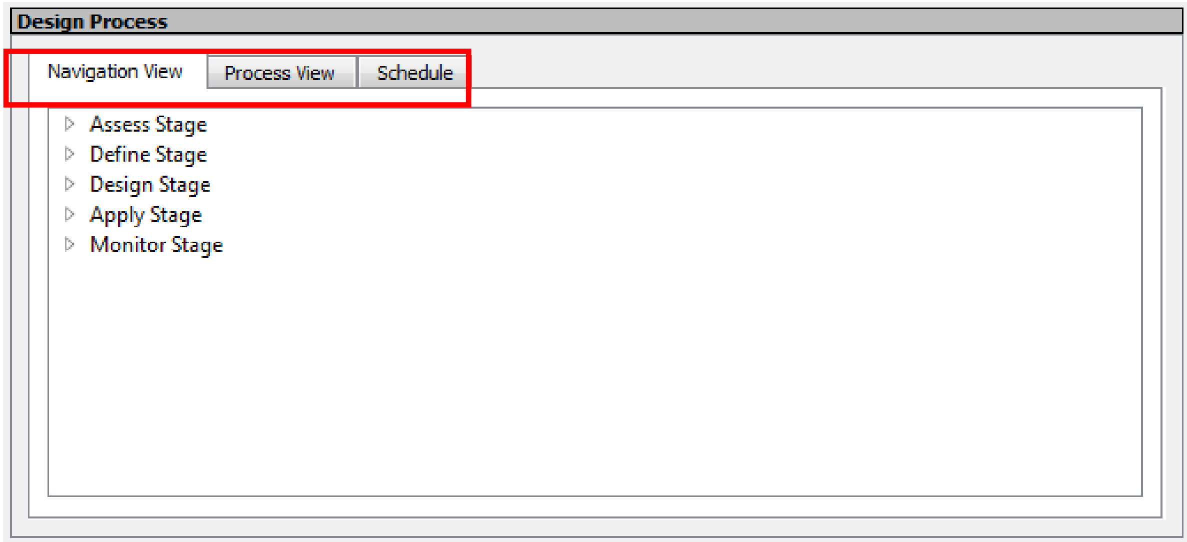


Figure 4-7 Navigation Tab

2) Factors

Each stage includes 9-factors (Figure 4-8): (1) Site and Climate, (2)Form and Massing, (3) Internal Configuration, (4) External Enclosure, (5) Environmental Systems, (6) Energy Systems, (7) Water Systems, (8) Material Use and Embodied Energy, and (9) System Interdependencies.

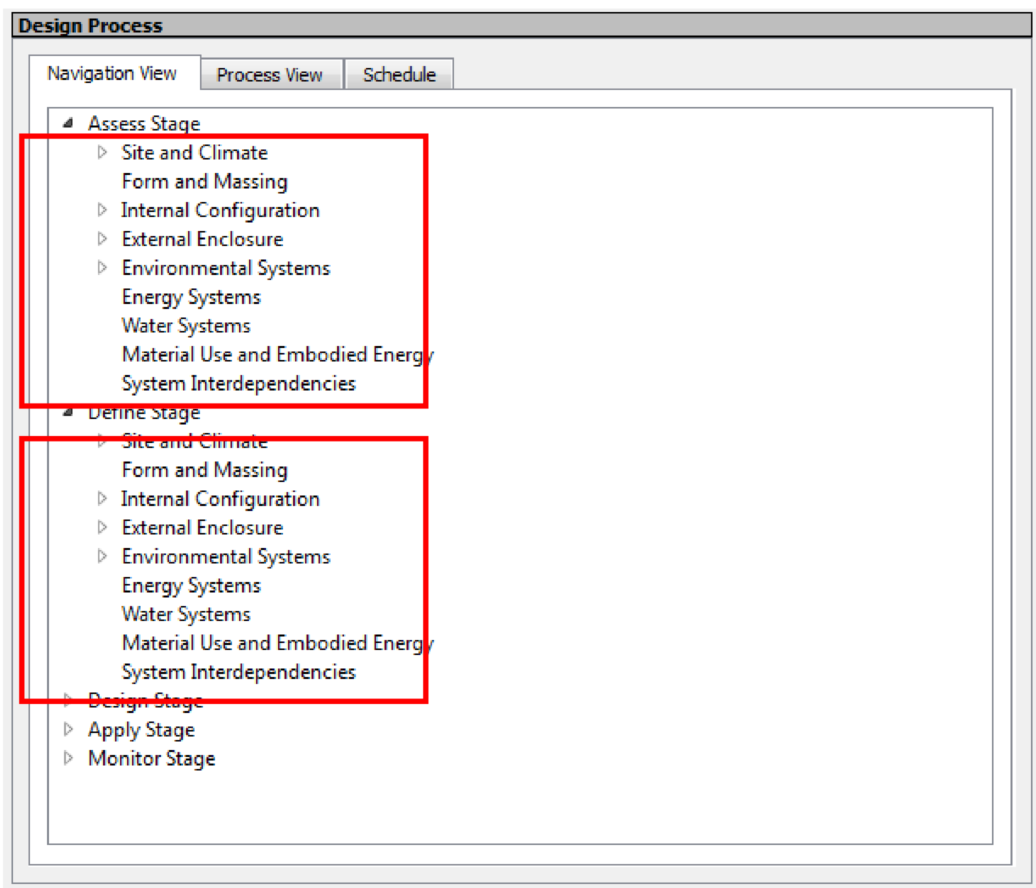


Figure 4-8 Factors in each stage

3) Root tasks/Task definition
Under each factor are root tasks/tasks. They are aggregated information from lower level - tasks/process activities. In
Figure 4-9 Root Tasks/Tasks Overview shows root tasks/tasks for the "External Enclosure" in "Design Stage".

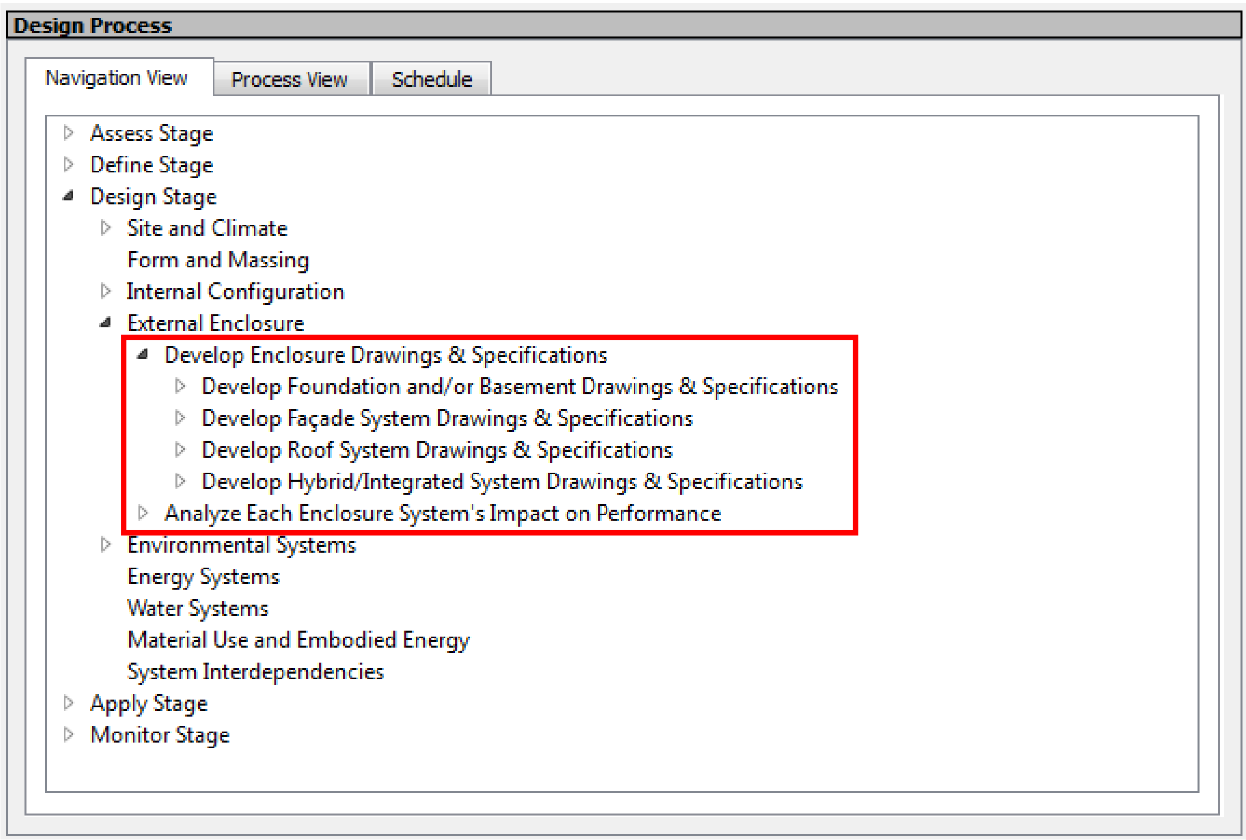


Figure 4-9 Root Tasks/Tasks Overview

Definition: Figure 4-10 Root task/Task definition pop-out window (Right click "Develop Facade System Drawings & Specifications" then choose "Edit") can be used to define the root task/task in terms of name, description, and viewing the aggregated input, output, actors defined in lower level (children) tasks/process activities.

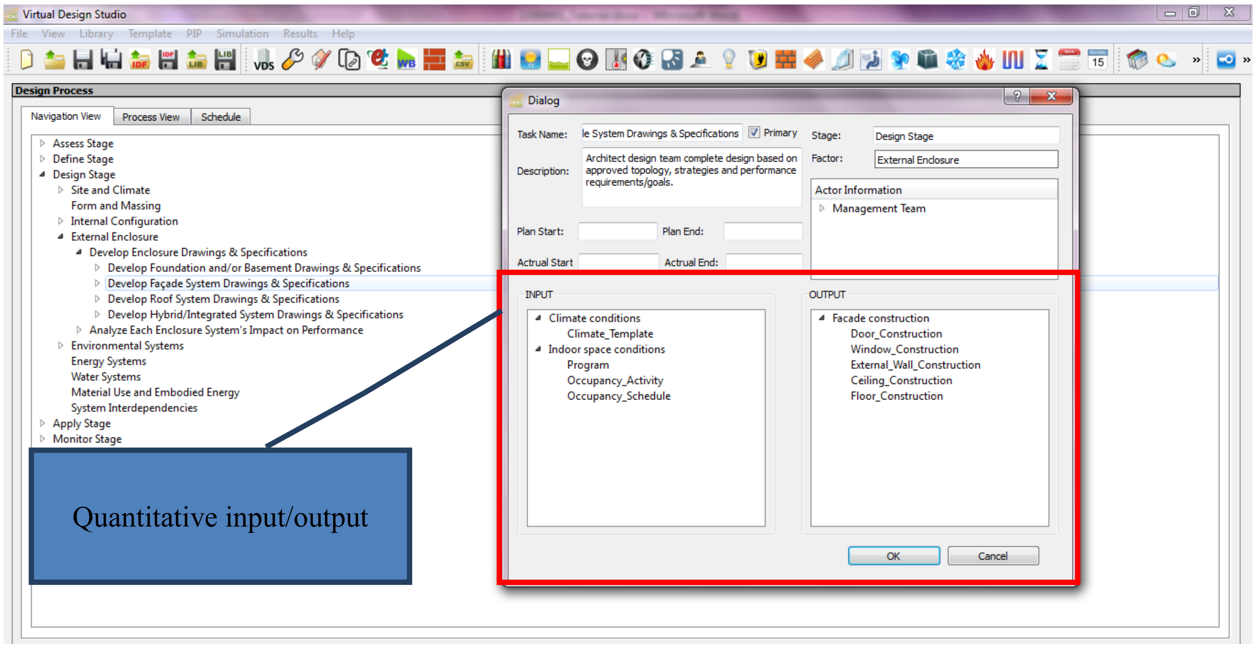


Figure 4-10 Root task/Task definition pop-out window

4) Process Activity Definition and Interdependence
Top level "Root Task" can be decomposed into unlimited lower level "Task" based on user needs. The lowest level is "Process Activity" as shown in Figure 4-11.

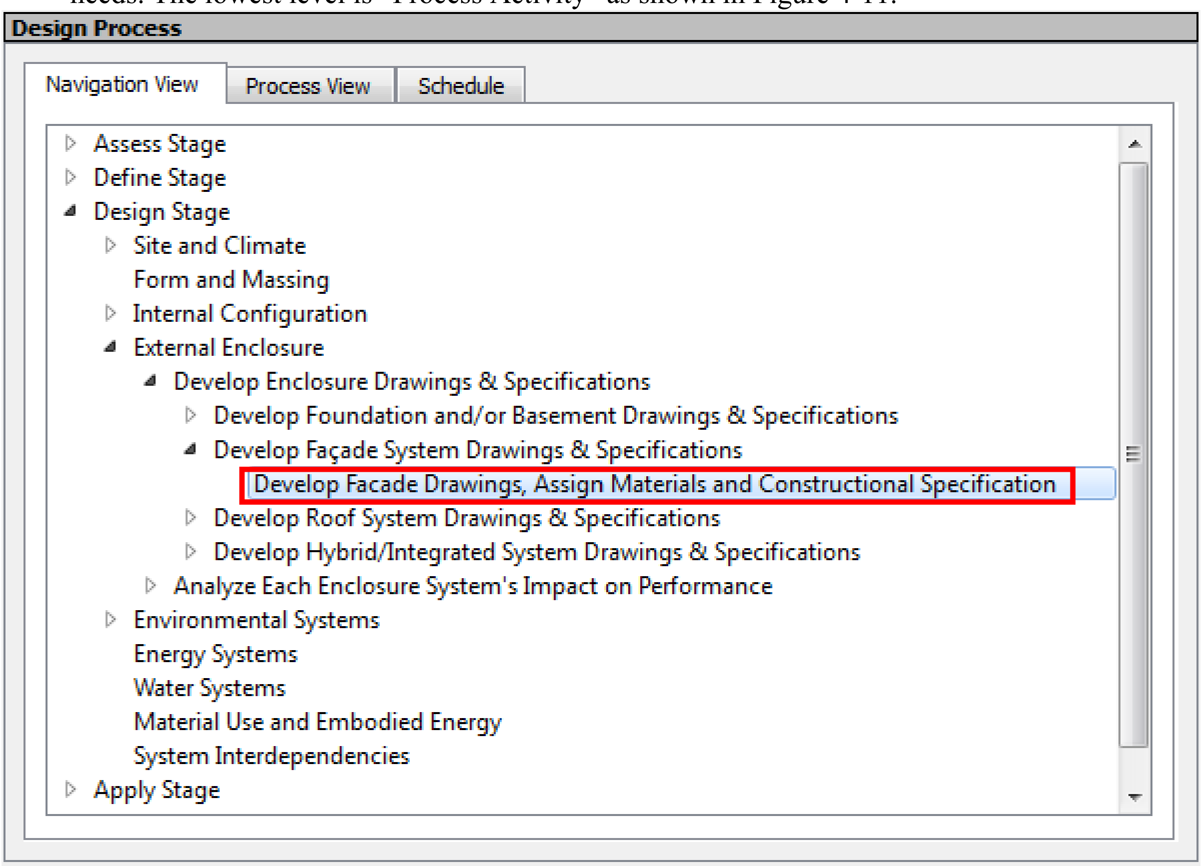


Figure 4-11 Process Activity

Definition: Right-click "Develop Facade Drawings, Assign Materials and Constructional Specification," then click "Edit" to define the input, output of a "Process Activity" and interdependencies among "Process Activities". It contains a process activity's basic information such as: name, description, stage, actor, schedule and input, output information listed on "Quantitative", "Qualitative" and "References" tabs, respectively.

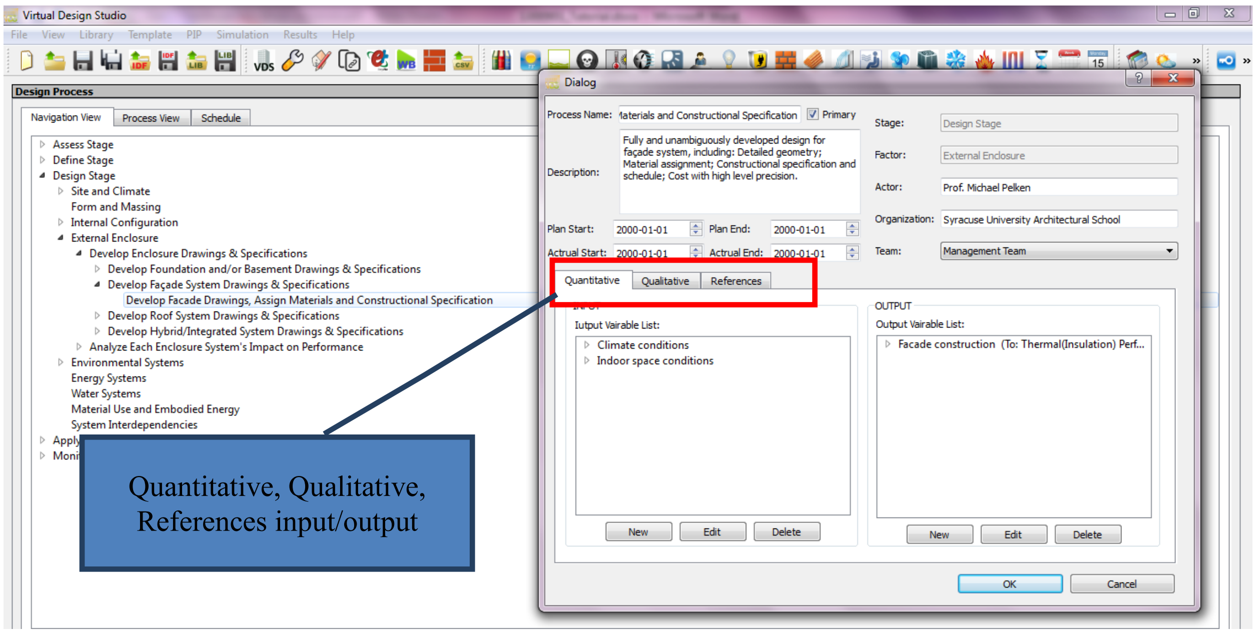


Figure 4-12 Process Activity definition pop-out window

Interdependency between Process Activities:
The interdependencies between different process activities can be found in GUI setting. The main purpose is to support the process diagram generation. For example, the same item added as a process activity's output will be shown as an input in its respective process activity, demonstrating the nature of its interdependency.

- Select "Facade Construction (To Thermal (Insulation) Performance)" then click "Edit" to open the dialog box in order to customize the output for this task, as seen in Figure 4-13. In this example, click "Enclosure aesthetic influence memo" in the left list, then click "Add" in the middle of two lists.
- In Figure 4-13, the "Connection to task," showing current process activities, has interdependence to other task/process activities. In this example, "Develop Facade Drawings, Assign Materials and Constructional Specification" has interdependence with "Thermal (Insulation) Performance", which means the output of "Develop Facade…" is the input of "Thermal (Insulation) Performance". Then click "OK" to confirm the change.

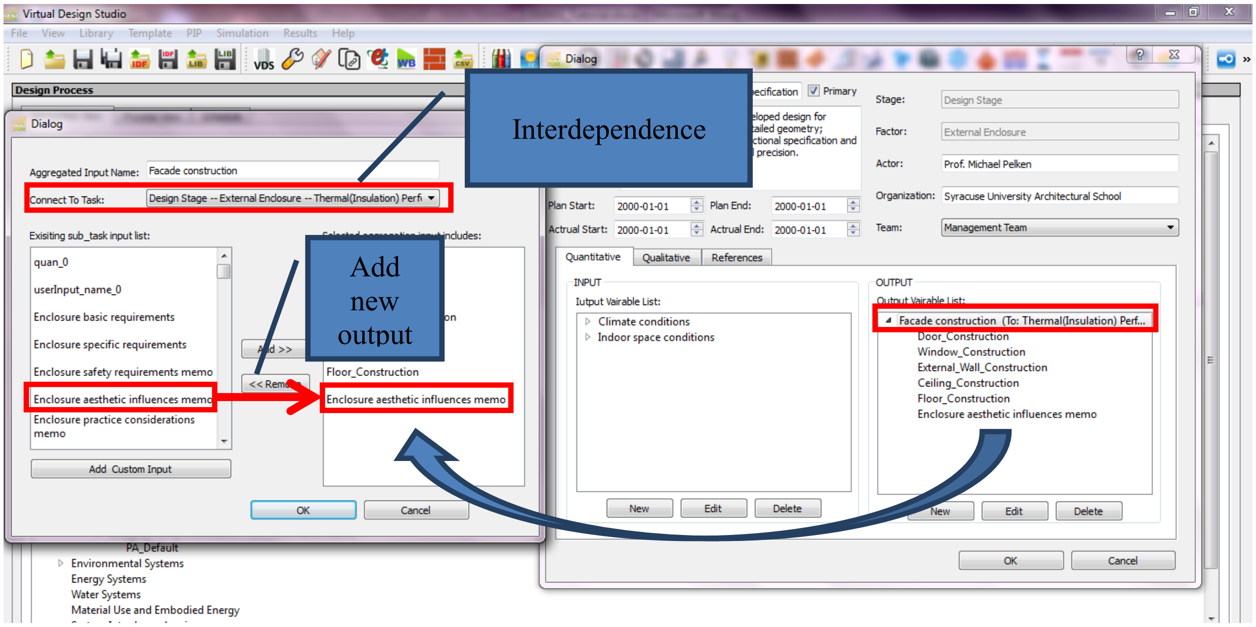


Figure 4-13 Add items in Output

- In order to verify the interdependence, users can open “Thermal (Insulation) Performance” dialog (right-click “Thermal (Insulation) Performance” then select edit). Below, Figure 4-14 shows “Facade Construction” in the input list, and contains all the items in output of “Develop Facade Drawings, Assign Materials and Constructional Specification” including the option to add a new item.

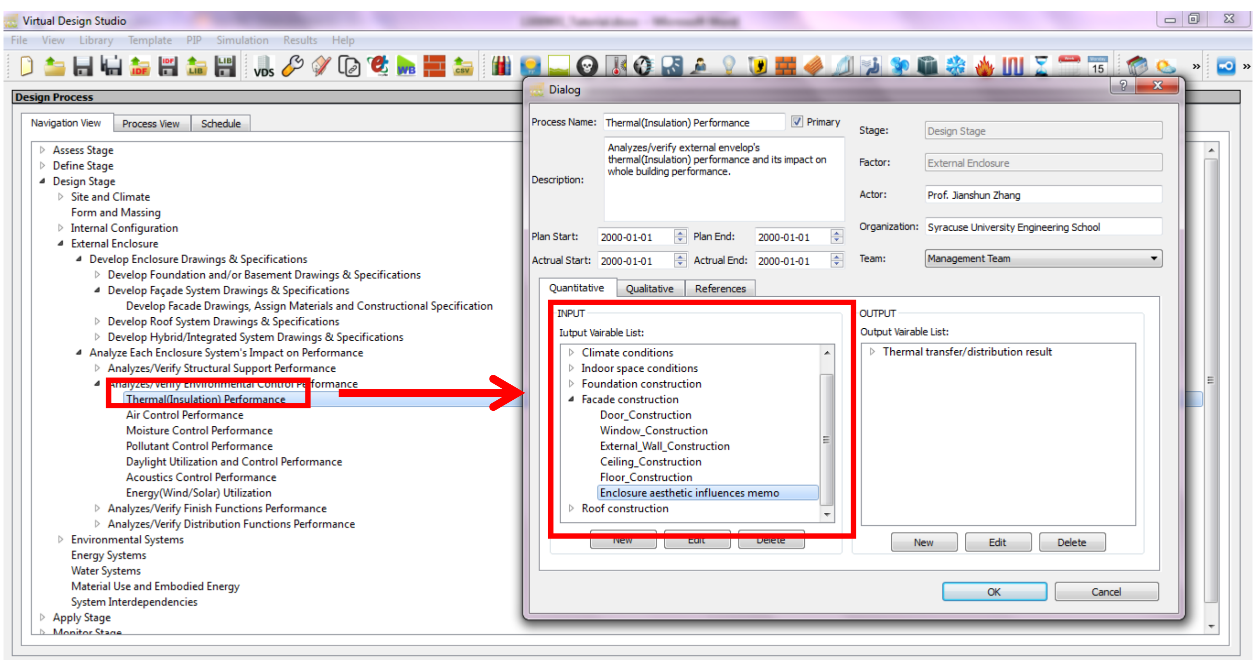


Figure 4-14 Interdependence between two tasks/process activities

VDS integrates project and task management features (VDS team manager) and dependency features in PIP’s (Process Integration Platform) document repository. Details about PIP locate in 4.6.3.

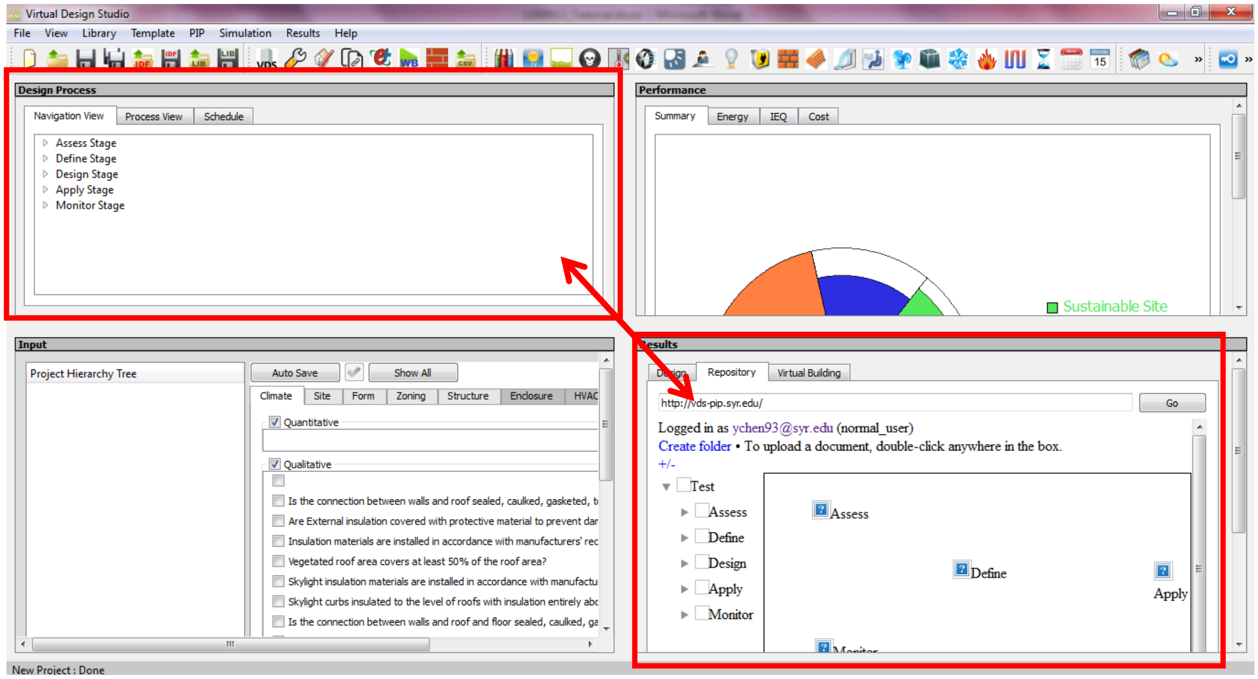


Figure 4-15 Design process relates to PIP

Users can do couple performance simulations for the same building as well. For example, in Figure 4-16, users can change types of external wall construction from library and then run simulation individually. Different performance will be displayed for comparison.

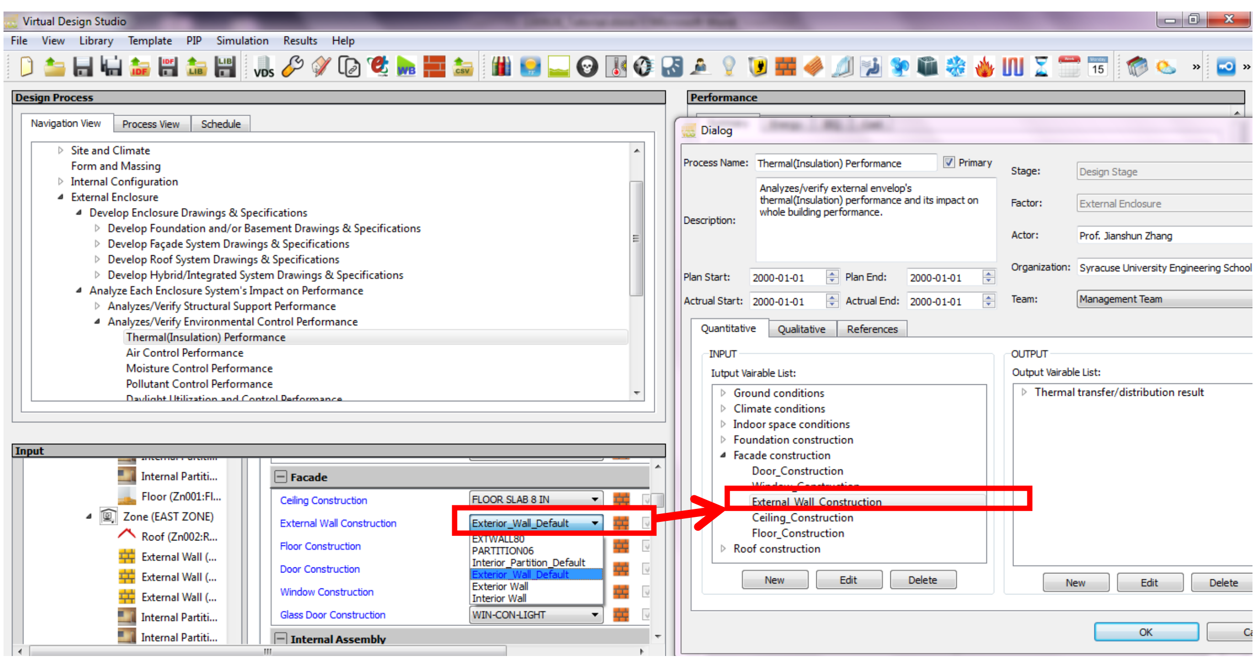


Figure 4-16 Change External Construction for different model performance

In future VDS, all of quantitative, qualitative and reference input value will be reflected in the Input Quadrant. The output in each task/process will be computed iteratively and the results will be sent for the next task/process activity.

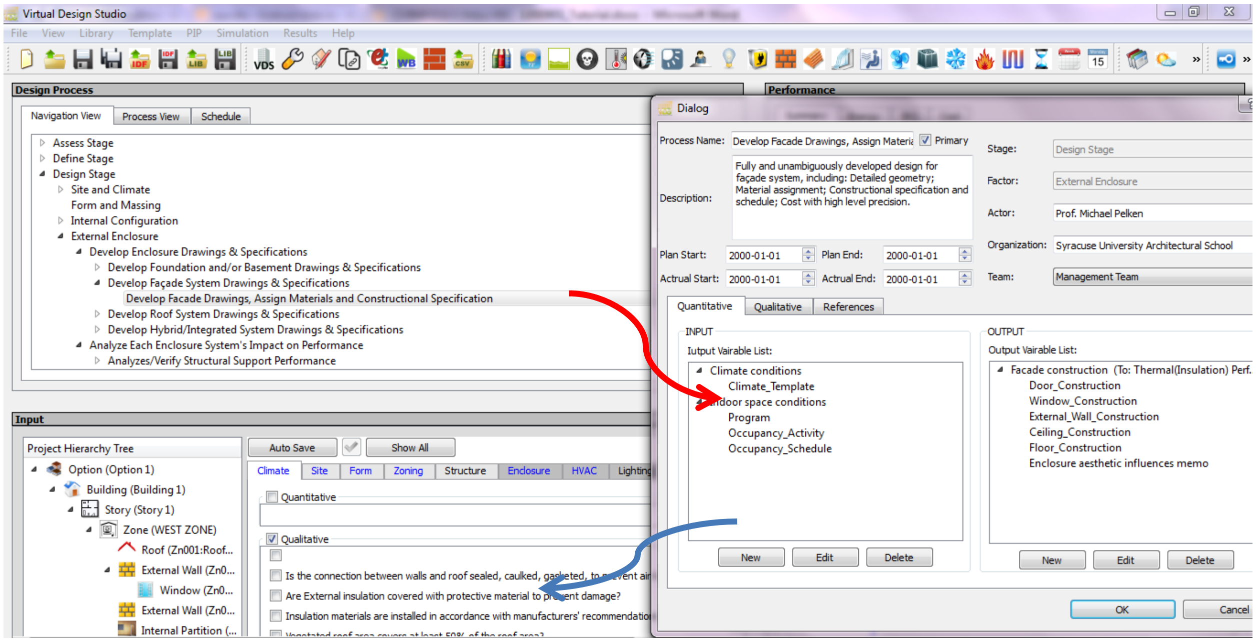


Figure 4-17 Design Process function in VDS

As mentioned before, “Process View” and “Schedule” are not available currently.

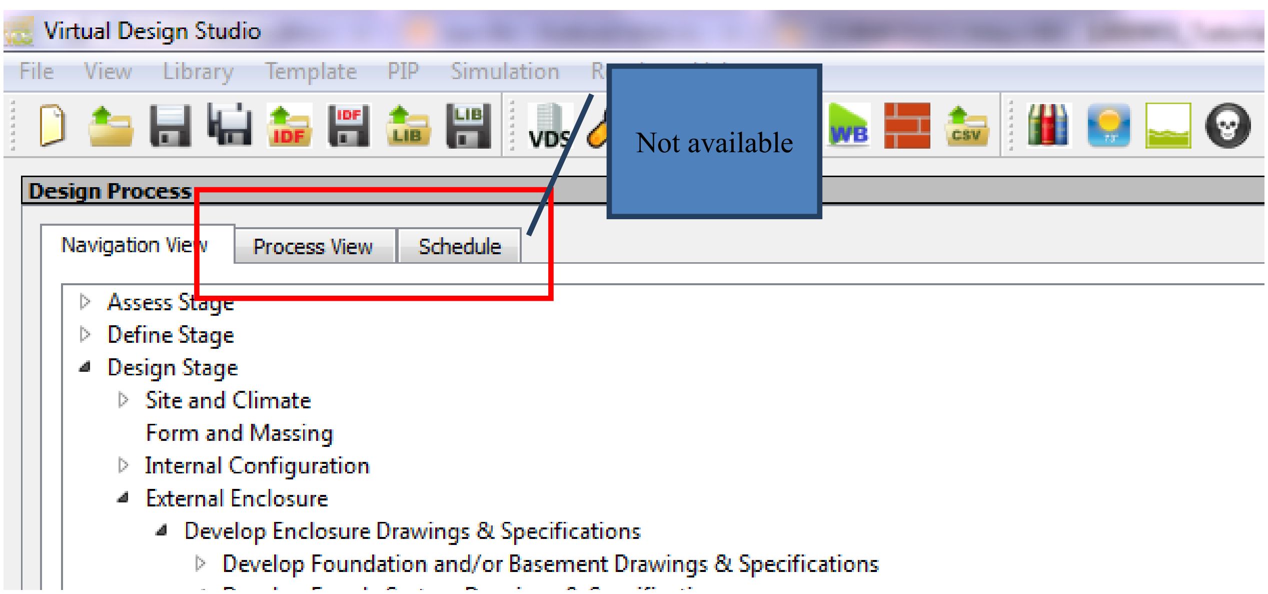


Figure 4-18 Process View & Schedule NOT AVAILABLE

4.3 Step 3: Create and Modify Building Geometries

Before creating building geometry, users should gather information for climate and site as performance frame work. For the simulation process, users need to provide information about the proposed building geometry or particular components such as zoning that are intended to be evaluated.

In VDS itself geometries cannot be created/modified. Users can create it in SketchUp with the OpenStudio plugin (as mentioned in 2.1.2.1), and then import the model to VDS. SketchUp 8 can convert

2D DXF and 3D CAD models for use in EnergyPlus. Details can be found in SketchUp "Help > OpenStudio User Guide>Tutorials".

4.3.1 Create Geometry

Here are steps to create geometry. A Detailed two-floor example (with 6-room zones) is given in Appendix A, which shows detailed steps to create building geometries and help users to build a valid model.

- When users open SketchUp with OpenStudio running, or any time a new IDF file is started, OpenStudio loads the NewTemplate.idf file located in the OpenStudio plugin directory. This file comes pre-populated with some basic EnergyPlus objects such as schedules, construction modes, and location (the default location is Chicago and can be amended as required).
- Building zones can be created using the New Zone Tool. Detail steps can be found in "Getting Started" in SketchUp OpenStudio Plugin tutorial. The help files are located in your local SketchUp plug-in directory under OpenStudio/doc/help.
- Surface matching can be used to identify interior and exterior surfaces of a building envelope. Detail steps can be found in "Matching Surface" in SketchUp OpenStudio Plugin tutorial.The help files located in your local SketchUp plug-in directory under OpenStudio/doc/help.
- After finishing the necessary editing in the building geometry and properties save it as .idf file.

4.3.2 Import Building Geometry

- Import IDF files (Figure 4-19). Choose "File->Import->Import from IDF" to select file.

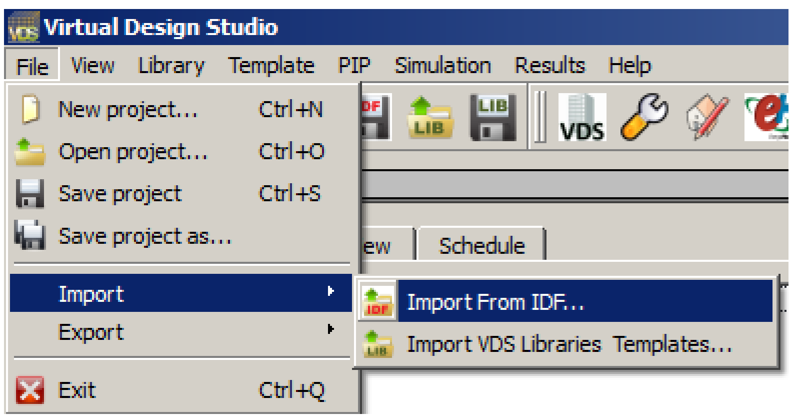


Figure 4-19 Import IDF from an existing model file

- Users can choose a completed geometry "3Zone_VAVwithReheat_V720.idf" in "Example" folder as an example.

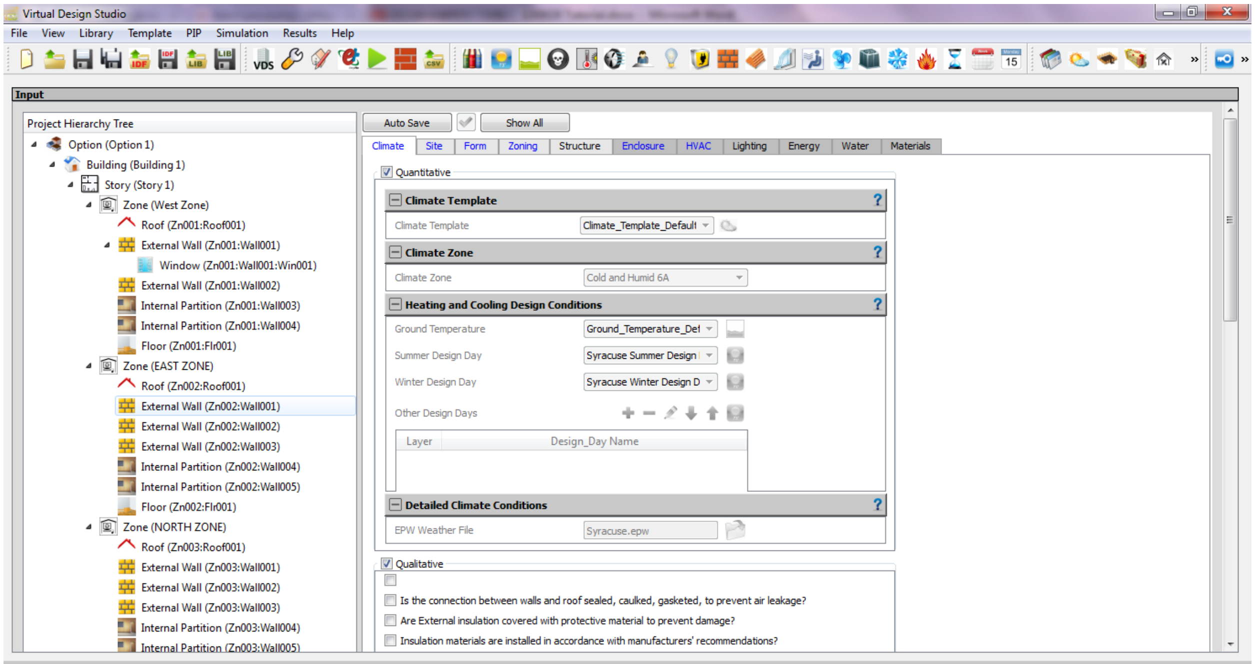


Figure 4-20 Select IDF from file

In the “Import IDF to a Building” dialog box (Figure 4-20), users can see two options: Import Simulation Settings and User Default Templates.

(1) The simulation settings are used by all the buildings. When you import an IDF file, it contains all those information (except the reference building setting). Users can choose to override the settings in the given IDF file (YES), or choose to keep the existing ones (NO). Simulation settings can be determined later in VDS’s menu “Simulation>Simulation Options”,

(2) Default Templates include various parameters (not including geometry) such as climate, zone conditions, constructions, and HVAC systems. Users are encouraged to import Default Templates to save simulation model development time. Imported Templates can be modified to fit specific requirements and it is also possible to import other templates in VDS. Detail operations will be illustrated in “4.4 Step 4”.

As 2-floors example in 4.3.1, after importing idf file, the building is shown in Quadrant 3: Results.

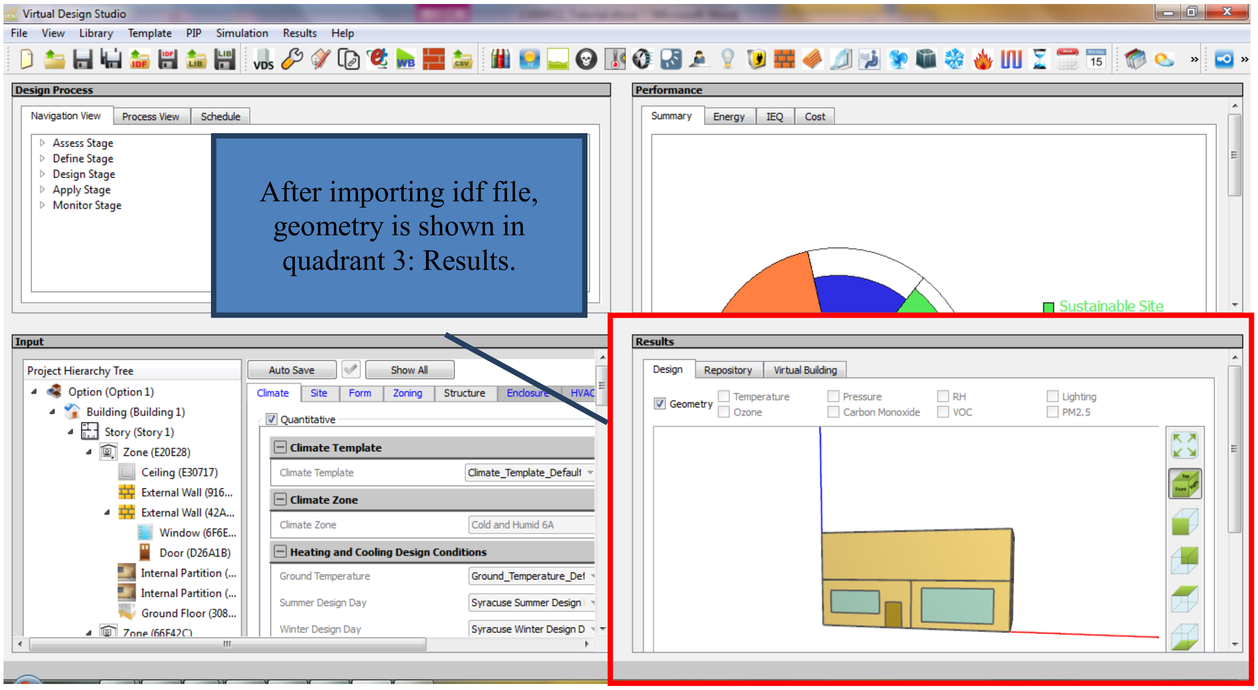


Figure 4-21 After Importing Geometry

4.3.3 Modify Geometry

If users intent to modify current geometry, click "Simulation>Run SketchUp" in the menu to activate SketchUp. Below are steps to edit geometry in SketchUp.

- Choose the building or design option that needs to be modified (Figure 4-22)

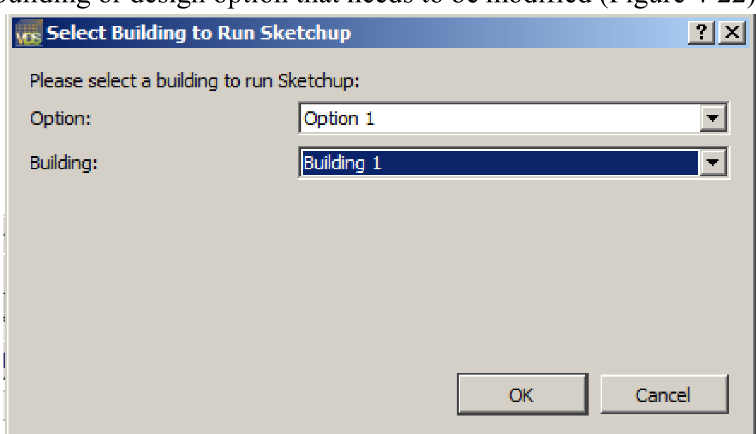


Figure 4-22 Choose building

- After modifying the geometry in SketchUp, save as .idf file and close SketchUp window (details in Appendix A).The new building file will be located in "Temp" folder. It would automatically pop up Figure 4-23 with new option and building names, which cannot be the same as before.

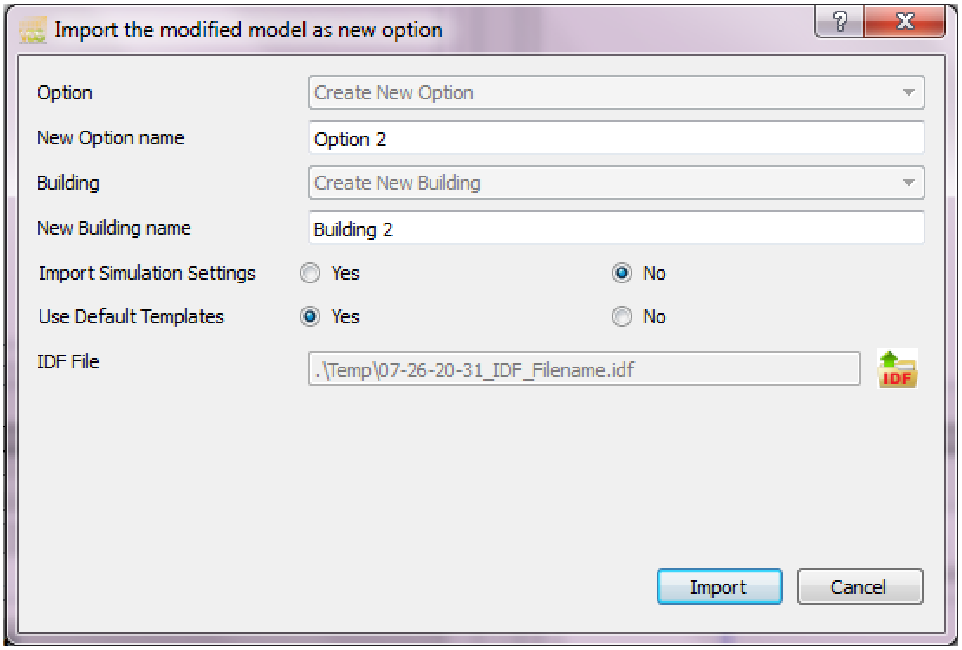


Figure 4-23 Re-import geometry

- After the modified geometry has been re-imported successfully, the two options: Option 1 and Options 2 will be available in the project tree view as shown below (Figure 4-24). The two options are used to compare results in different geometry design in the future, but comparison is currently not available. Users can run simulation for 2 options individually. The results can be read from the "Temp" folder.

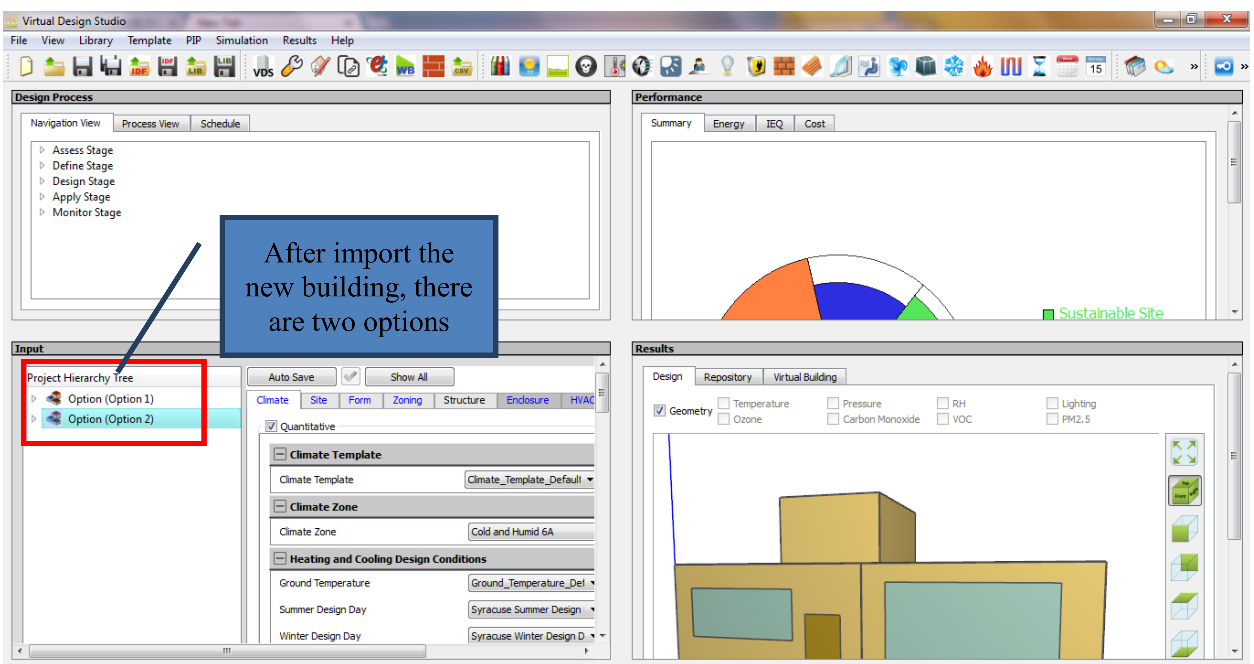


Figure 4-24 After Re-import

4.4 Step 4: Design Input Parameters

After importing the building's geometry, respective input parameters such as climate, site, zoning, enclosure, HVAC parameters are required in VDS to simulate the model. More details about how to input and model are in 4.4.2. After properties are assigned, users can update a new model, but all data of last model will be saved for the new one. Figure 4-25 shows the quadrant for input parameters as mentioned in 3.1.1.2.

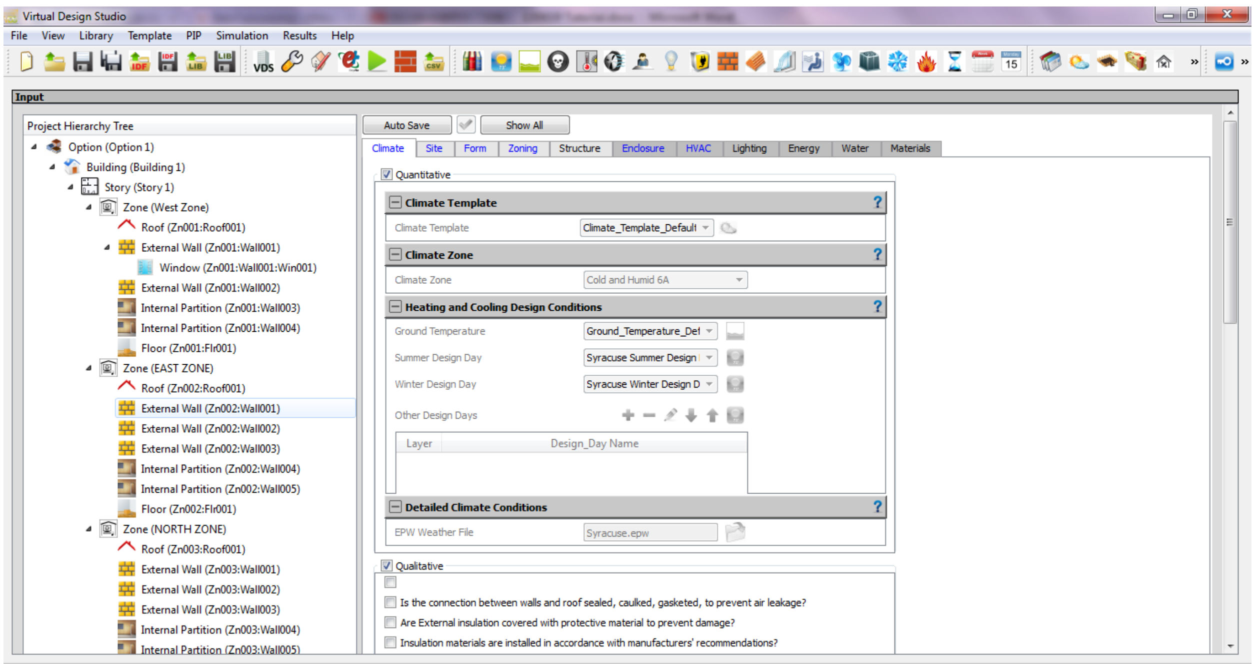


Figure 4-25 Enlarged and different views for orientation

4.4.1 Input level

There are several input levels represented in the tree view. The top level is called "parent level", while the corresponding levels below the parent level are called "children level". For example, "Option" is "Building" parent level and "Building" is "Option" children level. The relationship of levels is shown in Figure 4-26.

On the right of parameter input box (Figure 4-35), there are two options: "Applied" and "Inherited". "Applied" means the parent level parameter would be applied to all the children level. "Inherited" means children level would inherit parent level parameters. Only "Inherited" is available in the current version.

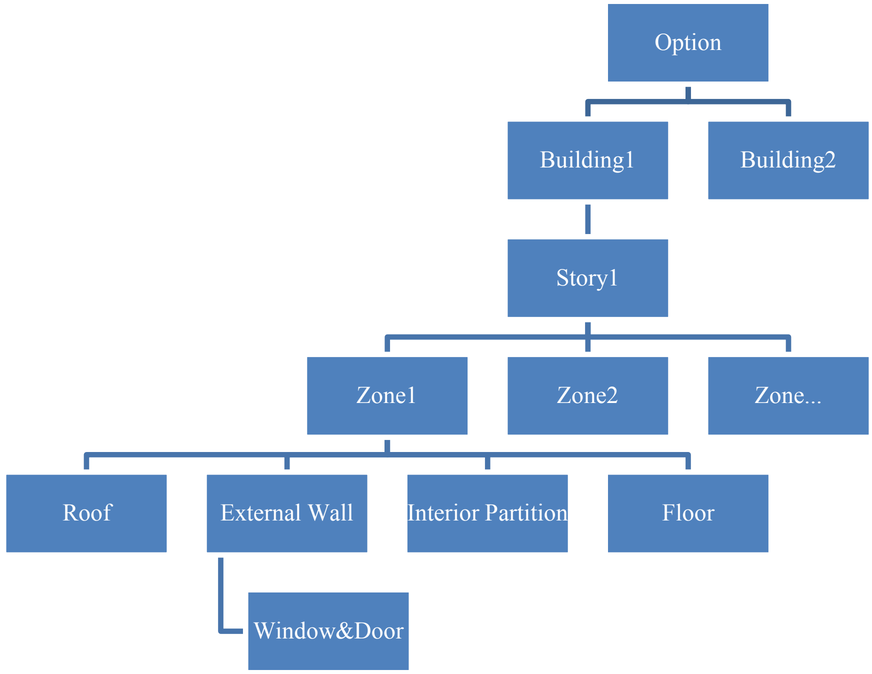


Figure 4-26 Examples of “Level” in building

Different parameters can be set in different levels. For example, the climate parameter is only applicable for the “Option” the top level (as shown in Figure 4-26, “Option” level located on the top). “Climate” parameters in “Option” level can be representative for all buildings located in the same city. Thus, there is no need to set climate parameters in each building.
Table 4-1 illustrates parameter setting availability for different levels.

Table 4-1 Input availability at different level of building structure

	Climate	Site	Form	Zoning	Enclosure	HVAC
Option	○	○	●	○	○	○
Building	●	○	●	○	○	○
Story	●	●	●	○	○	○
Zone	●	●	●	○	○	○
Wall/Roof…	●	●	●	●	○	●

Key: ○ - available; ● - disabled for corresponding planning or design level.

4.4.2 Parameter Settings

In the current version of VDS, none of the included parameter settings have direct relationship with the defined working stages but all parameters must be assigned to simulation model. They are used as a consistent set of criteria throughout the process. Table 4-2 shows an overview of parameter requirements for Climate, Site, Zoning, Enclosure and HVAC systems (currently they are implemented).

Table 4-2 Summary of VDS Input Parameters for Each Design Factors

Climate	Site/Building	Form/Massing	Zoning	Enclosure	HVAC
Template	**Template**	**Template**	**Template**	**Template**	**Template**
Climate zone • Climate Zone • Subzone*	**Location** • Latitude • Longitude • Elevation • Time zone • Shape and size*	**Shape** • Volume to surface ratio# • Building height# • Story height# • Shape function*	**IEQ Requirements** • Thermal comfort • Outdoor Ventilation rate (Pollutant and odor limits) • Lighting quality* • Acoustic quality*	• Envelope Type	• **System Type**
Heating/cooling design conditions • Ground temperature • Winter design day • Summer design day • Other Design Days	**Building position** • Angle from north X (E-W direction)* • Y (N-S direction)* • Z (Elevation)*	**Floor space** • Number of floors# • Number of zones# • Total floor area#	**Occupancy** • Number of people • Schedule • Activity • H.A.M.P generation rates	**Roof** • Roof • Skylight	**Space conditioning** • Supply air • Supply water * • Reheat coil • Room air distribution* • Standalone unit* • Passive and hybrid systems (not included)
Detailed climate • EWP weather file • Temperature • RH • Wind speed • Wind direction • Air pressure • Solar radiation • Precipitation	**Landscape & surrounding environment** • Terrain type • Ground reflectance • Thermal radiation* • Shadowing* • Wind function* • Pollution function* • Noise function*	**External Surface** • Window fraction# • Wall area# • Window area # • Shading effect*	**Lighting** • Number of lights • Schedule • Light type & power • H.A.M.P generation rates	**Façade** • Ceiling/floor • Exterior walls • Exterior windows • Exterior doors •	**Air handling system** • Air supply system • Conditioning capacity* • System and components* • Control* • Natural ventilation systems (not included)
Atmosphere pollution • Ozone • Carbon monoxide • VOC • PM2.5			**Equipment (or process)** • Number of equipment • Schedule • Equipment type & power • H.A.M.P generation rates	• **Internal Configuration** • Interior partitions • Interior windows • Interior doors	**Water supply system** • Hot water supply system • Chilled water supply system • System and components* • Control*
			Pollutant Source and Sink • Ozone • Carbon monoxide • VOC • PM2.5	**Foundation/ Basement** • Ground floor • Below-Grade wall	

Conditioning: heating, cooling, humidification and dehumidification;
H.A.M.P: heat, air, moisture and pollutants;
Lib: selectable from library, details in chapter 5
UD: user definable.
*: place holder for further implementation
#: calculated from geometry information

In the current version of VDS, only "Quantitative" parameters are available. The examples below illustrate parameter settings in different levels.

1) “Climate” setting in “Option” level,
2) “Enclosure” setting in “Building” level,
3) “Zoning” setting in “Zone” level,
4) “HVAC” setting in “Building” level.

Example 1: Climate-Option level

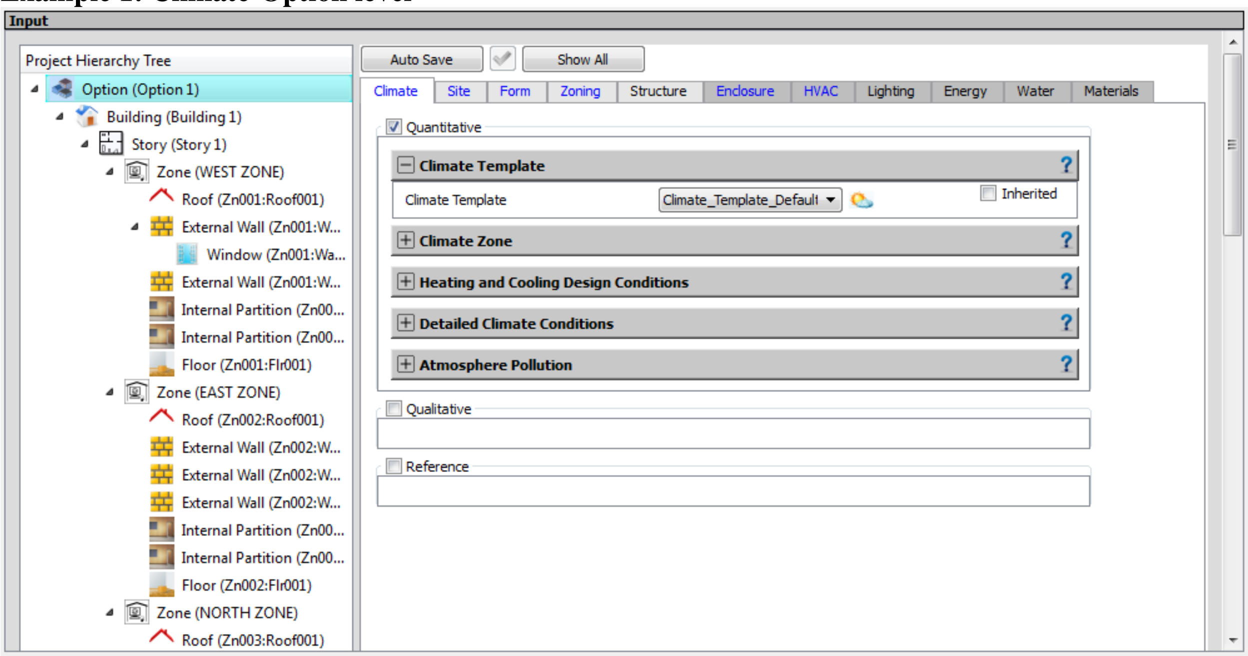


Figure 4-27 Climate Template

1) Click “+” on the left to expand list. In “Climate Template” (Figure 4-27 Climate Template), click (Climate_Template Library), then import a climate template. After that, all parameters (“Climate Zone”, “Heating and Cooling Design Conditions”, “Detailed Climate Conditions”, “Atmosphere Pollution”) in climate will be set and would be used as default. More details about template can be found in 5.2.

   Note: On the right of (Climate_Template Library), there is a check box “Inherited”, because “Option” is the top level, it would inherit void value as default.
2) If users set “Climate Template” as empty, “Climate Zone”, “Heating and Cooling Design Conditions”, “Detailed Climate Conditions” and “Atmosphere Pollution” information should be set one by one.

a) In “Climate Zone”, users can choose from a drop down list (Figure 4-28).

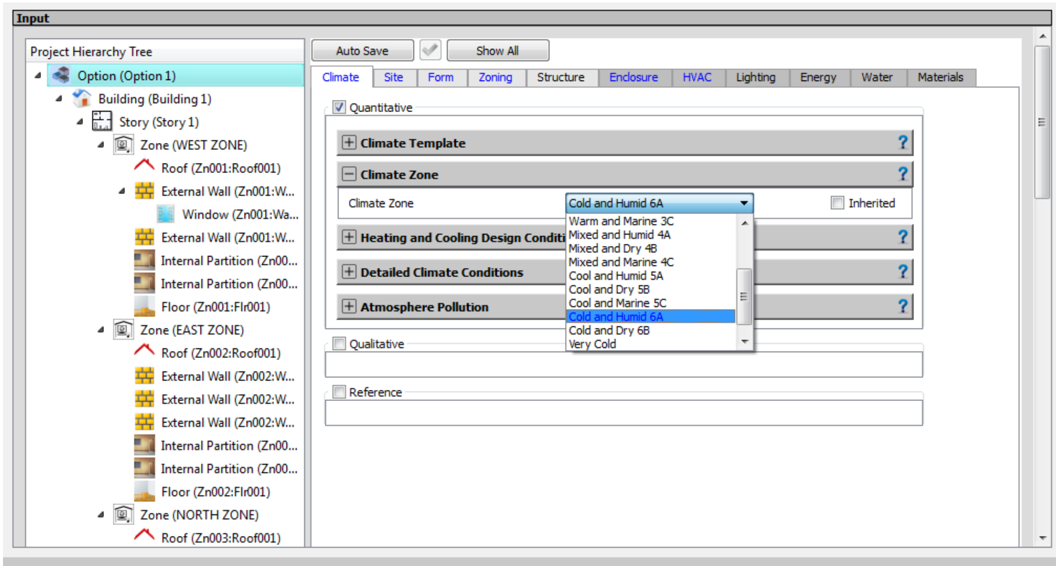


Figure 4-28 "Climate Zone" Setting

b) In "Heating and Cooling Design Conditions" (Figure 4-29), "Ground Temperature", "Summer Design Day", "Winter Design Day" can be selected via a drop down list or chosen from a corresponding library. More details about library are in section 4.1.

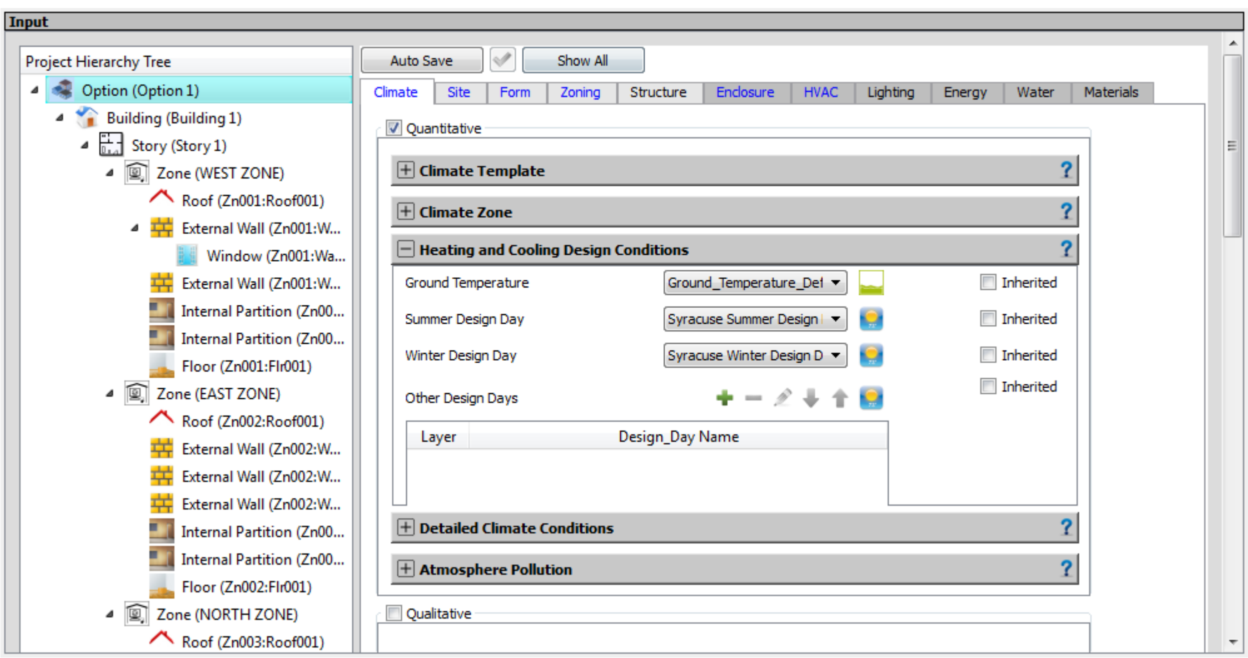


Figure 4-29 "Heating and Cooling Design Conditions" Setting

If "Other Design Days" has to be selected, follow these steps:

- Click to open "Design_Day Library" (Figure 4-30).

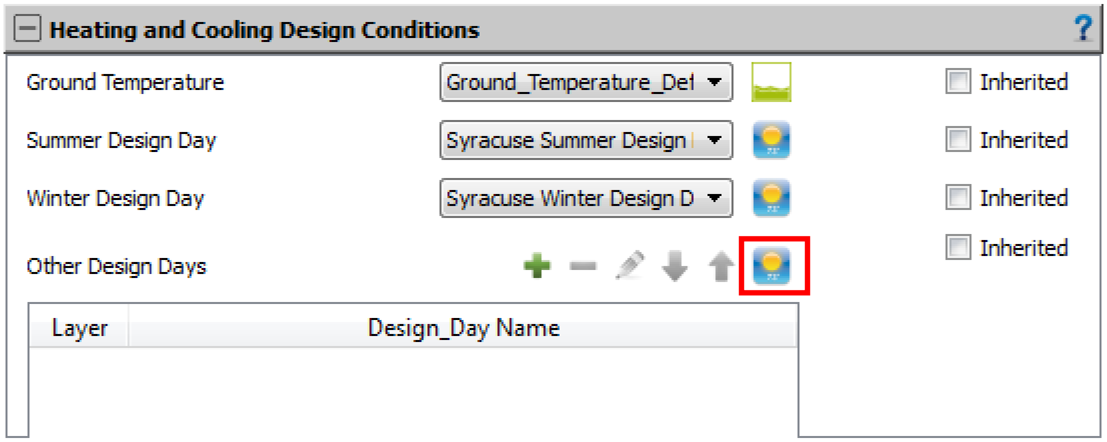


Figure 4-30 Choose “Design_Day Library” in “Other Design Days” setting

- Build a new library (Figure 4-31) in “Others” (Right click “Others” and select “New”).

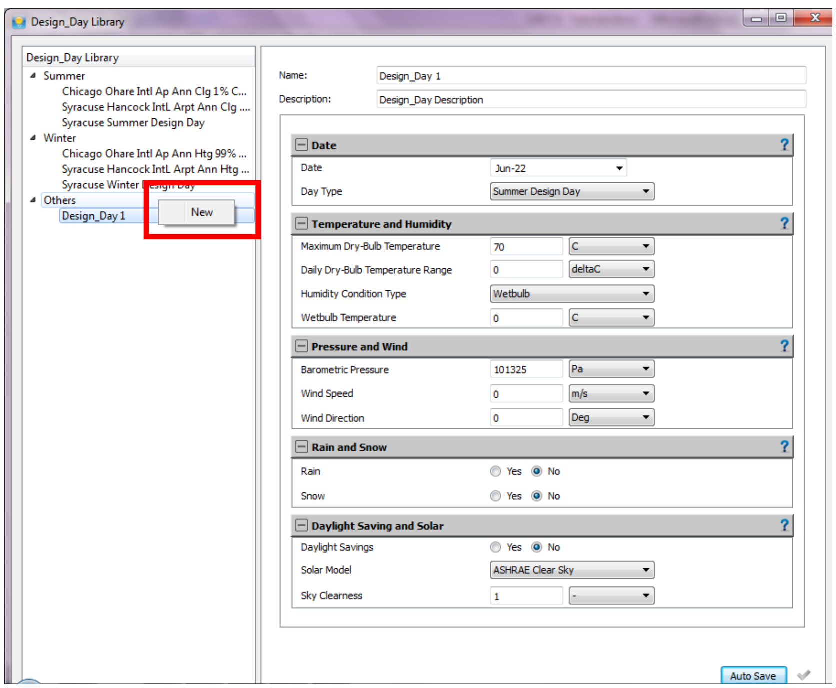


Figure 4-31 Setting “Design_Day Library” for “Other Design Days” setting

- Click “+” to add the new “Design_Day Library” in “Others” subject. The “Design_Day1” item can be deleted by clicking “-“, can be edited by clicking . If there are several items, clicking can reorder them.

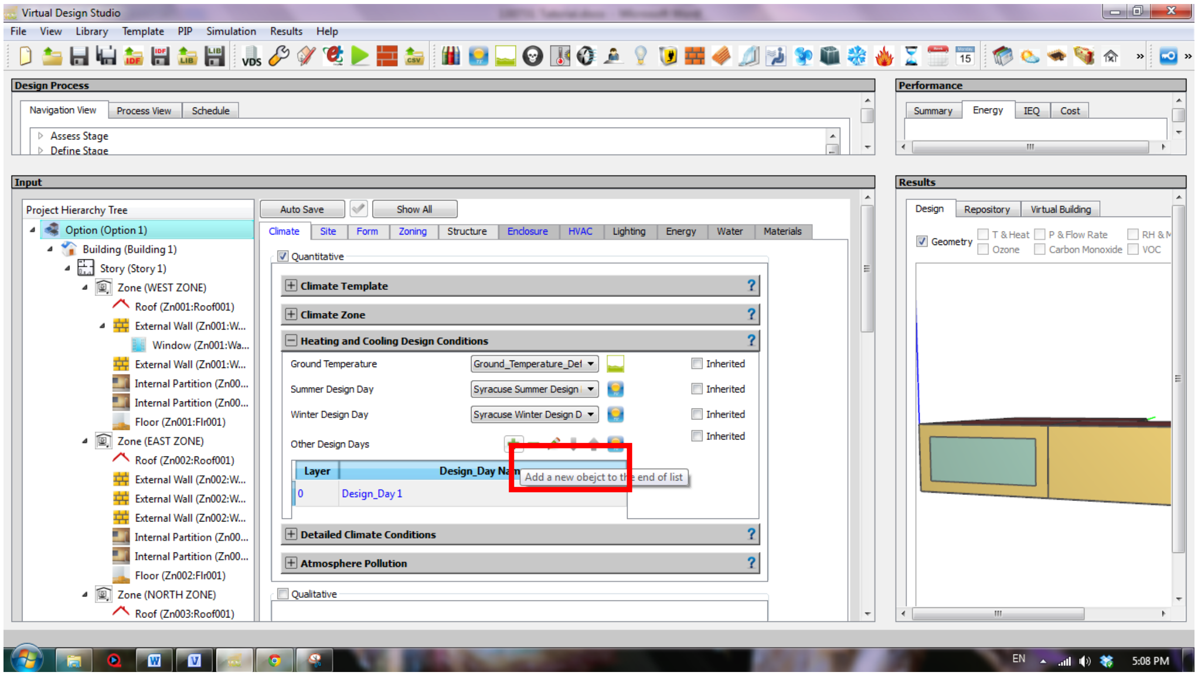


Figure 4-32 “Other Design Days” setting

c) In “Detailed Climate Conditions” and “Atmosphere Pollution”, click to browse folder to choose corresponding files. Currently, all files are set as default for COE building simulation.

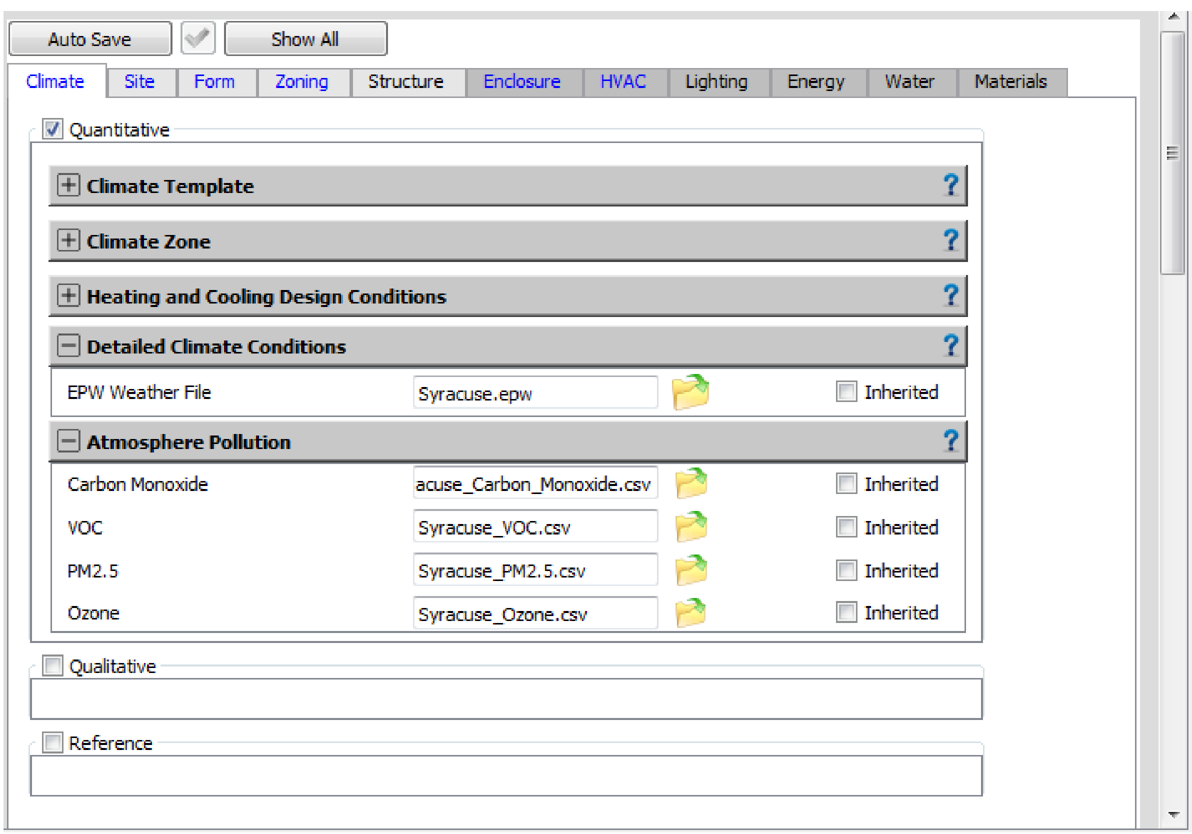


Figure 4-33 “Detailed Climate Conditions” and “Atmosphere Pollution”

Example 2: Enclosure-Building level

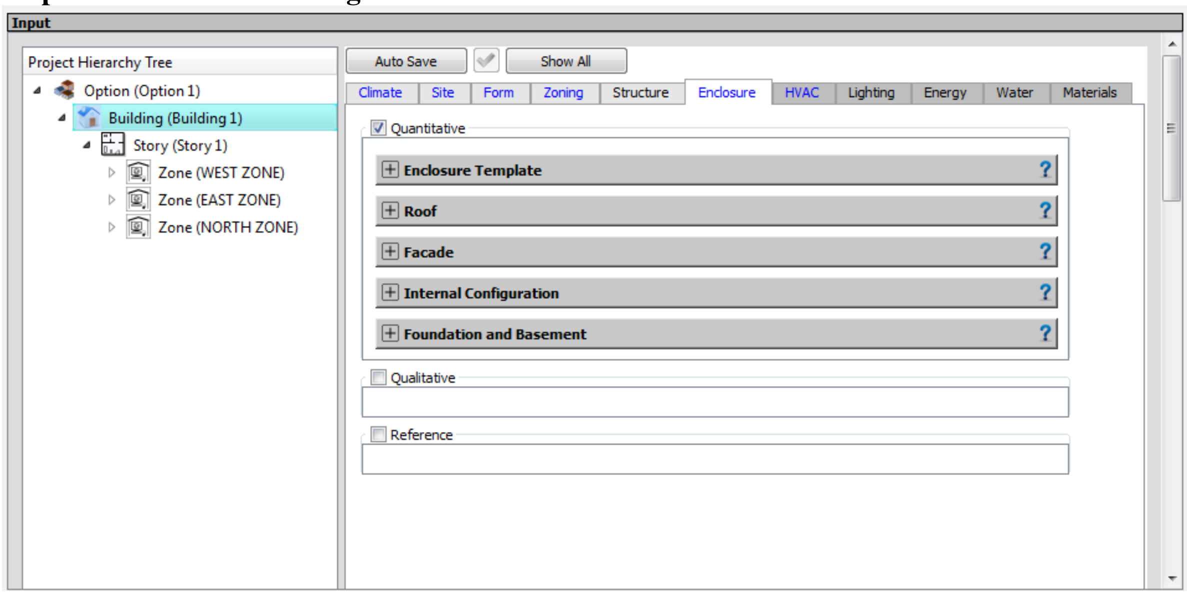


Figure 4-34 Input Enclosure Parameters

In the current version of VDS, only “Quantitative” inputs are available. “Enclosure Template”, “Roof”, “Facade”, “Internal Configuration” and “Foundation and Basement” constitute the “Enclosure” input. The following section illustrates how to input parameters in Building level:

1) Click “+” on the left to expand list. In “Enclosure Template” (Figure 4-35), click  to open Enclosure_Template Library, then import an enclosure template from the library. All of the data, unit and type are referred from ASHRAE standard 90.1/62.1 and DOE reference building (NREL, 2011). After importing template, all parameters (“Roof”, “Facade”, “Internal Configuration”, “Foundation and Basement” in Figure 4-36) in enclosure will be set and would be used as default. Users can also create their own template. More details about the use of templates can be found in 5.2. After adopting template, users can also customize all parameters one by one.

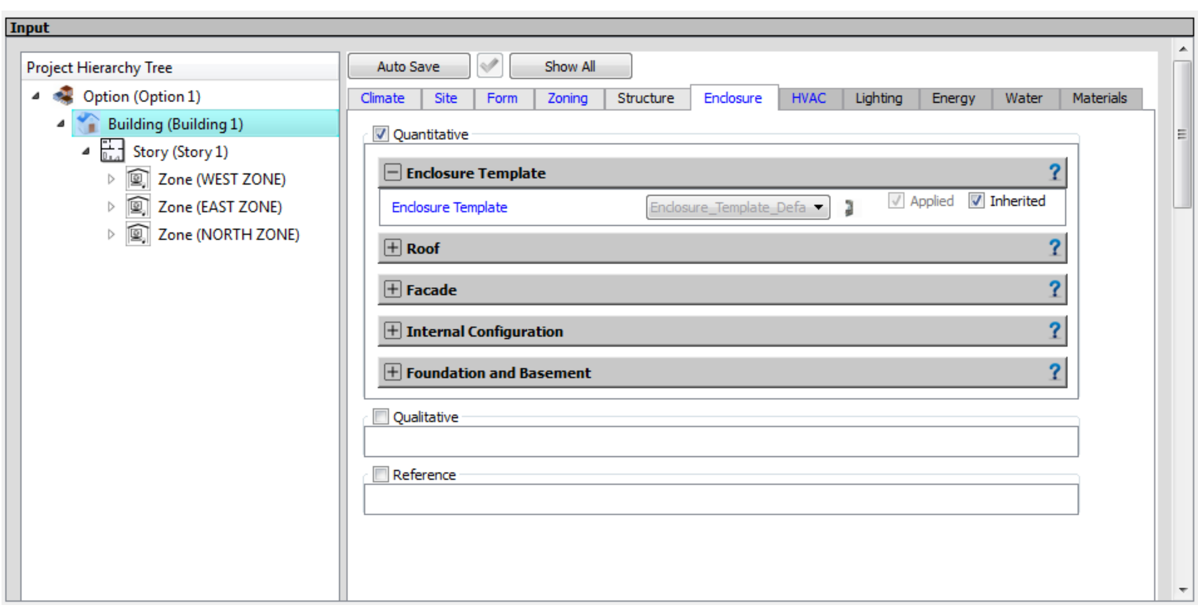


Figure 4-35 Enclosure Template

2) If users set “Enclosure Template” empty, which means didn’t use template. Users should customize “Roof”, “Facade”, “Internal Configuration”, “Foundation and Basement” one by one. These parameters can be selected via a drop down list or chosen from a corresponding library (Construction Library). More details about library are in section 4.1.

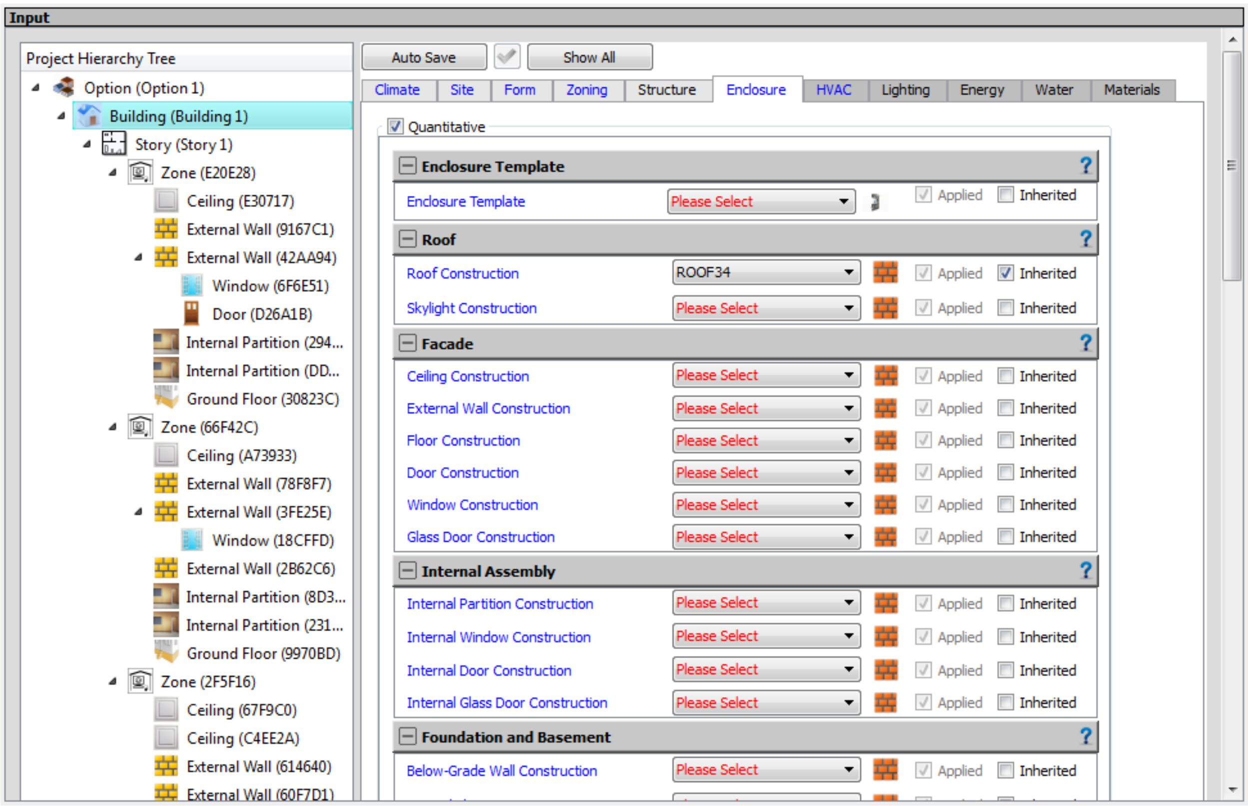


Figure 4-36 “Roof”, “Facade”, “Internal Configuration”, “Foundation and Basement” Setting

Example 3: Zoning/Zone level

In current VDS, only “Quantitative” inputs are available. “Zoning Template”, “Program”, respective “IEQ Requirements”, “Occupancy”, “Lighting”, “Equipment”, “Initial Pollution Condition”, “Pollution Source and Sink” and “Windows and Doors Opening Control” constitute the “Zoning” input. The following section illustrates how to input parameters:

1) Click “+” on the left to expand list. In “Zoning Template” (Figure 4-37), click (Zoning_Template Library), then import a zoning template. After that, all parameters “Program”, “IEQ Requirements”, “Occupancy”, “Lighting”, “Equipments”, “Initial Pollution Condition”, “Pollution Source and Sink” and “Windows and Doors Opening Control”) in zoning will be set and will be used as default. More details about template can be found in 5.2.

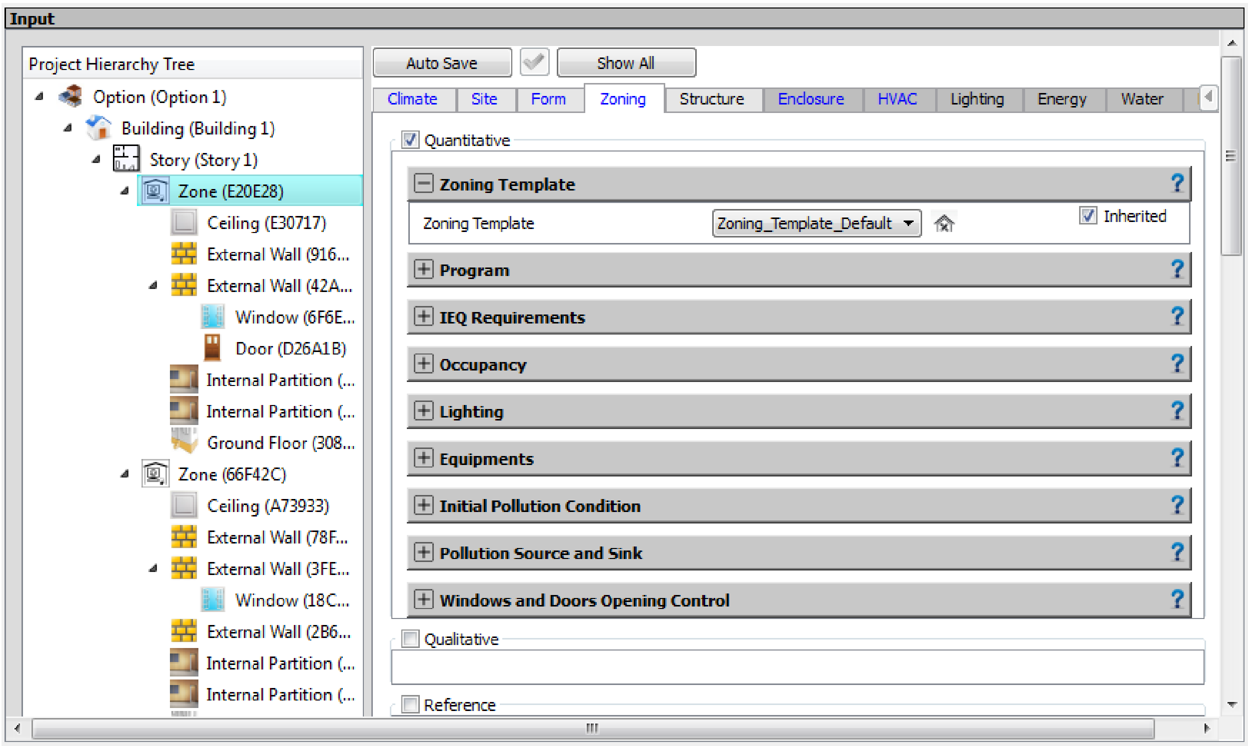


Figure 4-37 Zoning setting overview

2) If users set "Zoning Template" empty, users should assign "Zoning Template", "Program", "IEQ Requirements", "Occupancy", "Lighting", "Equipments", "Initial Pollution Condition", "Pollution Source and Sink" and "Windows and Doors Opening Control" parameters one-by-one. In setting "Program" (Figure 4-38), users can select from drop-down list. All of the options in the list are set as default and cannot be changed.

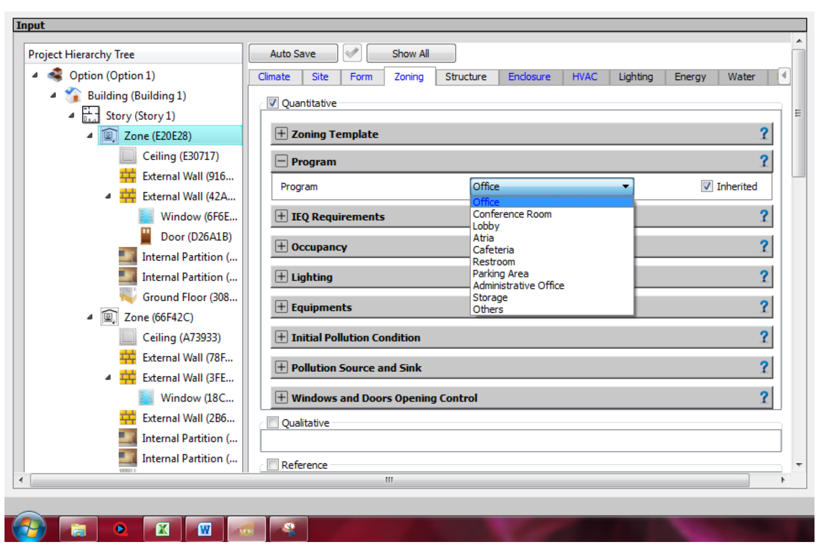


Figure 4-38 "Program" in "Zoning"

a) "IEQ Requirements", "Occupancy", "Lighting", "Equipments" and "Natural Ventilation Control" (Figure 4-39) parameters can be chosen from a corresponding library on the right. More details about library are in section 4.1.

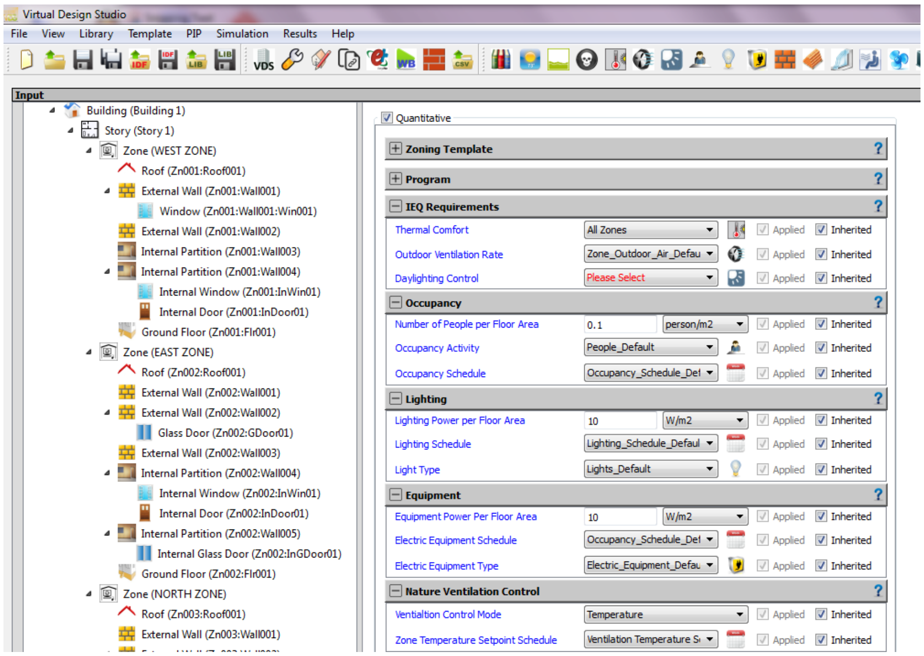


Figure 4-39 "IEQ Requirements", "Occupancy", "Lighting", "Equipments"

b) In setting "Initial Pollution Condition" (Figure 4-40), users can type data in blank rectangle.

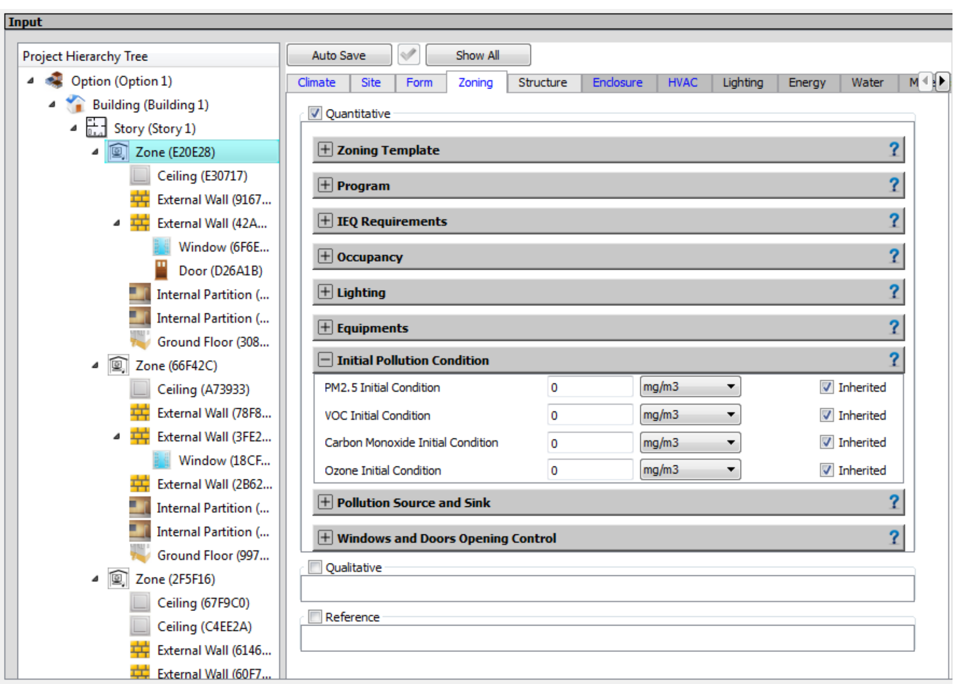


Figure 4-40 "Initial Pollution Condition"

c) In setting “Pollution Source and Sink” (Figure 4-41), Click “+” to add the new “Contaminant Condition” or click to choose from “Contaminant_Condition Library”. The “Design_Day1” item can be deleted by clicking “-“or can be edited by clicking . If there are several items, clicking item can order them. Or

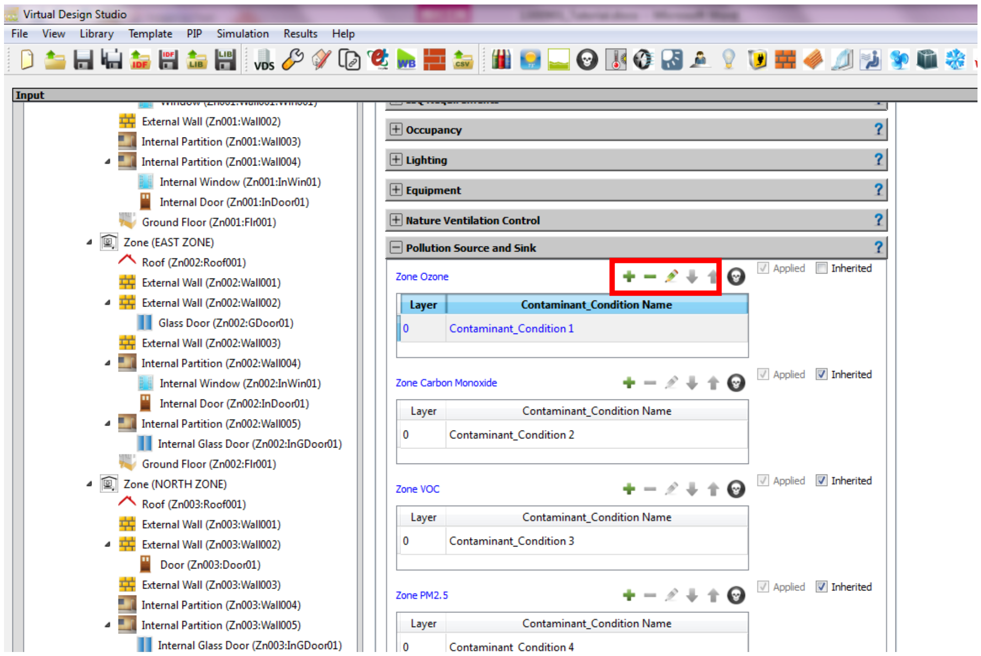


Figure 4-41 “Pollution Source and Sink”

Example 4: **HVAC- Building level**

1) Click “+” on the left to expand list. In “HVAC Template” (Figure 4-42), click (HVAC_Template Library), then import a HVAC template. After that, all parameters in HVAC will be set and would be used as default. More details about template can be found in 5.2.

Note: On the right of (HVAC_Template Library), there is an option: “Inherited”. If “Inherited” is chosen, children level (“Story” level) will inherit parents level (“Option” level) parameters.

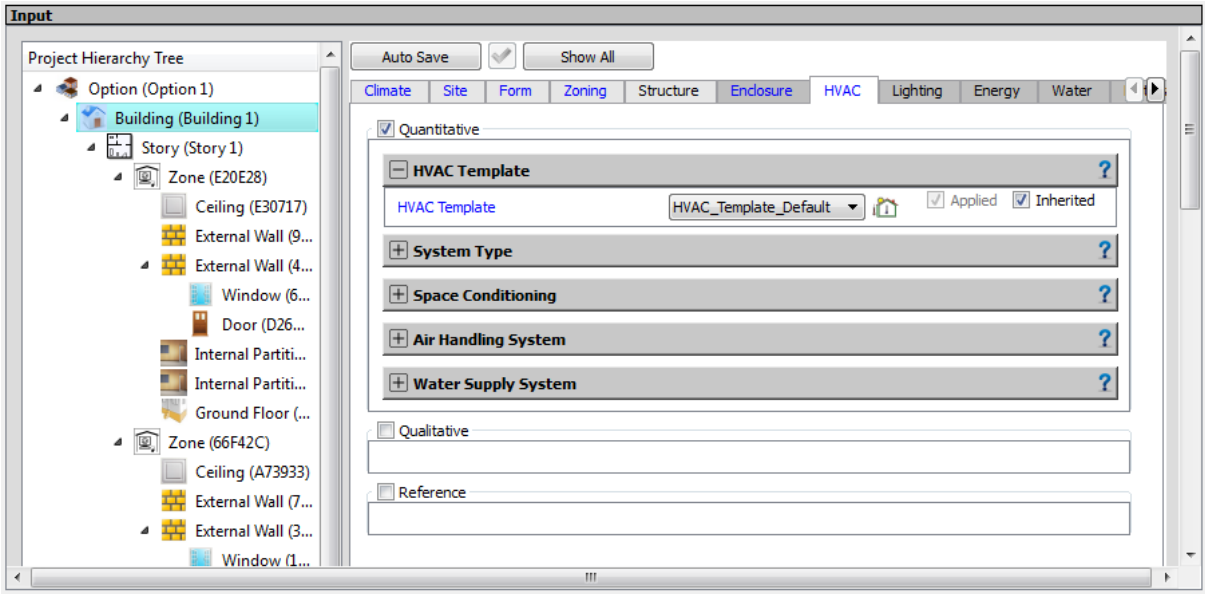


Figure 4-42 HVAC setting overview

If users set "HVAC Template" empty, the parameters listed below should be set one by one. In setting "HVAC Template Type", users can choose from drop-down list:

Ideal system;
VAV with reheat + chiller & boiler;
VAV with reheat + GSHP (Ground Source Heat Pump);
100% Outdoor air system + Fan coil + Chiller & boiler;
100% Outdoor air system + Fan coil + GSHP; is available.

Other parameters can be selected from corresponding library on the right of input box.

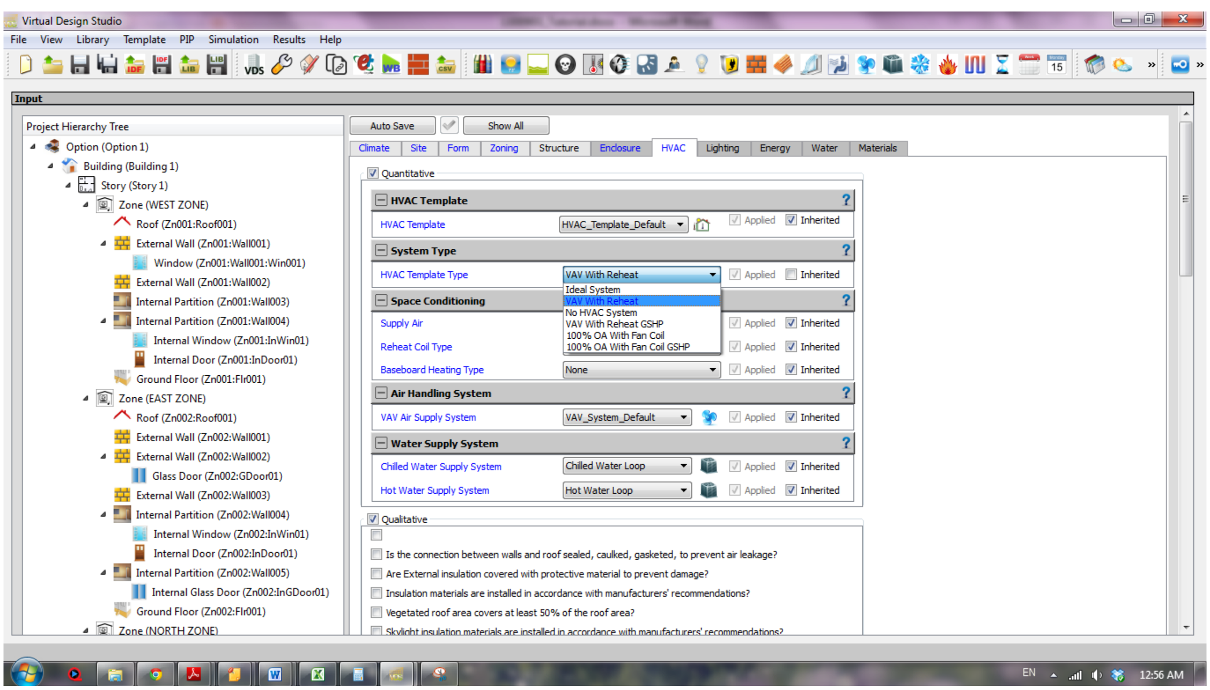


Figure 4-43 HVAC setting

4.5 Step 5: Run Simulation

The Whole Building Energy & IEQ Simulation model integrates an enhanced CHAMPS-Multizone model and EnergyPlus to evaluate building energy performance, indoor air quality, thermal comfort, and daylighting performance as affected by the various design factors. EnergyPlus will focus on the heat, moisture, and lighting simulation, while CHAMPS-Multizone will focus on the air and pollutant simulation.

The CHAMPS-BES (BEESL at Syracuse University, 2013) can be used to simulate 2-dimensional hygrothermal performance of building envelope systems. Computational fluid dynamics (CFD) can be used to analyze the zone air distribution. Radiance (LBNL, 2013d) can be used for lighting simulation. And Building Life-Cycle Cost (BLCC) programs (NIST, 2013) can be used for the analysis of capital investments in buildings.

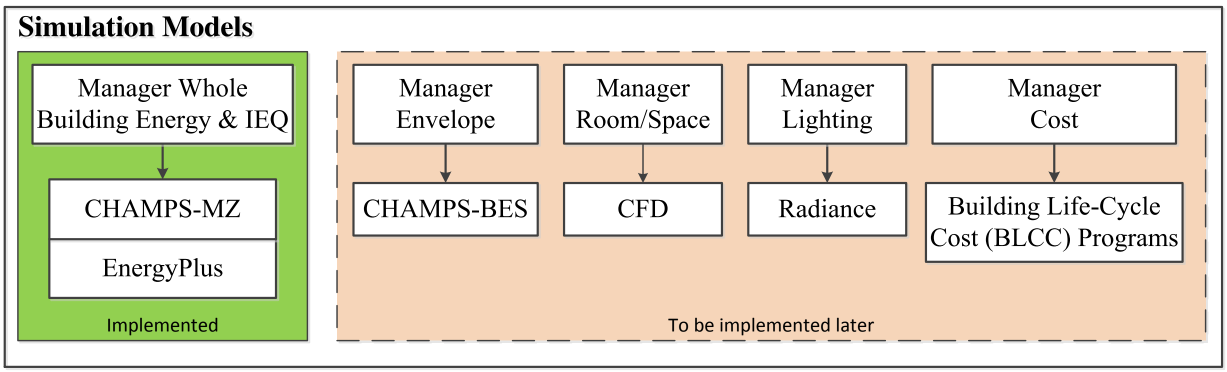


Figure 4-44 Simulation Models in VDS framework

4.5.1 Energy Plus

EnergyPlus is a whole building energy simulation program that engineers, architects, and researchers use to model energy use in buildings. EnergyPlus models building envelope, heating, cooling, lighting, and ventilation systems (US DOE, 2012a). EnergyPlus simulation is based on the input parameters in "Input" quadrant. In current VDS, it can offer "Temperature & Heat", "RH & Moisture" and "Lighting" result. Run the envelope simulation using the following steps:

- Choose "Simulation → Run EnergyPlus" to open EnergyPlus.
- Select design option for simulation (Figure 4-45).
- Wait for simulation result (Figure 4-46).

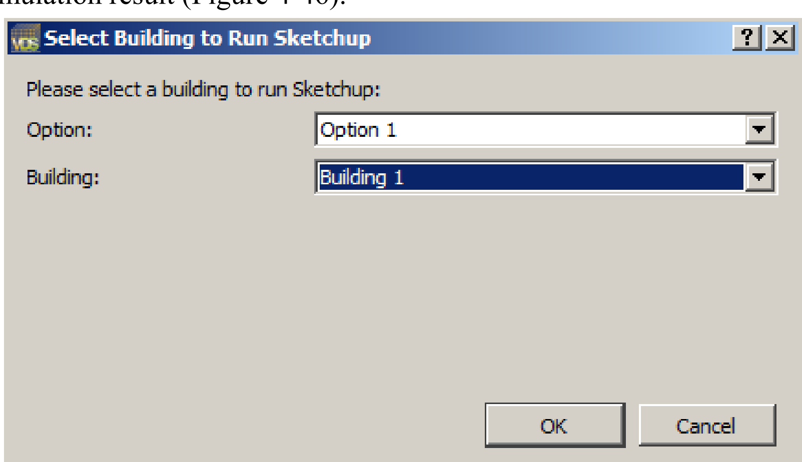


Figure 4-45 Select design option to be simulated

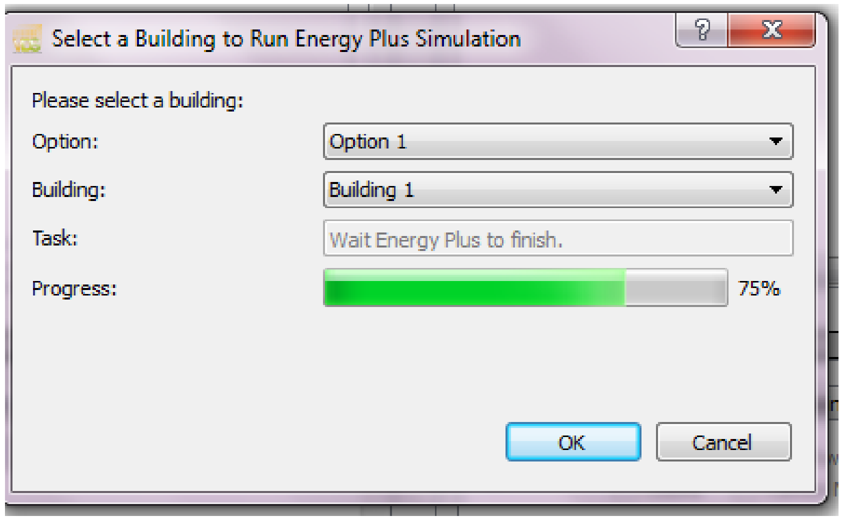


Figure 4-46 Run Simulation

4.5.2 Champs Multizone (to be added)

4.5.3 Read Envelope Simulation Results

- Click "OK" in Figure 4-47. All results will be saved in "Temp" folder.

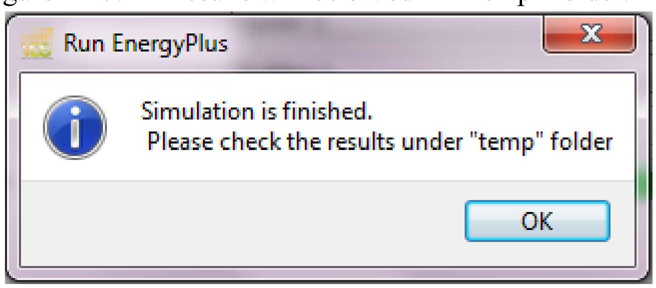


Figure 4-47 Simulation finished 1

- Click "OK" in Figure 4-48 to load the simulation result file automatically and view the results.

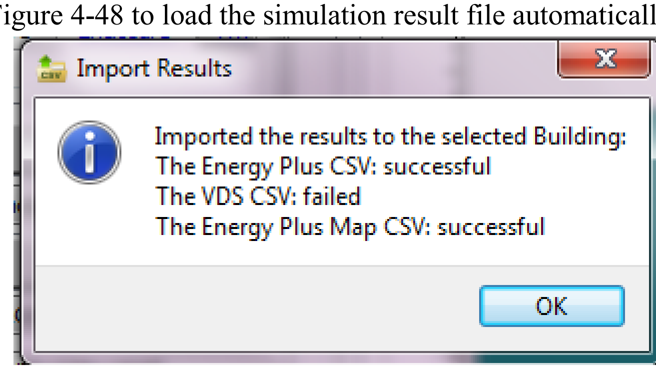


Figure 4-48 Simulation finished 2

4.6 Step 6: View Design Results

After importing the idf file, users can view only "Geometry" results in the third Quadrant. Successful simulation results about Temperature & Heat, RH & Moisture and Lighting can also be viewed in this quadrant.

4.6.1 3D Design View

The viewer allows 2D and 3D information display. Figure 4-49 3D Geometry shows the 3D geometry of a building.

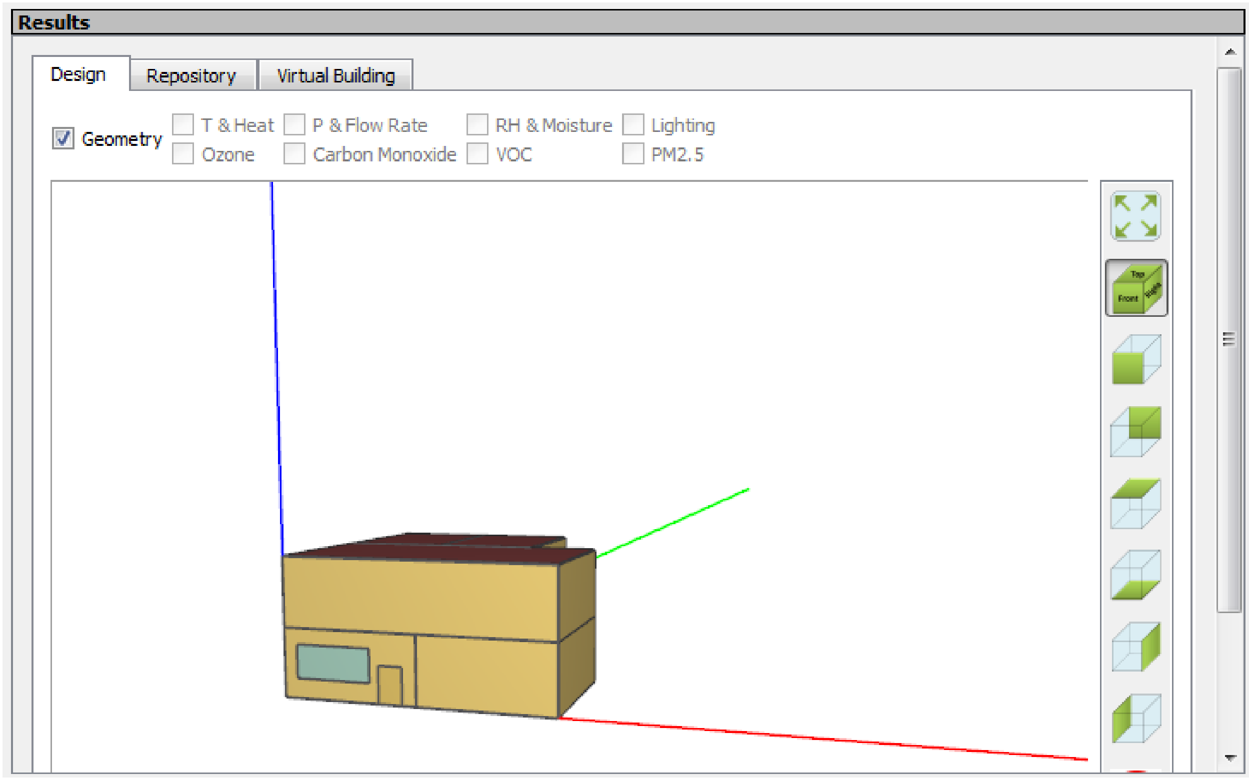
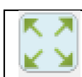
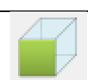
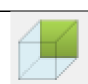
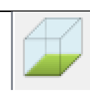
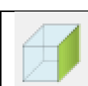
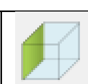


Figure 4-49 3D Geometry

On the right of window there are several icons to help users view geometry more conveniently. All of the icon functions are shown in Table 4-3.

Table 4-3 Geometry icon

									
Fit	Perspective view	Front View	Back View	Top View	Bottom view	Right View	Left View	Reset	Detail Visualization

Note:
Fit button: fit the drawing to the screen.
Reset button: reload the building if geometry is changed.
Detail Visualization: Show transparence for windows and glass doors. And be able to show complex geometry. Figure 4-50 shows the function of “detail visualization”.

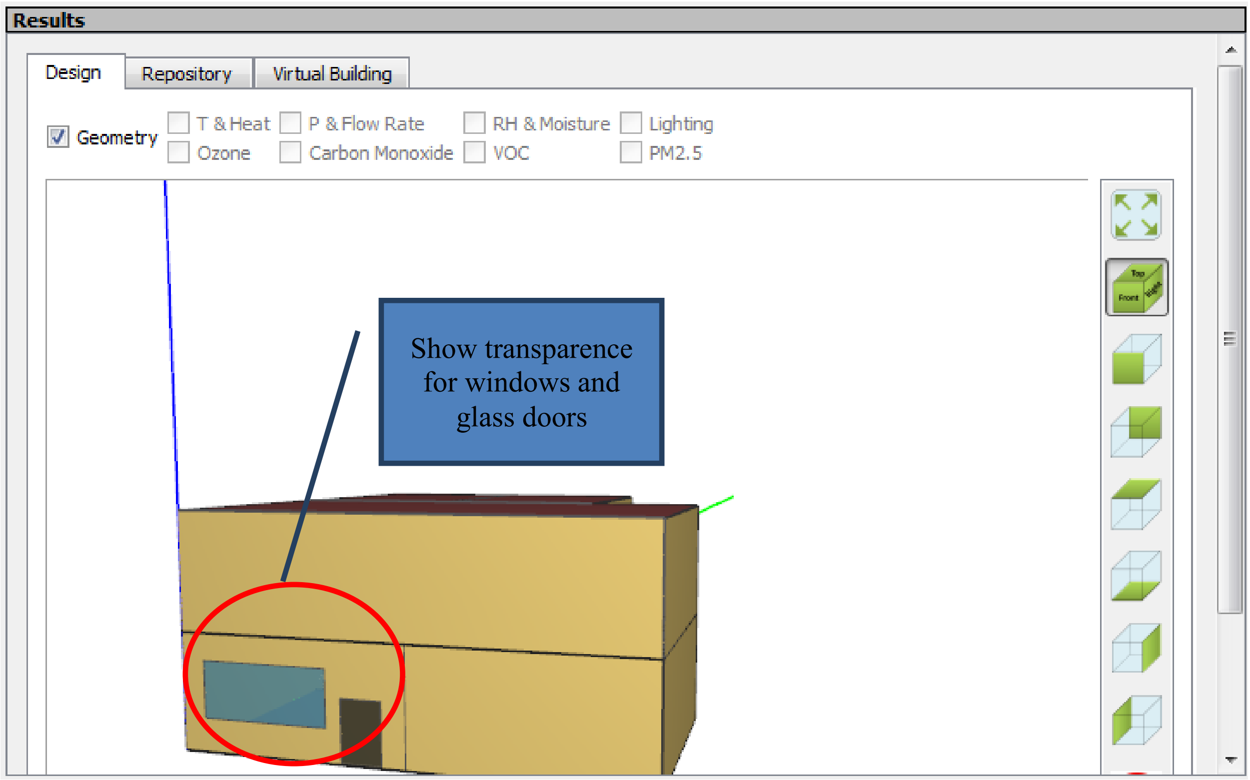


Figure 4-50 Detail Visualization

4.6.2 Other Results View

After running EnergyPlus simulation, the "Geometry", "Temperature & Heat", "RH & Moisture" and "Lighting," results will be saved to each individual building component such as Story (Figure 4-51) and Zone (Figure 4-52).

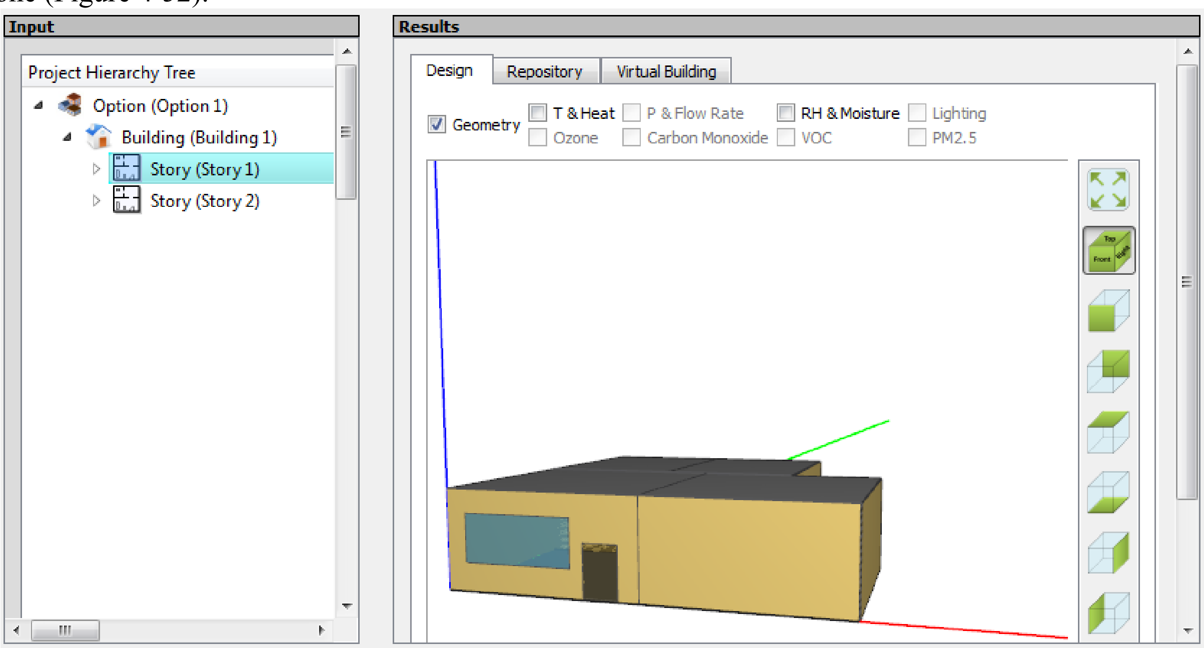


Figure 4-51 Story Results Overview

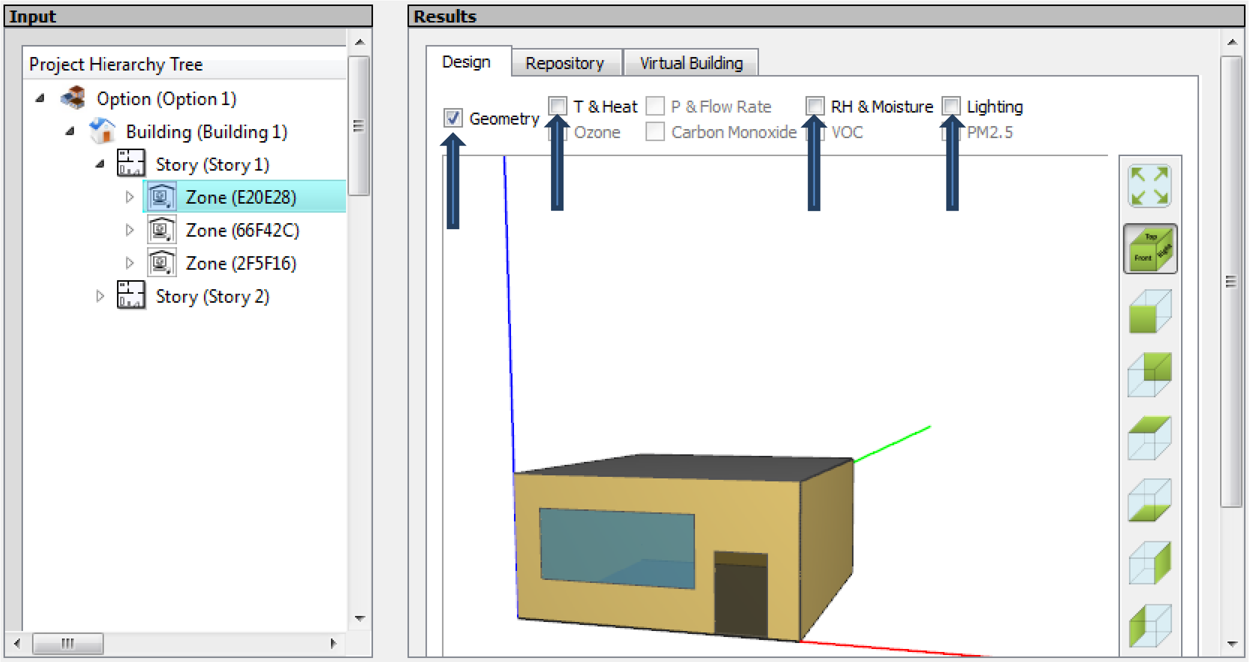


Figure 4-52 Zone Results Overview

When the selected building component (for example Zone in Figure 4-52) contains simulation results, the corresponding check box will become available in the result quadrant, which can be seen in Figure 4-52.

Click the corresponding result and move the time bar as shown in Figure 4-53 to view the results for different time periods. An example as mentioned in 4.3.2 can help users to view results. After EnergyPlus simulation, select "Story" component and tick "T (Temperature) &Heat" option. The figures below show Temperature & Heat result of Story1 (Figure 4-53 Date Time: 1/21 5:00 and Figure 4-54 Date Time: 7/21 7:00).

Note: North is up in all of plan view.

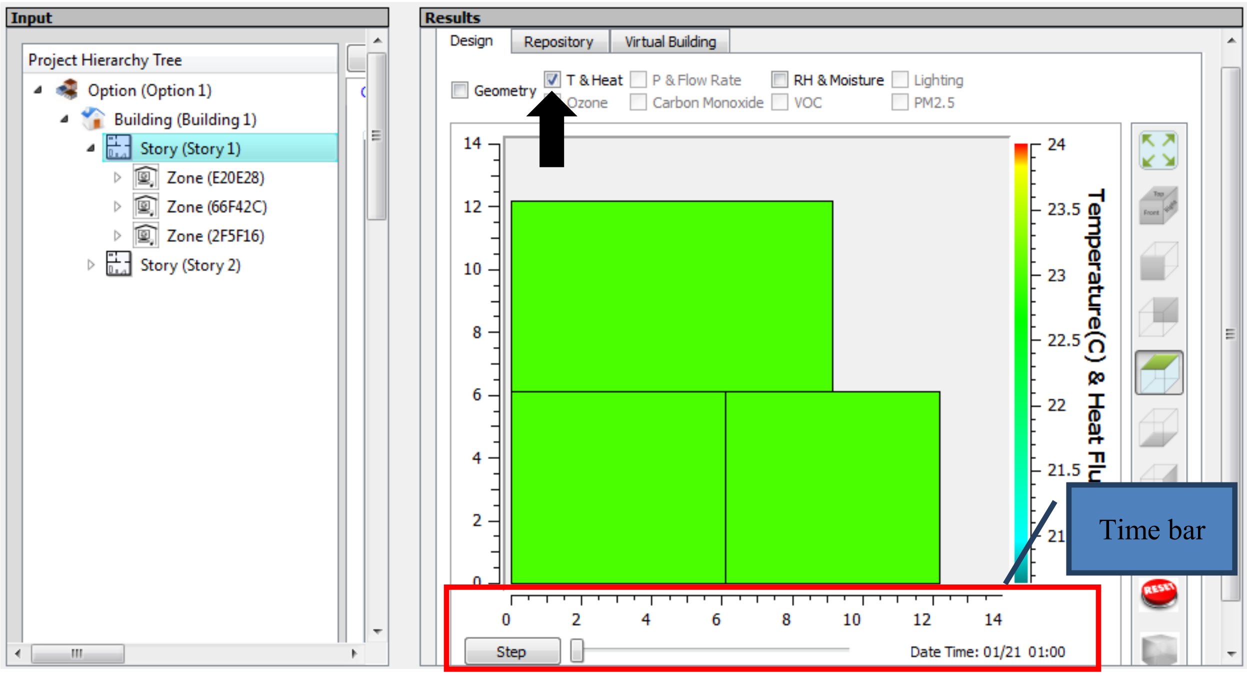


Figure 4-53 Temp. & Heat Flux (Date Time 1/21 1:00)

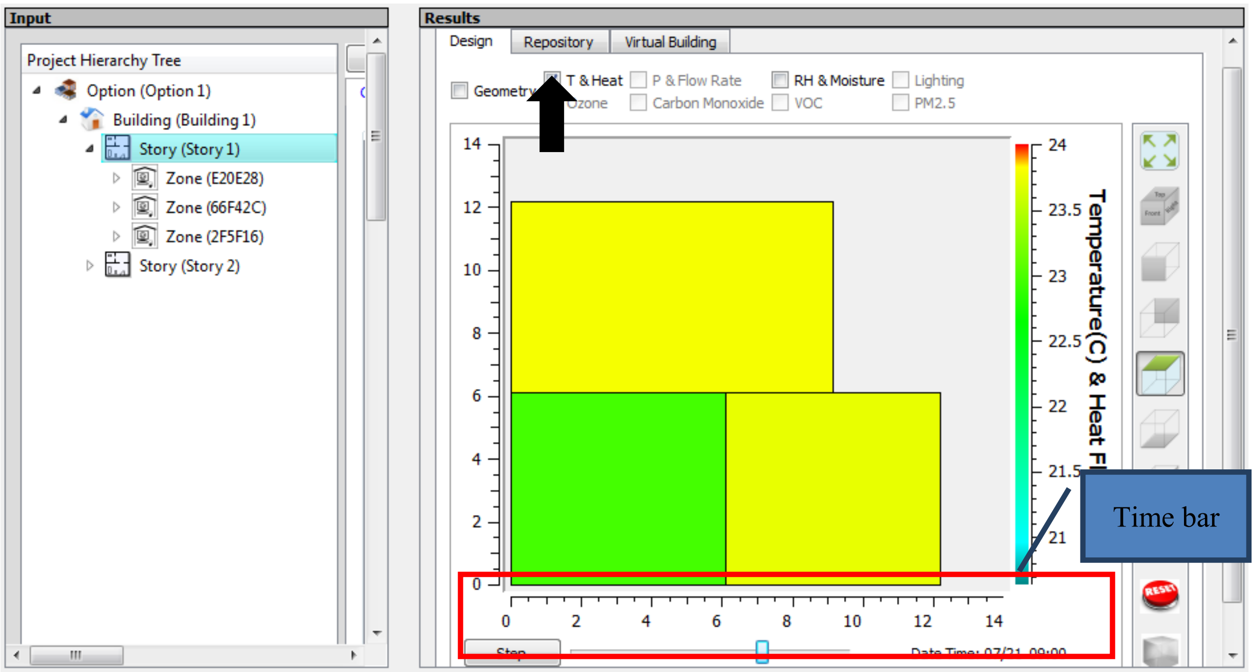


Figure 4-54 Temp. & Heat Flux (Date Time 7/21 9:00)

4.6.3 Process Integration Platform (PIP)

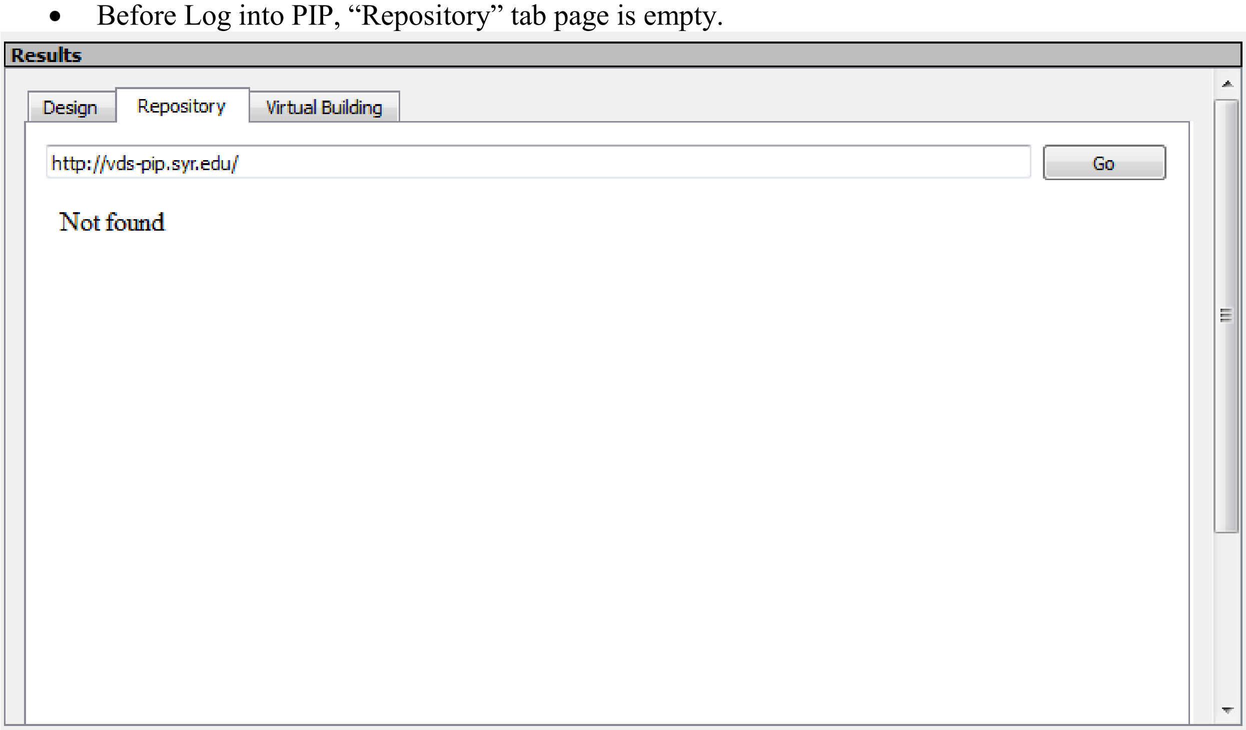
A shared mental framework of project information can enhance a project team's performance by identifying information relationships and data dependencies that provide project teams with the right project data at the right time. The Process Integration Platform (PIP) (Flager et al. 2009) provides this informational view by graphically representing project information or documents along with associated data dependencies using common web browsing technologies. VDS builds on these concepts by integrating project and task management features (VDS team manager) with PIP's document repository and information dependency features to provide teams with an enhanced collaboration environment. Further, since PIP document services are inherently shared, team members are provided with timely and consistent information among all members. Another benefit derived from PIP's document dependency capability is the ability to notify team members when upstream data changes creates a need to revisit dependent documents for accuracy in light of the data changes.

VDS-PIP is a web-based technology. The task process structure of a VDS project is maintained by VDS and tasks are simply registered with PIP for the purpose of performing search functions. Initially, the task structure is populated in PIP using a project specific template based on the associated project tasks. Independently, the project information structure and associated information dependencies are maintained by PIP as user upload or create documents. That is, VDS manages the team's task relationships and PIP manages the data relationships created within the process. Documents are created in VDS-PIP by accessing the repository within VDS, selecting the associated task, and finally upload any document or URL name.

A "Repository" tab in "Result" quadrant is for document sharing over an internet server through the VDS-PIP. The "Repository" button links directly to the VDS-PIP web interface via the web browser.

In general, VDS is only required to authenticate the user and then display the associated PIP window within the VDS GUI.

- Before Log into PIP, "Repository" tab page is empty.



- Click "PIP –> Login" to active PIP and Figure 4-55 pop up. Enter user ID and password go to data repository. Currently, users can log in by default User ID and Password.

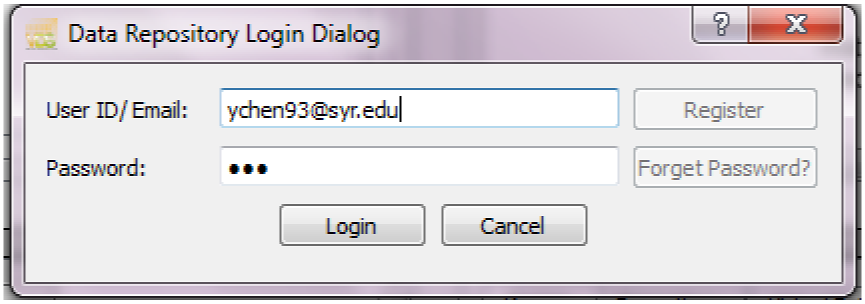


Figure 4-55 PIP login dialog

- Choose one of the projects in "Listing projects" to begin (Figure 4-56).

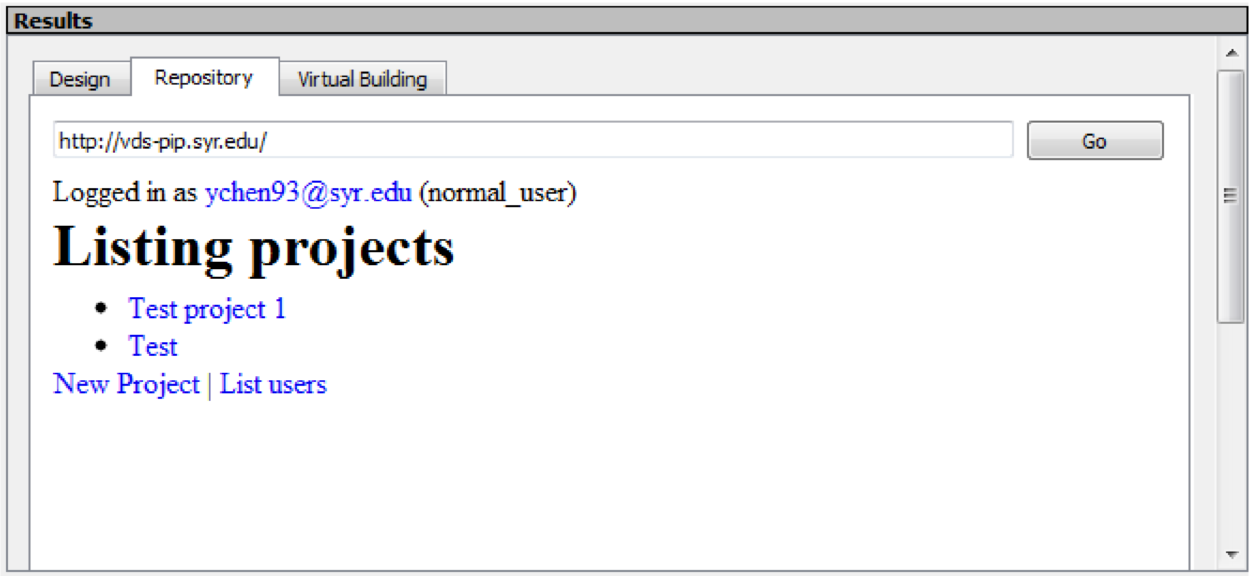


Figure 4-56 PIP repository

- An example "Test project 1" is shown in Figure 4-57 for VDS-PIP display. Here we see a project tree on the left and various documents for "Identify Sites" task shown on the right. Double-click task "Identify Sites", the arrowed lines connecting the documents represent informational relationships between the documents.

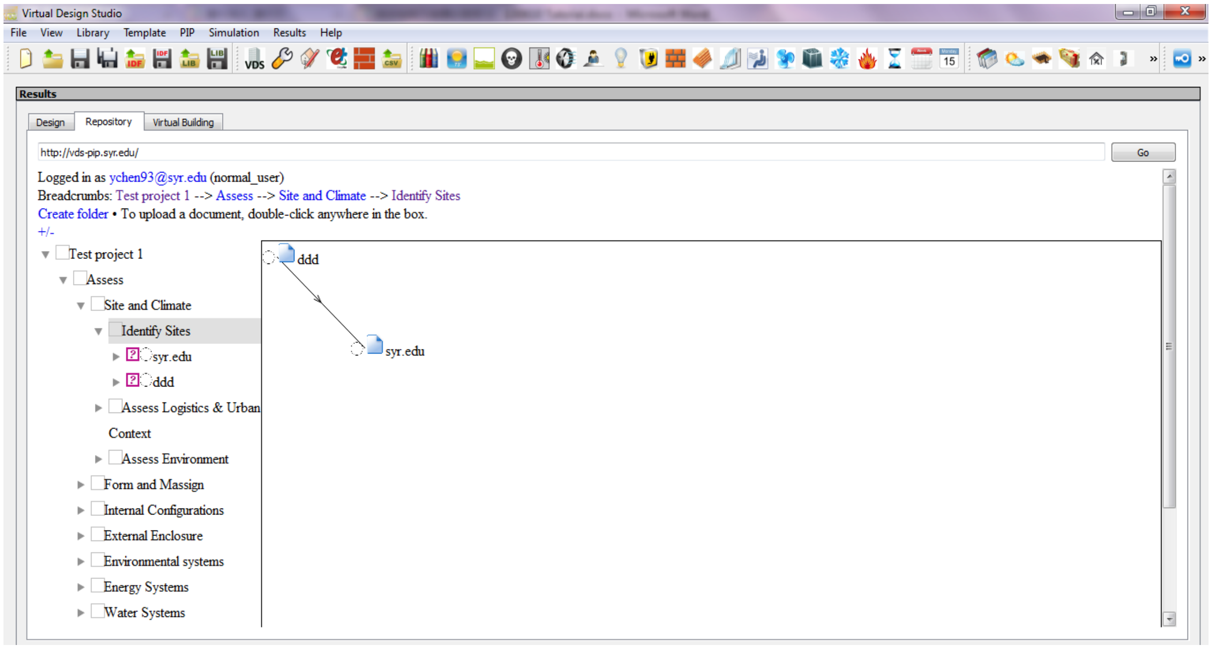


Figure 4-57 Example VDS-PIP user display with Edit Dialog insert

- Double clicking the associated task (ie., “syr.edu”) will pop-up a window (Figure 4-58) that is a document edit dialog. In addition to the basic document information, the document edit dialog shows the document’s dependencies, status, and history.

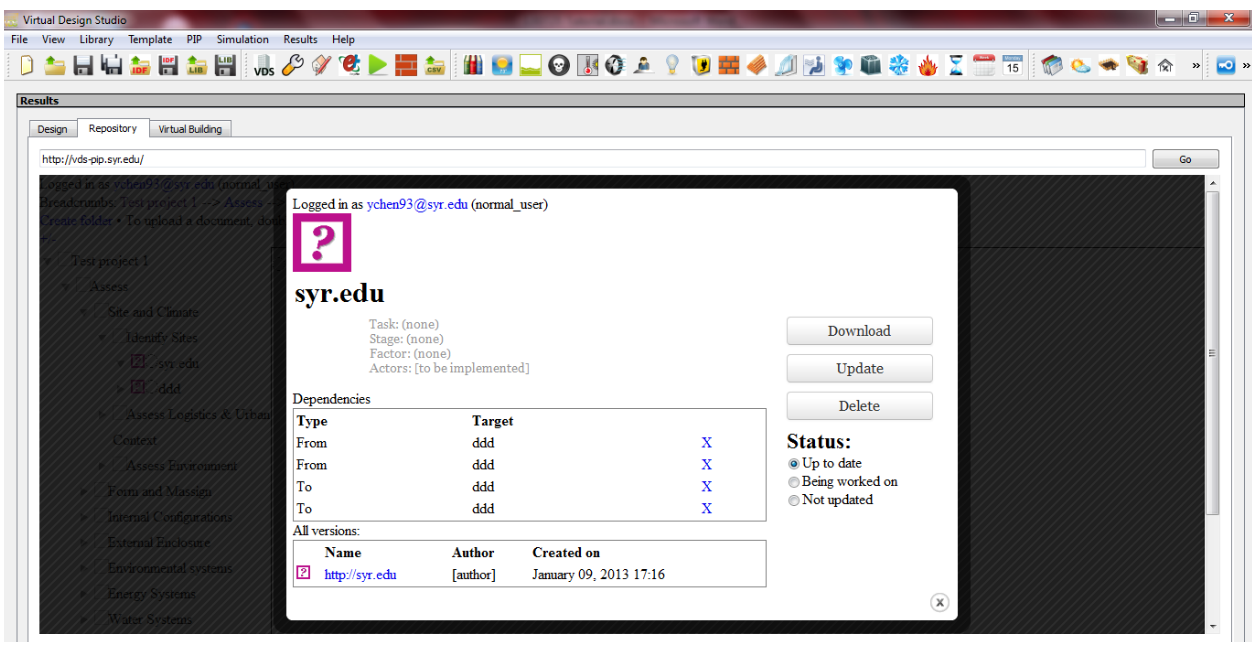


Figure 4-58 Document edit dialog

- Click “Update”, and upload any document or URL name as exampled in Figure 4-59 (currently, users cannot upload URL name).

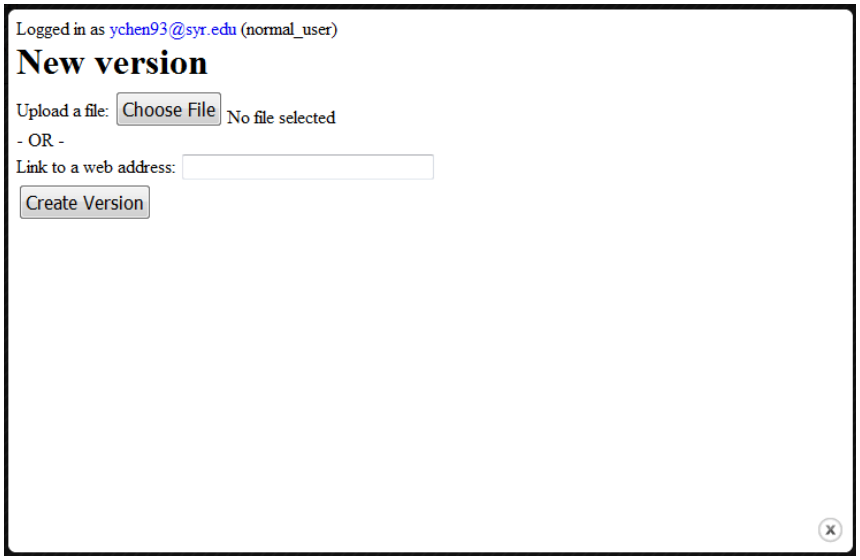


Figure 4-59 Upload URL name

4.6.4 Virtual Building (Monitor)

4.7 Step 7: View Performance

(To be implemented)

5 Library & Template in Parameter Input

Users can select corresponding templates or input elements one-by-one using libraries in Step 4: Design Input Parameters. This chapter is designed to give users more information about the library and templates, including their functions, how to use them, and how to modify them.

5.1 Library

Parameters can be selected from a library (on the right of each drop down list) as mentioned in 4.4.2 or via a drop-down list. At the same time, the items in the drop-down list are created by the library. As the library contains various detailed information in the parameters setting, it is more convenient to choose from library instead of typing in all the parameter properties. Different library serves to different template, Table 5-1 Library list shows libraries corresponding to different templates.

Table 5-1 Library list

Libraries	Applied Templates
Design Day Library	Climate Template
Ground Temperature Library	Climate Template
Contaminant Condition Library	Climate Template
Thermal Comfort Library	Zoning Template
Outdoor Ventilation Rate Library	Zoning Template
Occupancy Activity Library	Zoning Template
Light Type Library	Zoning Template
Electric Equipment Type Library	Zoning Template
Construction Library	Enclosure Template
Material Library	(Applied in Construction Library)
Window Material Library	(Applied in Construction Library)
Zone Supply Air Library	HVAC Template
Air Supply System Library	HVAC Template
Water Supply System Library	HVAC Template
Chiller Library	(Applied in Water Supply System Library)
Boiler Library	(Applied in Water Supply System Library)
Run Period Library	
Schedule Library	Zoning Template
Daily Schedule Libray	(Applied in Schedule Library)

Below shows how to import, view and edit library:

- Import Library
  - Click “File->Import-> Import VDS Libraries Templates” to active VDS Library Import Dialog (Figure 5-1).

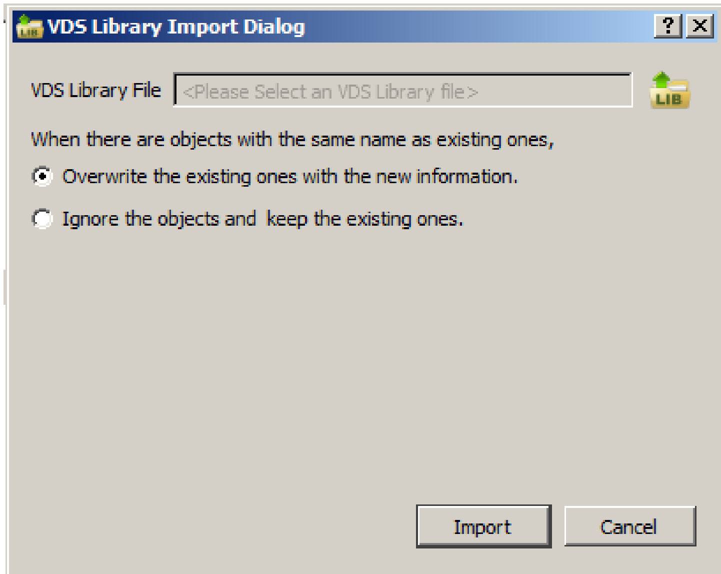


Figure 5-1 Import Library

- Click  in dialog to import "VDSdefaultlibrary" located in data file (Figure 5-2). VDS Developers created "VDSdefaultlibrary" as a basic library that contains some libraries data for reference.

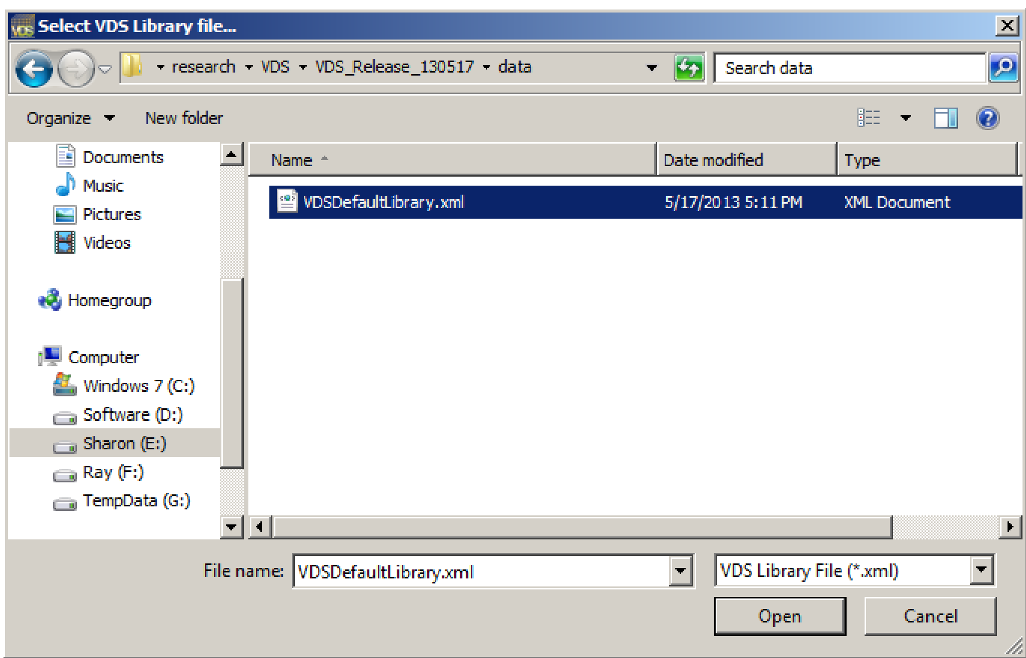


Figure 5-2 Library Location

- View library
  - Click "Library" in menu and select one of libraries to view. Click "Library->All Libraries" to active window, which refers all libraries.
  - Reference to Table 5-1 Library list shows libraries corresponding to different templates.

- Edit library

  Example 1: Design_Day Library

  - Take "Design Day Library" as an example. Click "Library->Design Day Library" to active window as Figure 5-3.

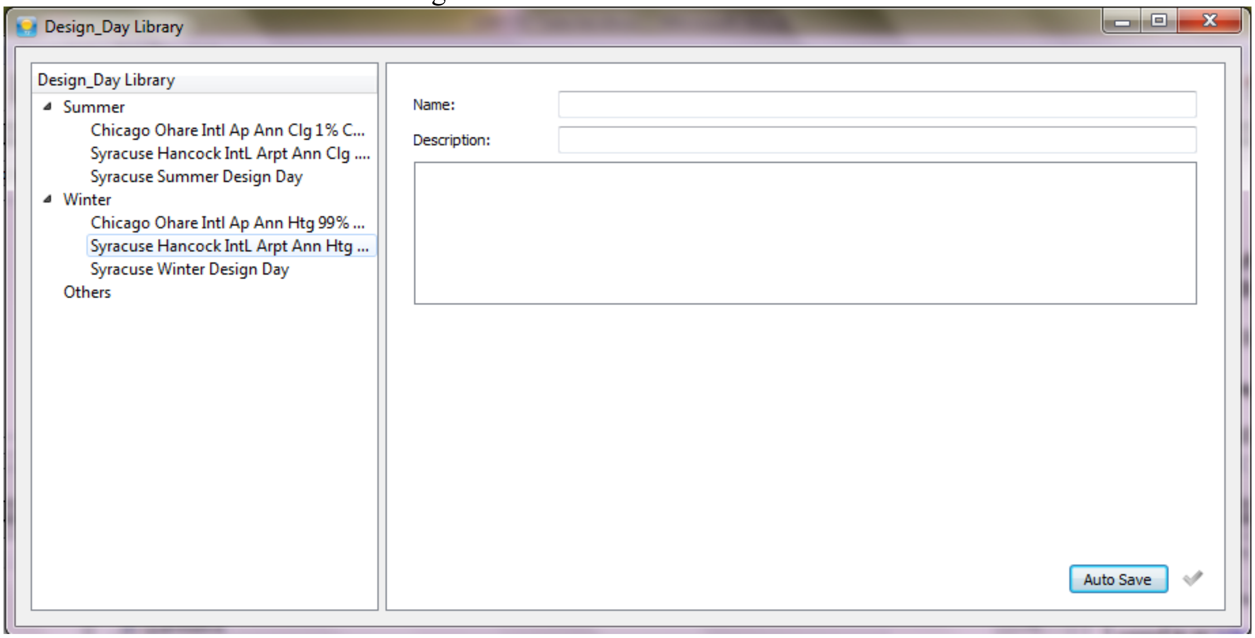


Figure 5-3 Active "Design Day Library"

  - **Right click** "summer" and click "**New**" (Figure 5-4) to create a new library.

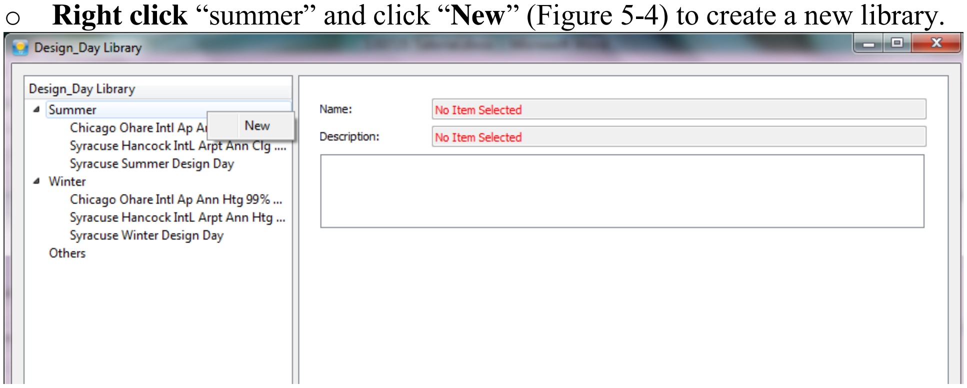


Figure 5-4 Creating Library

  - **Click** new library"Design_Day1" then input parameters in it as Figure 5-5. Usually, blank rectangle is for data, drop down list is for unit and type. All data, unit and type can be referred from ASHRAE 90.1/62.1/189.1.

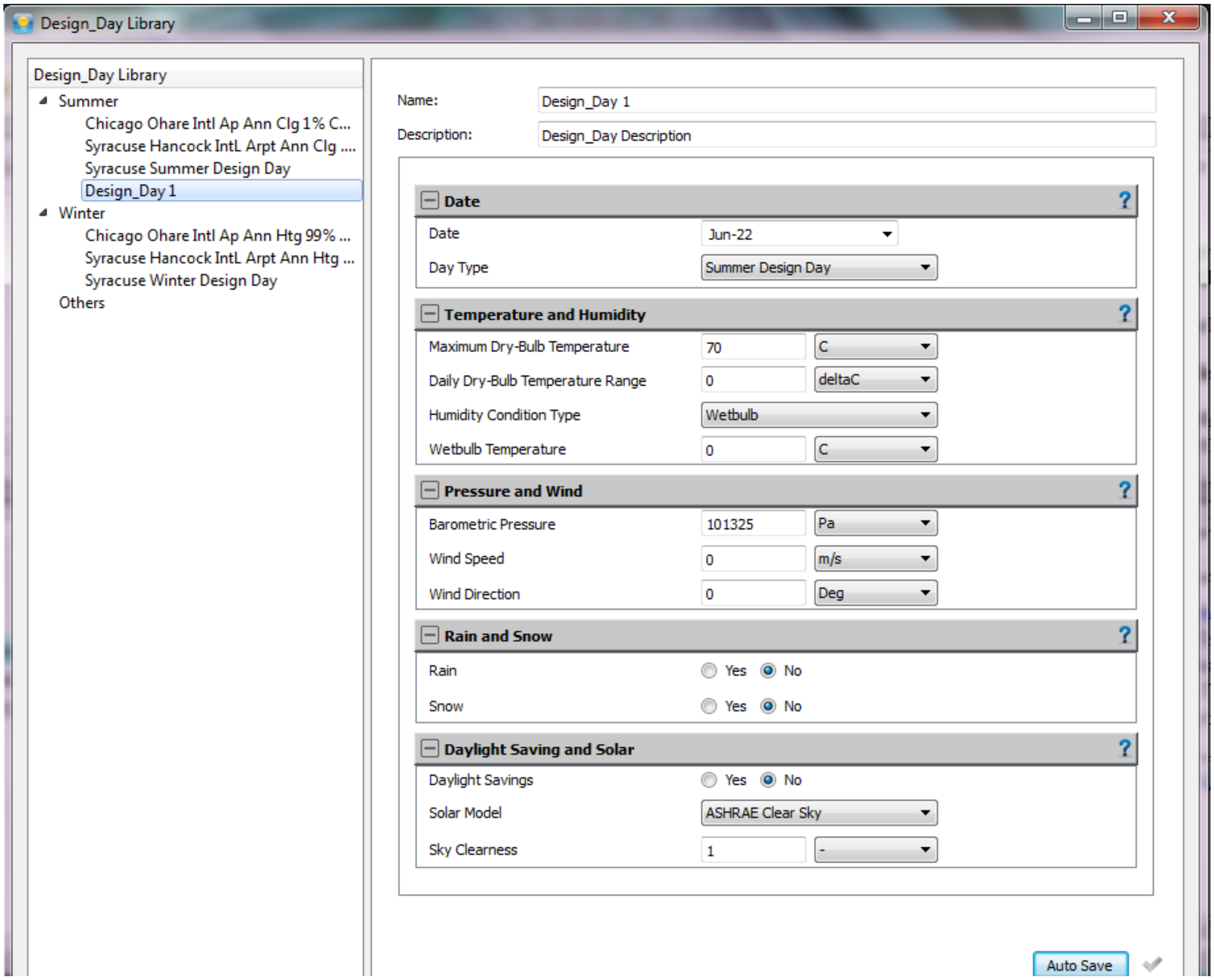


Figure 5-5 Input Library

- Close the window, the new library will be available.
- Right click and select "Delete" to delete template (Figure 5-6).
- Saving Library file. Click "File->Export-> Export VDS Libraries Templates".

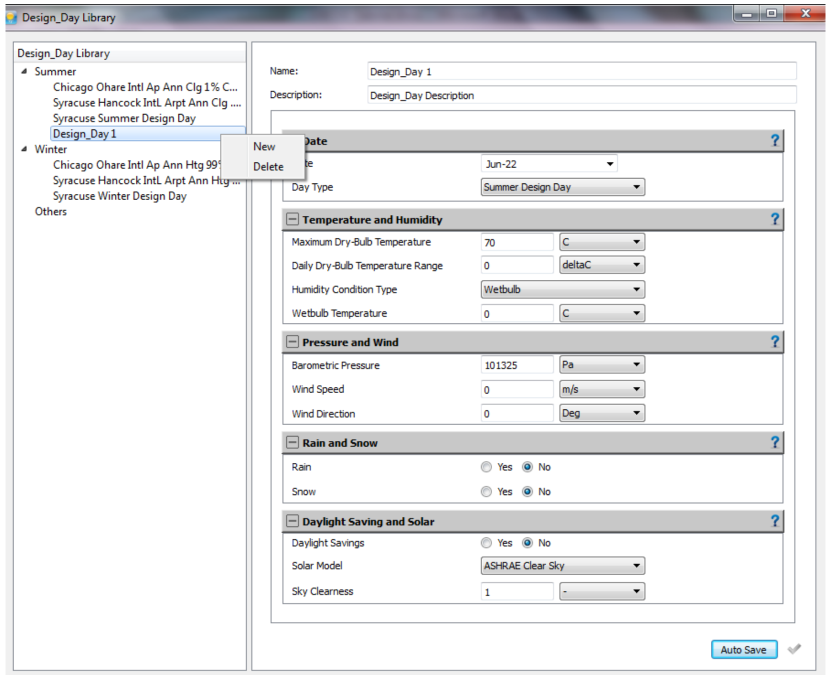


Figure 5-6 Delete Library

There are three ways to input parameters, Table 5-2 illustrates different libraries correspond to input ways. How to input is shown below:

1) All parameters can be typed in a blank box, as shown in Figure 5-5;
2) Click "+" to add the new item. Items can be deleted by clicking "-", can be edited by clicking . If there are several items, clicking  can reorder them. See the construction library as an example in Figure 5-7.
3) Parameters need to be referred from other libraries. As shown in Figure 5-8 Occupancy Library, schedule parameter should be referred from schedule library, users should build schedule library first.

Table 5-2 Library Input Type

Libraries	Parameter Input Type
Design Day Library	1)
Ground Temperature Library	1)
Contaminant Condition Library	1)
Thermal Comfort Library	1)
Outdoor Ventilation Rate Library	1)
Occupancy Activity Library	3)
Light Type Library	1)
Electric Equipment Type Library	1)
Construction Library	2)
Material Library	1)
Window Material Library	1)
Zone Supply Air Library	1)
Air Supply System Library	1)
Water Supply System Library	2)
Chiller Library	1)

Boiler Library	1)
Run Period Library	1)
Schedule Library	3)
Daily Schedule Library	1)

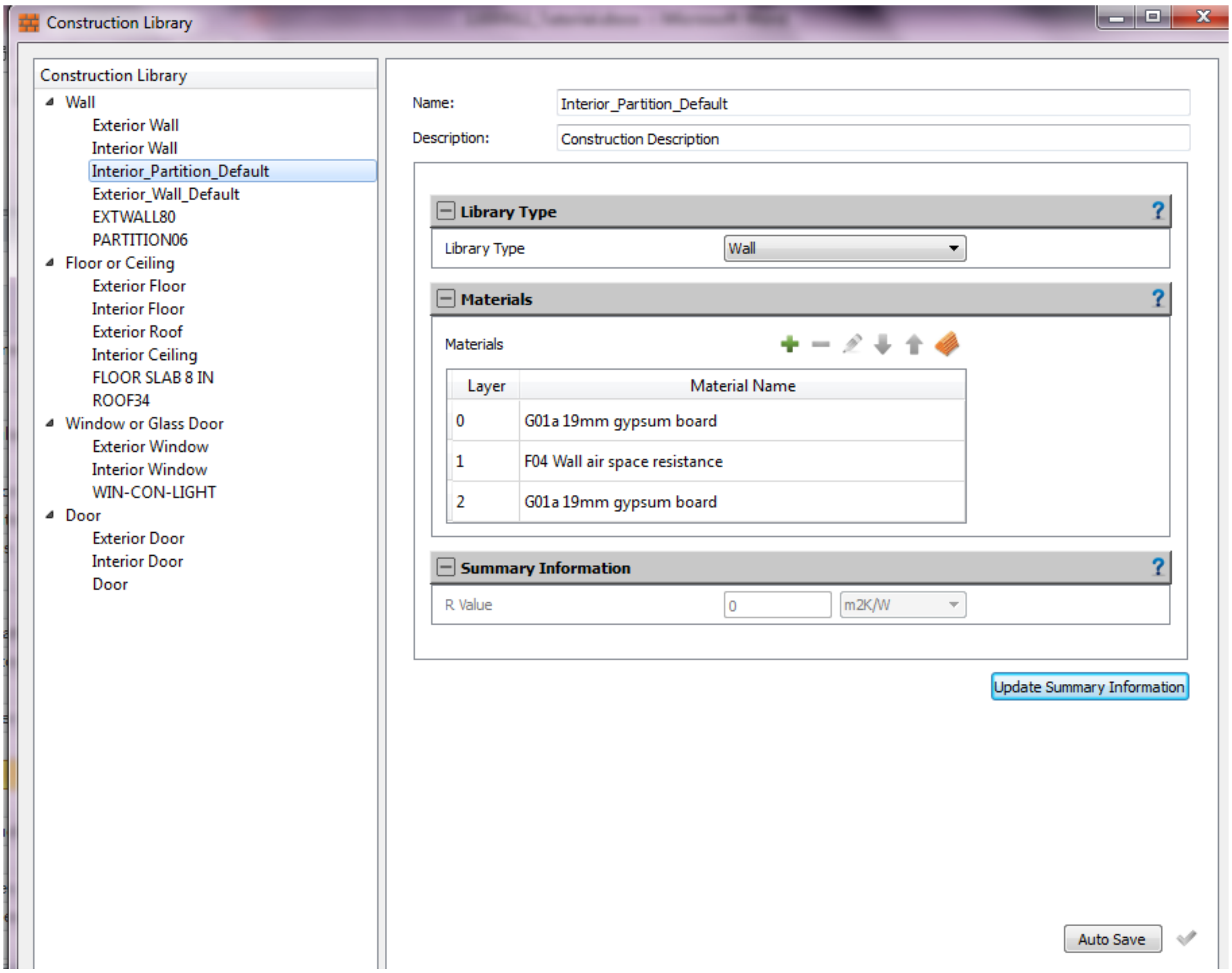


Figure 5-7 Construction Library

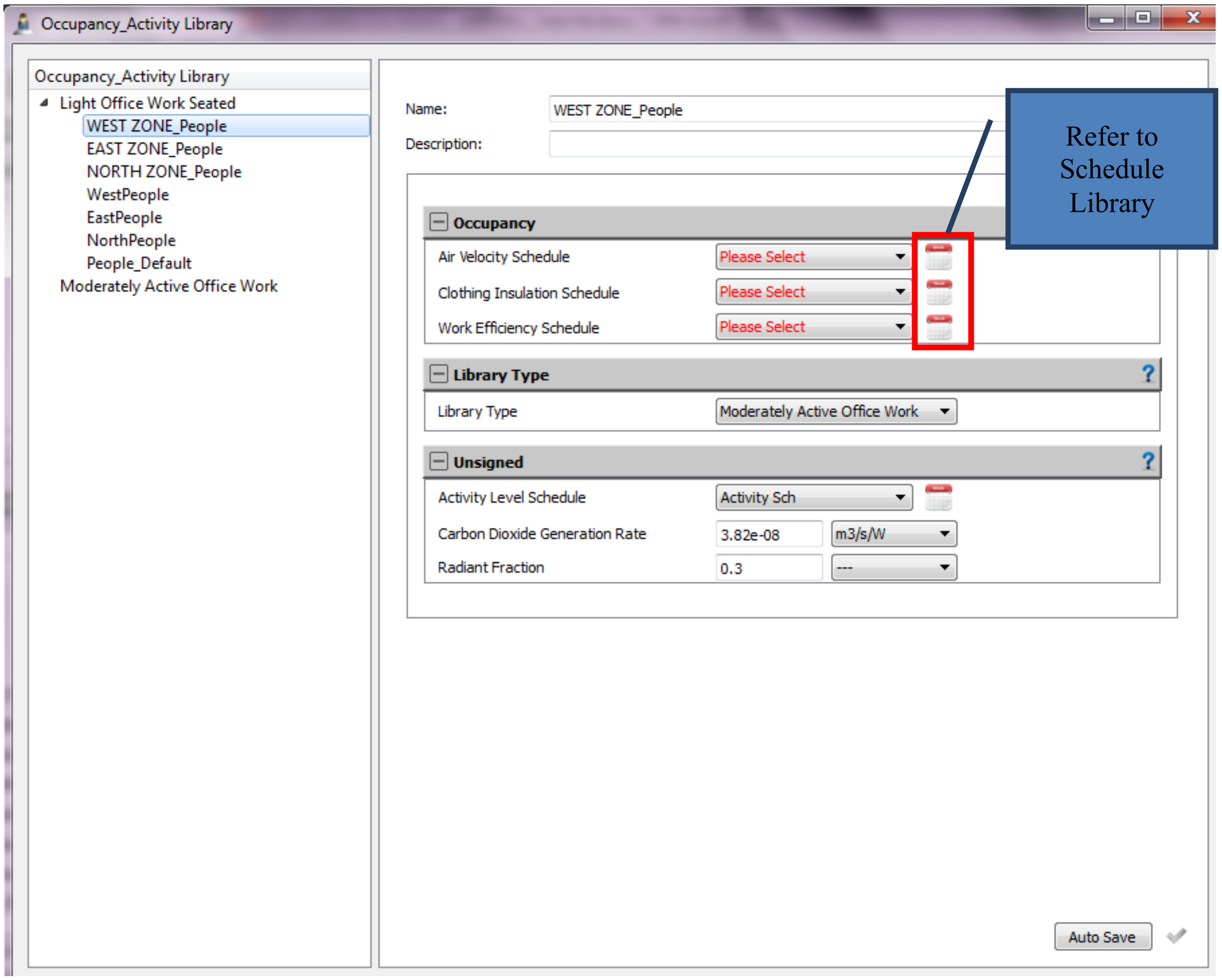


Figure 5-8 Occupancy Library

5.2 Template

"Template" is a form for systematically and logically presenting design input parameters. For each "Template", a pop-up window page provides a form for completing the input entries. VDS has 5 templates currently: (1) Climate, (2) Site, (3) Zoning, (4) Enclosure, and (5) HVAC systems. Each template consists of data in libraries. In each category, users can select corresponding templates instead of inputting elements one-by-one.

- Import Template
  - Click "File->Import-> Import VDS Libraries Templates" to active VDS Template Import Dialog (Figure 5-9).

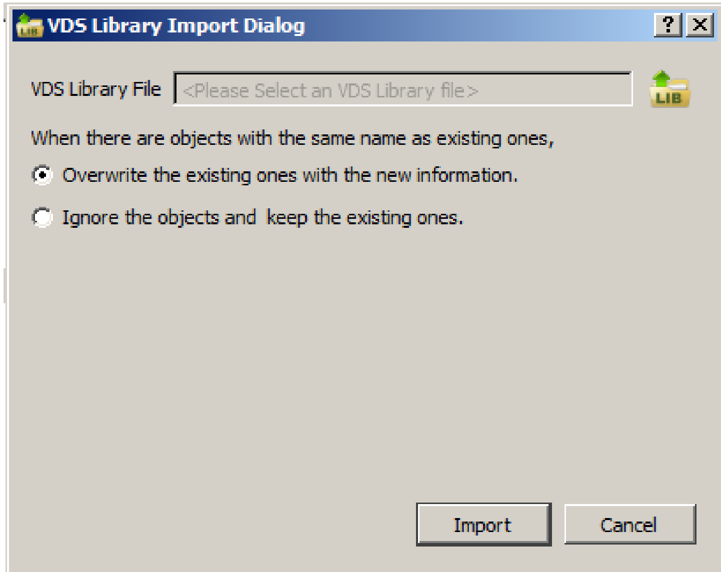


Figure 5-9 Import Template

- Click  in dialog to import "VDSdefaultlibrary" located in data file (Figure 5-2). VDS Developers created "VDSdefaultlibrary" as a basic library that contains some library data for reference.

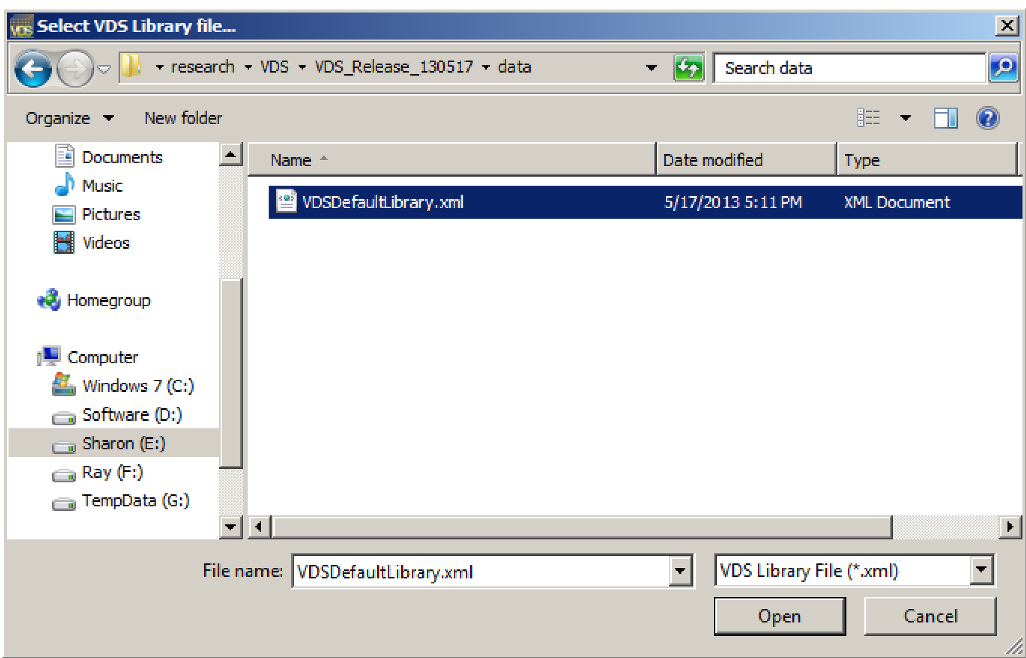


Figure 5-10 Library Location

- View Template
  - Click "Template" in menu and select one of the templates to view. Click "Template->All Templates" to active the window, which refers to all templates.
- Edit Template

- Take “Climate_Template Library” as an example. Click “Template-> Climate_Template Library” to activate window as in Figure 5-11.

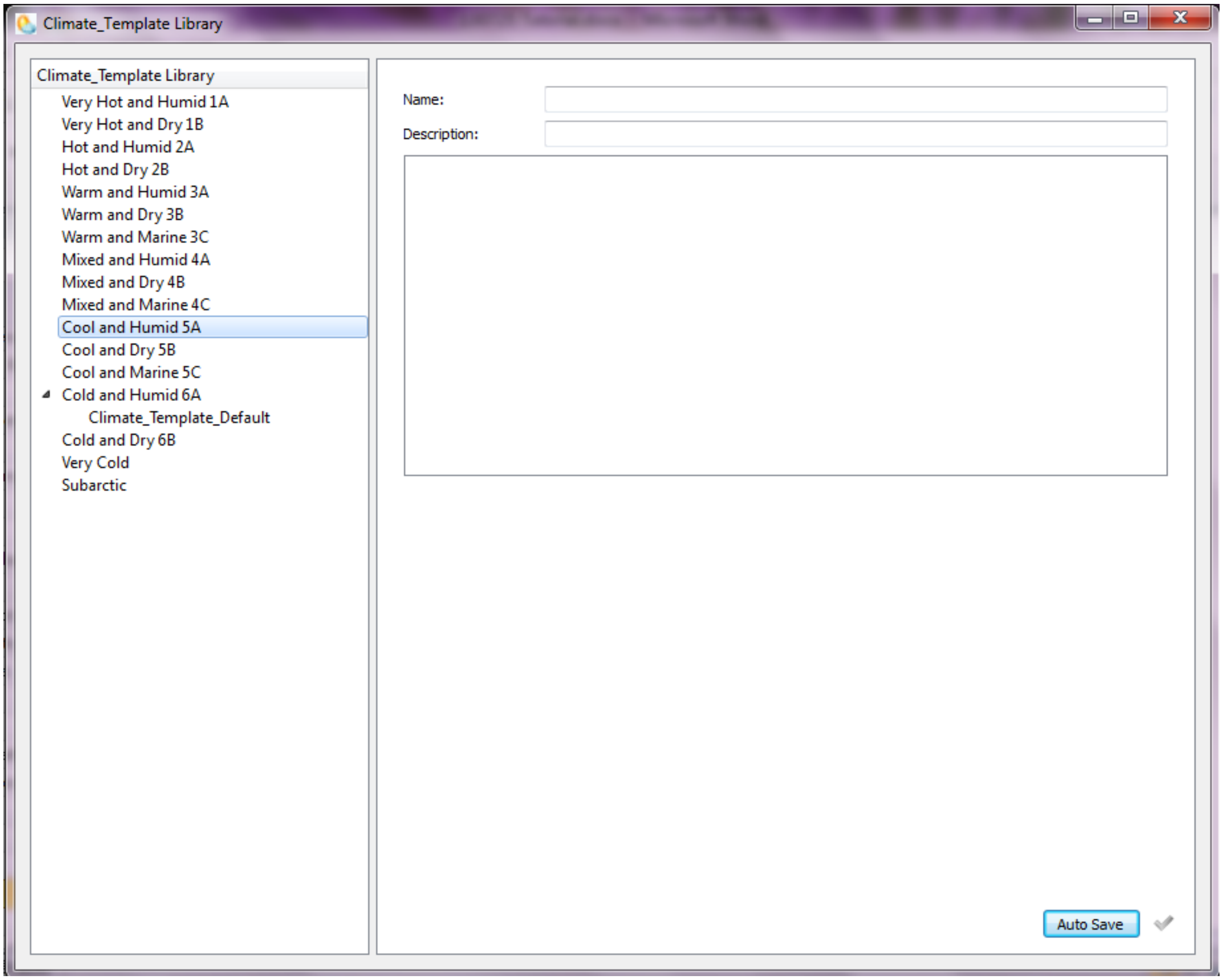


Figure 5-11 Active “Design Day Library”

- **Right click** “Cool and Humid 5A” and click “**New**” (Figure 5-12) to create a new template.

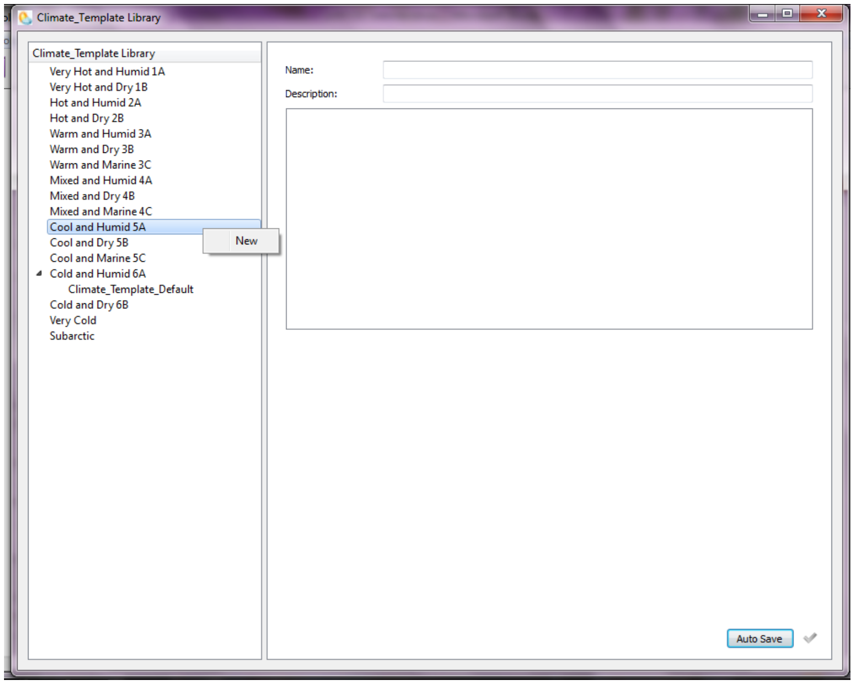


Figure 5-12 Creating Template

- **Click** new template "Climate_Template 1" then input parameters in it as Figure 5-13.

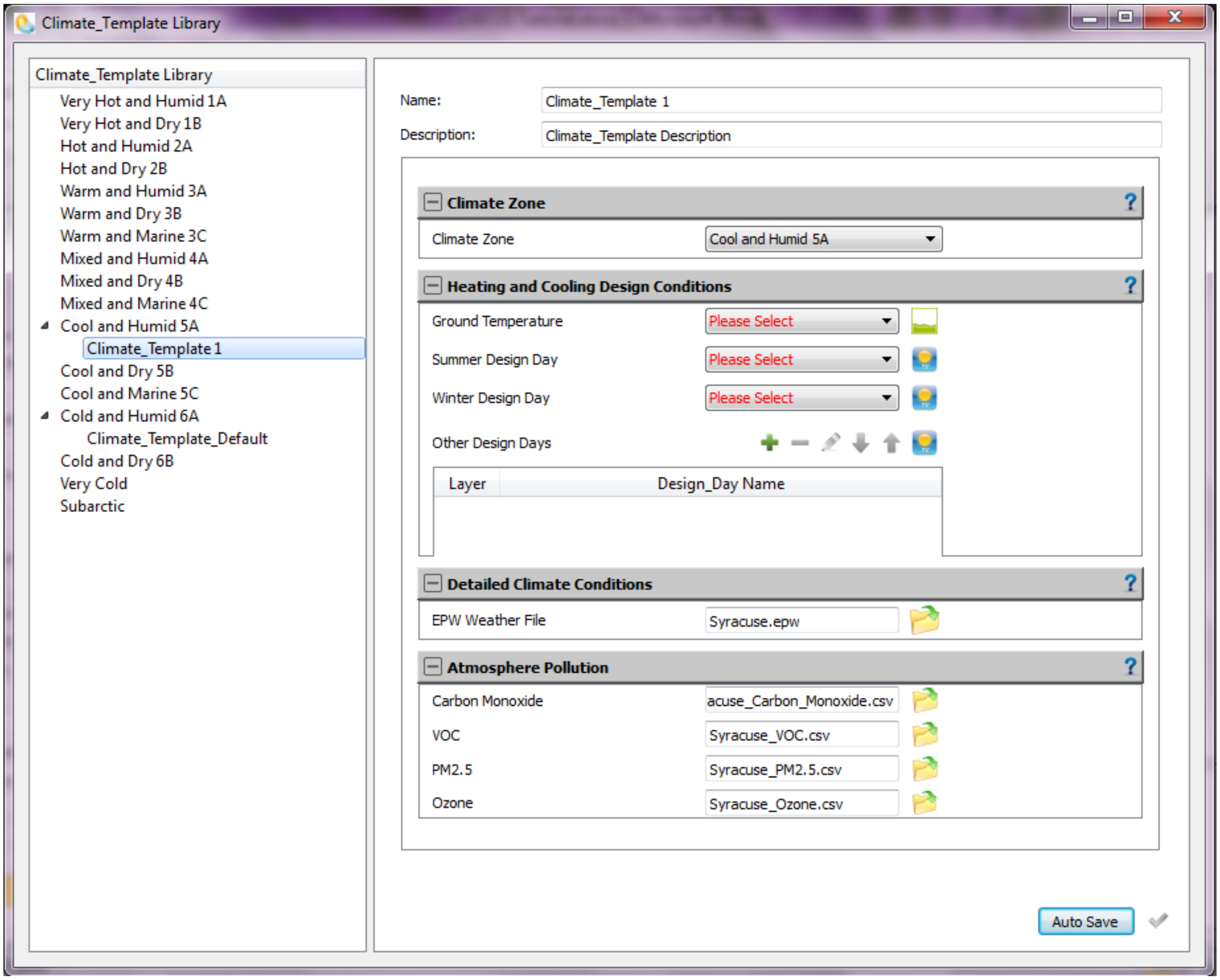


Figure 5-13 Input Template

- Right click and select "Delete" to delete the template (Figure 5-14).

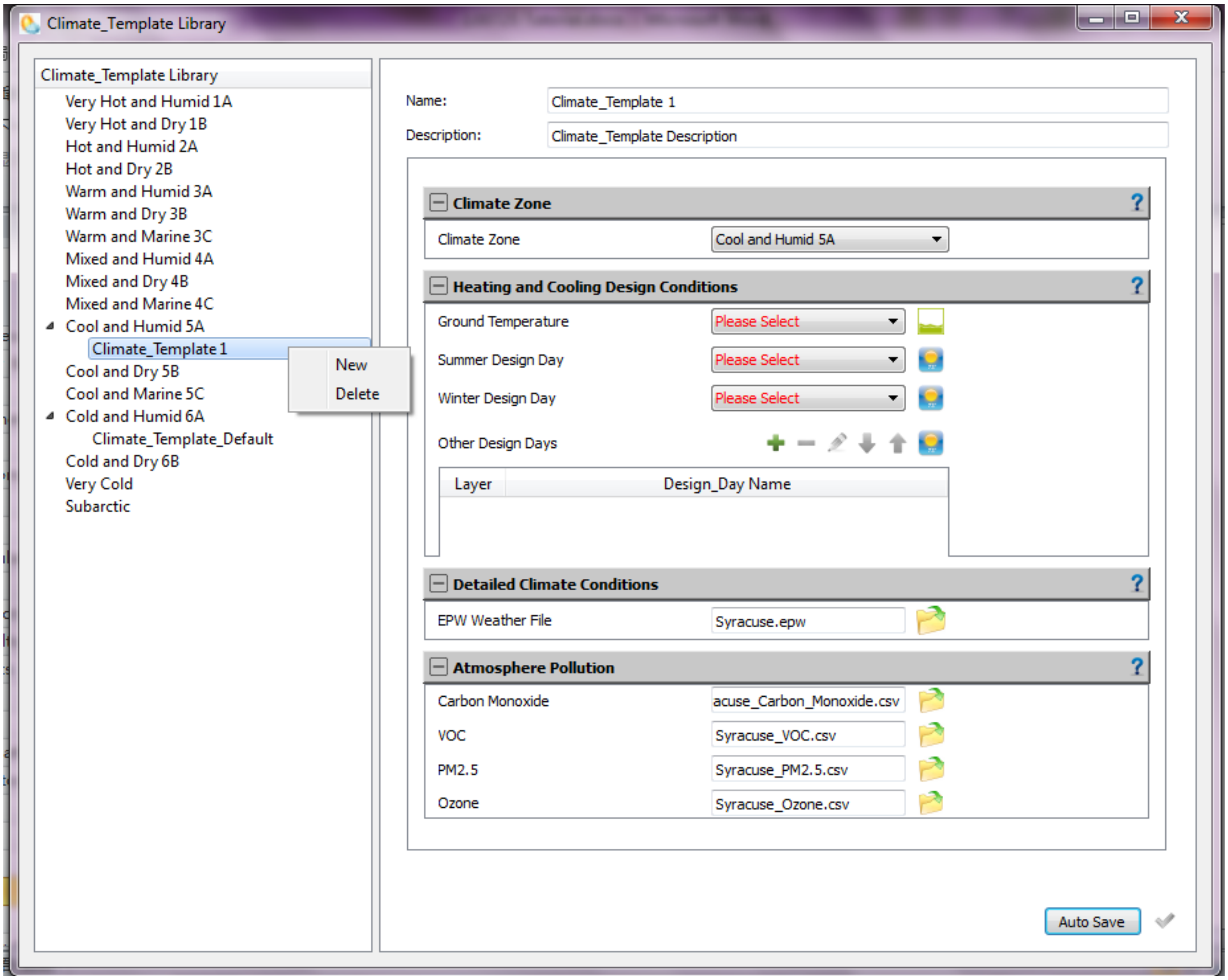


Figure 5-14 Delete Template

- To Save Template file, Click "File->Export-> Export VDS Libraries Templates"

References

[1] M. Pelken, Zhang, J.S., Y. Chen., Z. Meng, S. Semahegn, and F. Lin. 2013. Virtual Design Studio: Interdisciplinary Design Processes. Building Simulations – an International Journal. Volume 6, Issue 3

[2] Zhang, J.S., M. Pelken, Y. Chen., Z. Meng, S. Semahegn, and F. Lin. 2013. Virtual Design Studio: Introduction to the overall and software framework. Building Simulations – an International Journal. Volume 6, Issue 3.

[3] Google (2013). SketchUp Software Homepage. Available from http://www.sketchup.com/intl/en/product/index.html. Accessed May. 2013.

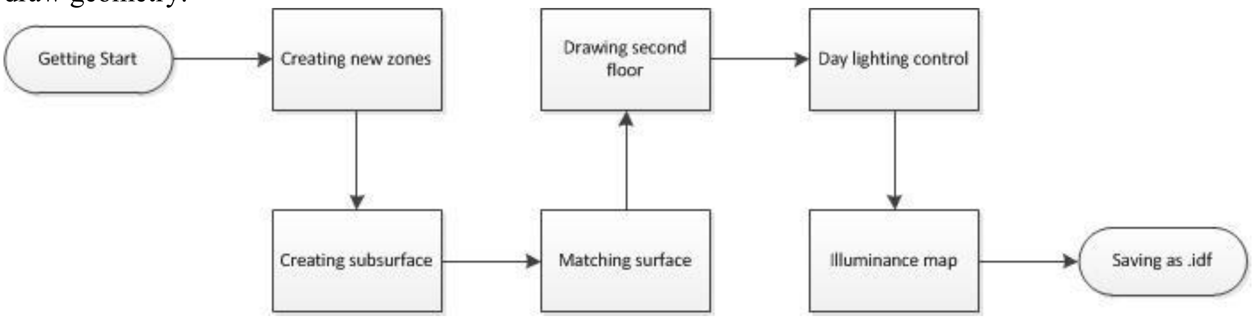
[4] OpenStudio Software (2013). Available from http://apps1.eere.energy.gov/buildings/energyplus/openstudio.cfm. Accessed May. 2013.

[5] OpenStudio plugin User Guide (2013).

[6] Jianshun Zhang, Michael Pelken, Yixing Chen, Daniel J. Rice, Zhaozhou Meng, Shewangizaw Semahegn, Lixing Gu, Hugh Henderson, Wei Feng and Francesca Ling, " Development of an Integrated Computer Simulation Environment for Performance Based Design of Very-low Energy and High IEQ Buildings "

Appendix A (SketchUp+OpenStudio)

This appendix shows how to create a two floor building model. Here's the flowchart to illustrate how to draw geometry:



A.1 Step 1: Getting Started

When you first open SketchUp with OpenStudio running, or any time you start a new IDF file, OpenStudio loads the NewTemplate.idf file located in the OpenStudio plugin directory. This file comes prepopulated with some basic EnergyPlus objects such as schedules, constructions, and location (the default location is Chicago).

A.2 Step 2: Creating New Zones

- After starting a new IDF file, create your first zone with the New Zone Tool. After selecting the tool from the OpenStudio Toolbar, click in the model where you want the zone origin to be.

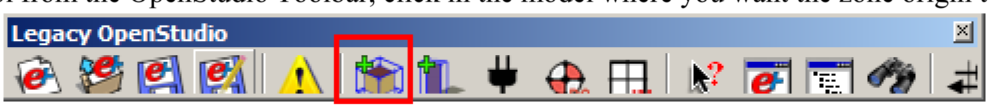


Figure A.2-1: OpenStudio Toolbar in SketchUp

- After you insert the zone you should see a blue bounding box around your selected zone.

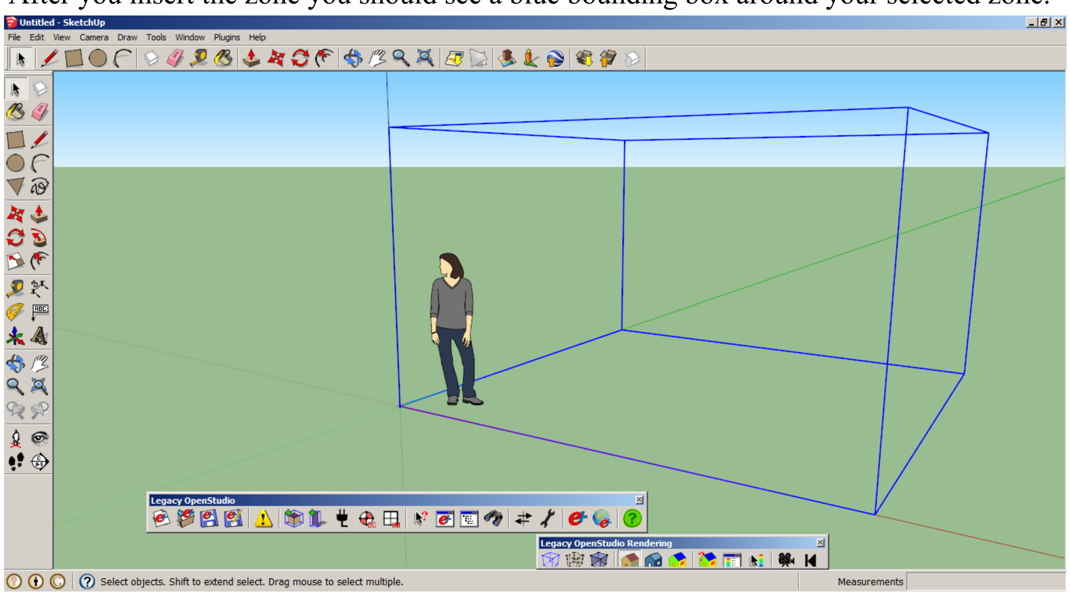


Figure A.2-2: Insert Zone

- You can press “Enter” to activate your zone. Once you do have the zone activated, it should appear like it does below. Your blue solid bounding box is now a dashed line.

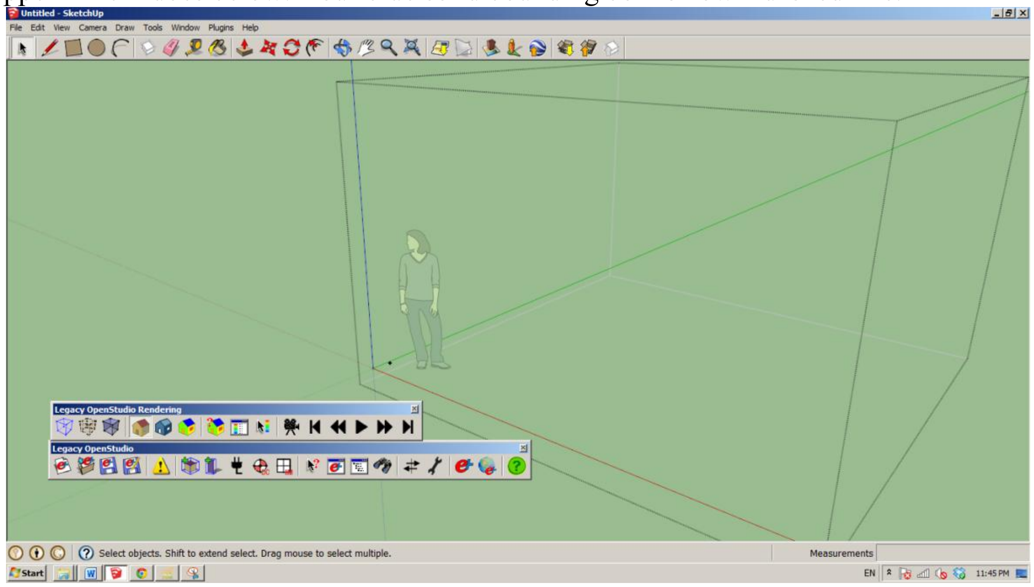


Figure A.2-3: Active Zone

- Now you can begin drawing surfaces within your zone. Your first surface will typically be a floor. You may draw the floor with the Rectangle Tool or one of the other SketchUp drawing tools, such as the Line Tool. Note that SketchUp uses the right hand rule, based on vertex entry order, to determine the outward normal direction for new surfaces EXCEPT for surfaces drawn on the z = 0 plane. Surfaces drawn on the z = 0 plane are assigned outward normal pointing down, correct for floors, regardless of vertex entry order.

Figure A.2-4: Drawing Toolbar

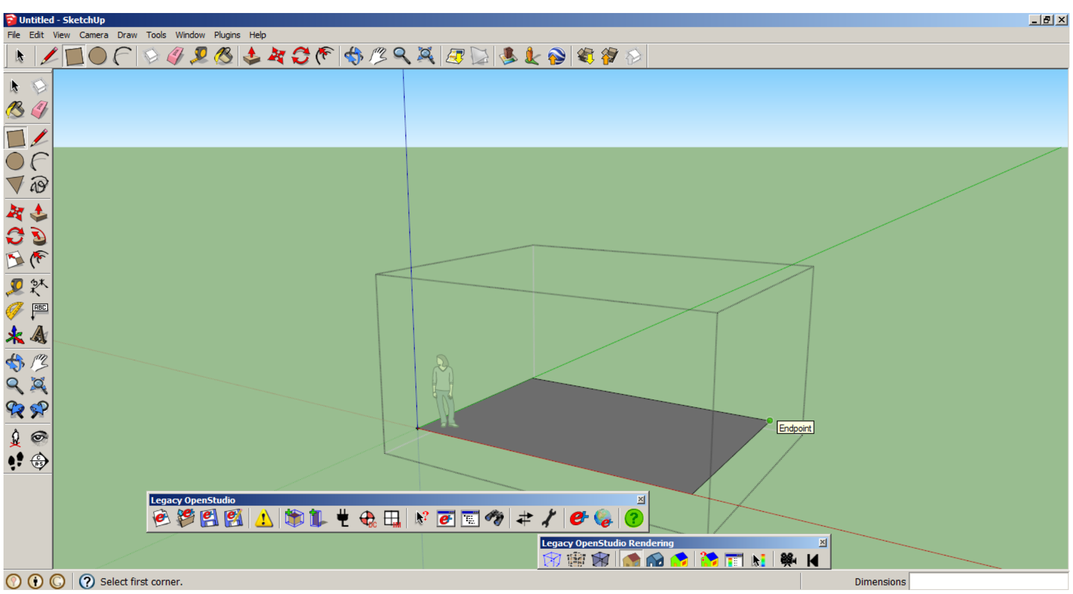


Figure A.2-5: Create Surface

- After the floor is drawn use the Push/Pull Tool to extrude the floor surface. This extrusion will create new surfaces and OpenStudio will infer their type (wall or roof) based on the surface's outward normal. Again you can create geometry with the Line or other tools, but Push/Pull works very well for extruding a floor to create walls and a ceiling. OpenStudio has a color scheme to allow floors, walls, and roofs to be easily identified. Throughout OpenStudio, darker colors are used to identify the outside of a surface, while lighter colors identify the inside. If a surface is oriented the 'wrong way' you may right click on it and select Reverse Face.

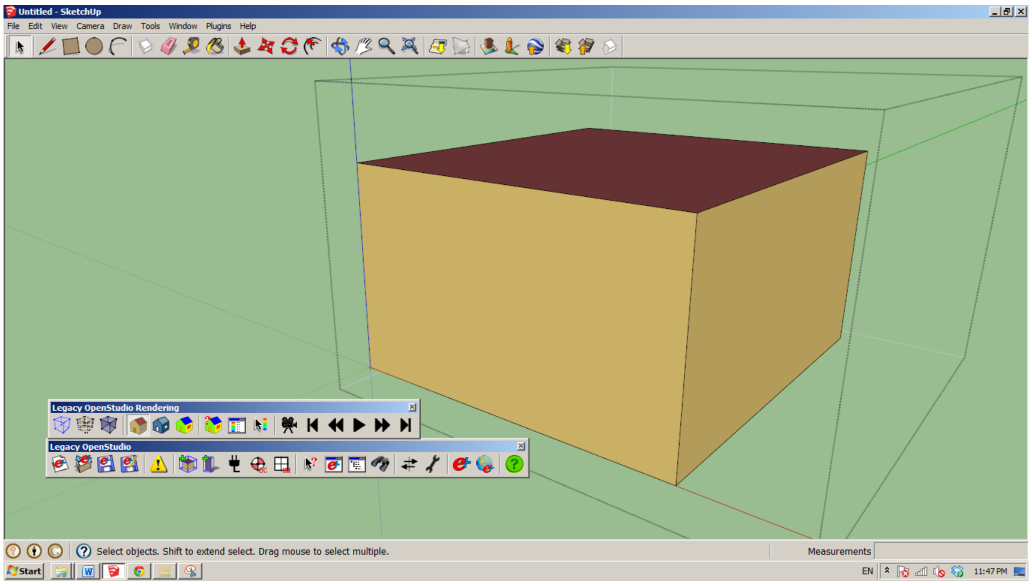


Figure A.2-6: Push to a room

A.3 Step 3: Creating Subsurfaces

Once you have four walls and a roof, you can start adding subsurfaces to your model. Subsurfaces are, as their name suggests, surfaces that sit within a base surface. This includes doors, windows and skylights.

 Use this to draw window and door, if one side of rectangle reach floor, it will be door. Others will be window.

There are a number of guidelines to follow with subsurface.

- Do not make a sub-surface as large as its base surface. If you want a full wall window, inset the window a small amount. This is easily done using the Offset Tool (available in the large SketchUp toolset).
- Do not all a sub-surface to share an edge with another sub-surface or a base surface.
- If you want to erase a sub-surface make sure to erase the edges and not just the face. You can either erase just the edges or double-click on the sub-surface to select the face and edges. Do not erase edges that are also part of the base surface edge. (e.g. the bottom of a door).
- Subsurfaces also have their own automatic color scheme. Doors are brown, and windows are a translucent blue. If you draw something and it is not the color you expected, that is a sign that something is wrong.

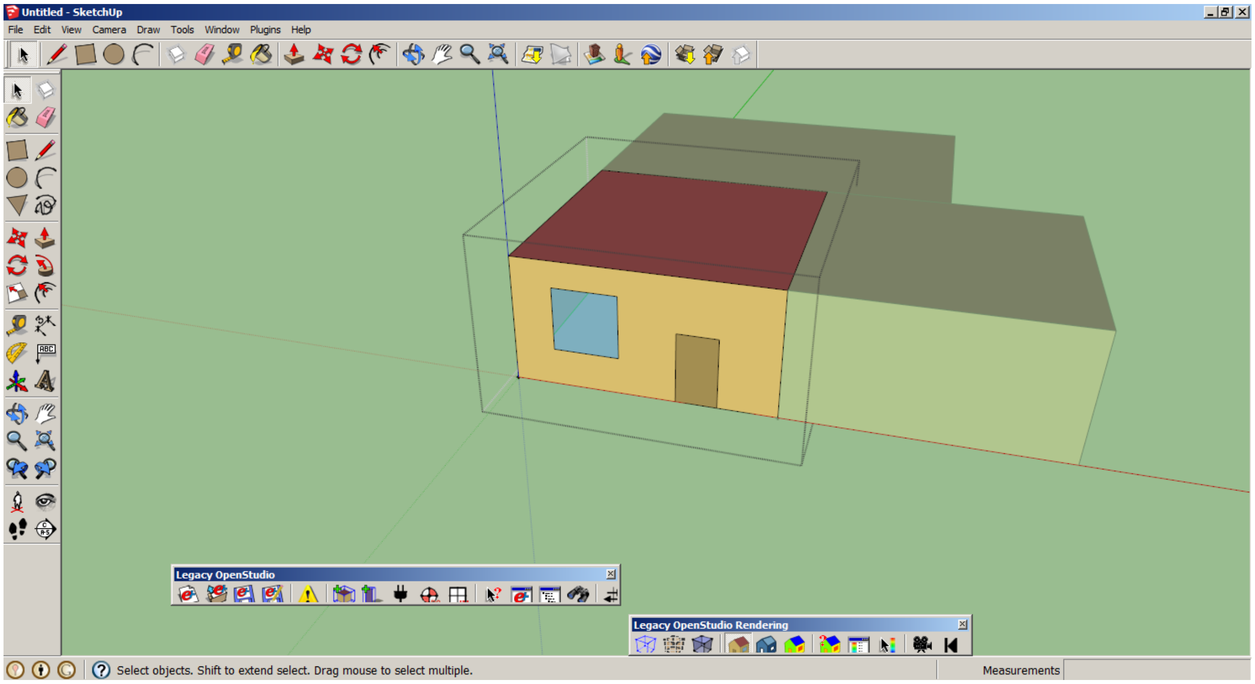


Figure A.3-1: Window and Door Drawing

A.4 Step 4: Matching Surfaces

This method uses SketchUp's drawing tools and inference locks.

- Enter into the zone where you want to draw your new surface, but leave the other zones visible.
- Use the line tool to draw lines that snap to objects in another zone. SketchUp will indicate this with a pop-up note that reads "Endpoint Outside Activity".
- You may have to navigate around the model with the pan and orbit tools to draw all the edges of your surface.
- If geometries in other zones are in your way, you can temporarily hide them. Select them and then right-click->hide, or go to "hide" in the edit menu.

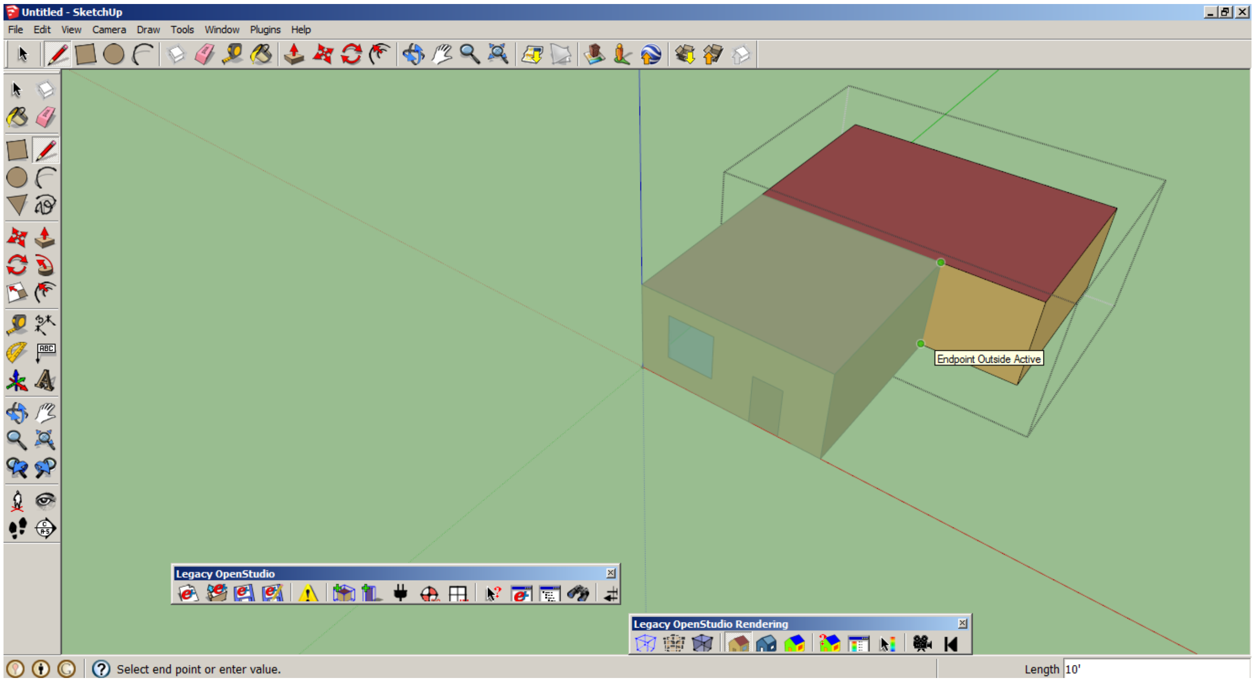


Figure A.4-1: Cut surface to be matched

The example above has a smaller zone sharing three edges with a larger zone.

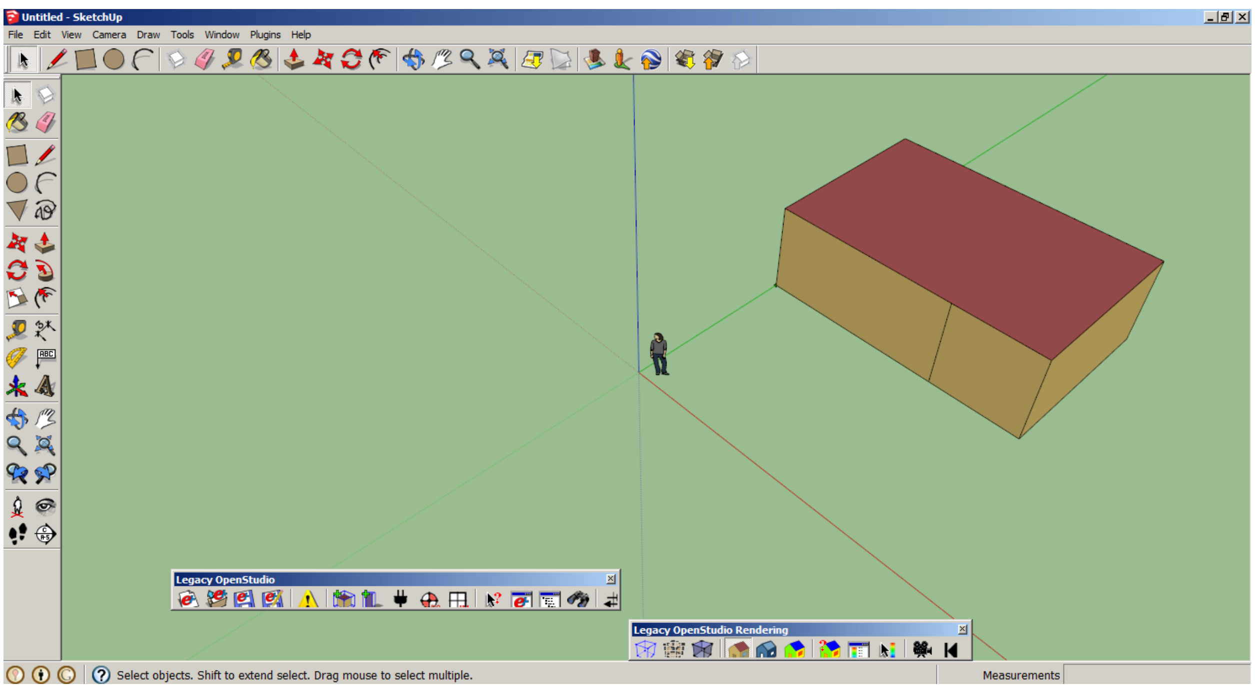


Figure A.4-2: After Cutting

The same operation should be done for other zones.

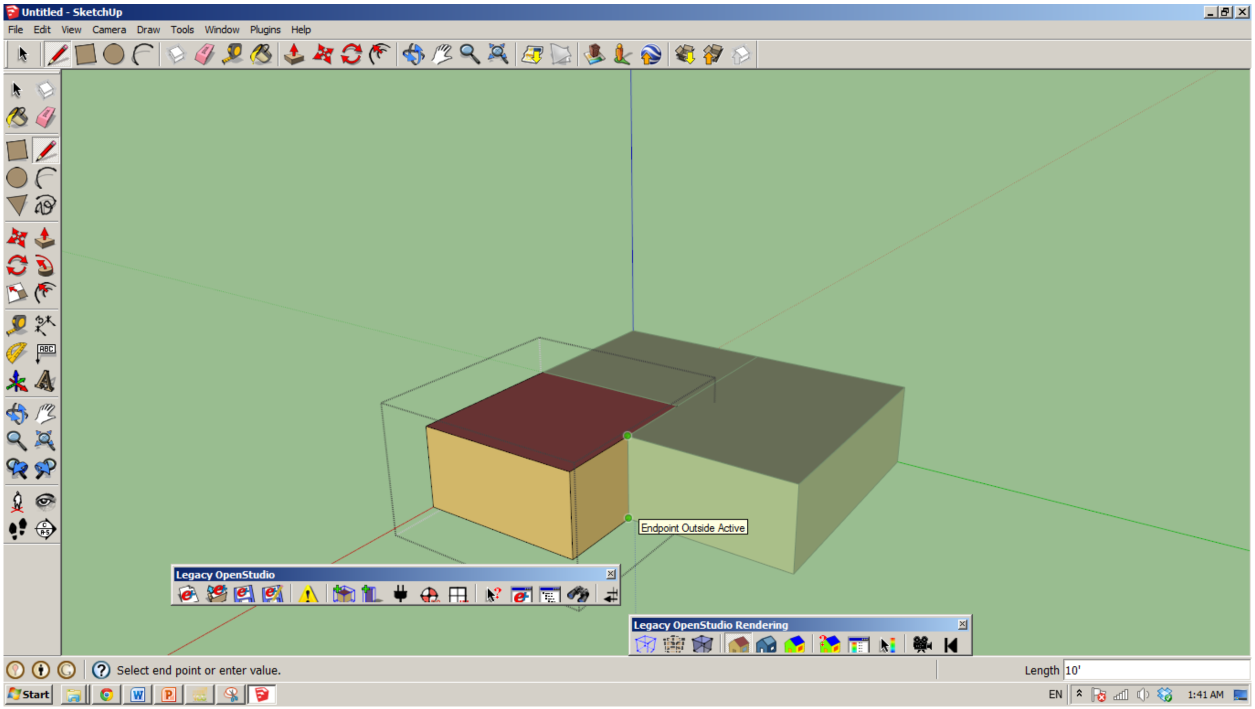


Figure A.4-3: Cut surface in other zones

- Surface Matching Tool

    - Once your surfaces are drawn, you can use the Surface Matching Tool to match them together.
    - You can match surfaces and subsurfaces for selected objects or for all objects in the model. This sets the boundary condition of each surface to point to each other and reassigns the default interior construction for that type.
    - You can also use this tool to unmatch surfaces. This resets their boundary conditions to be outdoors or ground and reassigns the default exterior construction for that type.
    - OpenStudio may not find some non-rectangular surfaces. You can match these manually using the Object Information Window. Change the Outside Boundary Condition to "Surface" and then identify the matching Outside Boundary Object.
    - You can obtain a report of the last match or unmatch performed in comma separated value (CSV) format to verify the operations that have been performed.

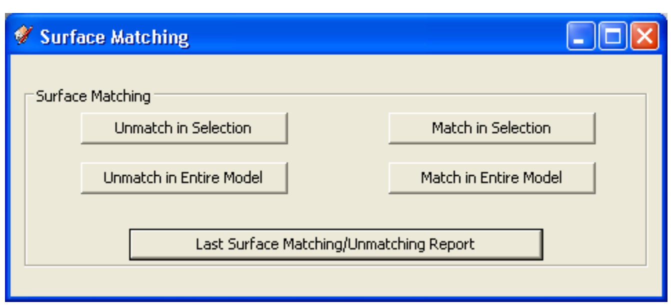


Figure A.4-4: Surface Matching Tool

After matching surface, surface can be divided to be exterior and interior.

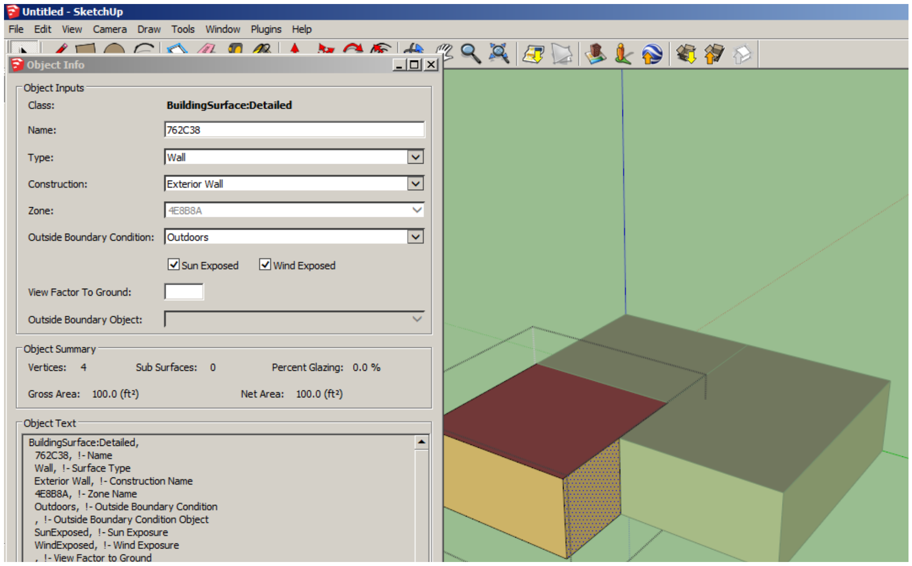


Figure A.4-5: Exterior Surface Information

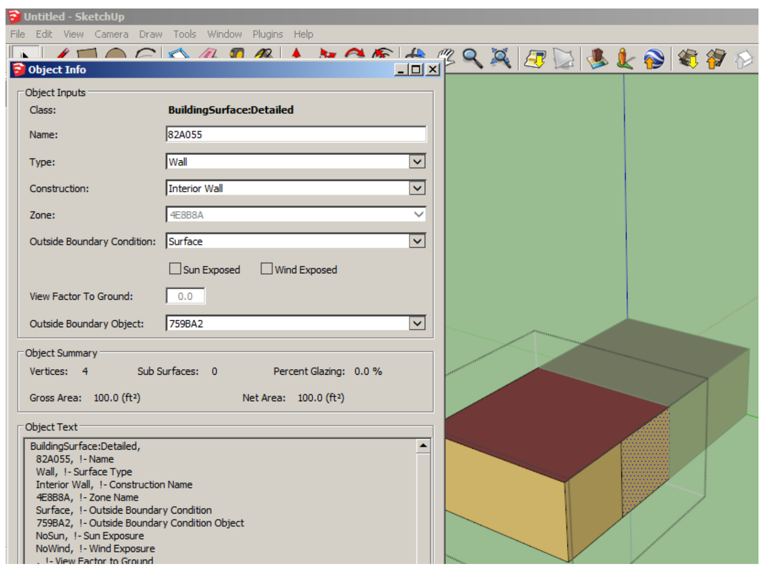


Figure A.4-6: Interior Surface Information

A.5 Step 5: Drawing Second Floor

- The second floor can be drawn following above steps. First to create a zone and origin located in the corner of first floor's roof.

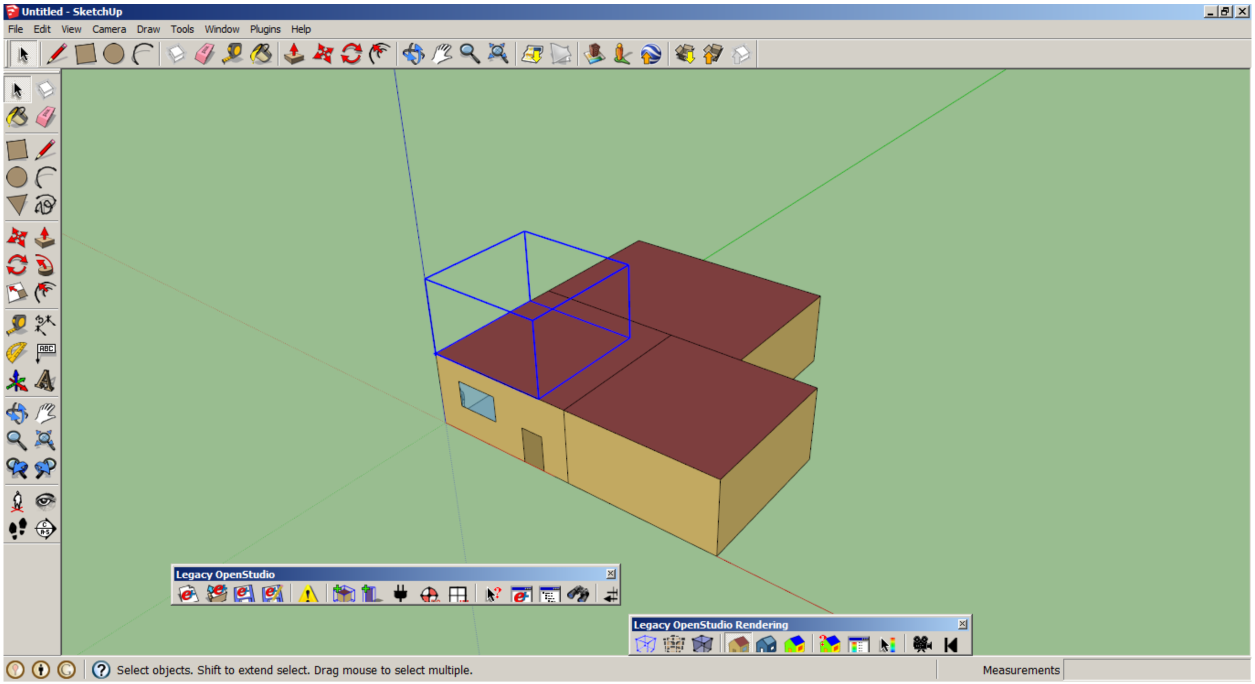
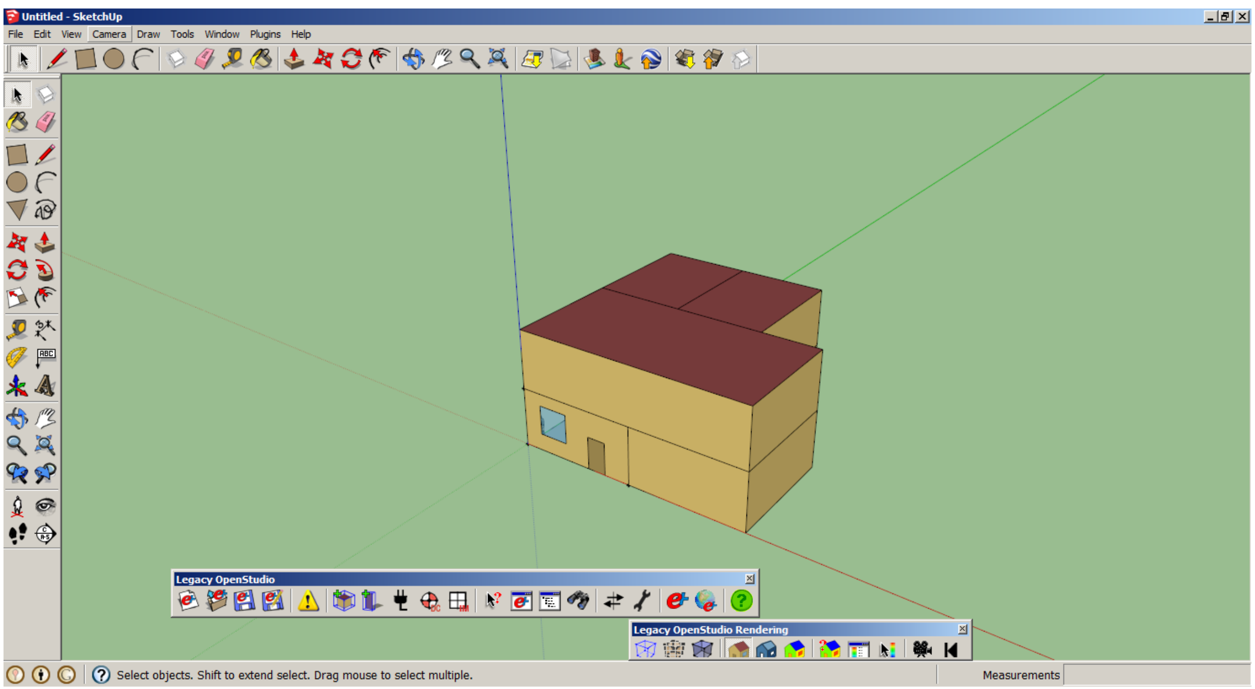


Figure A.5-1: Create Second Floor



FigureA.5-2: Final model

- Match ceiling and floor. Cut ceiling and floor then match them as first floor matching walls.

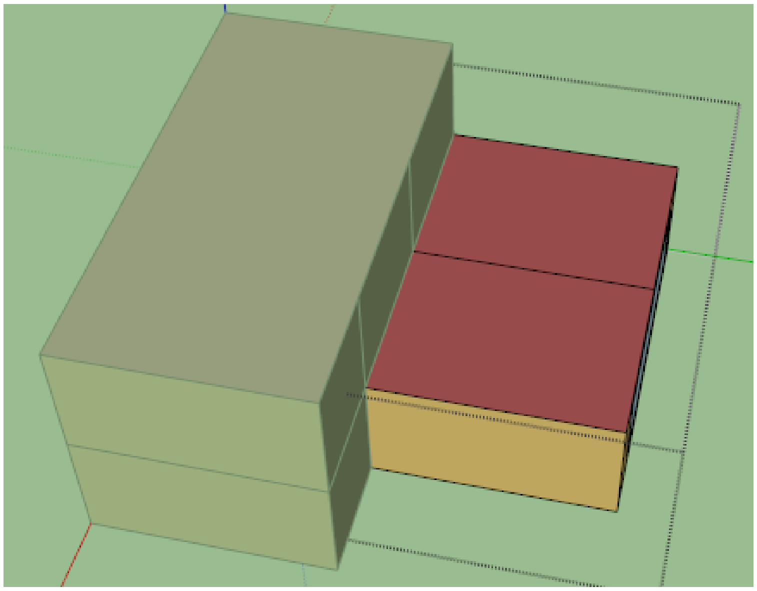


Figure A.5-3: Cutting ceiling

A.6 Step 6: Daylighting Control

A.6.1 Add a Daylighting: Controls Object

- Click  "Section plane" to expose interior details in the model. It will display a green plane in order to choose which plane you want to be hidden.

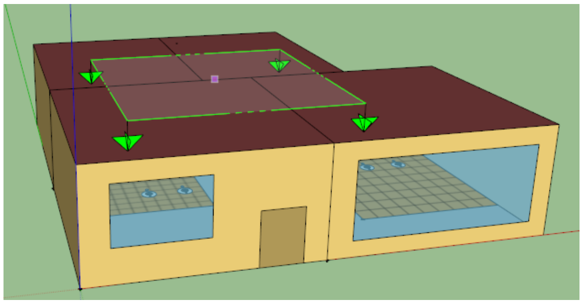


Figure A.6-1: Choose plane to hide

- After hiding top plane, model shows as below:

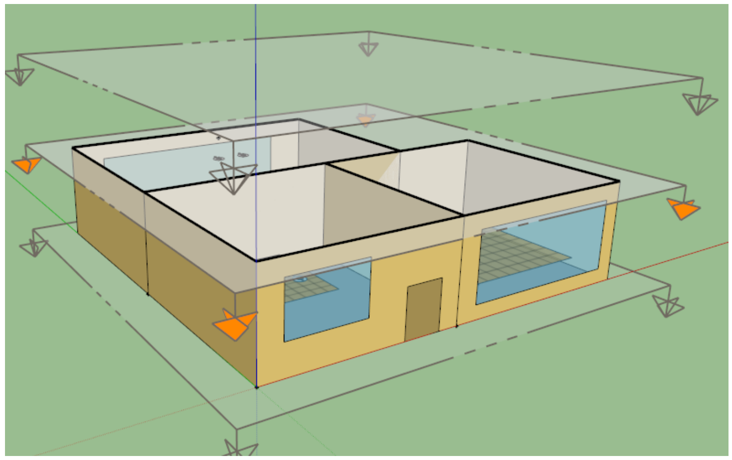


Figure A.6-2: After hiding top plane

- If you want to hide section plane so that drawing is more convenient, you can choose "Section Plane" from "View" then uncheck it.

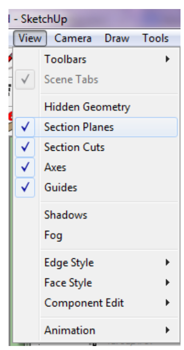


Figure A.6-3: "Section Plane" from "View"

- Model after hiding the section plane as shown below:

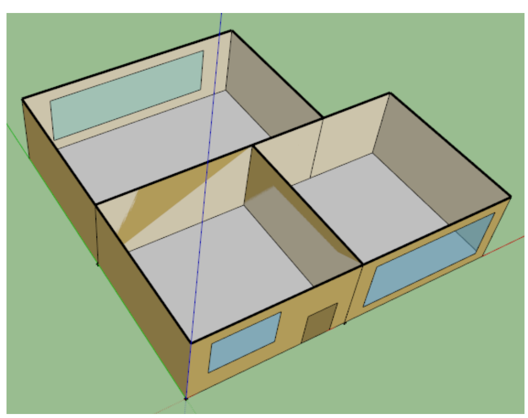


Figure A.6-4: Model after hiding section plane

- Enter into the zone where you want to place the Daylighting:Controls object. If you try to add Daylighting: Controls outside a zone you will see alert.

- Click on the toolbar button to activate the tool. Click on the model where you want to insert the Daylighting: Controls object. When you place the object, it will locate 30 inches above the surface, edge, or vertex you click on.

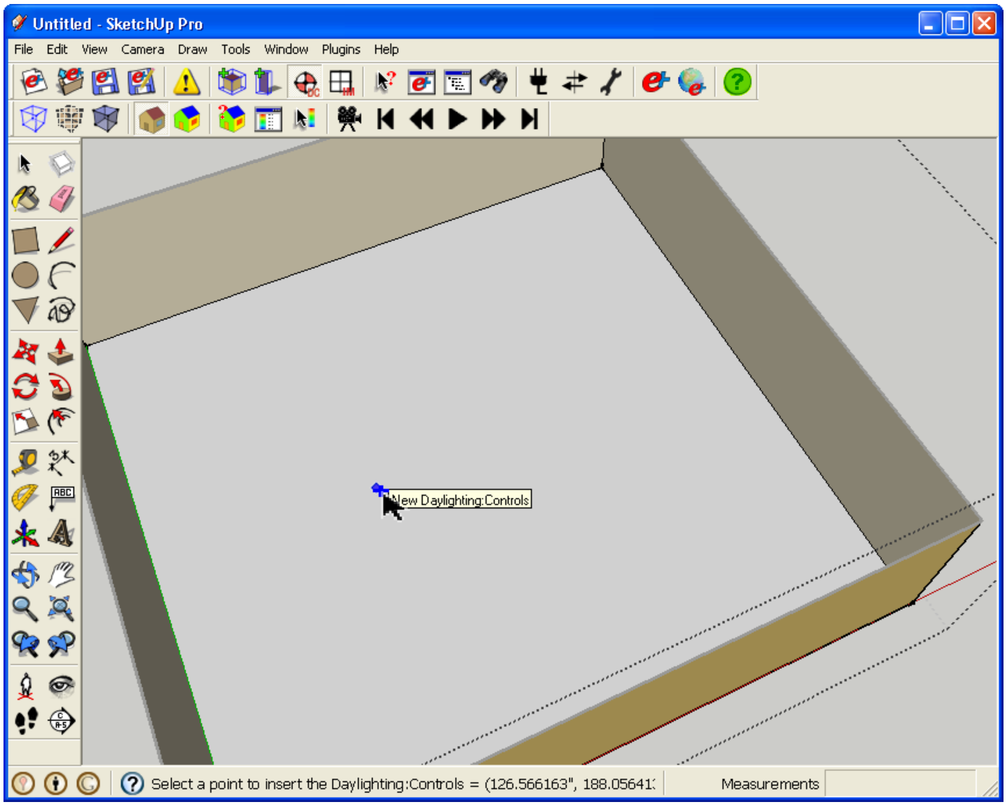


Figure A.6-5: Choose location for daylighting controls

- See below to learn how to relocate the Daylighting: Controls once you have placed them.
- You cannot add more than one Daylighting: Controls object to a single zone.
- To obtain results from EnergyPlus for your Daylighting: Controls, make sure the zone also has a Lights object. You can add lights through OpenStudio with the Zone Load tool.

A.6.2 Make Changes

- You can switch between one and two sensors and change the position of each sensor through the Object Info dialog box by clicking.

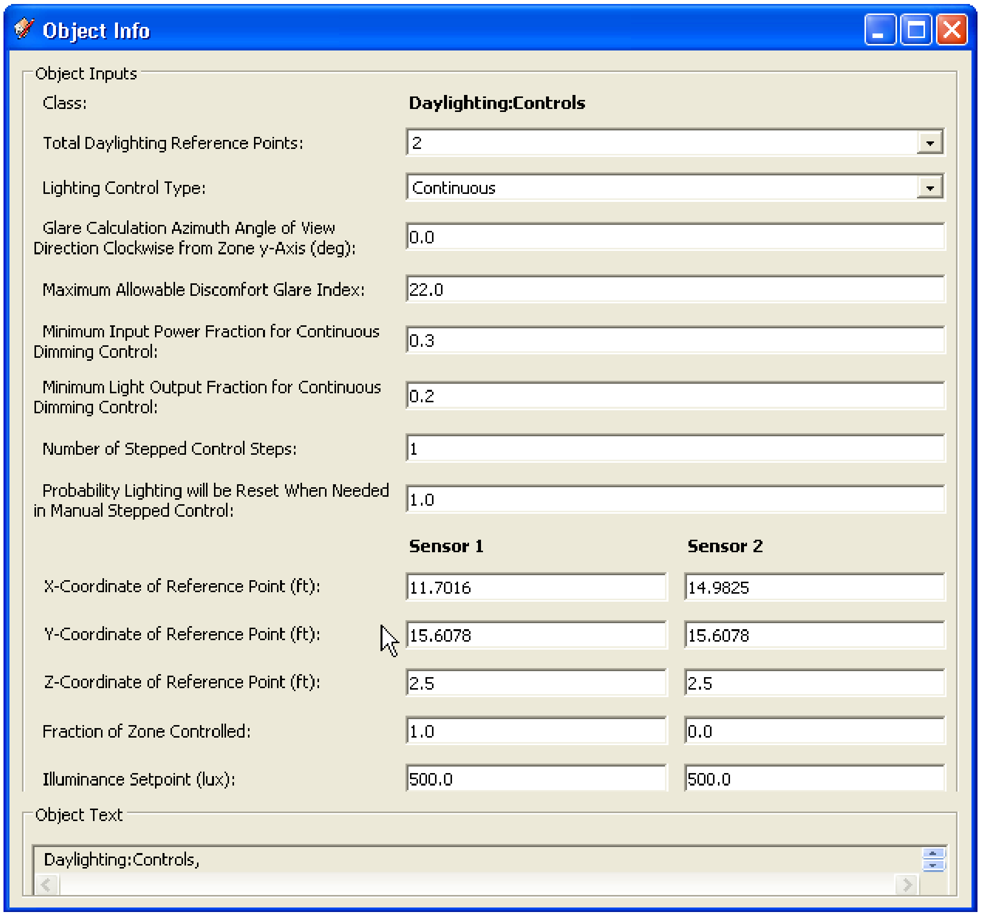


Figure A.6-6: Object information for daylighting control

- You can change the position of the sensors by double-clicking the Daylighting: Controls object and using SketchUp's move tool to drag the sensors around.

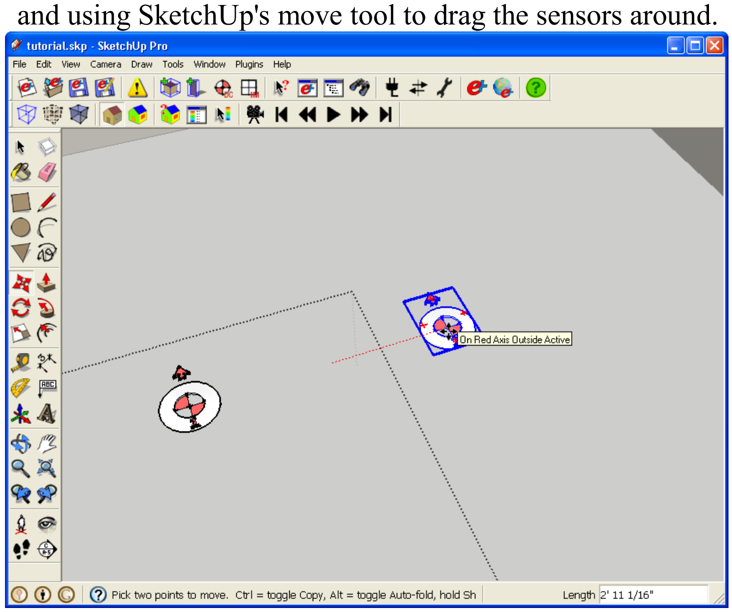
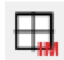


Figure A.6-7: Arrow for daylighting control

- The arrow on Daylighting:Controls object reflects the Glare Calculation Azimuth Angle of View Direction setting. Rotating the sensors does not change this setting.

A.7 Step 7: Illuminance Map

A.7.1 Adding an Output: Illuminance Map

- Enter into the zone where you want to place the Output:IlluminanceMap. If you try to add Output:IlluminanceMap outside a zone, you will see an alert.
- Click on the toolbar button  to activate the tool. Click on the model where you want to insert the Output: Illuminance Map. When you place the object it will be locate 30-inches above the surface, edge, or vertex you select.
- After you click, the scale tool will be active. There will be 8-pins you can use to scale. Clicking and dragging the edges will scale in one direction. Clicking and dragging the corner will scale in two.

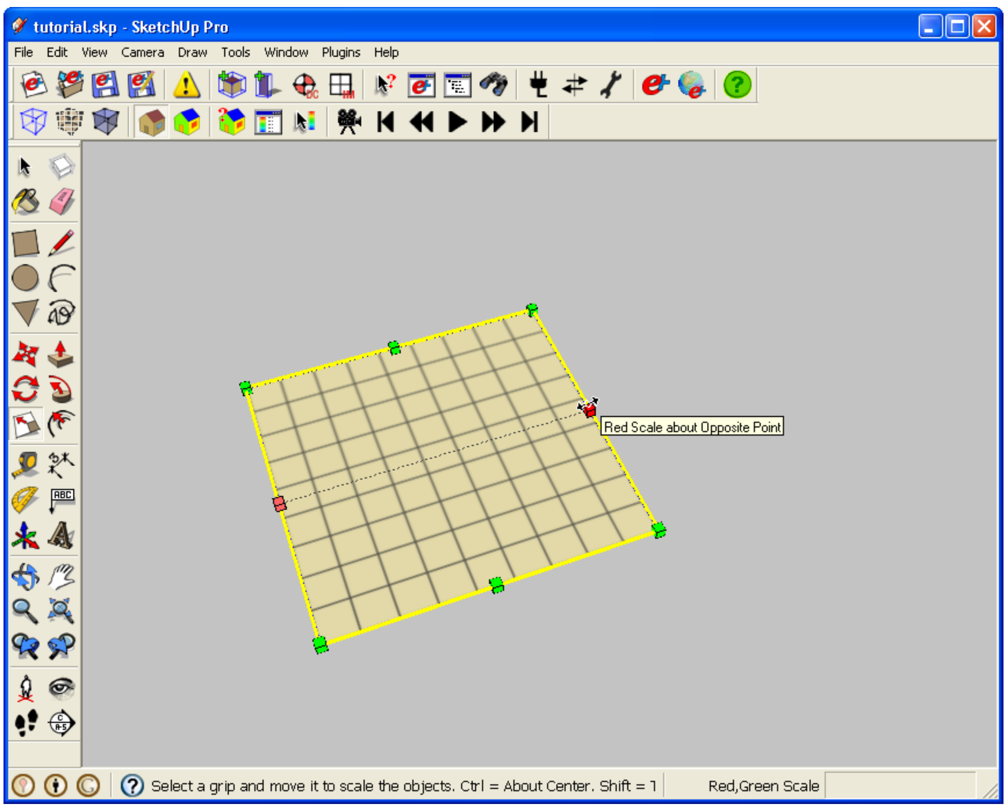


Figure A.7-1: Illuminance Map

- See below to learn how to relocate and resize the Output: IlluminanceMap.
- You cannot add more than one Output: IlluminanceMap object to a zone.
- To obtain results from EnergyPlus for your Output: IlluminanceMap you need to ensure that the zone has Daylighting: Controls and Lights objects.

A.7.2 Making Changes

- You can use the Scale Tool to change the size of the Output: IlluminanceMap (see the following figure). You have the same number of gridlines after scaling the Illuminance Map.

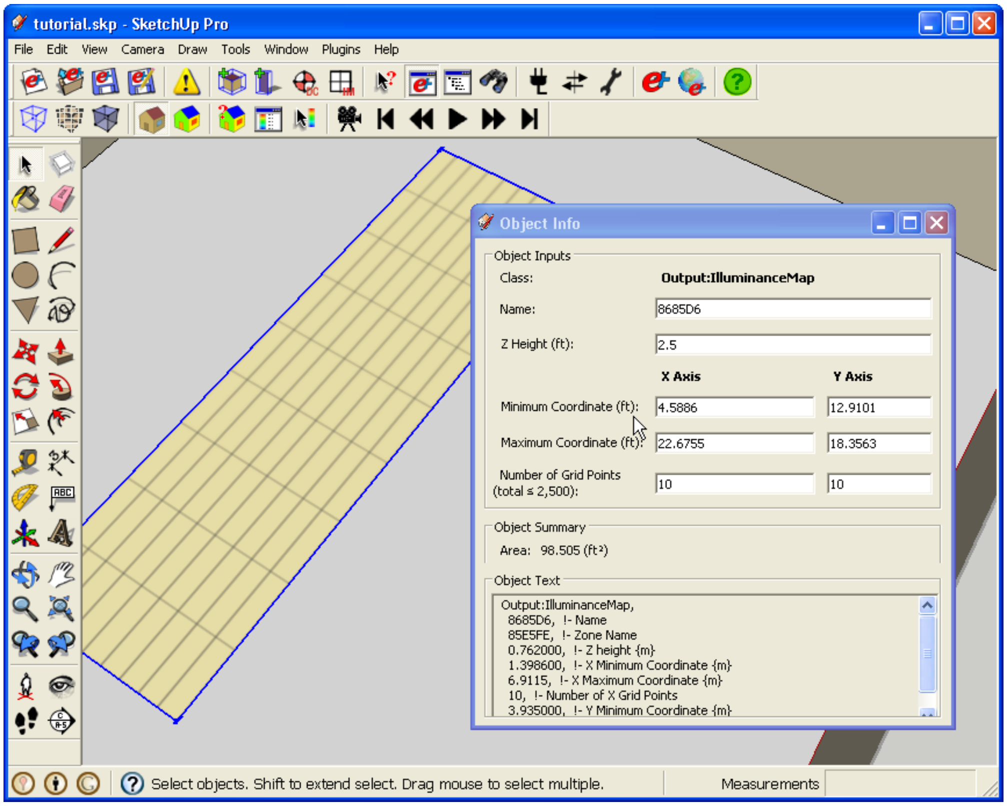


Figure A.7-2: Change Illuminance Map (Before)

- You can use the Move Tool to move the Output: IlluminanceMap.

- You can use the Object Info Dialog box to change the position and size of the Output: IlluminanceMap.

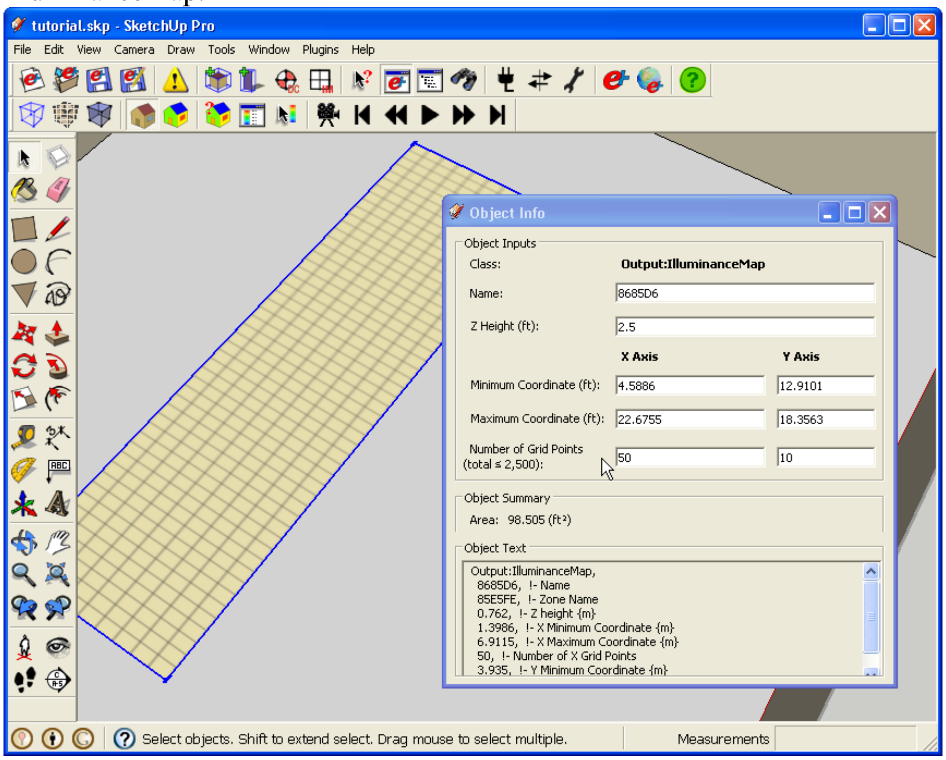


Figure A.7-3: Change Illuminance Map (After)

- You can use the Object Info dialog to change the number of grid points. The texture on the map will reflect the values you have for the grid points. Data is recorded at points where lines cross. The map above has 50x10 grid points, vs. 10x10 grid points on the previous image. EnergyPlus supports up to 2,500 grid points (e.g. 50 × 50 grid points) per Output:IlluminanceMap.
- After finishing all of the above steps, you can unhide top planes. To do this, uncheck the "Section Cuts" option in "View".

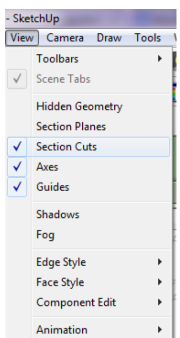


Figure A.7-4: Unhide top planes tool

A.8 Step 8: Save as .idf file

- Using icon. 'Create new', 'Open', 'Save' and 'Save as' .idf file in SketchUp must be done by following icon.

Figure A.8-4: OpenStudio File Toolbar