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Development of an Integrated Process, Modeling and Simulation Platform for Performance-Based Design of Low-Energy and High IEQ Buildings

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Abstract

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. The 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.

Based on the review and analysis of existing professional practices in building system design, particularly those used in U.S., Germany and UK, a generic process for performance-based building design, construction and operation was proposed. It included Assess, Define, Design, Apply, and Monitoring (ADDAM) stages. The current VDS focused on the first three stages.

The VDS considers the 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 the energy efficiency and IEQ

performance with particular focus on thermal, 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 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 predict 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 size five story office building that received the LEED Platinum Certification from USGBC.

Development of an Integrated Process, Modeling and Simulation Platform for Performance-Based Design of Low-Energy and High IEQ Buildings

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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 US. Buildings, including both residential and commercial buildings, 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 shares a large percentage of the total energy consumption. With the increasing concerns on energy and climate change, the concepts of "Low Carbon", "Energy Efficiency" and "Environmental Friendliness" have to be considered and applied in the full life cycle of buildings including conception, planning, design, construction, operation, retrofitting, reuse or demolition and dis-assembly.
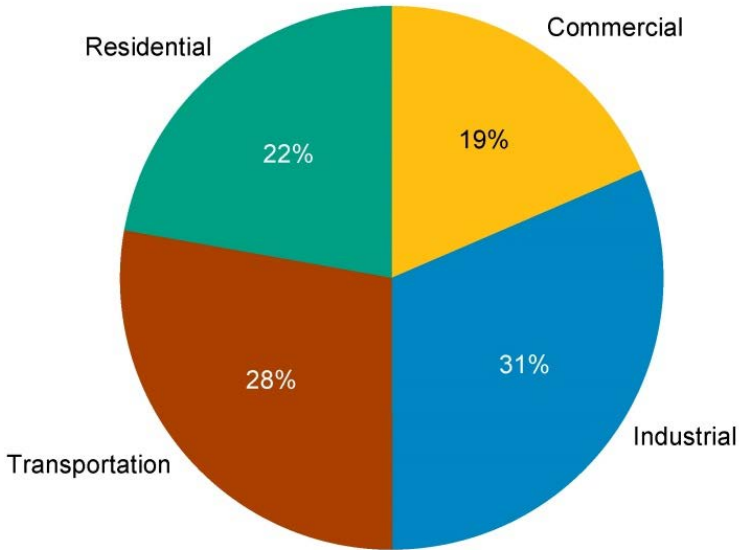
Figure 1-1 End-use sector shares of total energy consumption in 2011 (US EIA, 2013d)
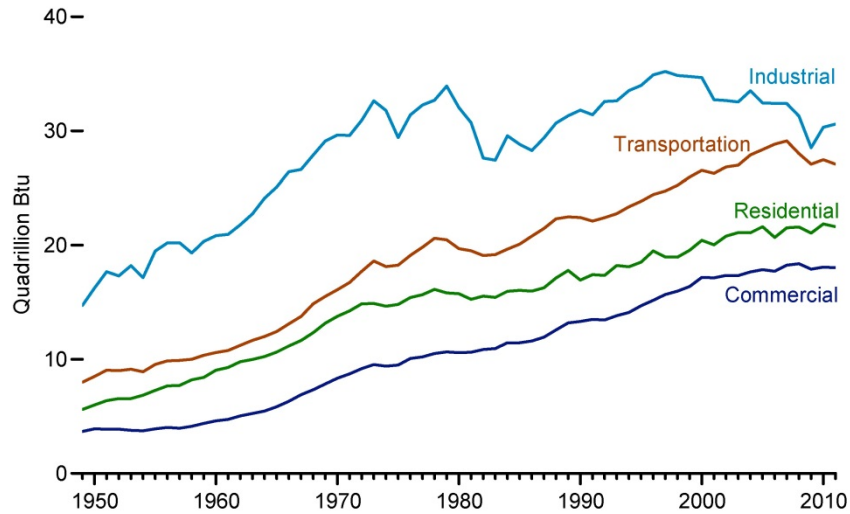
Figure 1-2 Total energy consumption by end-use sector in US from 1949 to 2011 (US EIA, 2013d)

Majority of the energy consumed in buildings are for conditioning the space for building occupants, including heating, cooling, lighting and ventilation (Figure 1-3). At the same time, 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 we strive to maximize energy efficiency of buildings.
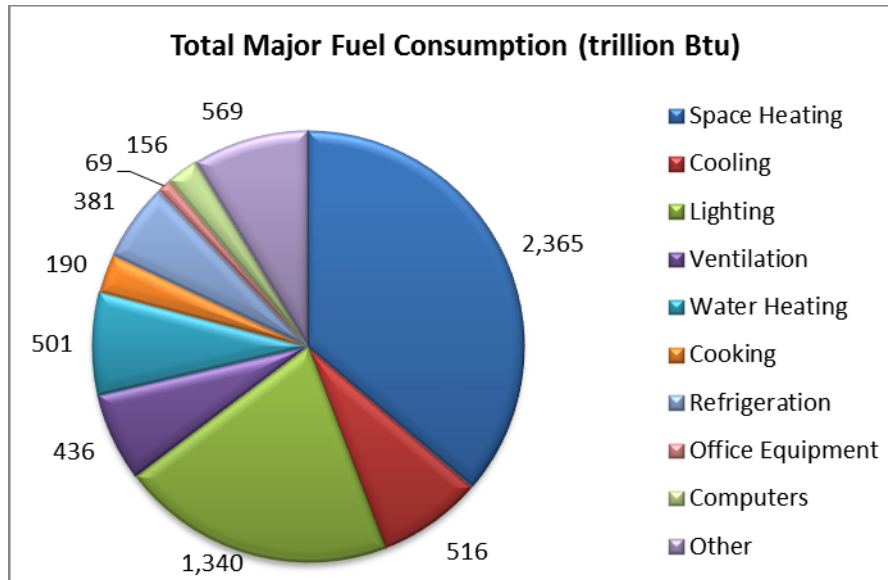
Figure 1-3 Major fuel consumption by end use for all buildings in US, 2003 (US EIA, 2013b)

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 the simulation and analysis. Moreover, these tools are isolated; therefore, they cannot evaluate the combined energy and IEQ performance.

Building design is a multi-disciplinary process requiring the coordination among all participating disciplines such as 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 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 yet providing better indoor climate and air quality. The 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, 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 the 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 of high performance buildings. VDS is intended to assist collaborating architects, engineers and project management team members throughout from the early phases to the detailed building design development. Moreover, it helps to facilitate the workflow and the 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.
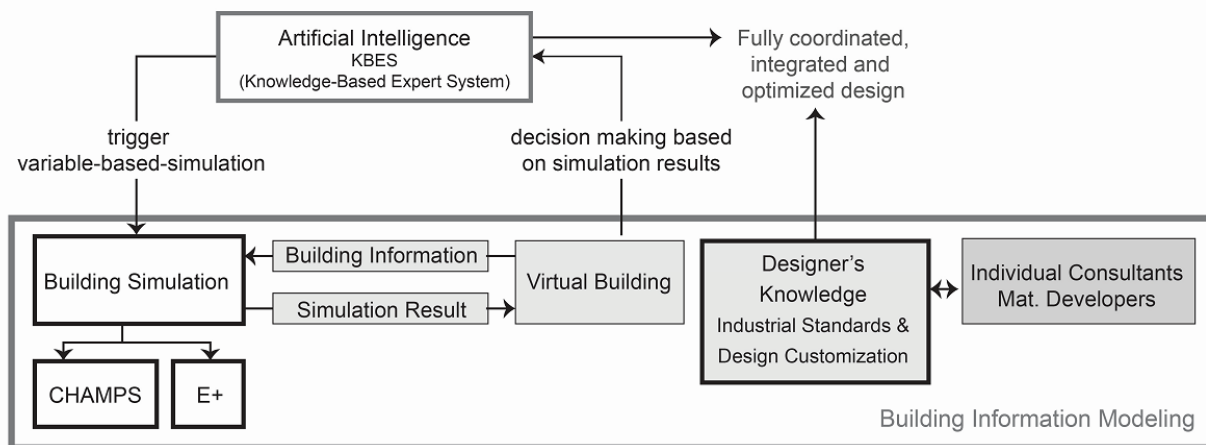
Figure 1-4 Composition of VDS

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The present project has been limited to 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 foreseeable 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 (55-2010 (ASHRAE, 2010a), 62.1-

2010 (ASHRAE, 2010b), and ASHRAE 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 dissertation

This dissertation 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 the 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.

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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 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 first provides a review of some existing leading building design and simulation tools. The performance-based design methodologies are then reviewed. Moreover, the building design processes are reviewed. Furthermore, it reviews the 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 for 402 building software tools for evaluating energy efficiency, renewable energy, and sustainability in buildings (US DOE, 2013a). This section only provides a review of some existing leading building design and simulation tools related to this research.

The Designer's Simulation Toolkit (DeST) (Yan, et al., 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 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 can help architects to evaluate building performance based on building information modeling (BIM). It can read BIM files generated by Revit for detailed building geometry inputs as well as 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. Moreover, it also 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 to sketch a building 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 oppose 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, CO_2 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 are listed 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".
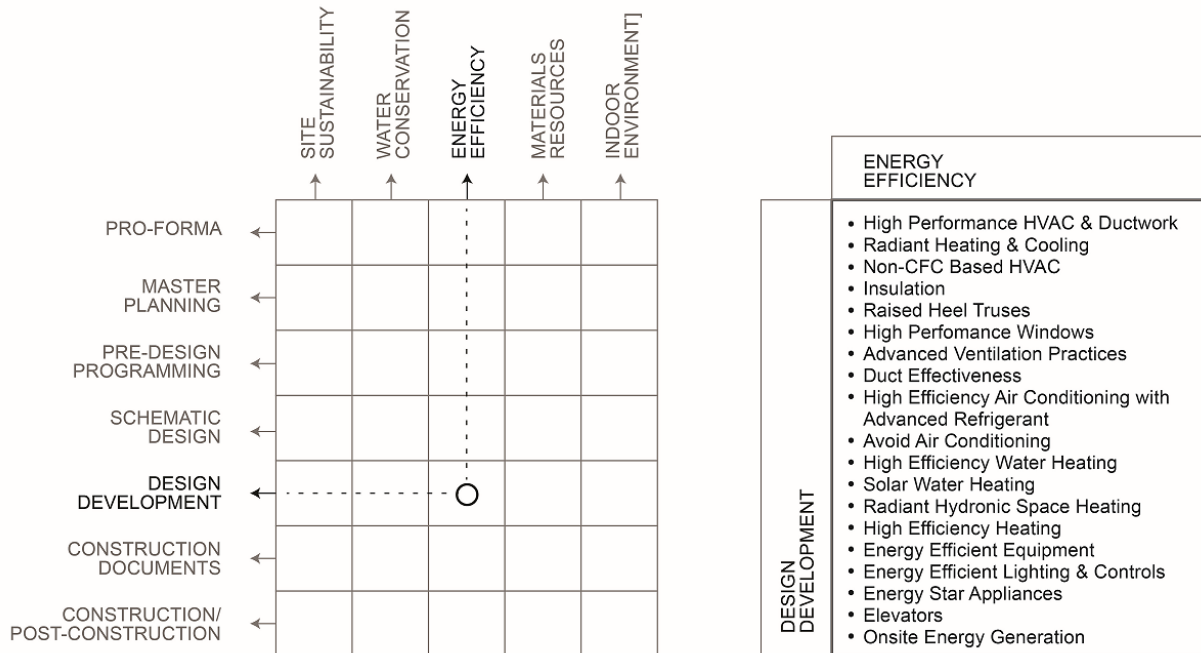
Figure 2-1 Green Matrix (Ratcliff, 2007)

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)

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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, the 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 for 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 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 and 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 therefore required and facilitated by the VDS. As the design process is typically not a completely 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 practice 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 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).

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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, the 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 • Site development • 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. • Optimize energy performance • On-Site renewable energy • Green power	**Energy Efficiency** • On-site renewable energy systems • Energycons. mgt. • Energy performance of 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 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.

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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 data base for the dissemination of planning and design results, the 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.
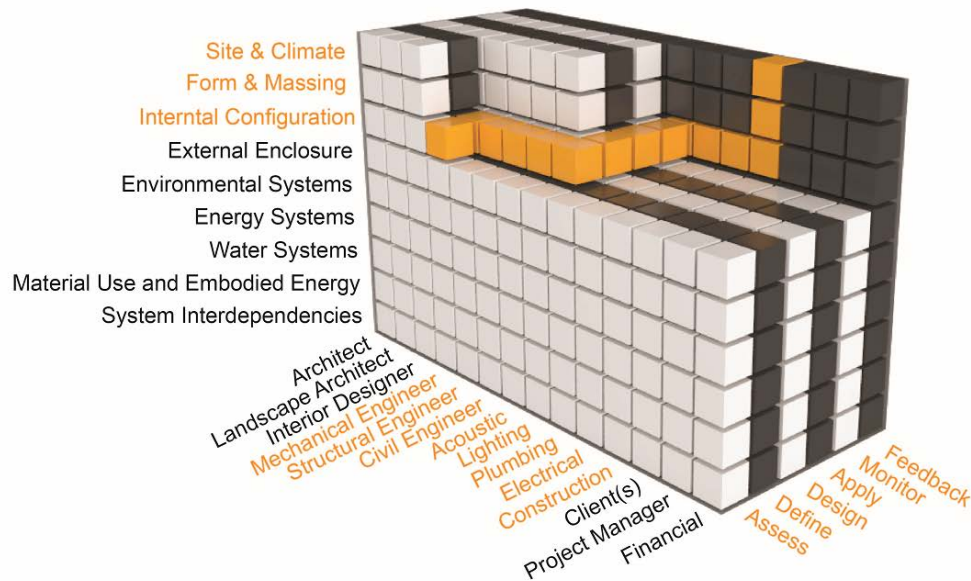
Figure 3-1 Three-dimensional "Magic Cube" matrix for VDS structure

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).
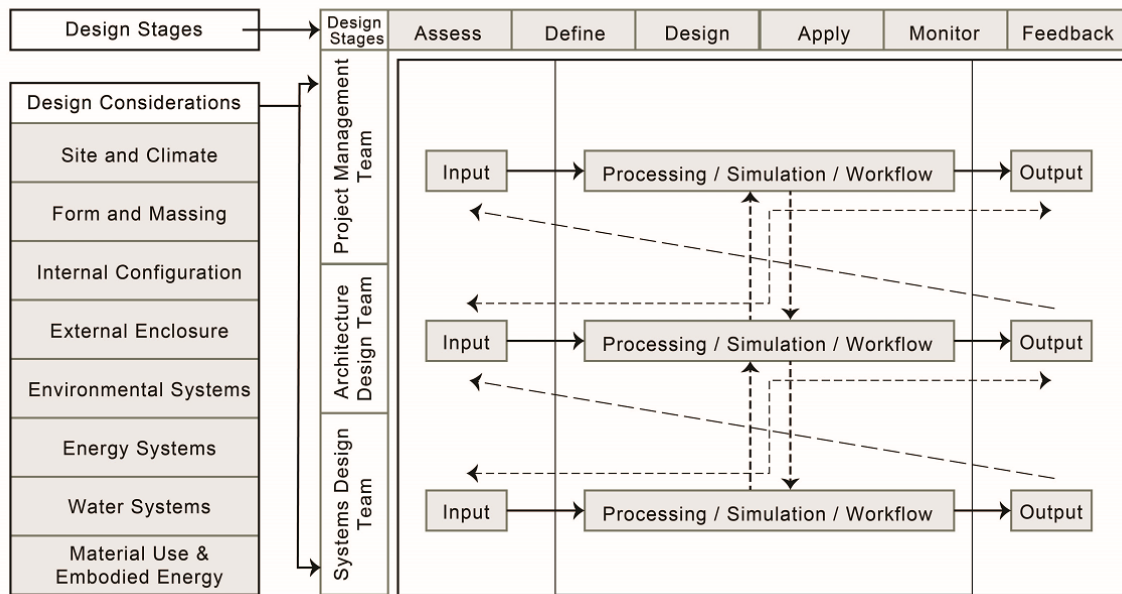
Figure 3-2 Input-Processing-Output methodology and feedback loops for VDS structure
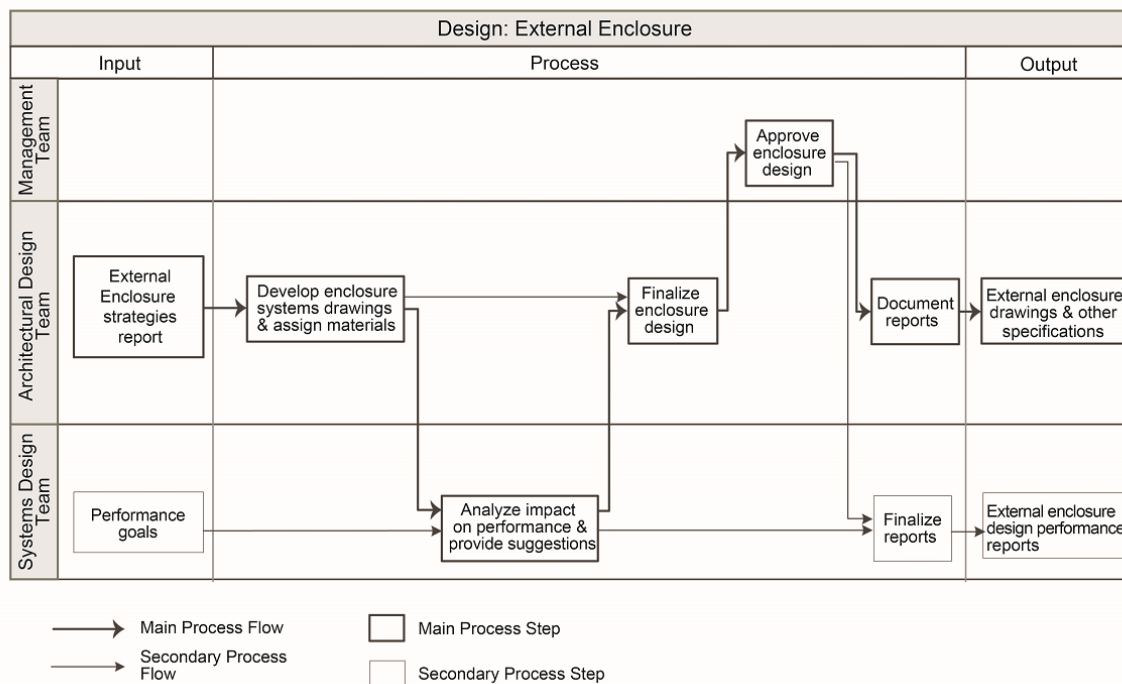
Figure 3-3 Developed Input-Processing-Output Rationale

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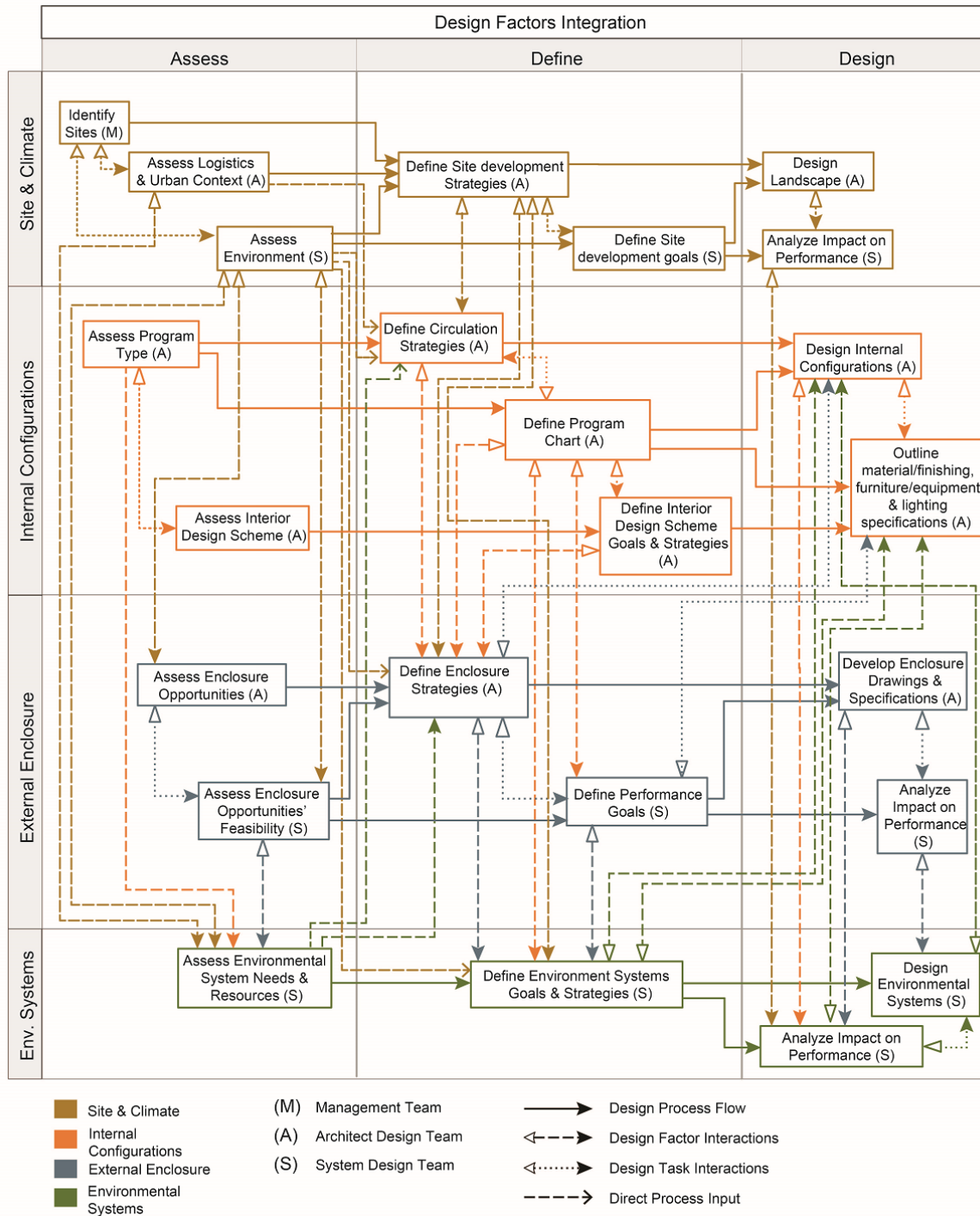
Figure 3-5 System Interdependencies and components cross-references in VDS structure

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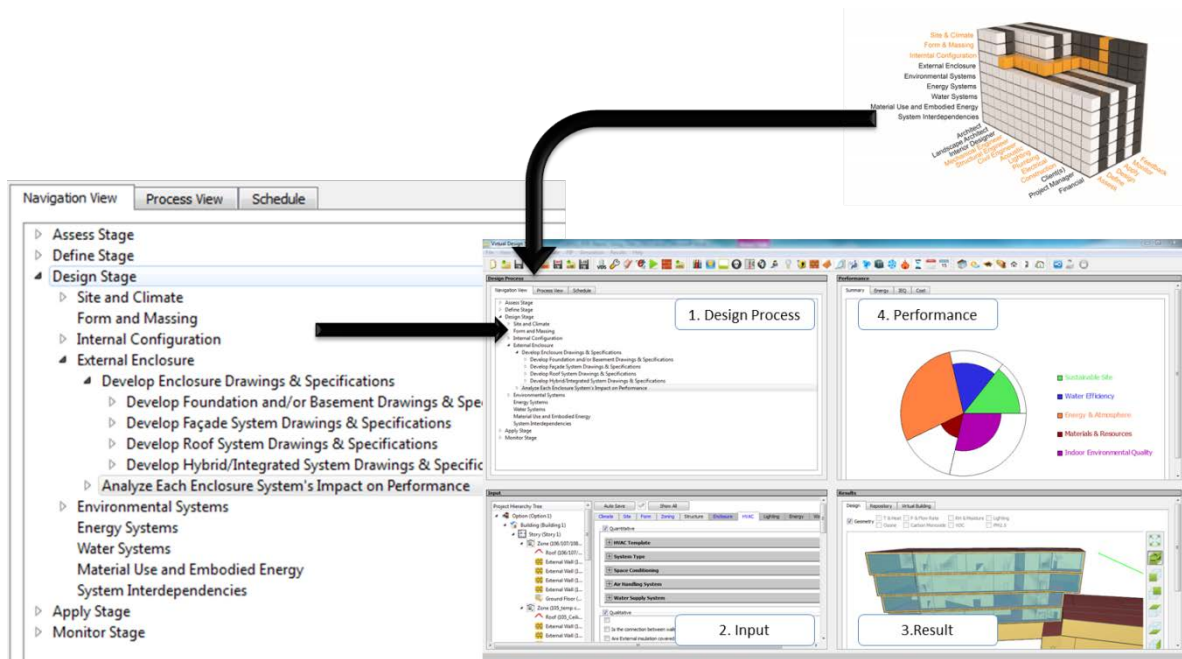
Figure 3-6 Development of VDS GUI based on established platform rationale

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.
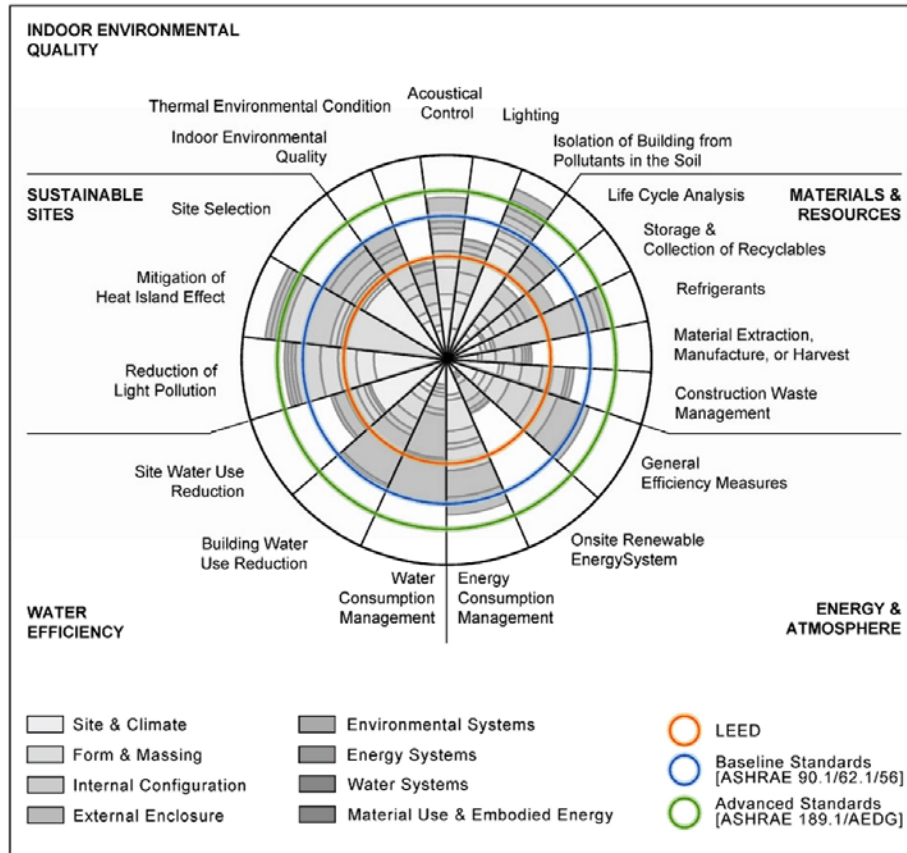
Figure 3-7 Pie chart for a systematic performance comparison

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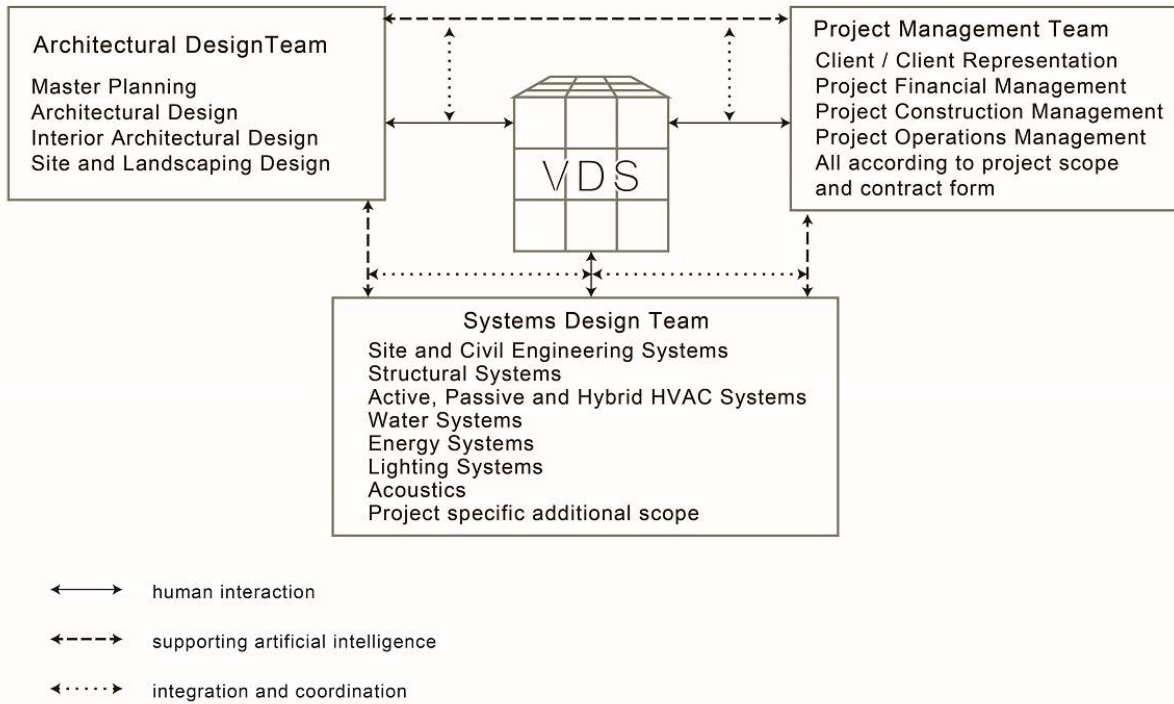
Figure 3-8 Coordination of Human Interaction and VDS supporting Artificial Intelligence

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.
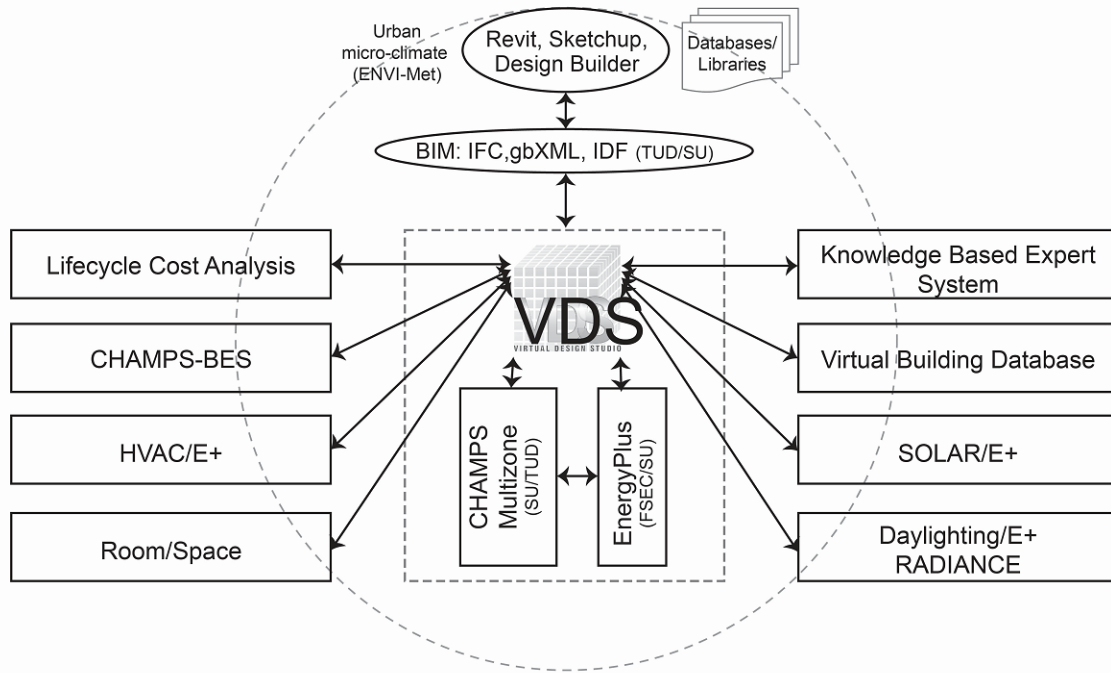
Figure 3-9 VDS Architecture and implementation plan

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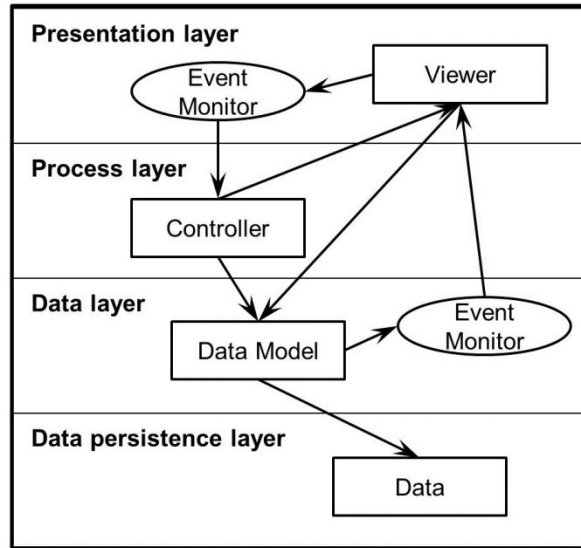
Figure 3-10 VDS MVC architecture pattern viewed in four software layers

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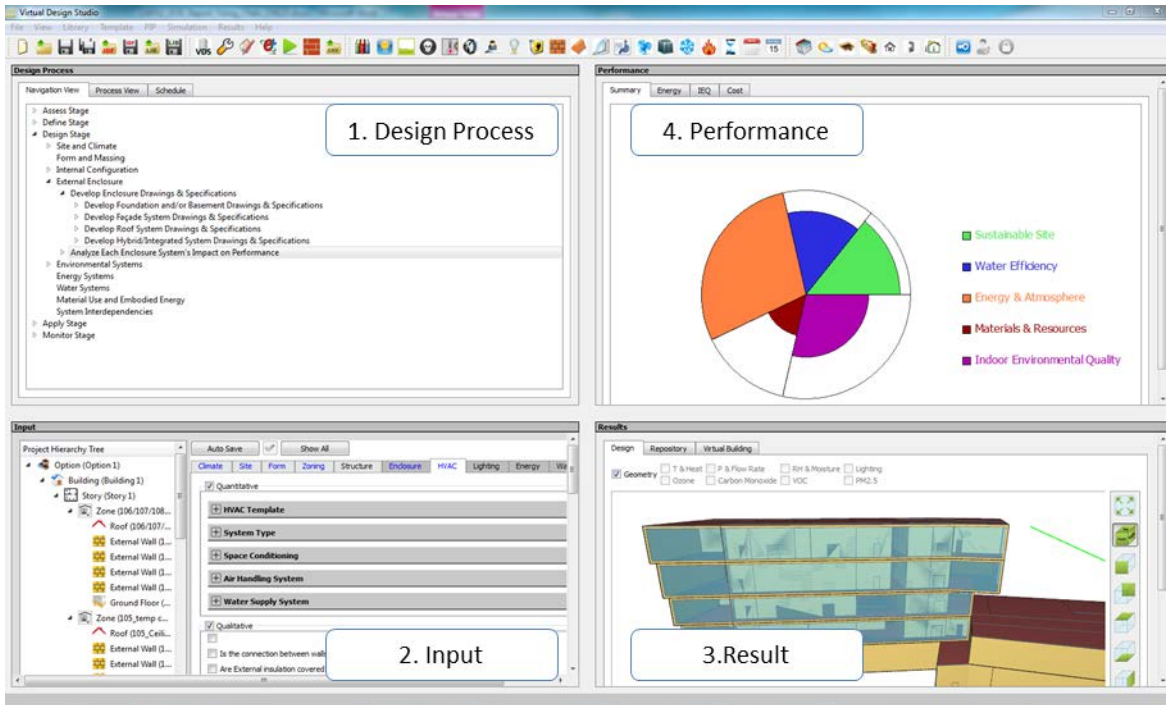
Figure 3-11 Four quads form (viewer) of VDS graphic user interface (GUI)

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.
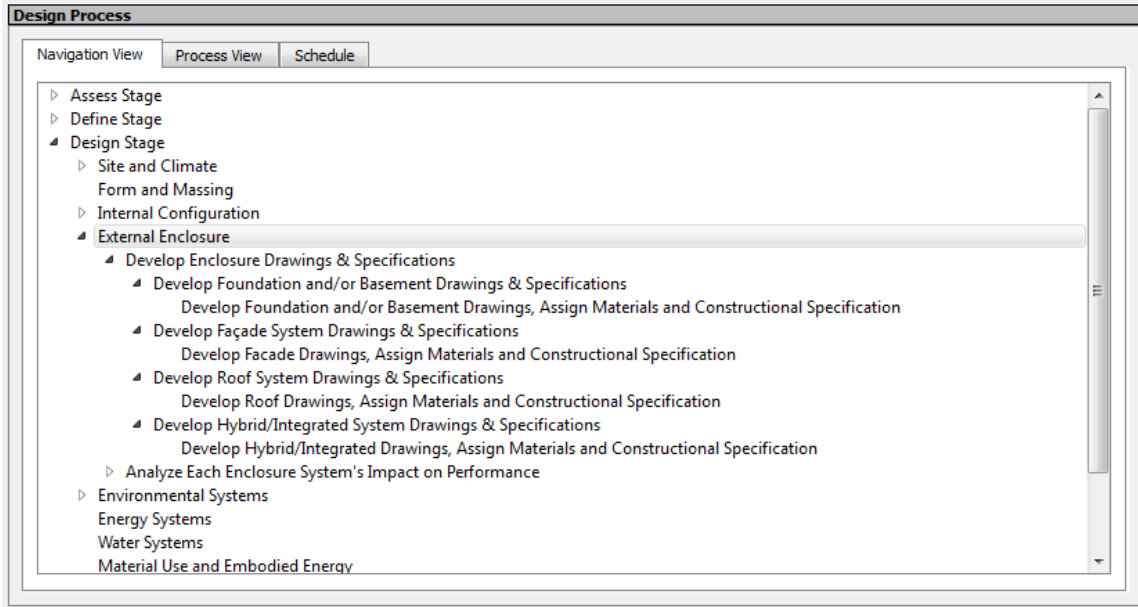
Figure 3-12 Navigation View in Design Process Window
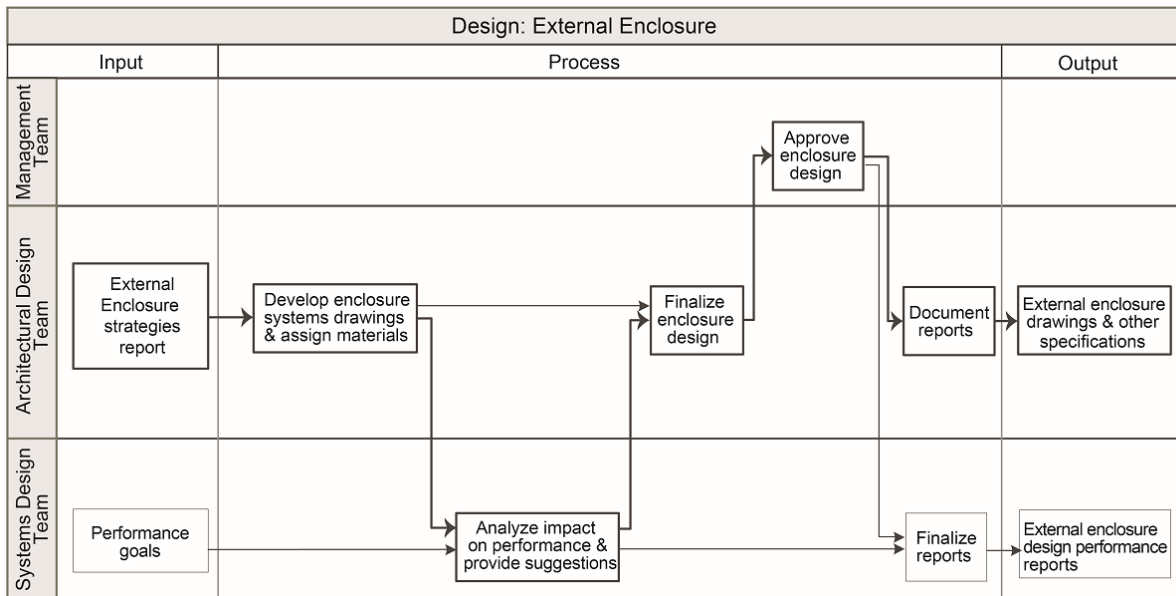
Figure 3-13 Sample of Process View in Design Process Window
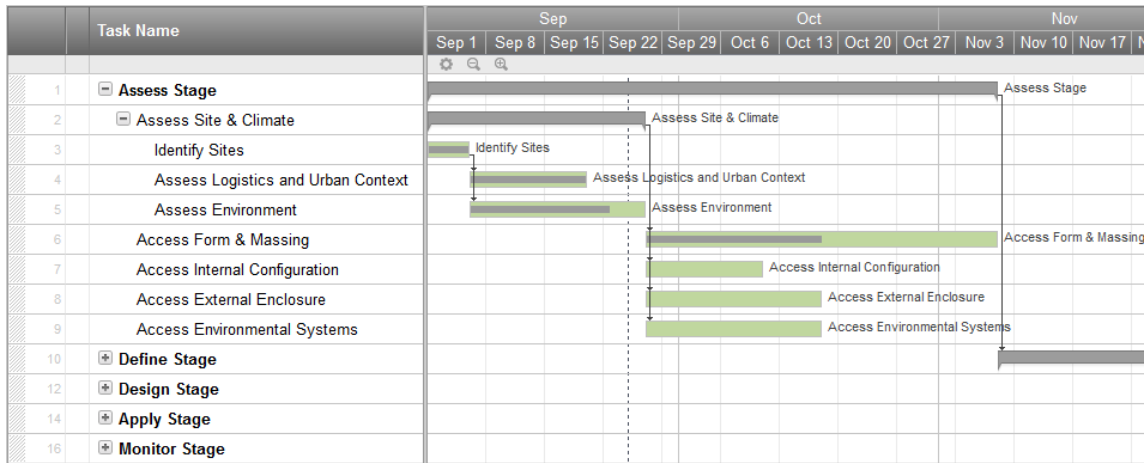
Figure 3-14 Sample of Schedule View in Design Process Window
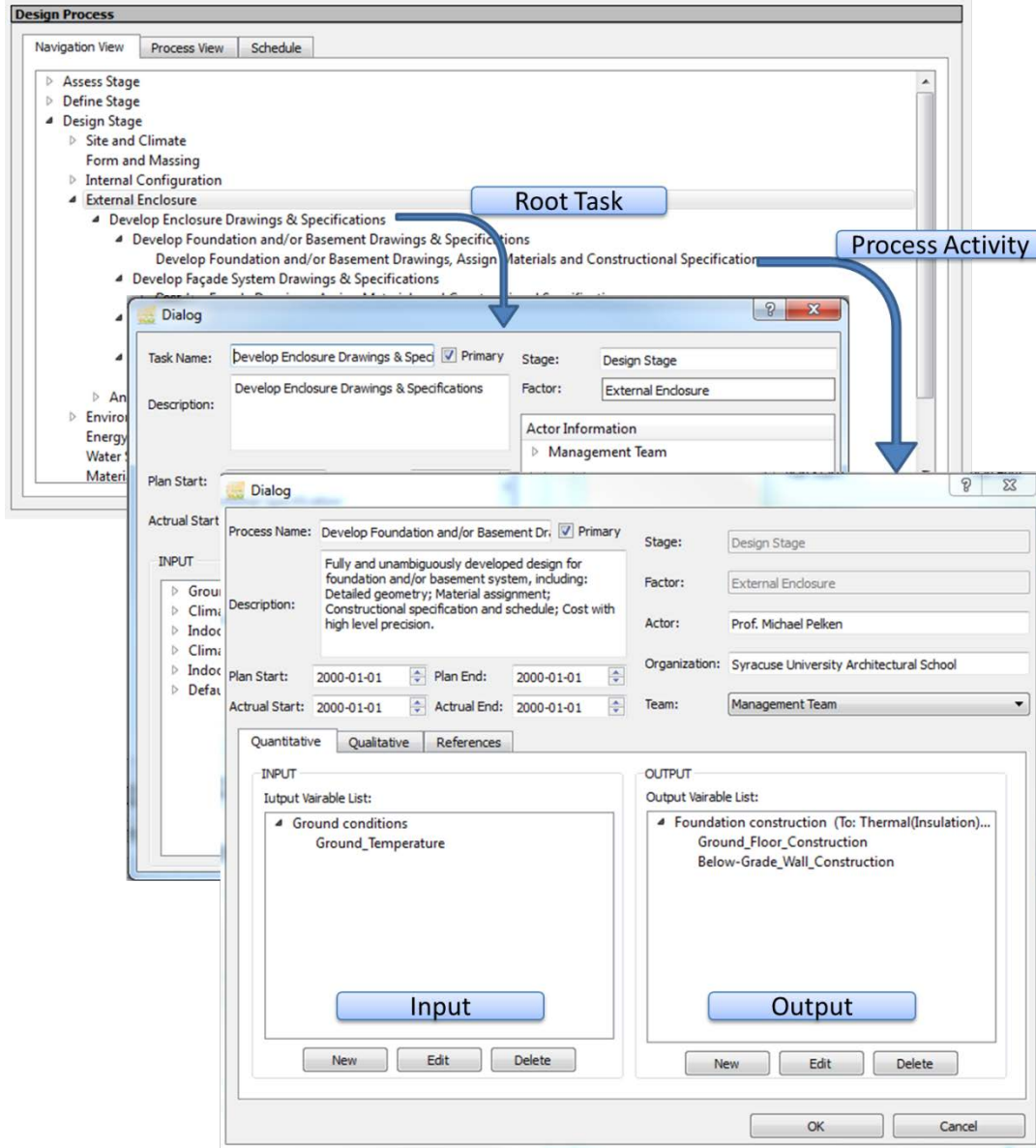
Figure 3-15 Hierarchy of tasks and their associated inputs and outputs

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.
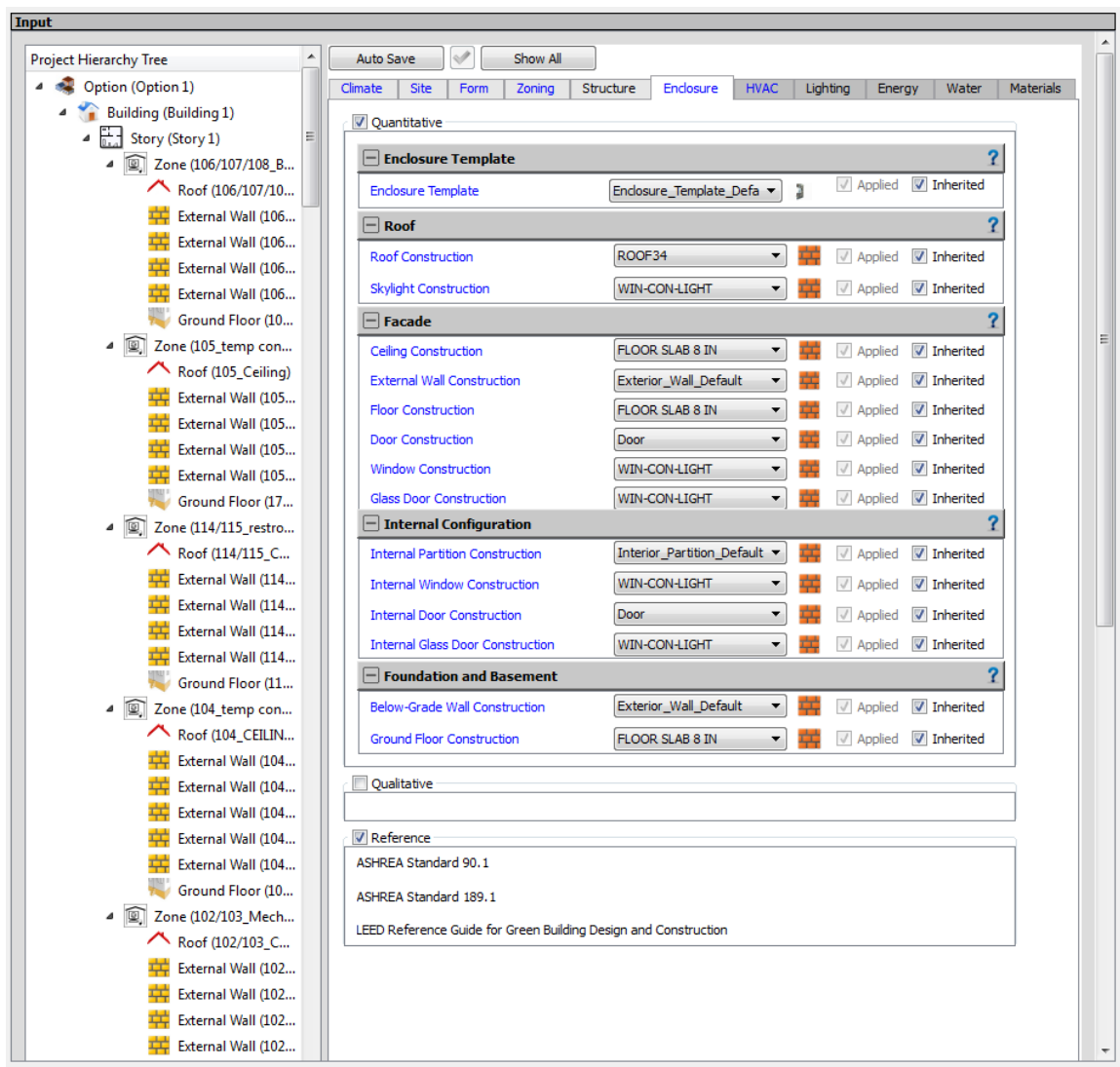
Figure 3-16 VDS design parameters organized by design factors (right) with displays filtered by

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.
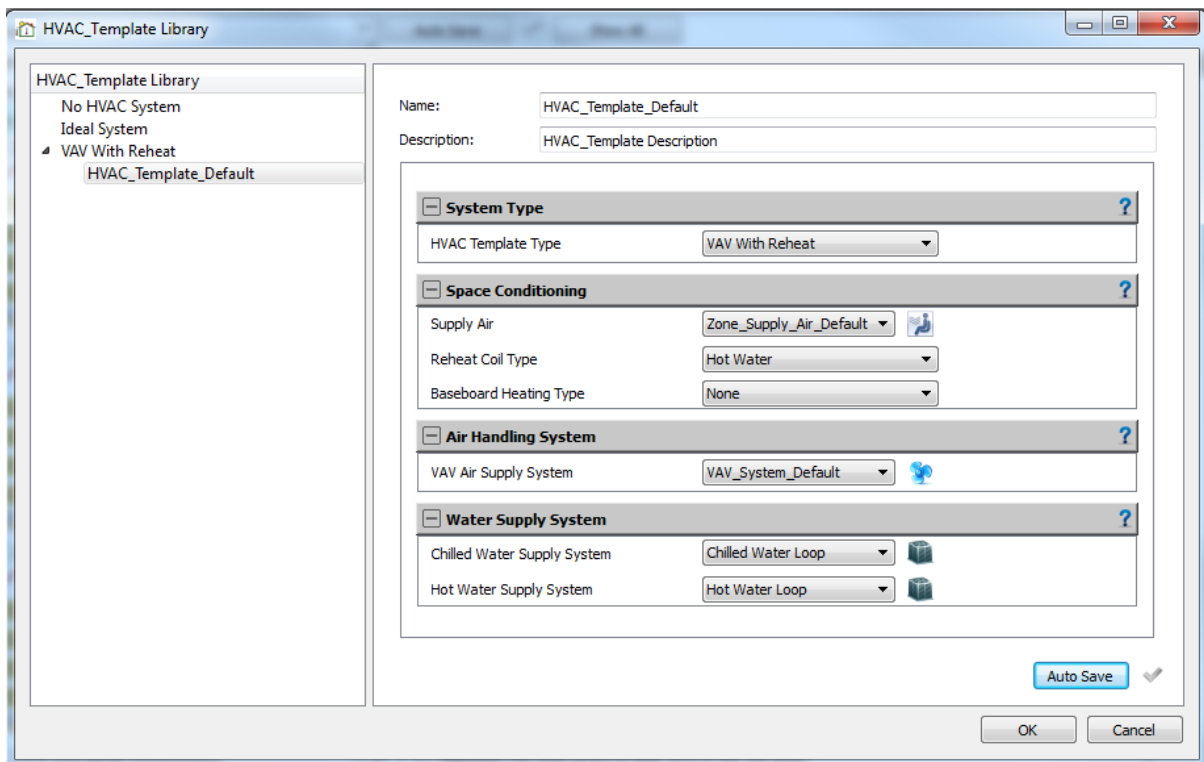
Figure 3-17 Input Parameters for HVAC Template

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
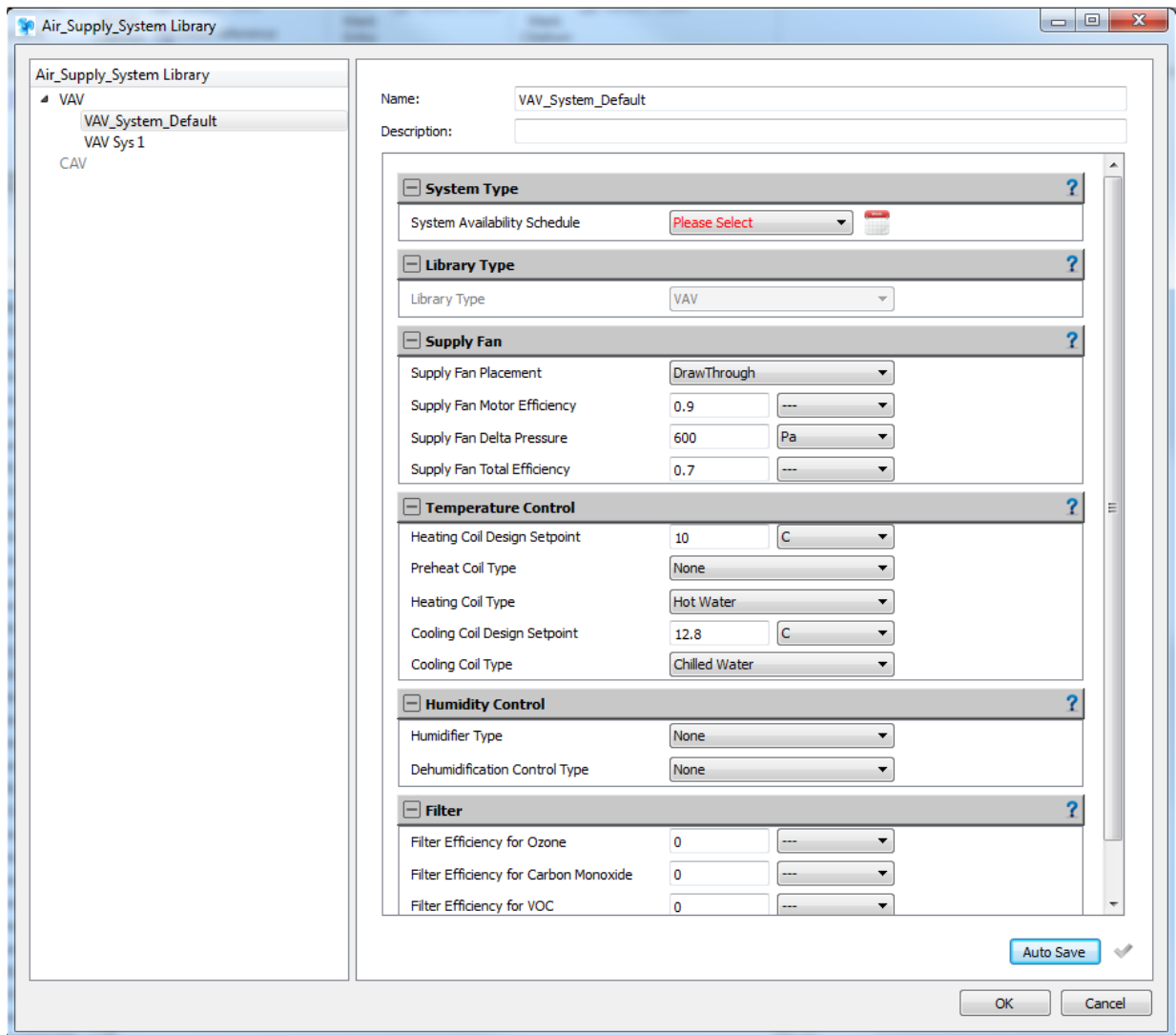
Figure 3-18 Input parameters for Air Supply System Library

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.
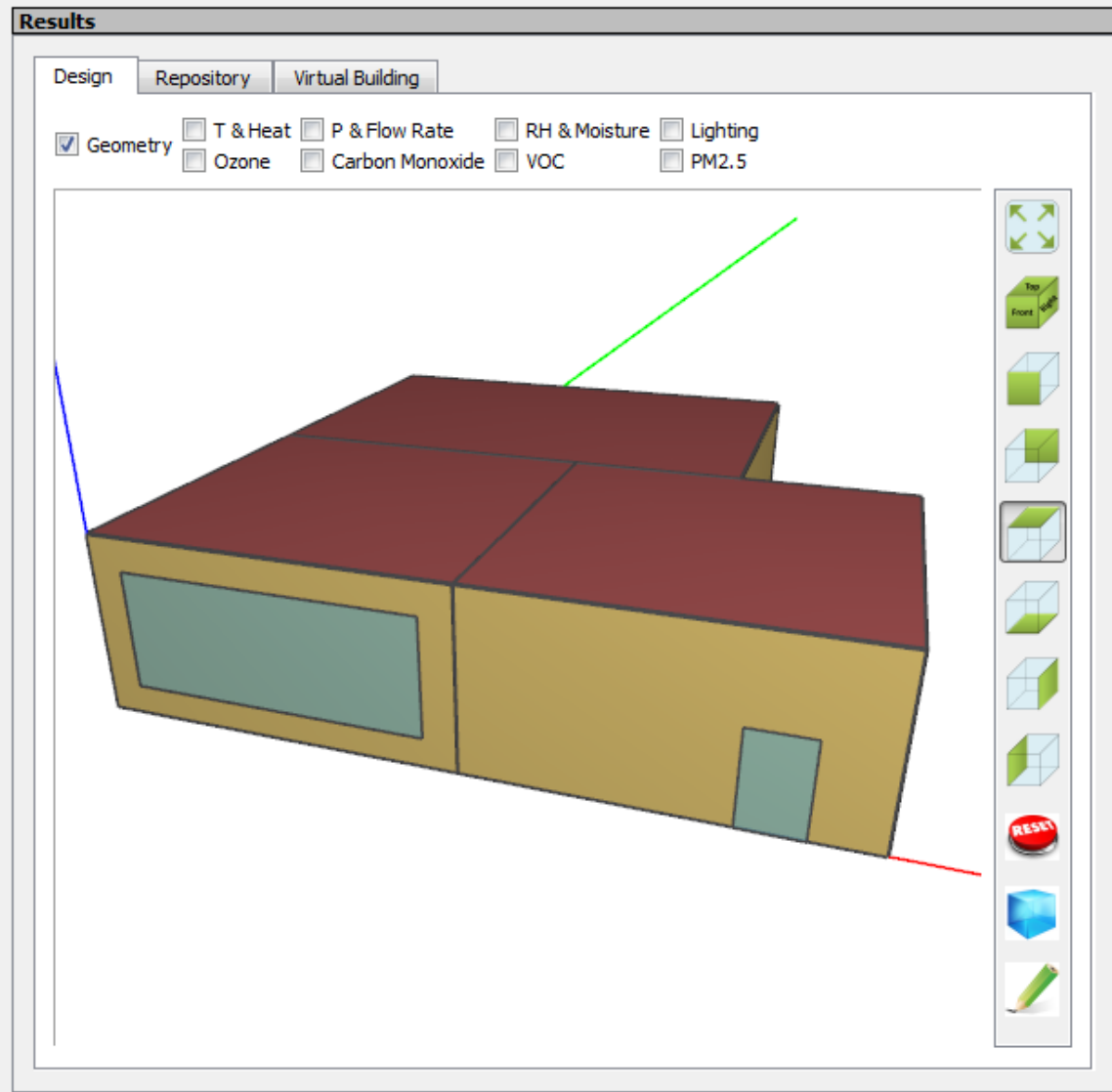
Figure 3-19 The "Design" of a 3-zone building in Result Window
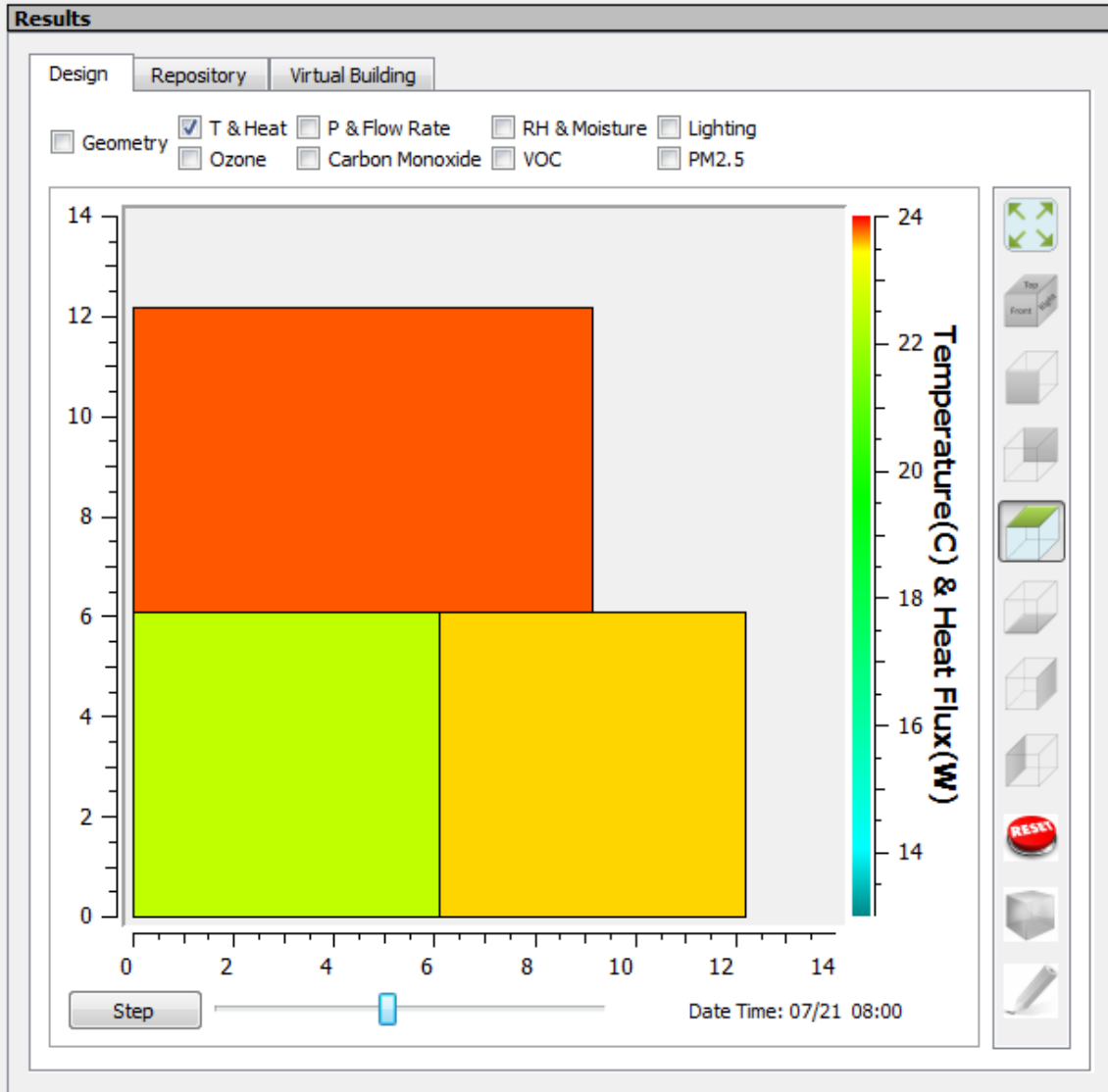
Figure 3-20 Temperature field of the 3-zone building at 8am on Jul. 21st in Result Window
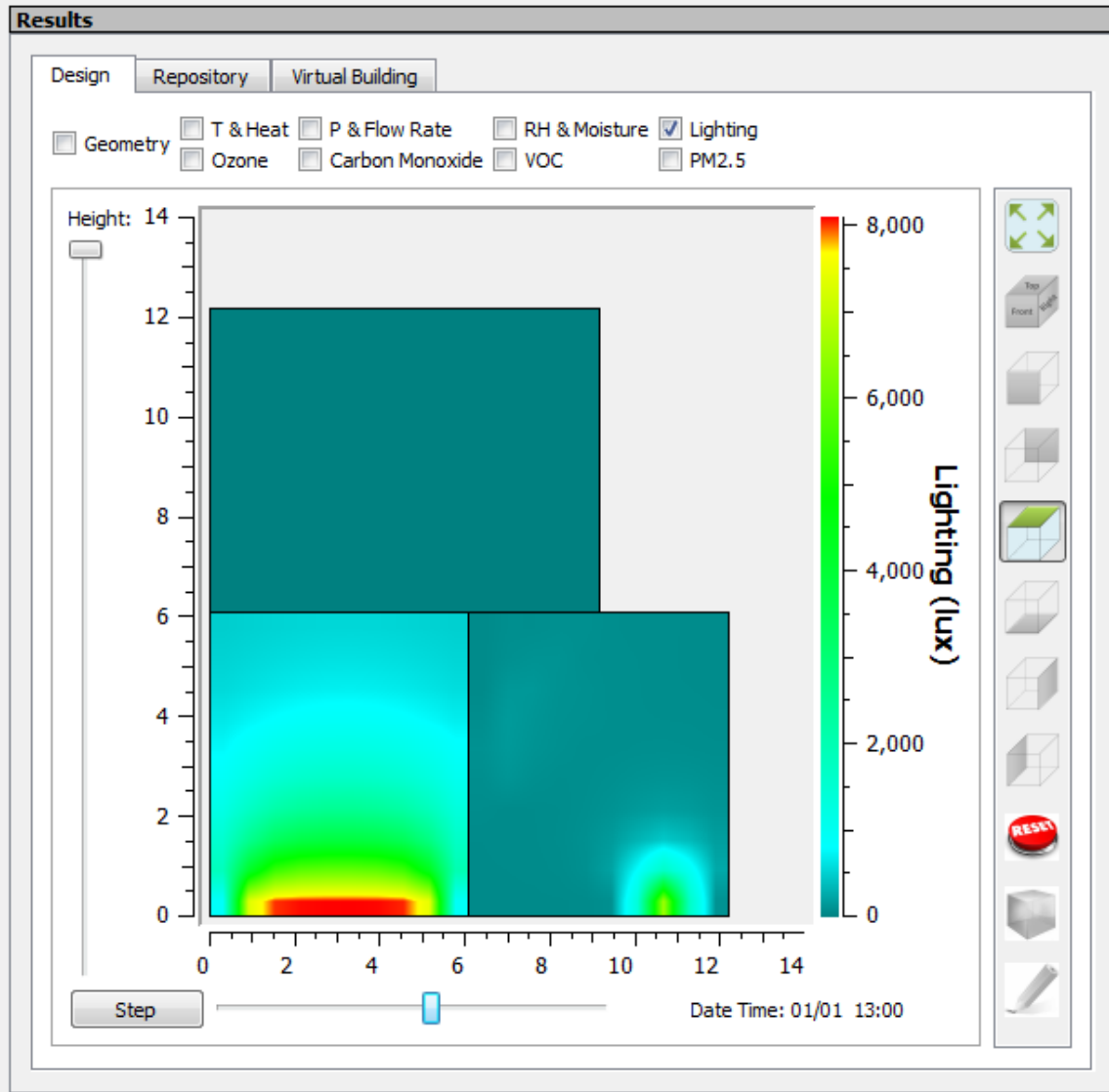
Figure 3-21 Lighting map of the 3-zone building at 1pm on Jan. 1st in Result Window

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.
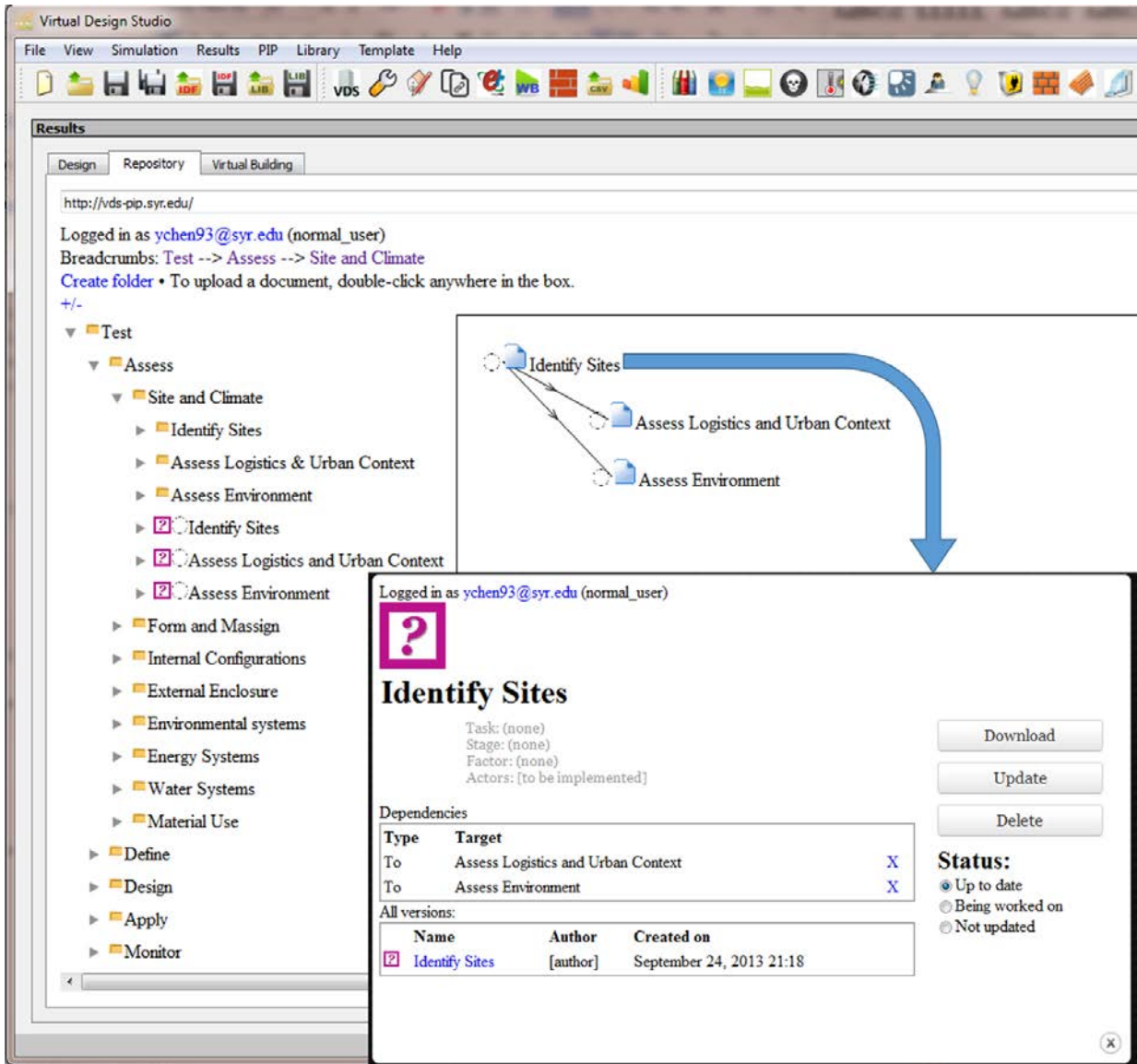
Figure 3-22 Repository Page in Result Window

(a) Temperature distribution   (b) Relative Humidity distribution
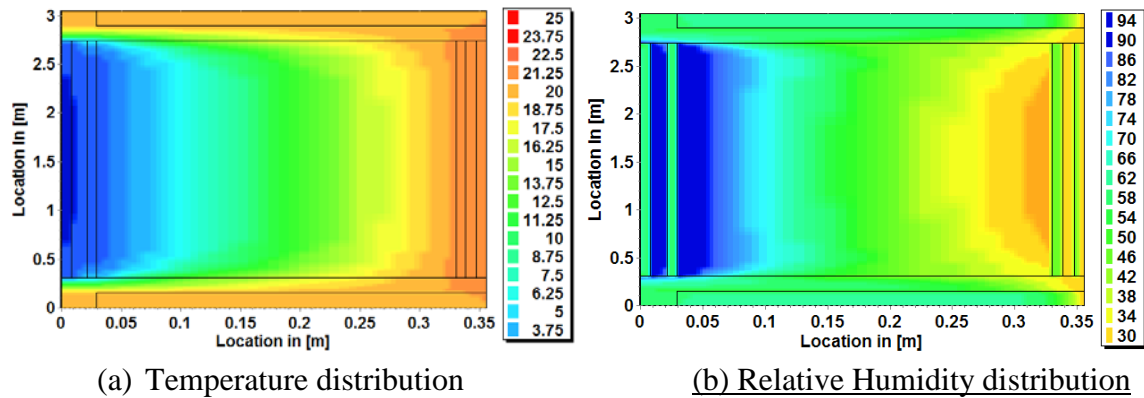
Figure 3-23 Sample Results of hygrothermal performance of a wall assembly simulated by
CHAMPS-BES

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.
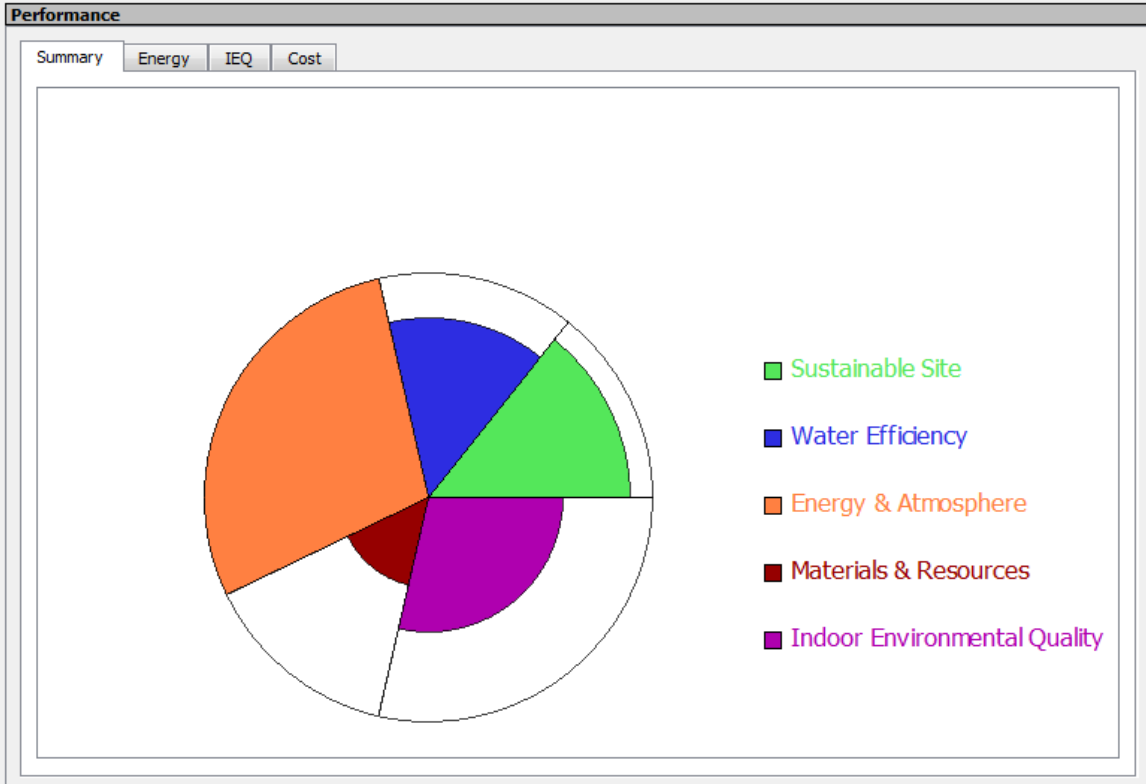
Figure 3-24 Proposed overall building performance summary view
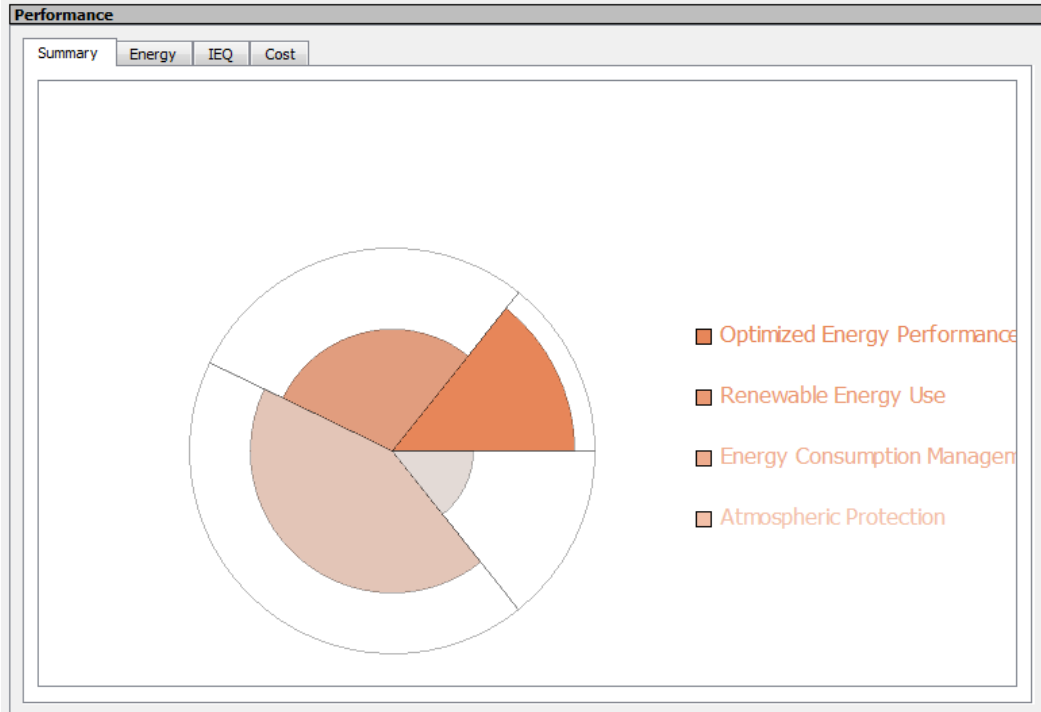
Figure 3-25 Energy & Atmosphere detail
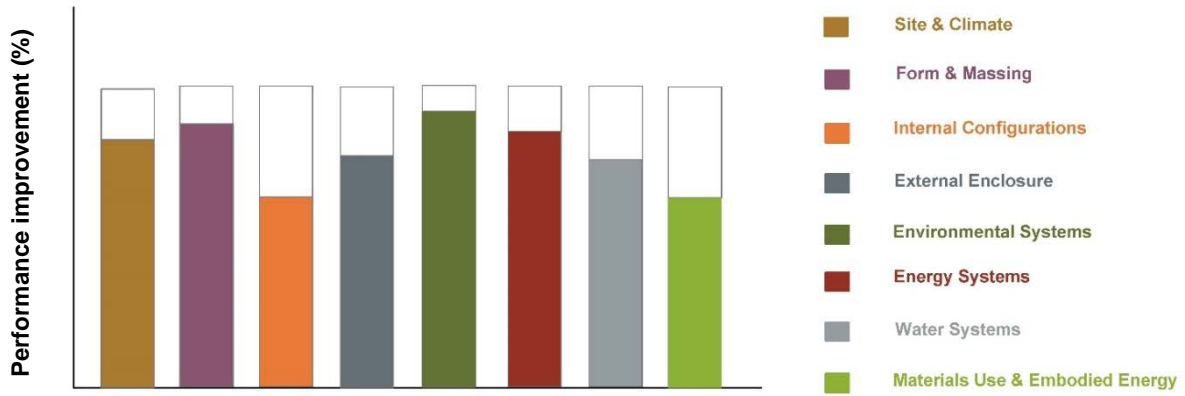
Figure 3-26 Performance improvement relative to reference building by design factor
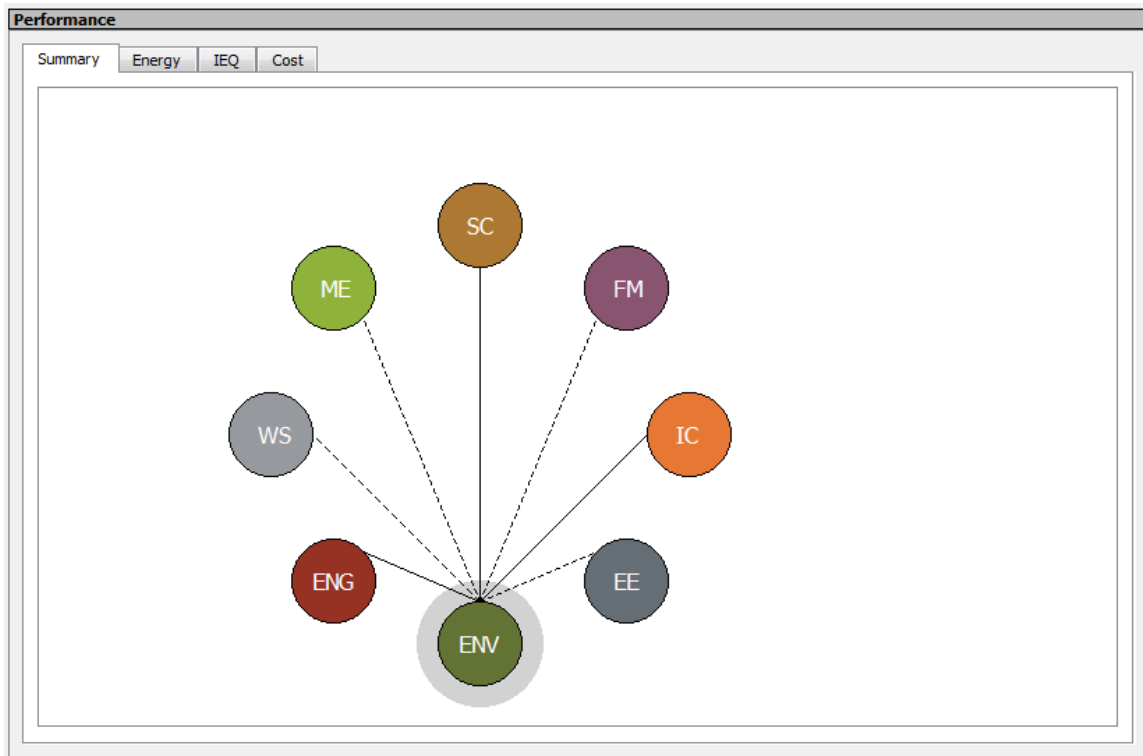
Figure 3-27 Design factor relationship map for the IAQ sub-performance aspect
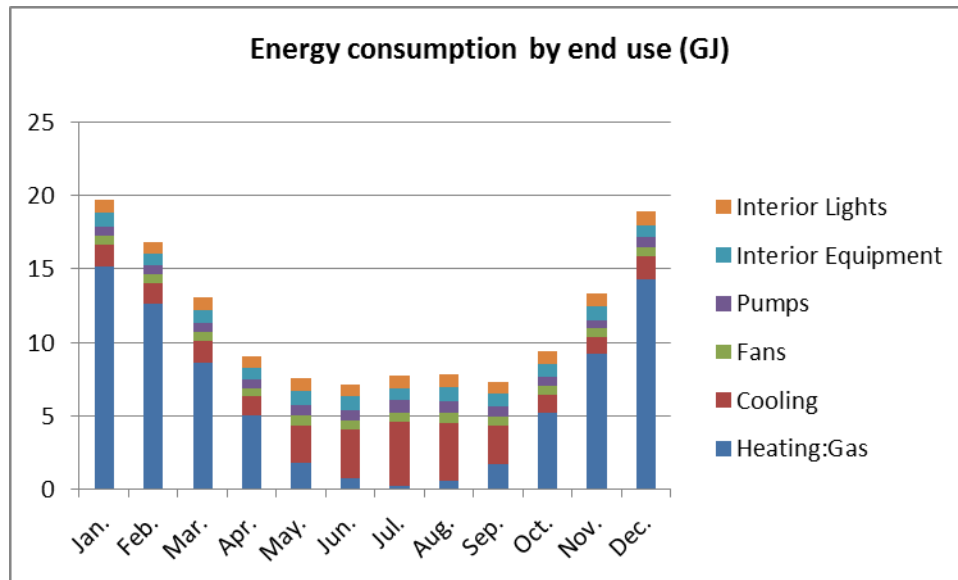
Figure 3-28 Sample of energy end use distribution in Performance Window

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

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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.
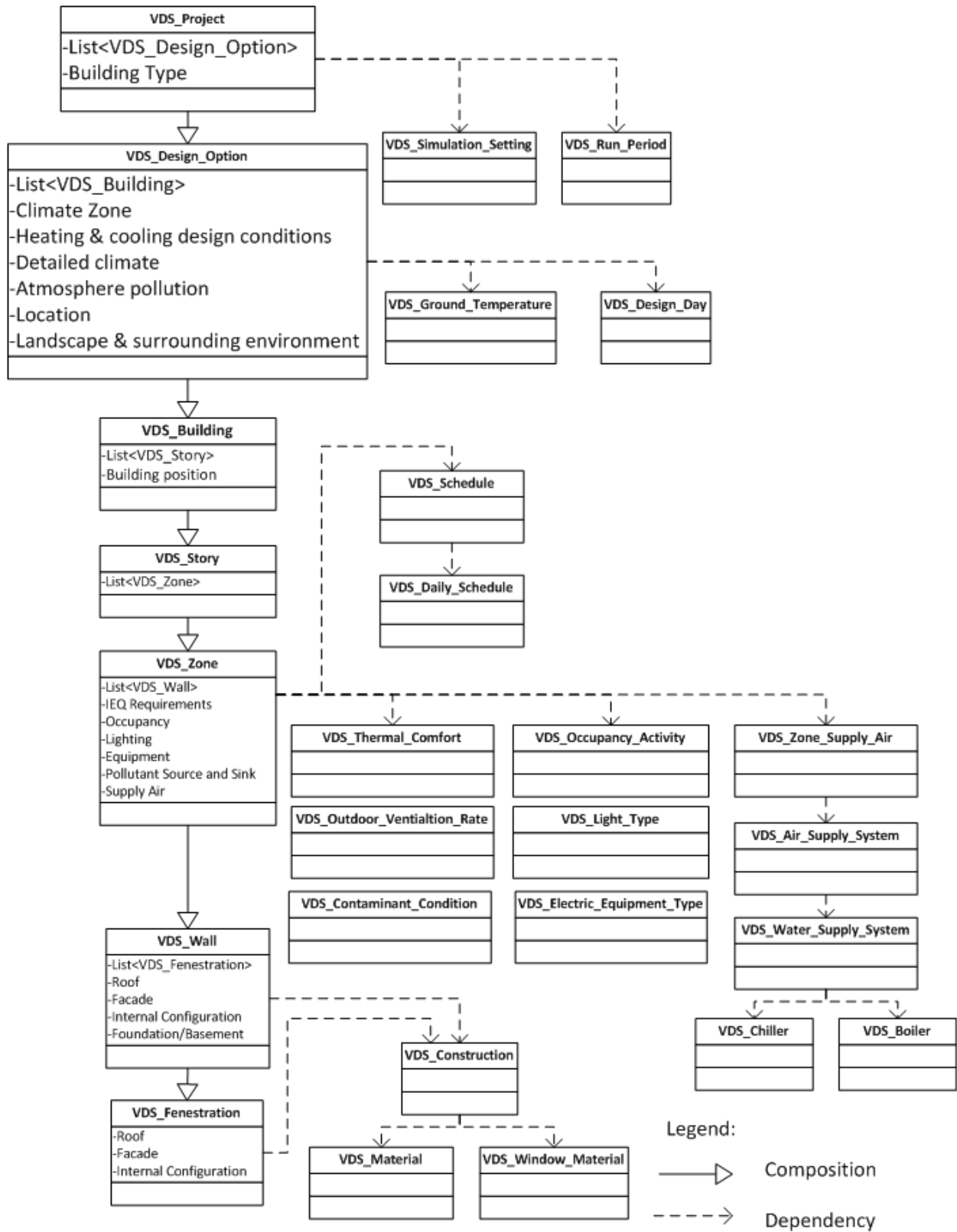
Figure 3-29 VDS data model: building related data

MagicCubeProject
-List<RootTask>

RootTask
-Stage
-Factor

Task
-List<Activities>children

CubeObject
-ID
-Name
-Desc
+getId()
+getName()
+getDesc()

Stage

Factor

Actor
-List<Actor>
-ParentActor

ProcessActivity
-Actor
-Status
-Parent
-DisplayOrder
-List<CubeDataObject>Inputs
-List<CubeDataObject>Outputs
-List<DependsOn>UsesAsInpput
-List<DependsOn>OutputUsedby
-Priority
-PlanStartTime
-PlanEndTime
-StartOn
-CompletedOn
+init()
+run()
+setStartOn()
+setCompleted()

«interface»
Activity
+getStage()
+getFactor()
+getActor()
+getStatus()
+getPlanStart()
+setPlanStart()
+getPlanEnd()
+setPlanEnd()
+getStartOn()
+getCompleted()
+getOrder()
+getMajSec()
+getChildern()
+getUses()
+getUsedby()

DependsOn
-Process: Activity
-List<>outputs : CubeDataObject
-List<>inputs : CubeDataObject

«interface»
CubeDataObject
+getId()
+getName()
+getDesc()
+getType()
+getLocation()

AbstractCubeData
+getLocation() : string=VDS

Quan
-SchemaId
+getType() : int=quant

Ref
-Content
+getType() : int=ref

Qual
-ReferenceName
-Content
-Status
-Point
+getType() : int=qual

AggrData
-Type
-Location
+getType() : int = Aggr

UserDefine
-Text
+getLocation() : string=PIP
+getType() : int=user

Legend ——▷ Inheritance   ----▷ Hold/Reference

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

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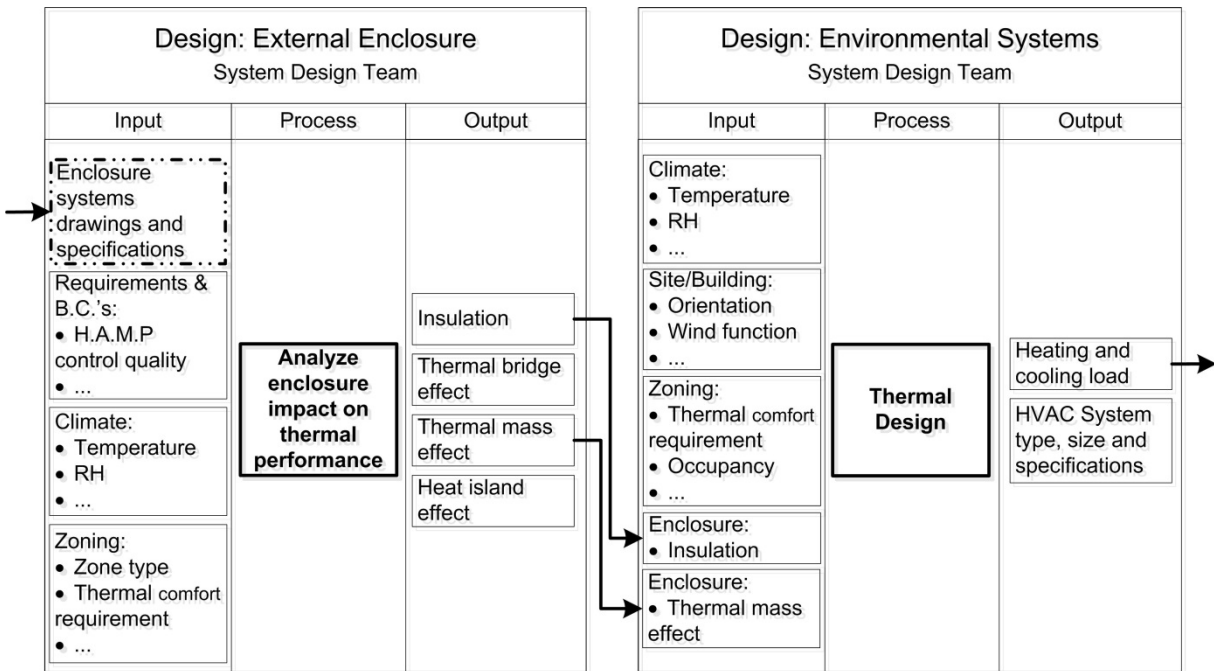
Figure 3-32 An example of the input-output dependency between two Process Activities

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.
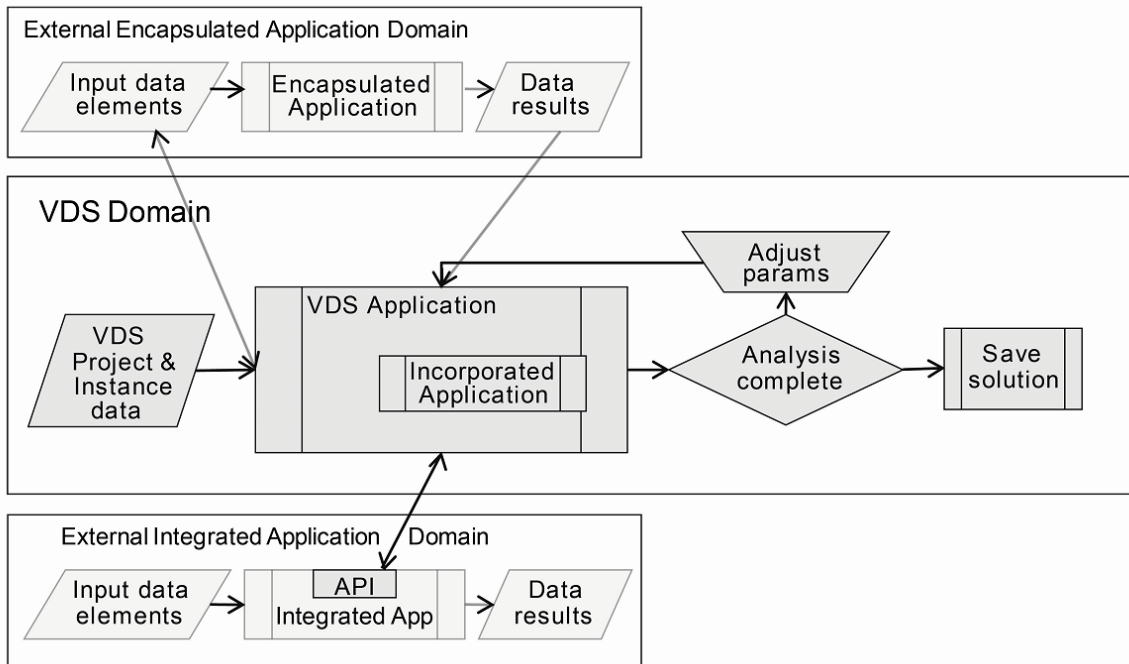
Figure 3-33 Three levels of external application interaction
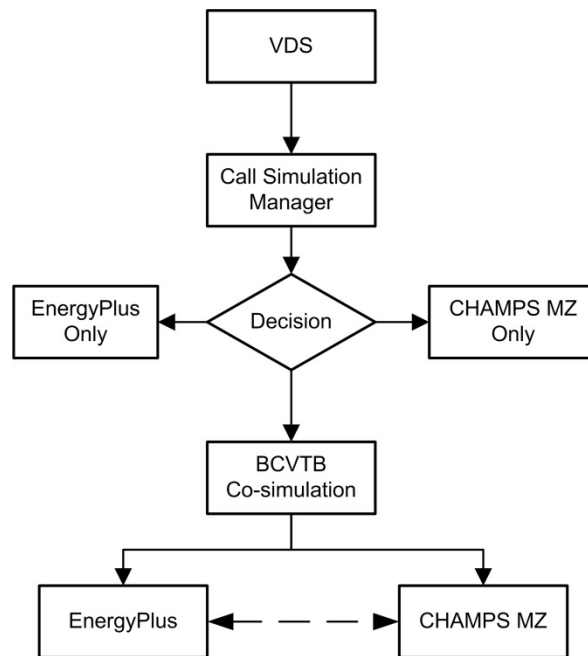
Figure 3-34 Integration of EnergyPlus and Incorporation of CHAMPS MZ into VDS

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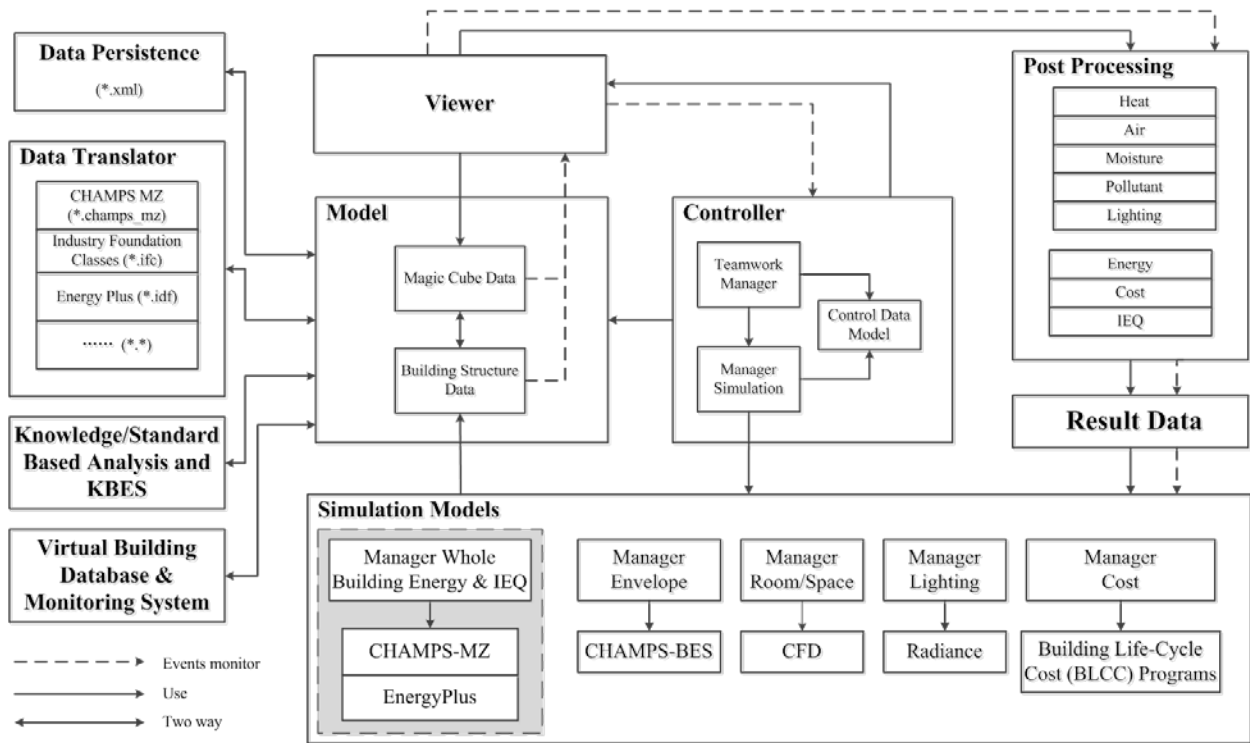
Figure 3-35 VDS software implementation scheme: modules and their relationships

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.

Design: External Enclosure

	Input	Process			Output
Management Team			Approve Encl. Design		
Architect Design Team	External Encl. Design Strategies Rep.	Develop Encl. Drawings and Spec.	Finalize Encl. Design	Document Rep.	External Encl. Construction Docs. and Spec.
System Design Team	Perf. Goal		Analyze Impact on Bldg. Perf.	Finalize Rep.	External Encl. Design Perf. Rep.

Design: Environmental Systems

	Input	Process			Output
Management Team			Approve Env. Sys. Design		
Architect Design Team			Review Env. Sys. Design		
System Design Team	Selected Site Assessment / Orientation and Massing / Internal Config. Design	Design Env. Sys.	Analyze Impact on Bldg. Perf.	Finalize Env. Sys. Design	Finalize Design	Env. Sys. Design

Legend

→ Main Process Flow

→ Secondary Process Flow

- - → Interdiscipline Collaboration

▢ Main Process Step

▢ Secondary Process Step

Figure 3-36 Illustration of the VDS-assisted collaborative design process for two design tasks
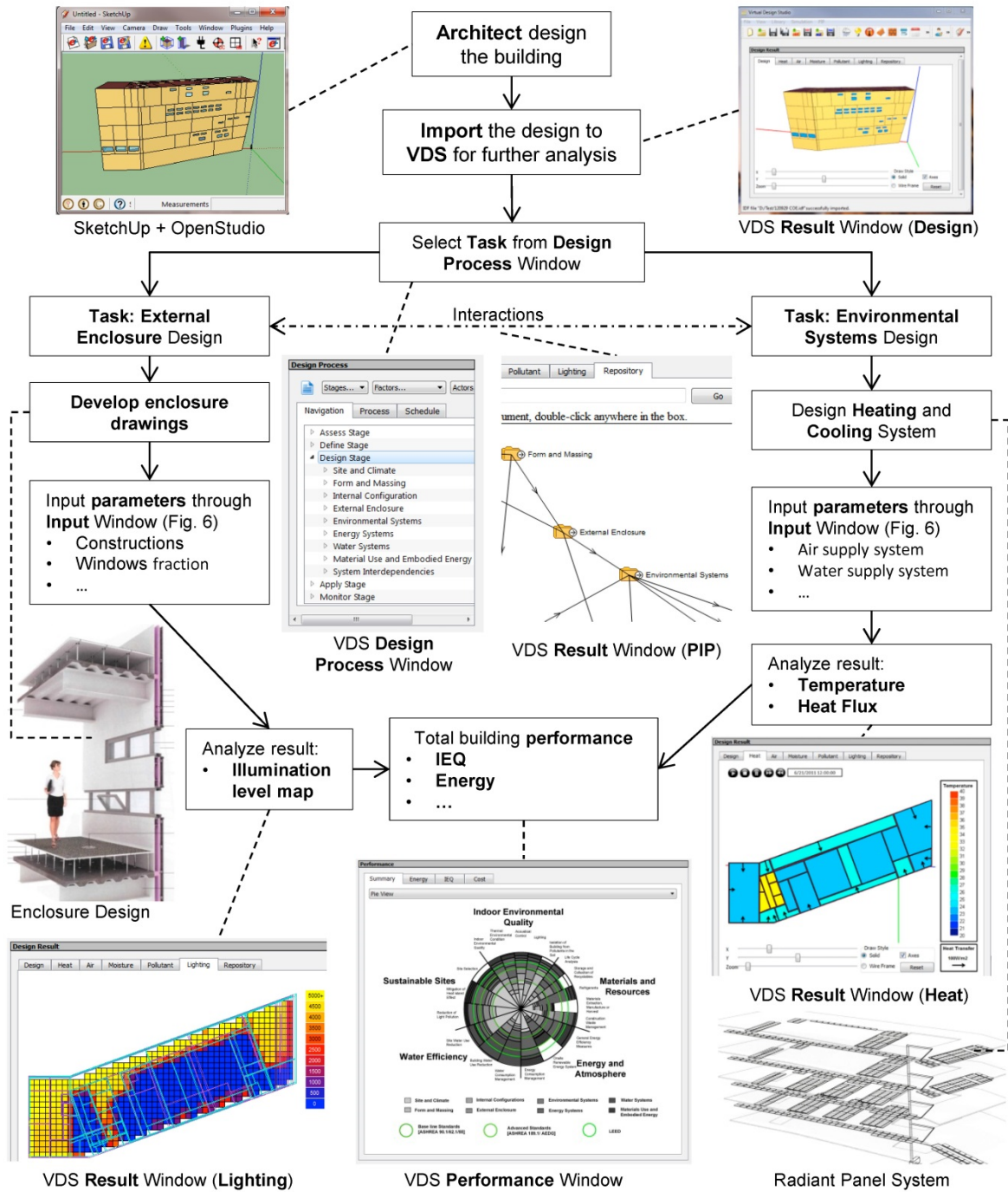
Figure 3-37 Illustration of a possible VDS work flow for two concurrent design tasks: external

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 are 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.
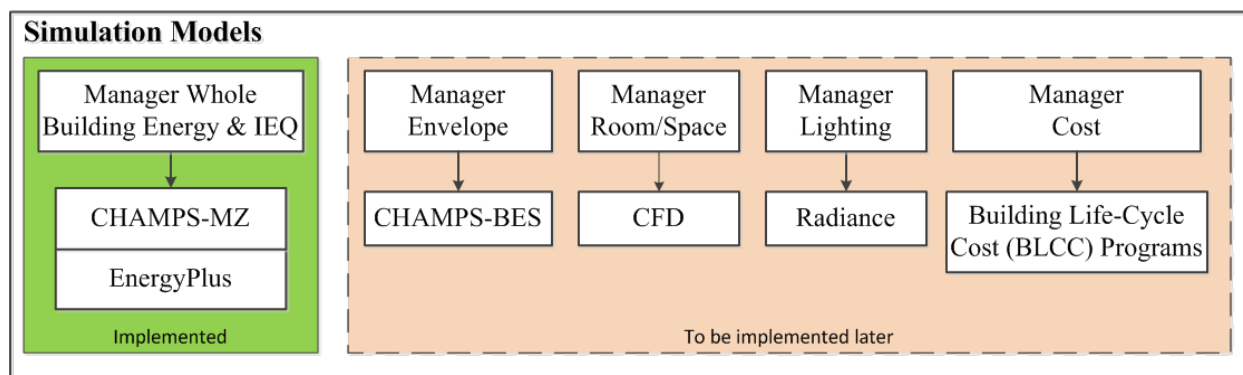
Figure 4-1 Simulation Models in VDS framework

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.
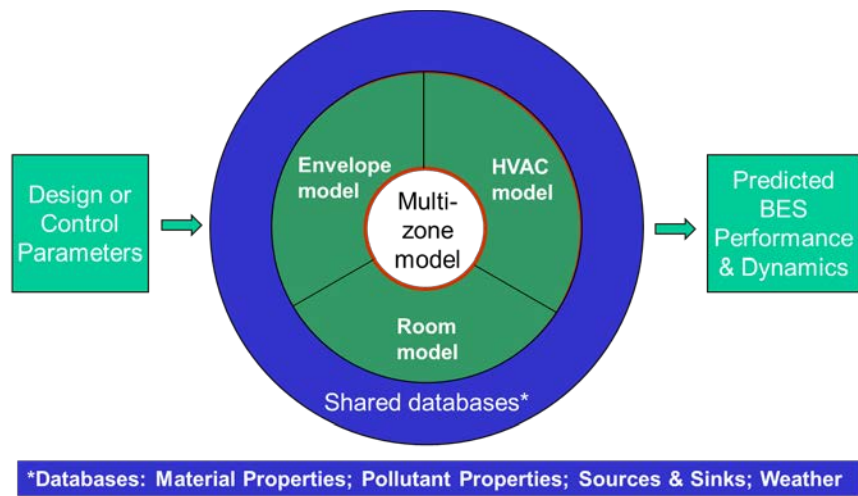
Figure 4-2 CHAMPS-Multizone software structure (Feng, 2012; Zhang, 2005)
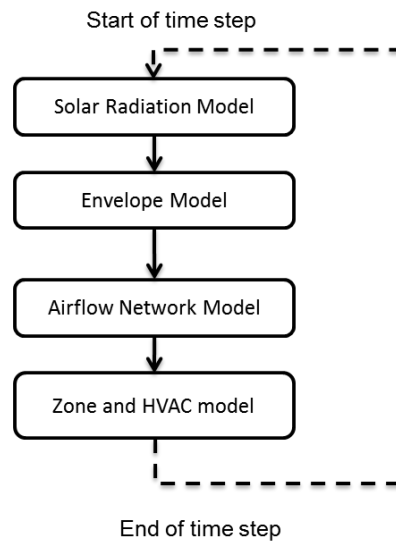
Figure 4-3 Flow chart of CHAMPS-Multizone

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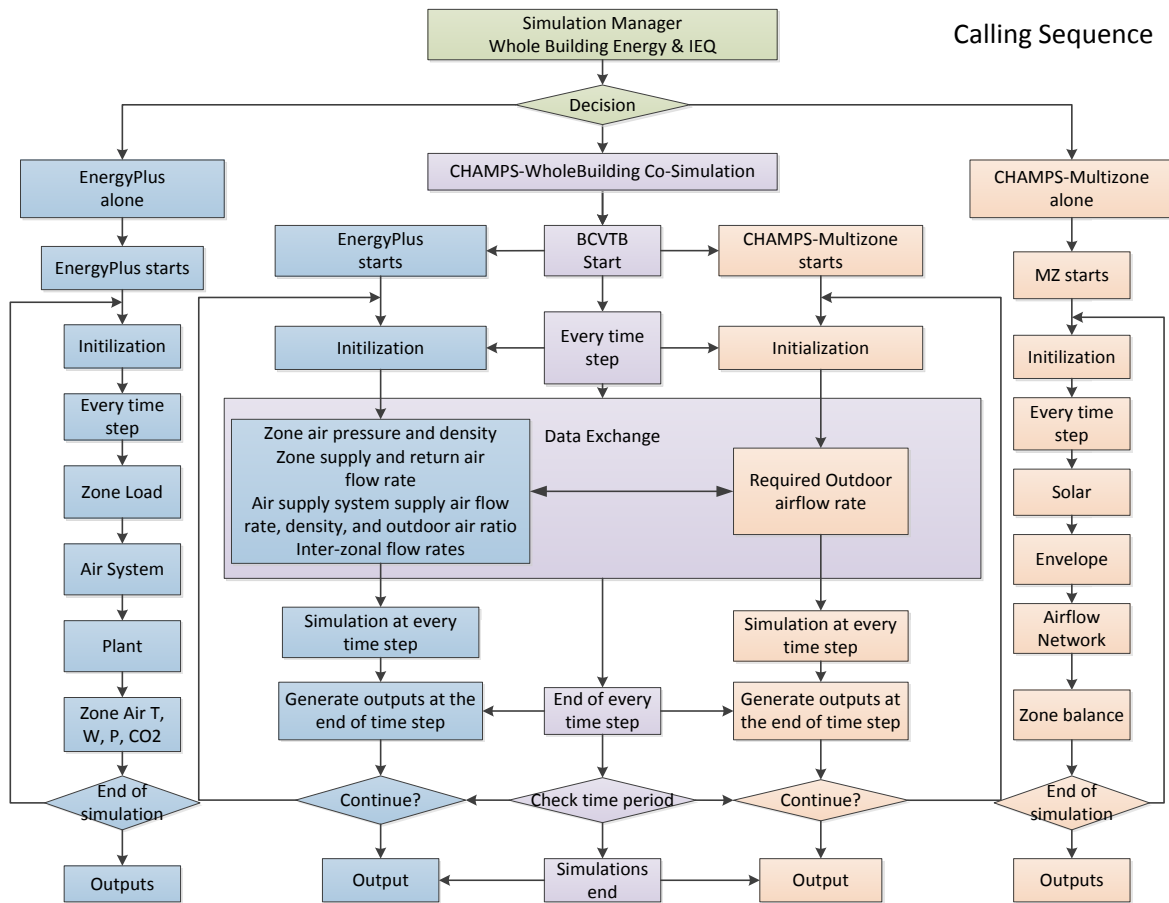
Figure 4-4 Flow chart of the Whole Building Energy and IEQ Simulation Manager

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.
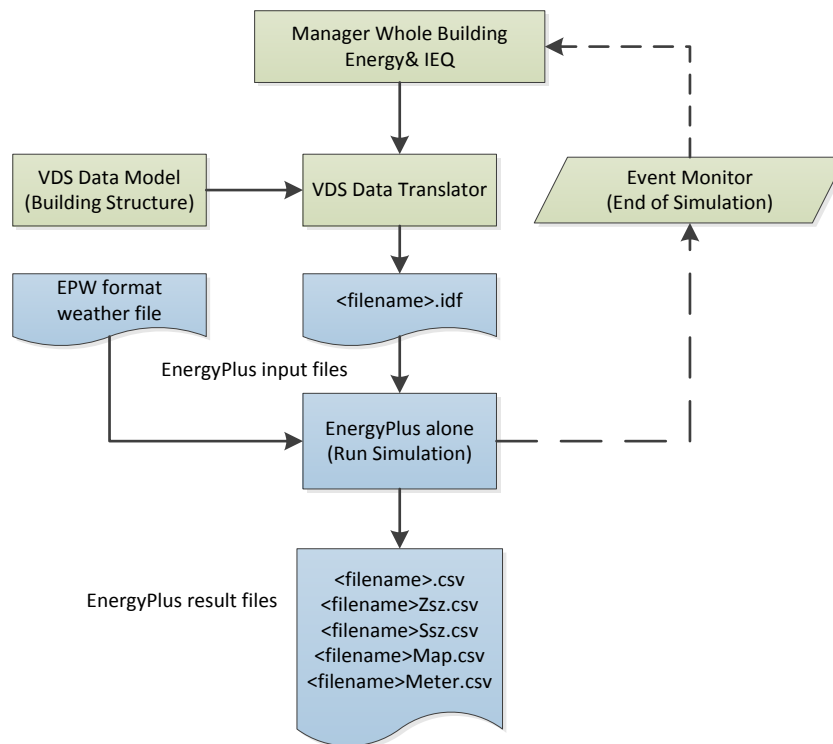
Figure 4-5 Flow chart of the EnergyPlus alone simulation
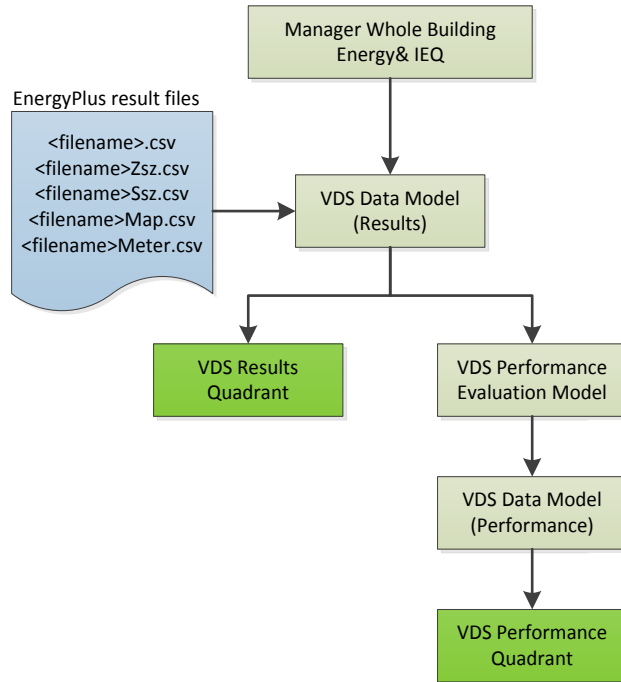
Figure 4-6 Flow chart of parsing EnergyPlus simulation results
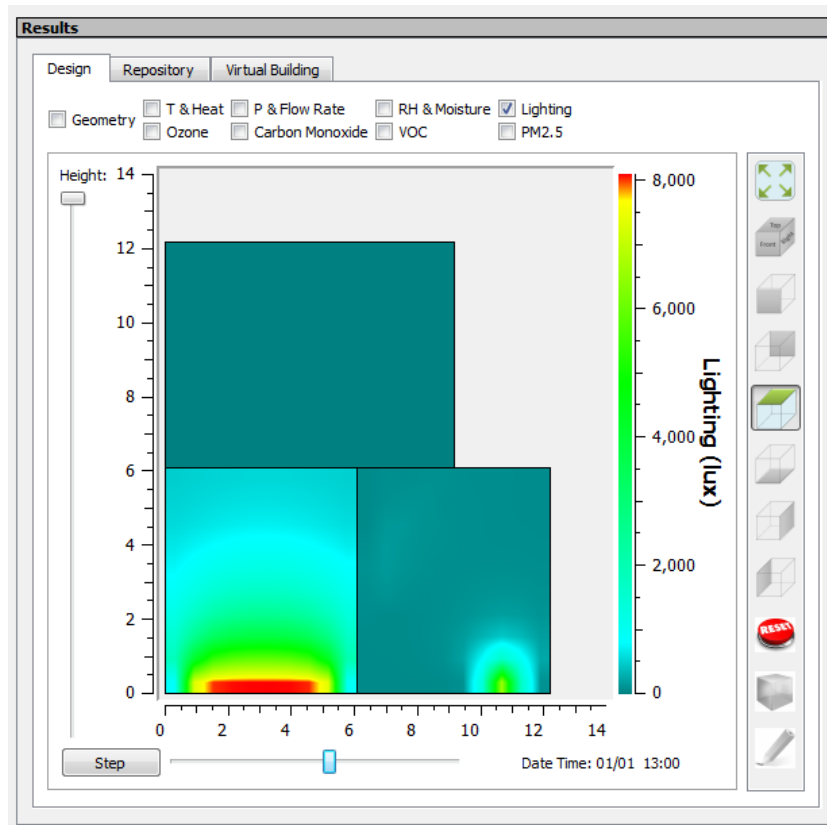
Figure 4-7 Example of daylighting illumination map in Results Quadrant
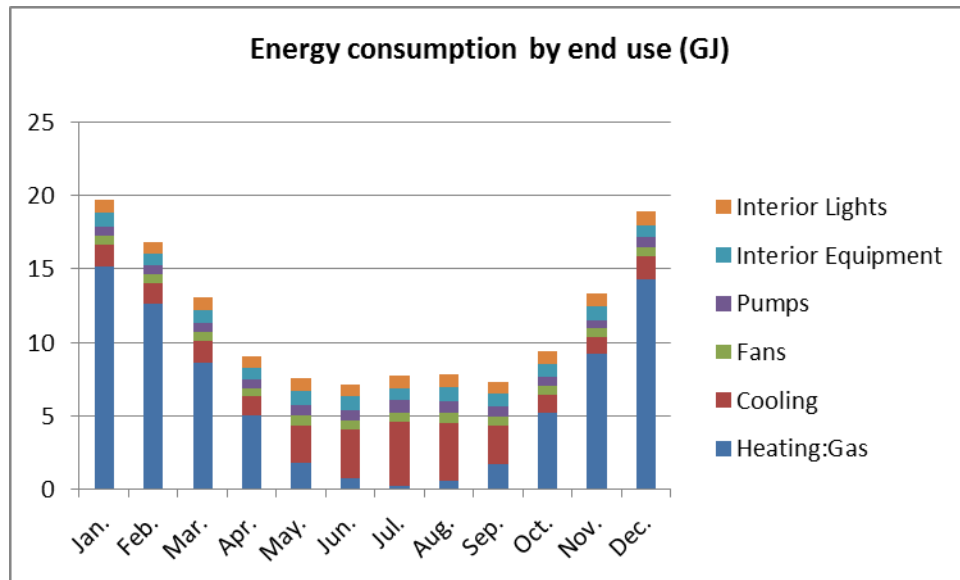
Figure 4-8 Example of monthly summary plots in Performance Quadrant

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 "HVACTemplate:Zone:VAV" object for the "VAV systems with boilers and water-cooled chillers" template.

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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	SizingPeriod:DesignDay
	Ground temperature	Site:GroundTemperature:BuildingSurface
Site	Site location	Site:Location
	Building position	Building
Form	Zone position	Zone
	Wall geometry	BuildingSurface:Detailed
	Window/door geometry	FenestrationSurface:Detailed
Zoning	Thermal Comfort	HVACTemplate:Thermostat
	Outdoor Ventilation Rate	HVACTemplate:Zone:VAV
	Daylighting Control	Daylighting:Controls
	Occupancy	People
	Lights	Lights
	Electrical equipment	ElectricEquipment
Enclosure	Construction	Construction
	Materials	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) systems	HVACTemplate:Thermostat
	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).
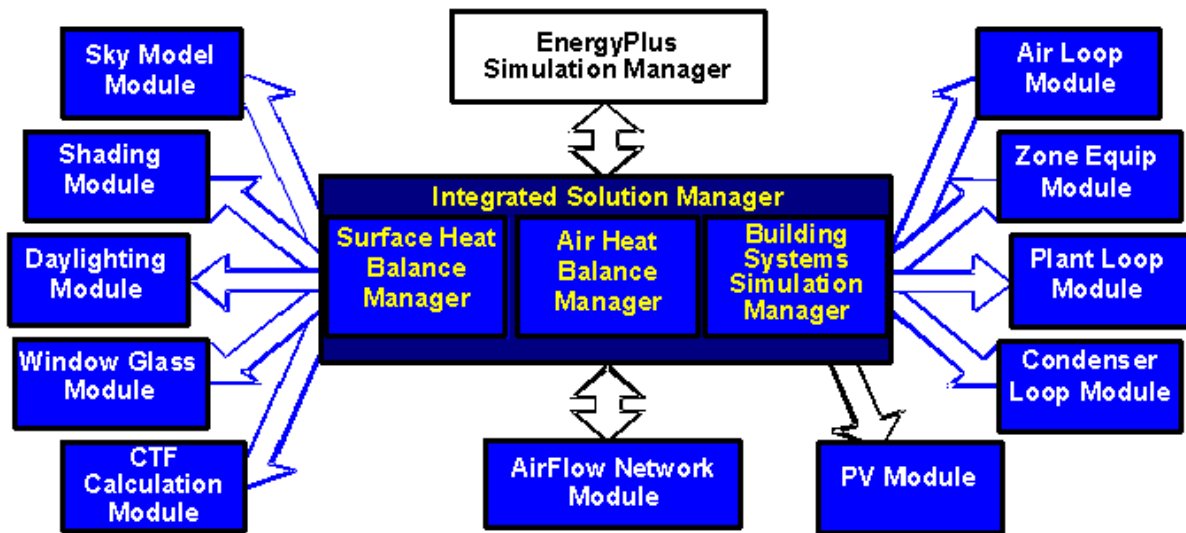
Figure 4-9 EnergyPlus program schematic (US DOE, 2012b)

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

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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.
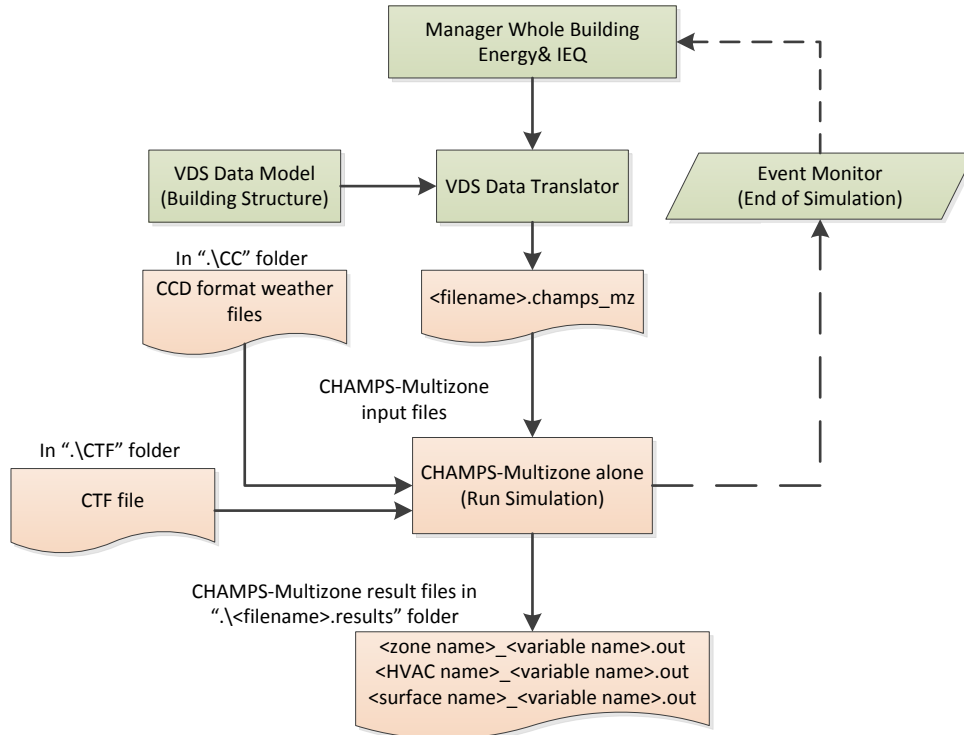
Figure 4-10 Flow chart of the CHAMPS-Multizone alone simulation
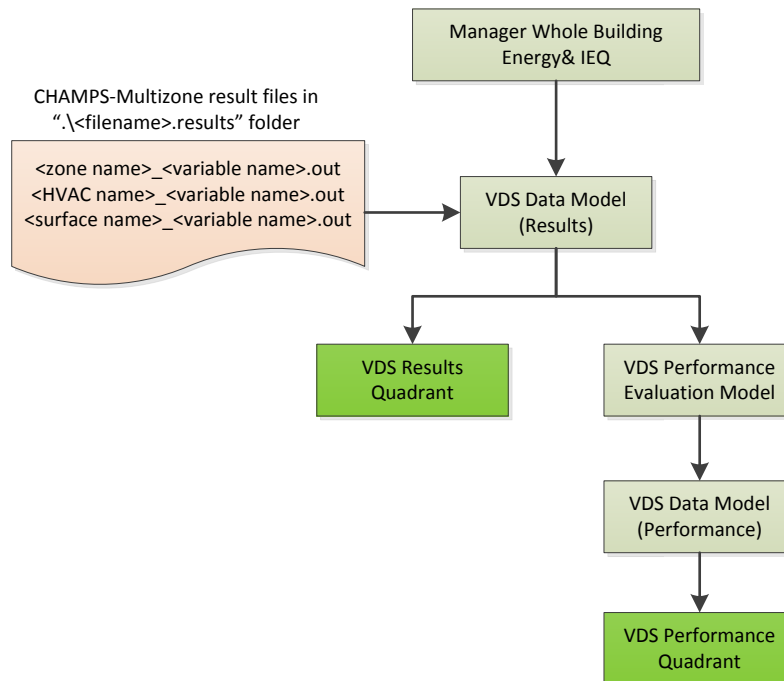
Figure 4-11 Flow chart of parsing CHAMPS-Multizone simulation results
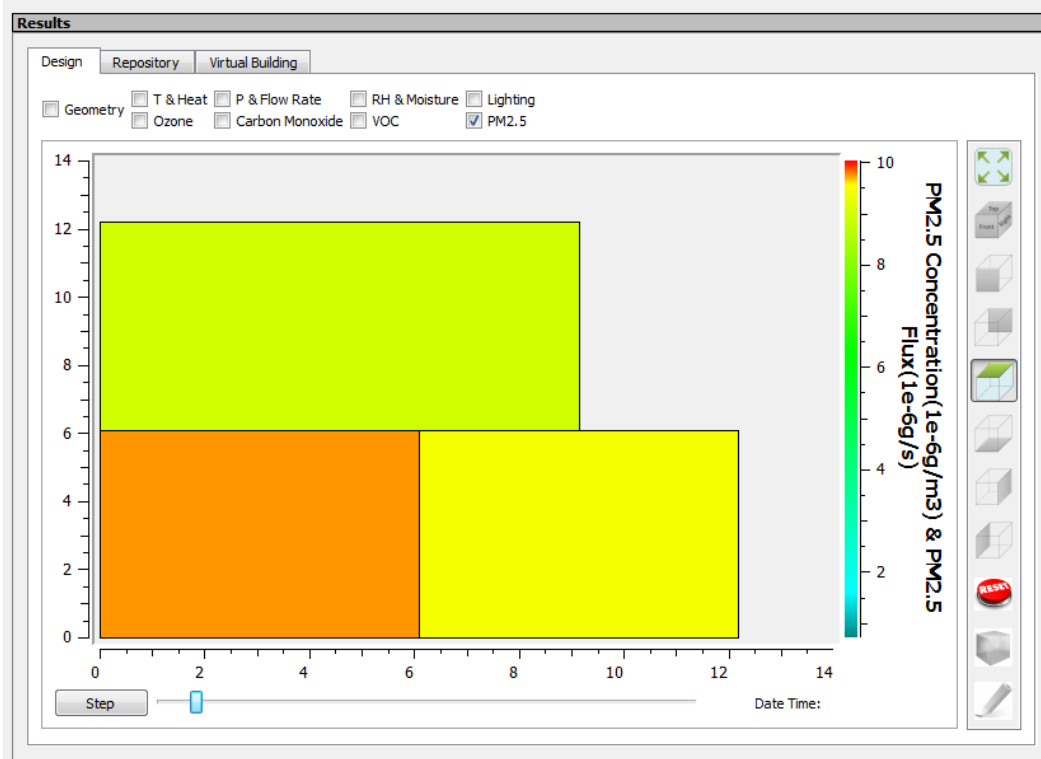
Figure 4-12 Example of PM2.5 concentrations in Results Quadrant

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	Ozone source and sink
		PM2.5 source and sink
		VOC source and sink
		Carbon monoxide source and sink
	Windows and doors opening control	Operation method and associated parameters
	Outdoor Ventilation Rate	Ozone limit
		PM2.5 limit
		VOC limit
		Carbon monoxide limit
	Zone air purifier	Zone Air purifier
	Supply air filter	Filter
HVAC	Recirculated air filter	Filter
	Outdoor air filter	Filter
	Mixed air 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.
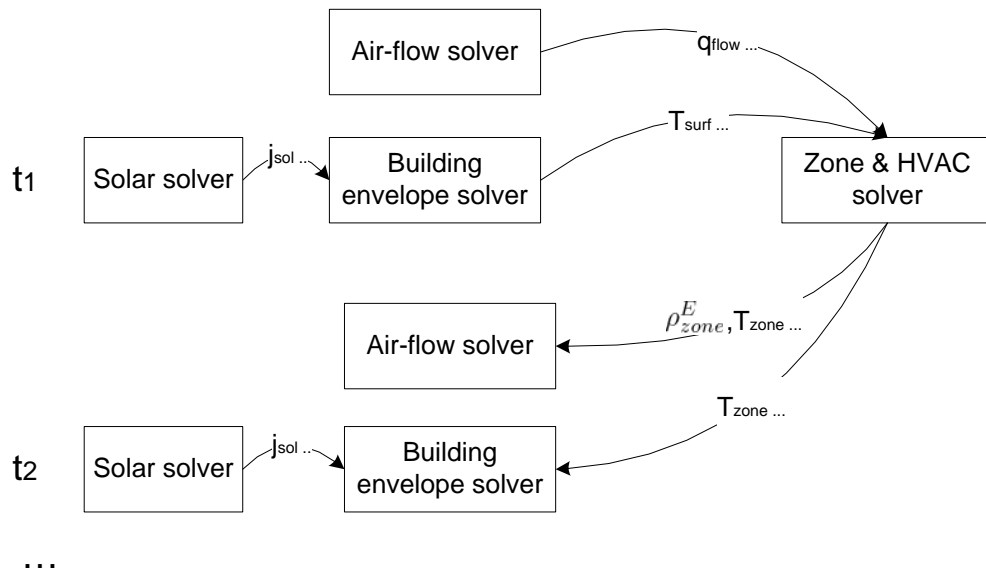
Figure 4-13 CHAMPS-Multizone solver scheme (Feng, 2012)

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-

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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.
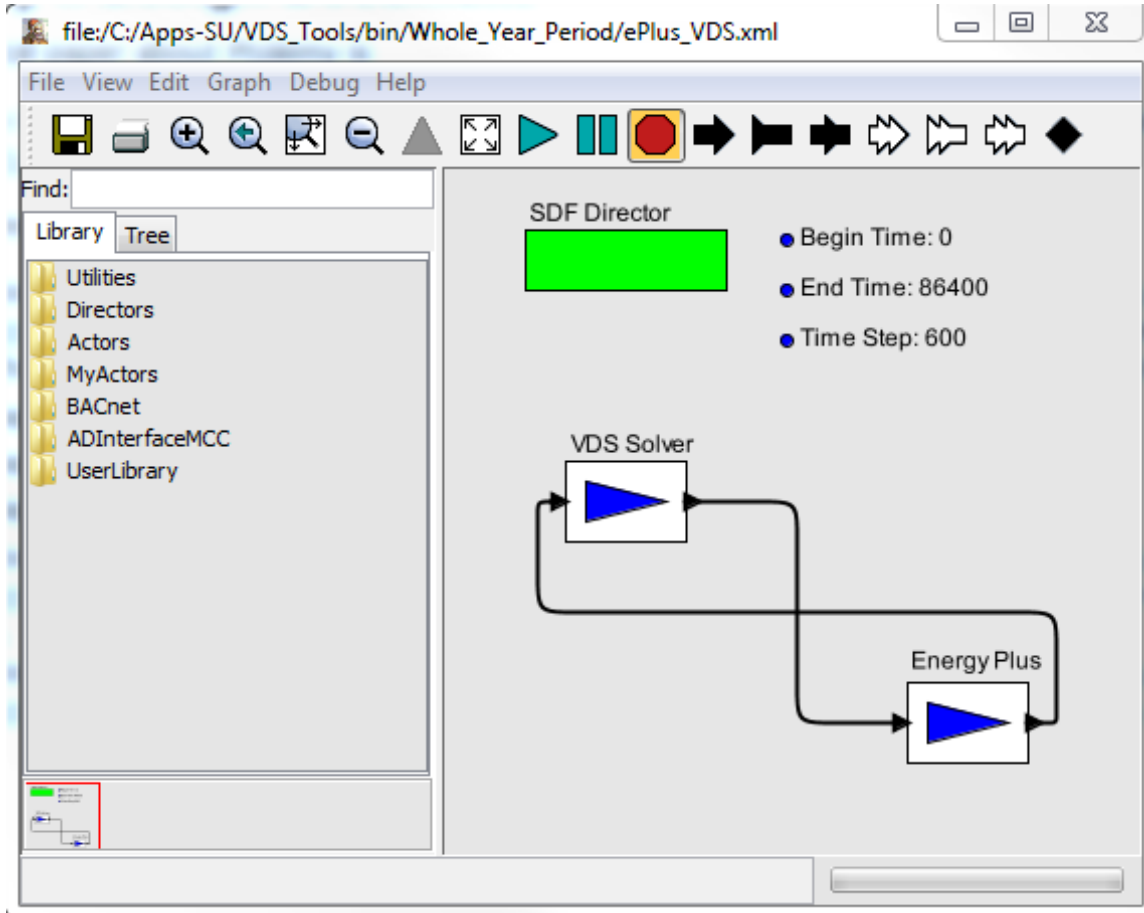
Figure 4-14 BCVTB GUI
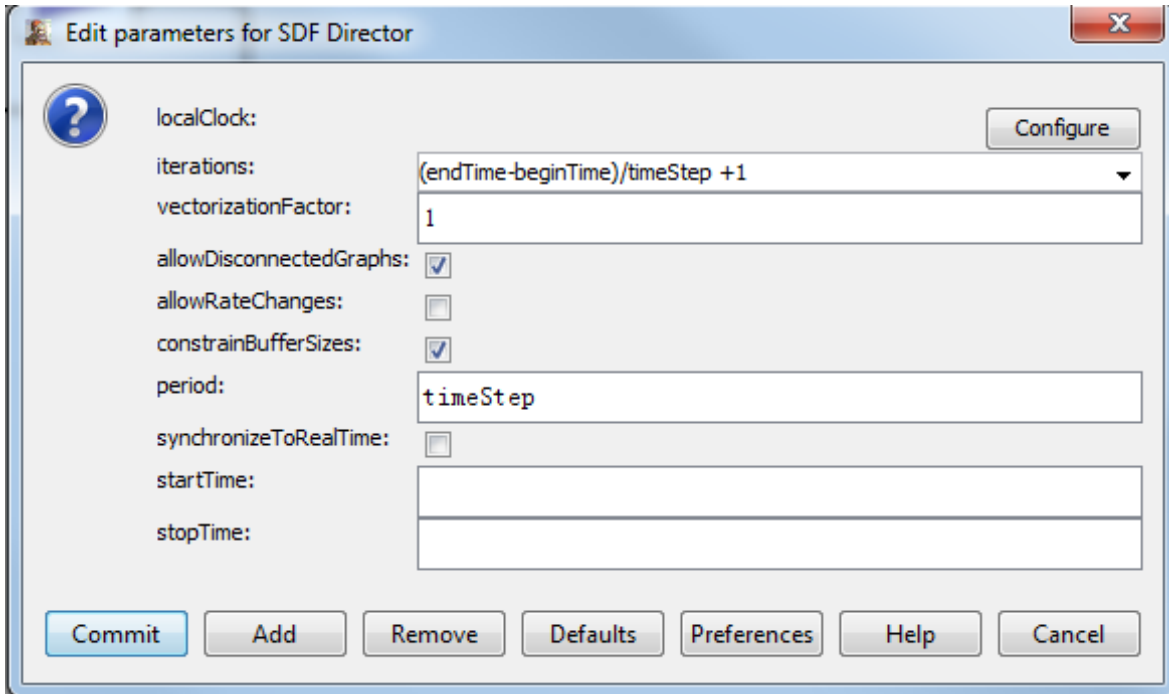
Figure 4-15 Configuration of the Synchronous Data Flow (SDF) director

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, et al., 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.
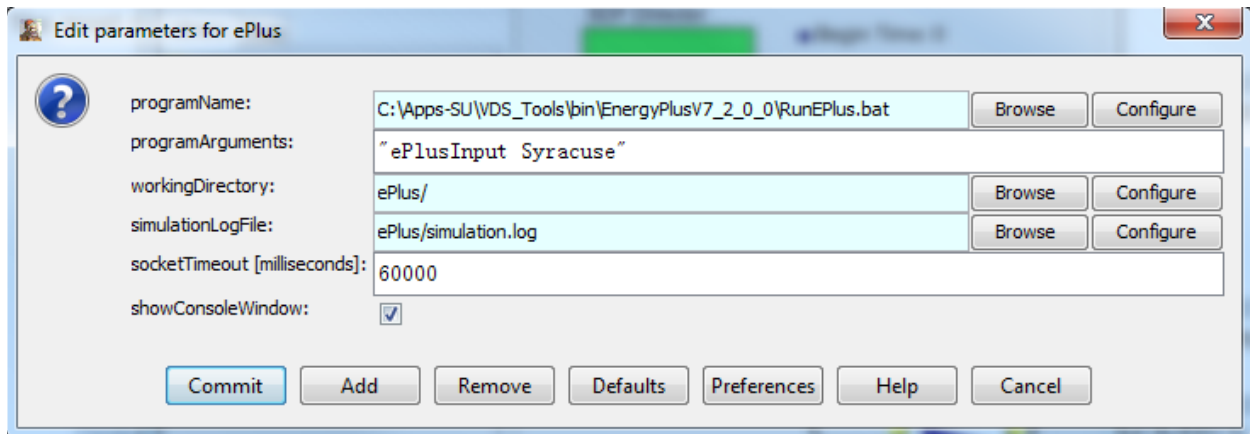
Figure 4-16 Simulator Actor for EnergyPlus in BCVTB
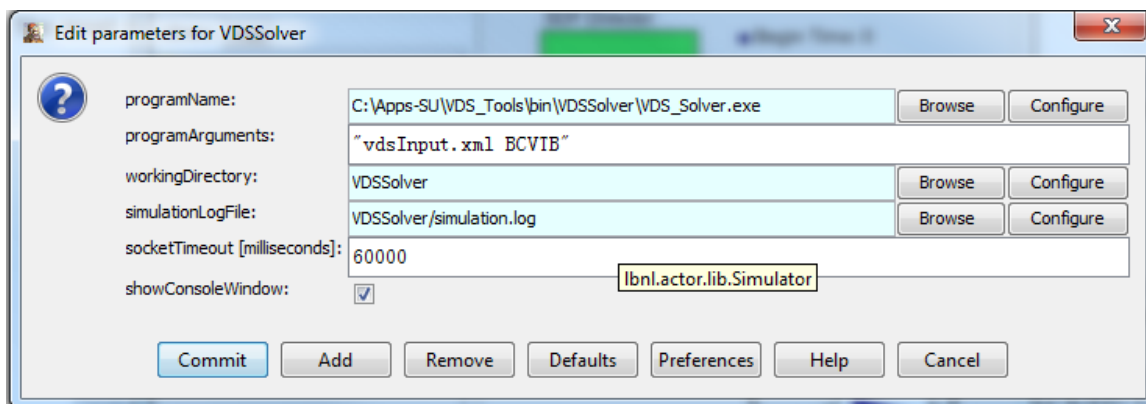
Figure 4-17 Simulator Actor for CHAMPS-Multizone in BCVTB

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.
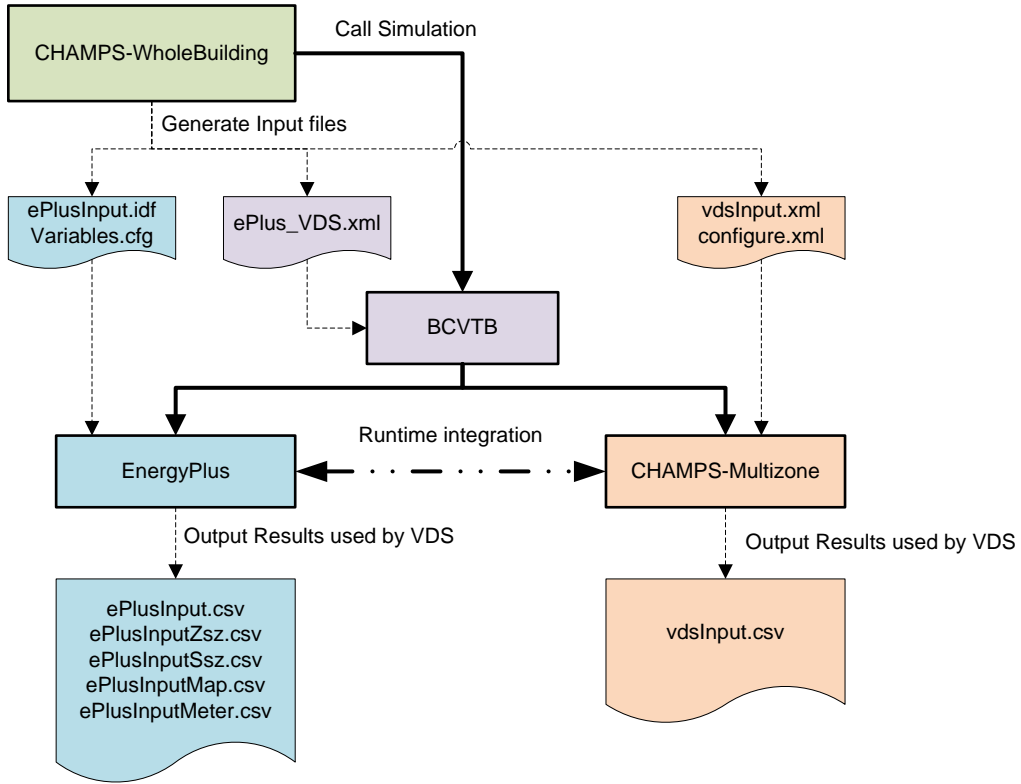
Figure 4-18 CHAMPS-WholeBuilding Co-Simulation flow
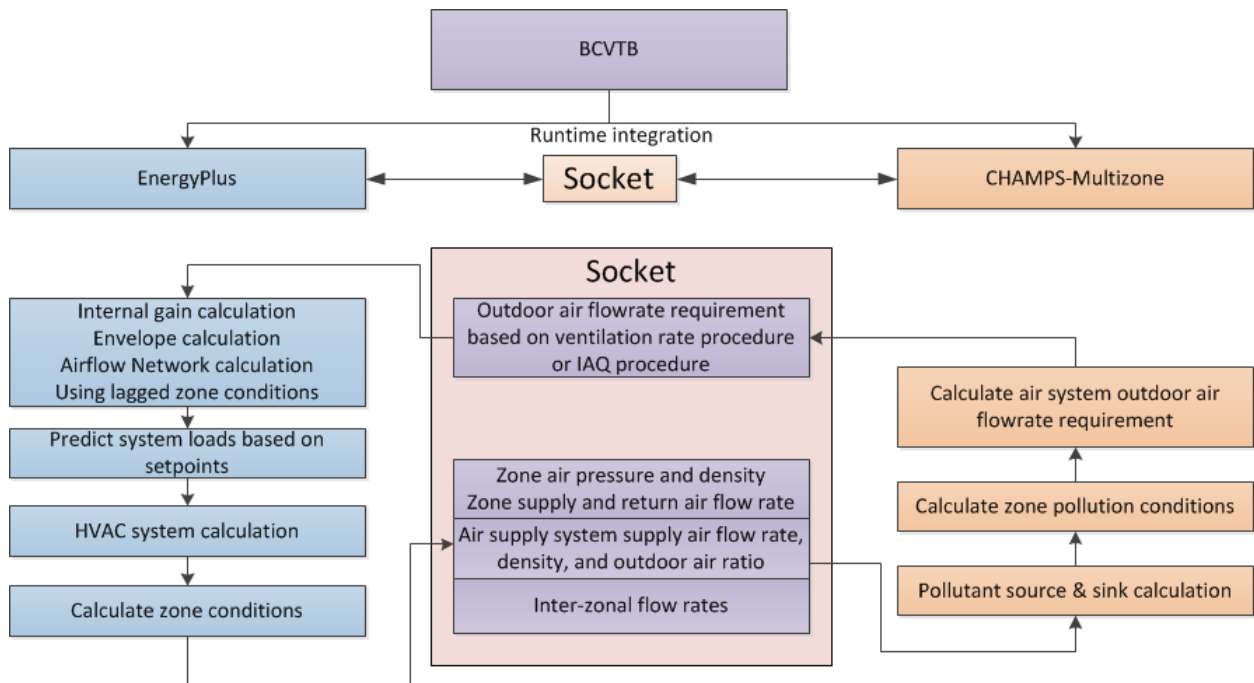
Figure 4-19 Runtime integration of EnergyPlus and CHAMPS-Multizone
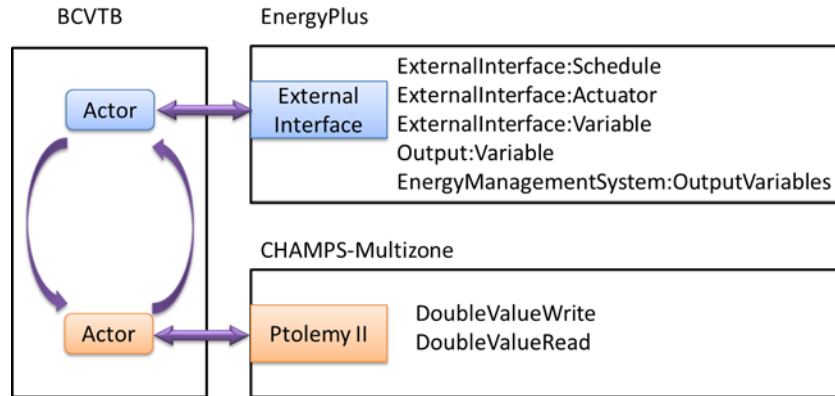
Figure 4-20 Data exchange architecture via BCVTB for EnergyPlus and CHAMPS-Multizone

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 airloops 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. Frist, 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

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saved in the "Read Array". CHAMPS-Multizone reads the variables from the array and preforms 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.
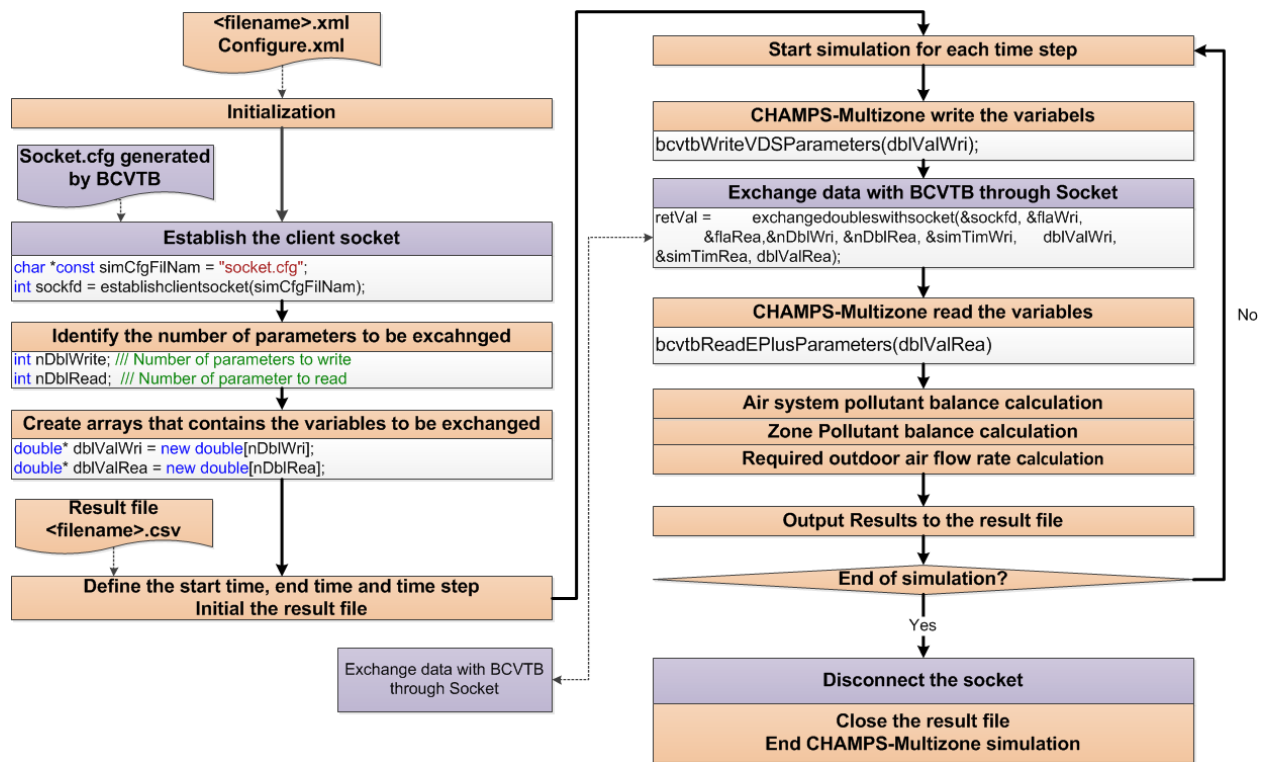
Figure 4-23 Flow chart of the enhanced CHAMPS-Multizone model

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.

$$S_{cc}(t) = G_{cc} - \frac{D}{\rho_a(t)} * \rho_c(t)$$ 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 $\quad$ = Current simulation time [s].

$\rho_c(t)$ $\quad$ = 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.

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

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

Where:

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

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

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

τ_c $\quad$ = 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:

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

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

Equation 4-6

$$V_m \frac{\partial \rho_{cs}(t)}{\partial t} = -S_{bl}(t)$$

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

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

Where:

V   = Volume of the zone [m³]

$\dot{m}c_i$ = 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.

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

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

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

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:

$$\rho_{c-before} = \rho_{c-after} \cdot (1 - \varepsilon)$$
<div align="right">Equation 4-11</div>

Where:

$\rho_{c-after}$ $\quad$ = 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.
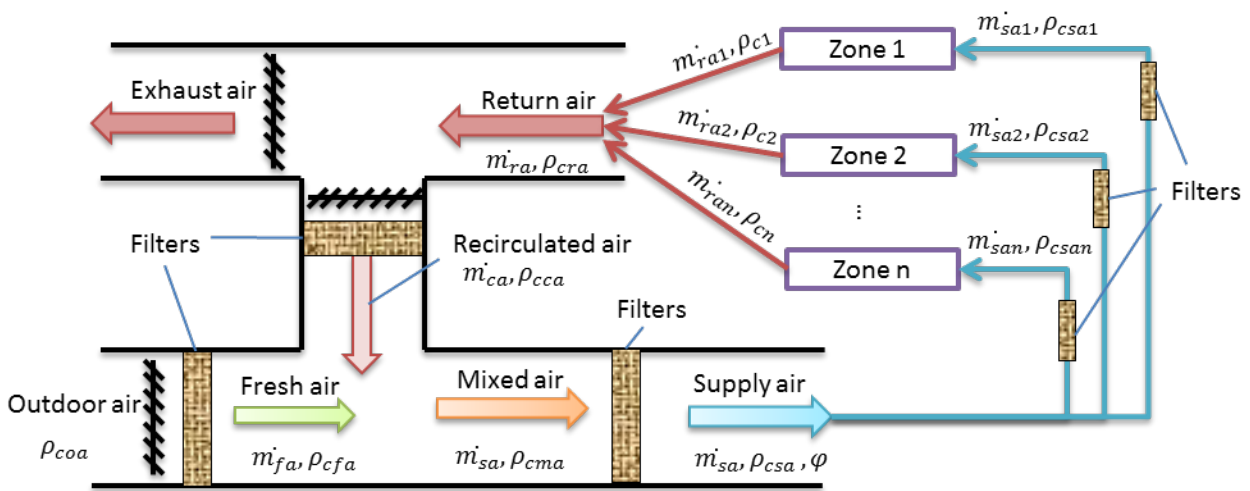
Figure 4-24 Schematic of the air supply system for pollutant balance calculation

o **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:

$$\rho_{cra} = \frac{\sum_{k=1}^{n}\left(\frac{\dot{m}_{rak}}{\rho_{ak}} \cdot \rho_{ck}\right)}{\sum_{k=1}^{n}\left(\frac{\dot{m}_{rak}}{\rho_{ak}}\right)}$$

Equation 4-12

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Where:

ρ_{cra} = Contaminant concentration in return air of the air supply system [mg/m³]

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

ρ_{ak} = Air density of zone k [kg/m³]

ρ_{ck} = Contaminant concentration in zone k [mg/m³]

o **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:

$$\rho_{cca} = \rho_{cra} \cdot (1 - \varepsilon_{ca})$$ Equation 4-13

Where:

ρ_{cca} = Contaminant concentration in recirculated air of the air supply system [mg/m³]

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

o **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:

$$\rho_{cfa} = \rho_{coa} \cdot (1 - \varepsilon_{oa})$$ Equation 4-14

Where:

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

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

o **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:

$$\rho_{cma} = \frac{\dfrac{\dot{m}_{ca}}{\rho_a} \cdot \rho_{cca} + \dfrac{\dot{m}_{fa}}{\rho_a} \cdot \rho_{cfa}}{\dfrac{\dot{m}_{sa}}{\rho_a}} = \frac{\dot{m}_{ca} \cdot \rho_{cca} + \dot{m}_{fa} \cdot \rho_{cfa}}{\dot{m}_{sa}}$$
<div align="right">Equation 4-15</div>

$$\dot{m}_{ca} = \dot{m}_{sa} - \dot{m}_{fa}$$
<div align="right">Equation 4-16</div>

$$\varphi = \frac{\dot{m}_{fa}}{\dot{m}_{sa}}$$
<div align="right">Equation 4-17</div>

Where:

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

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

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

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

φ = Outdoor air fraction [dimensionless]

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

o **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:

$$\rho_{csa} = \rho_{cma} \cdot (1 - \varepsilon_{sa})$$

Equation 4-18

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 flowrate requirement

The total air flowrate 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 4-19.

$$V_{bz} = R_p \cdot P_z + R_a \cdot A_z$$

Equation 4-19

Where:

V_{bz} = Breathing zone outdoor airflow rate [m3/s]

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

P_z = 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 (V_{oz}), 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 4-20.

$$V_{oz} = V_{bz}/E_z$$

Equation 4-20

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 (V_{ot}) shall be determined in accordance with Equation 4-21.

$$V_{ot} = V_{oz}$$

Equation 4-21

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 (V_{ot}) shall be determined in accordance with Equation 4-22.

$$V_{ot} = \sum_{i=1}^{N} V_{oz,i}$$

Equation 4-22

Where:

$V_{oz,i}$ = 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 4-23.

$$Vot = Vou/Ev \qquad\qquad \text{Equation 4-23}$$

Where:

V_{ou} = The design uncorrected outdoor air intake [m³/s]

E_v = System ventilation efficiency [dimensionless]

$$Vou = \sum_{i=1}^{N}(Rp \cdot Pz) + \sum_{i=1}^{N}(Ra \cdot Az) \qquad\qquad \text{Equation 4-24}$$

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 4-25 or Equation 4-28.

Single Supply Systems case:

$$Evz = 1 + Xs - Zd \qquad\qquad \text{Equation 4-25}$$

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.

$$X_s = V_{ou}/V_{ps}$$

Equation 4-26

Where:

V_{ps} = System Primary Airflow [m³/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 4-27

Where:

V_{dz} = Zone Discharge Airflow [m³/s]. The expected discharge (supply) airflow to the zone that includes primary airflow and locally recirculated airflow.

Equation 4-25 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 4-28

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.

$$Fa = Ep + (1 - Ep) \cdot Er \qquad \text{Equation 4-29}$$

$$Fb = Ep \qquad \text{Equation 4-30}$$

$$Fc = 1 - (1 - Ez) \cdot (1 - Er) \cdot (1 - Ep) \qquad \text{Equation 4-31}$$

Where:

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

Er = The zone secondary recirculation fraction.

$$Ep = Vpz/Vdz \qquad \text{Equation 4-32}$$

Where:

Vpz = 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 4-28 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.

$$Ev = min\ (Evz) \qquad \text{Equation 4-33}$$

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:

$$\frac{\partial \rho_c^t}{\partial t} = \frac{(\rho_c^t - \rho_c^{t-\delta t})}{\delta t} + O(\delta t) \qquad \text{Equation 4-34}$$

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

$$V\frac{(\rho_c^t - \rho_c^{t-\delta t})}{\delta t} = \sum_{i=1}^{n} \dot{m}c_i(\rho_c^t) + \sum_{i=1}^{N_{cc}} S_{cc,i}(\rho_c^t) \qquad \text{Equation 4-35}$$

$$+ \sum_{i=1}^{N_{ds}} S_{ds,i}(\rho_c^t) + \sum_{i=1}^{N_{bl}} S_{bl,i}(\rho_c^t) + \dot{m}c_{sa}(\rho_c^t)$$

For the pollutant concentration prediction case, the contaminant mass flowrate 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 flowrate from supply air using the contaminant limit. Equation 4-36 and Equation 4-37 shows the predicted contaminant mass flow rate from supply air.

Equation 4-36

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

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

Equation 4-37

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

Where:

$\dot{m}c_{sa,load}$ = the predicted contaminant mass flowrate 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 4-36 and Equation 4-37, the required supply air pollutant concentration from a zone can be determined as follows:

$$\rho_{csa,r} = \left\{ \left[V \frac{(\rho_{c,limit} - \rho_c^{t-\delta t})}{\delta t} - \sum_{i=1}^{n} \dot{m} c_i(\rho_{c,limit}) - \sum_{i=1}^{N_{cc}} S_{cc,i}(\rho_{c,limit}) \right. \right.$$

$$\left. \left. - \sum_{i=1}^{N_{ds}} S_{ds,i}(\rho_{c,limit}) - \sum_{i=1}^{N_{bl}} S_{bl,i}(\rho_{c,limit}) \right] \cdot \frac{\rho_a}{\dot{m}_{sa}} + \rho_{c,limit} \right\} \cdot \frac{1}{(1-\varepsilon_z)} \qquad \text{Equation 4-38}$$

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.

$$\rho_{csa,sr} = \min_{1 \le i \le N_z} (\rho_{csa,r,i}) \qquad \text{Equation 4-39}$$

Where:

$\rho_{csa,sr}$ = Required supply air pollutant concentration of the air supply system [mg/m³]

$\rho_{csa,r,i}$ = Required supply air pollutant concentration from zone i [mg/m³]

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

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

Apply Equation 4-39 to Equation 4-40, and solve the equation to obtain the required outdoor air fraction.

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

Equation 4-41

Equation 4-41 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:

$\varphi = 0$ *when* $\varphi_{sr} \leq 0$

Equation 4-42

$\varphi = \varphi_{sr}$ *when* $0 < \varphi_{sr} < 1$

Equation 4-43

$\varphi = 1$ *when* $\varphi_{sr} \geq 1$

Equation 4-44

4.2.5. Development of a new HVAC template type in EnergyPlus

One of the goals for the present project is to use the SyracuseCoE building to demonstrate VDS capabilities. The SyracuseCoE 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

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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.
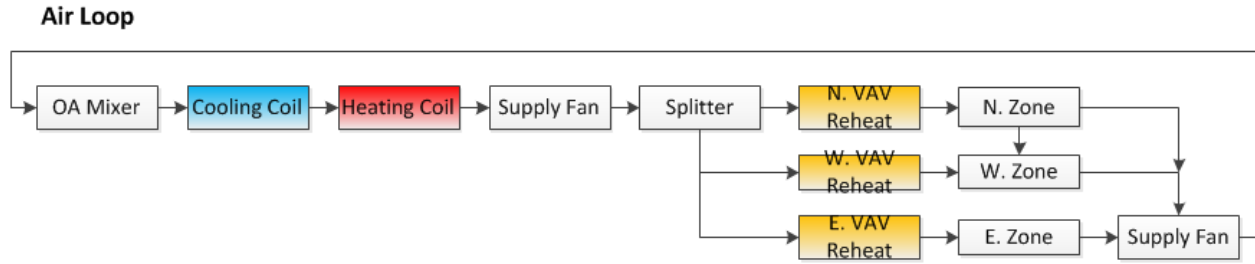
Figure 4-28 Air system loop diagram
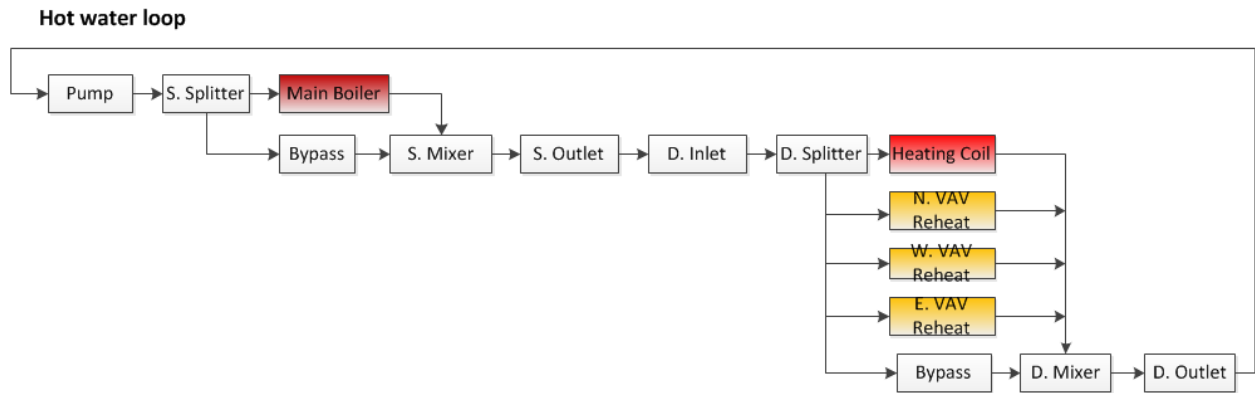
Figure 4-29 Hot water loop diagram
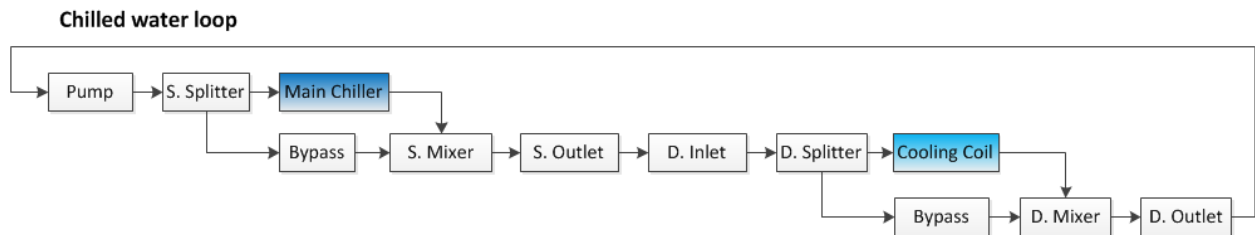
Figure 4-30 Chilled water loop diagram
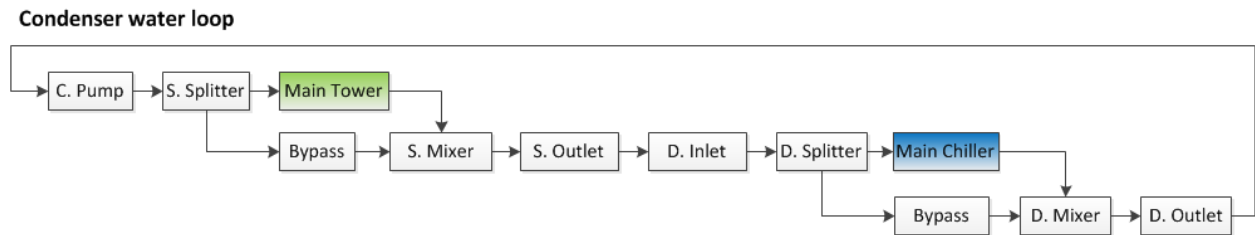
Figure 4-31 Condenser water loop diagram

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.
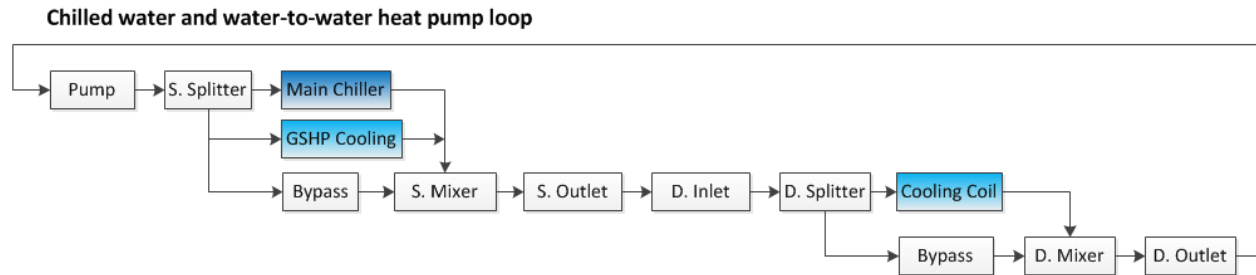
Figure 4-32 Chilled water loop and water-to-water heat pump loop diagram
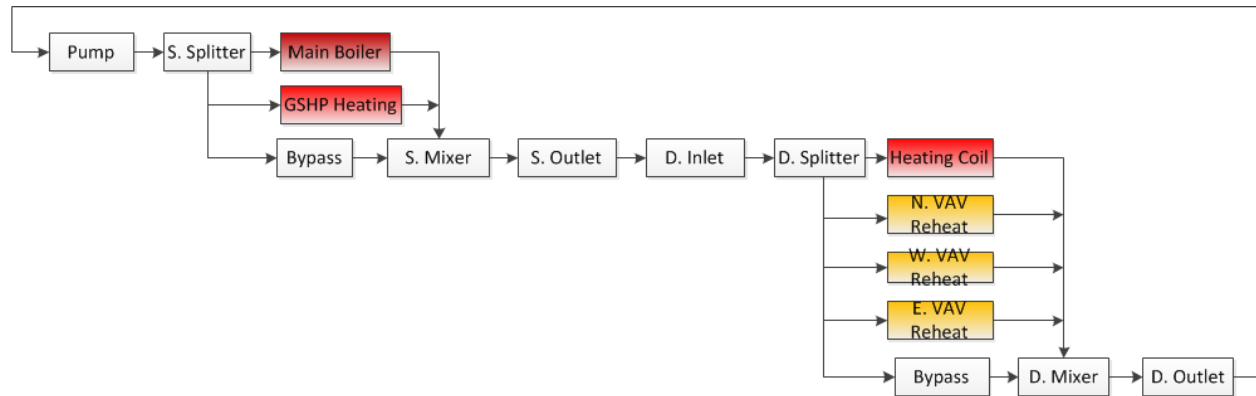
Figure 4-33 Hot water loop and water-to-water heat pump loop diagram
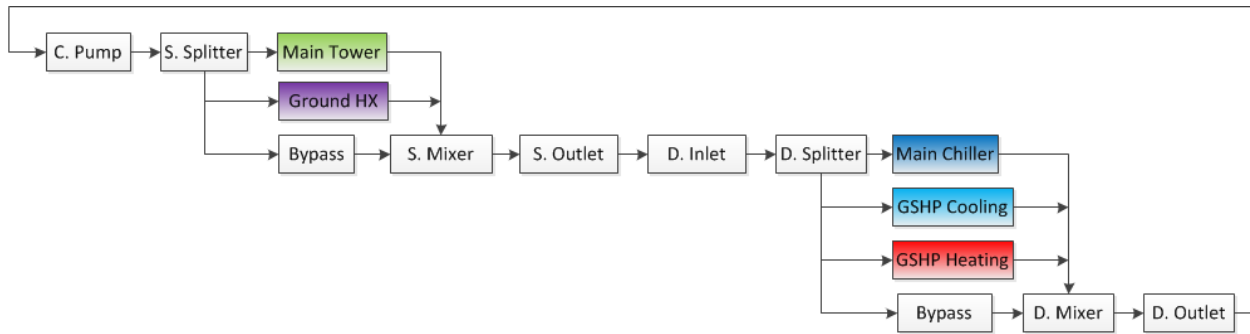
Figure 4-34 Condenser water loop and ground heat exchanger loop diagram

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.
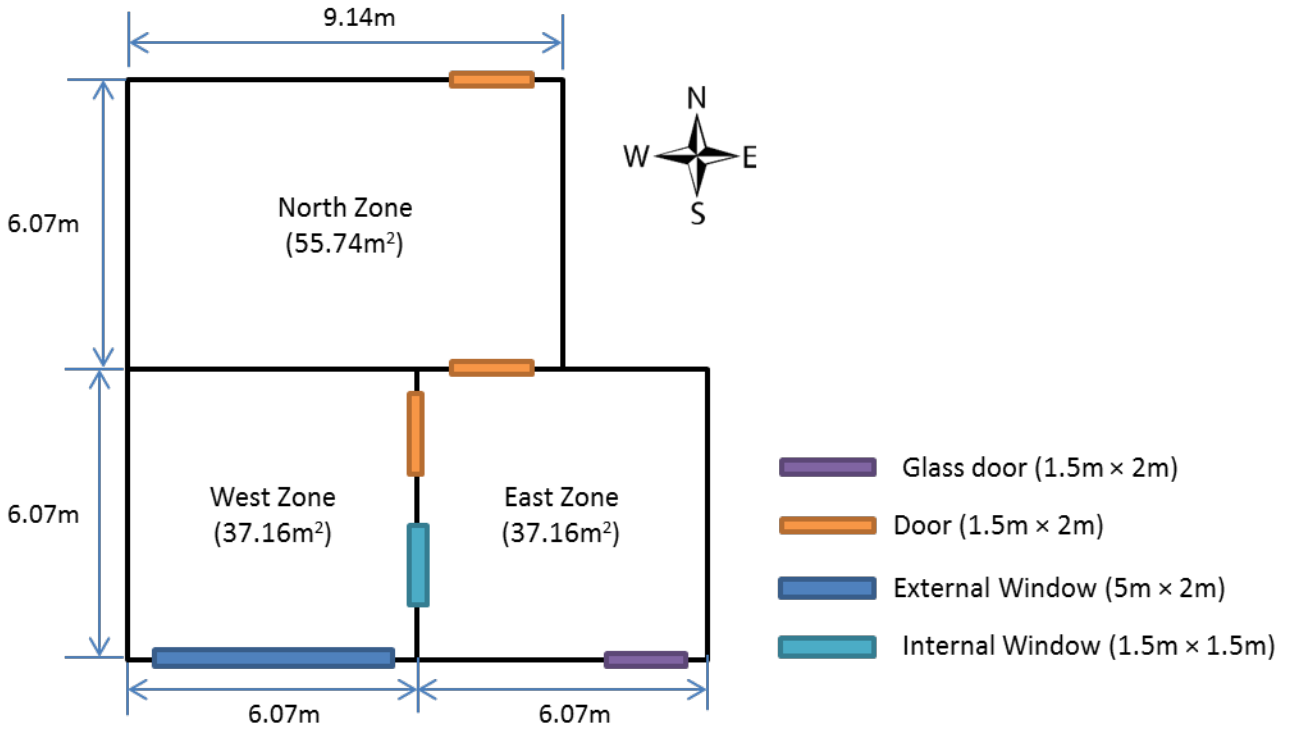
Figure 4-35 Schematic of the 3-zone office building
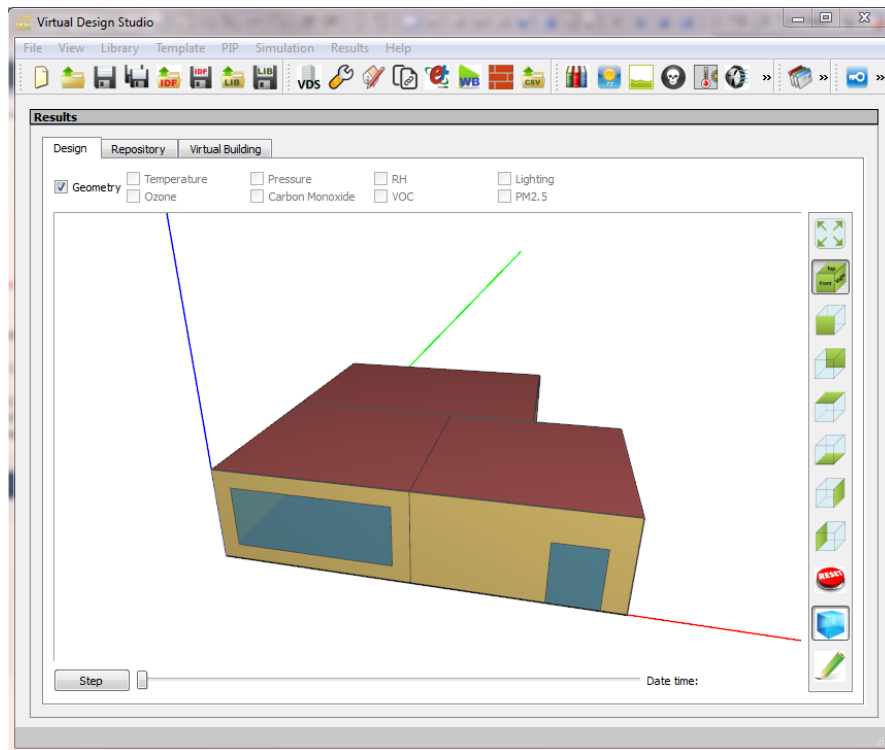
Figure 4-36 3-D geometry view of the 3-zone building in VDS result quadrant

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.
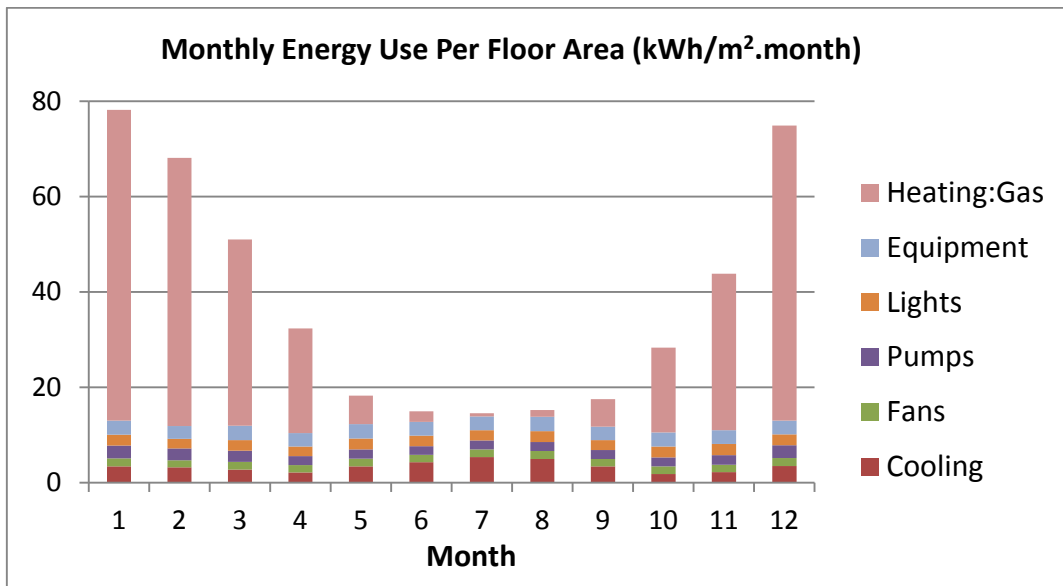
Figure 4-37 Monthly energy use per floor area

Annual Energy Consumption by End Use (kWh/m².year)

■	Cooling
■	Fans
■	Pumps
■	Lights
■	Equipment
■	Heating

41 9%

19 4%

25 5%

26 6%

35 8%

311 68%
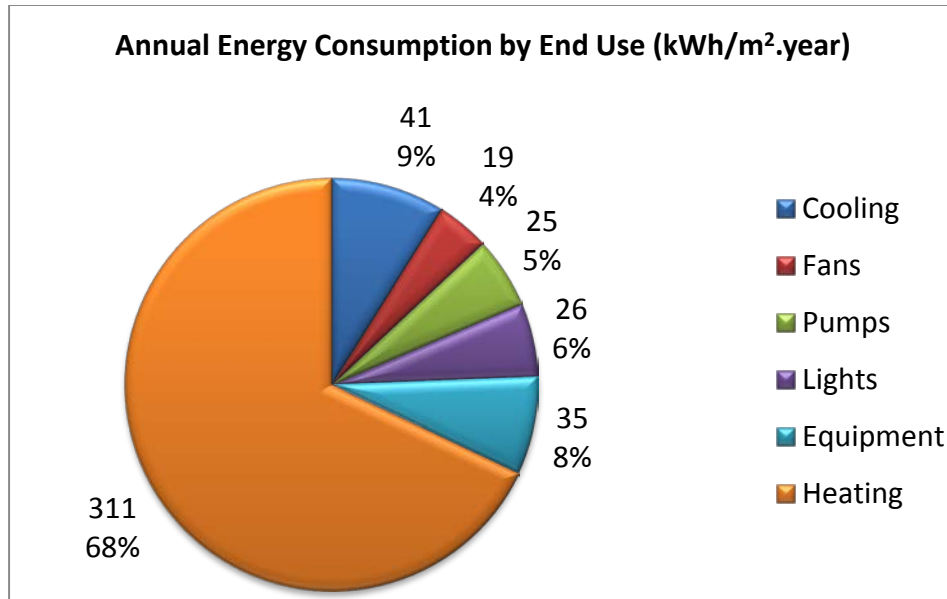
Figure 4-38 Annual energy consumption by end use

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.
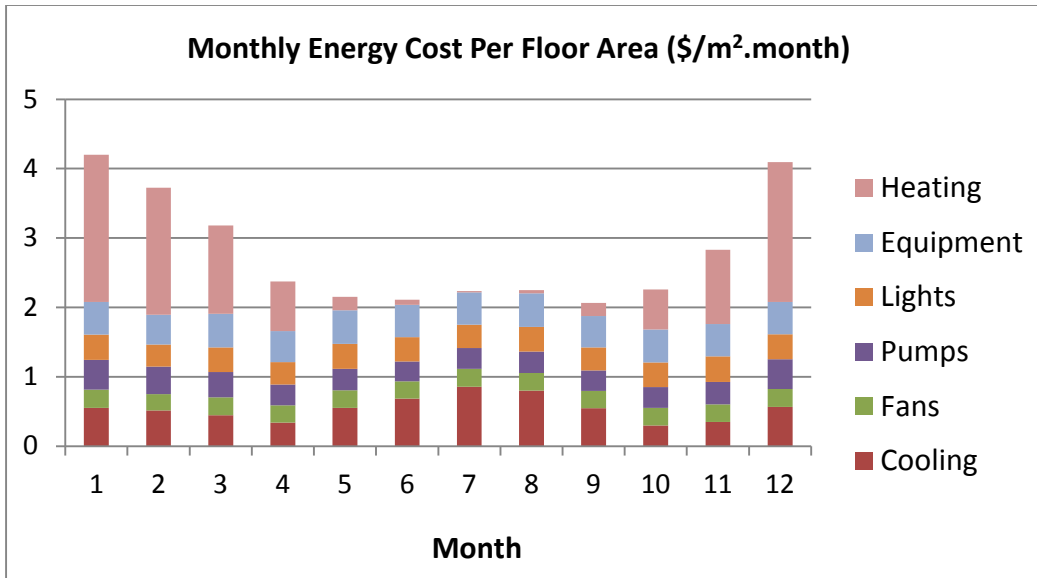
Figure 4-39 Monthly energy cost per floor area
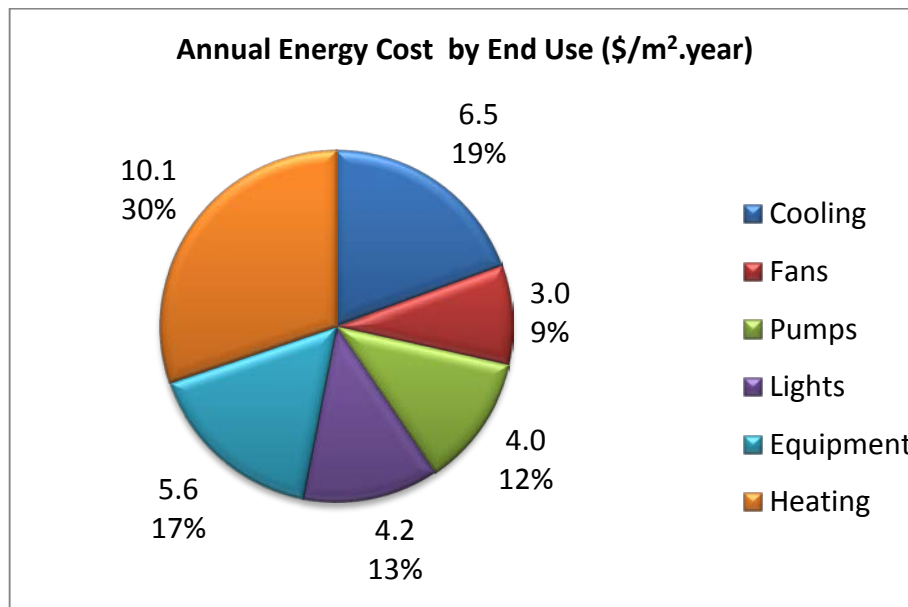
Figure 4-40 Annual energy cost by end use

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.
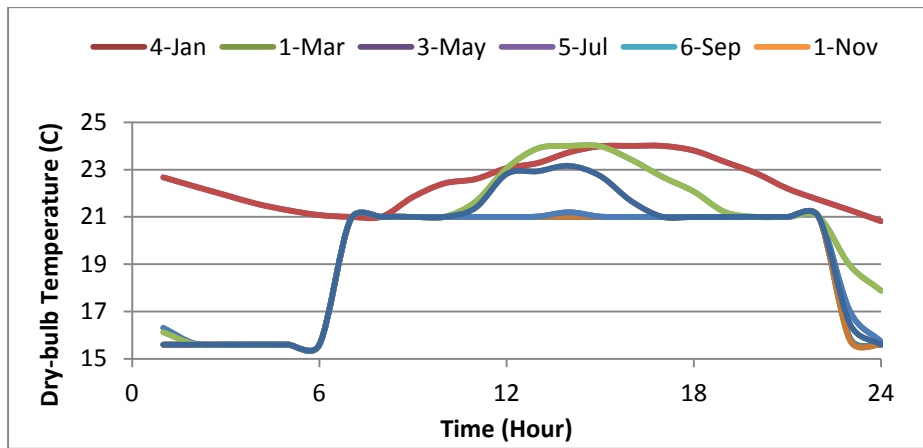
Figure 4-41 Hourly Dry-bulb temperature of West Zone for the selected days
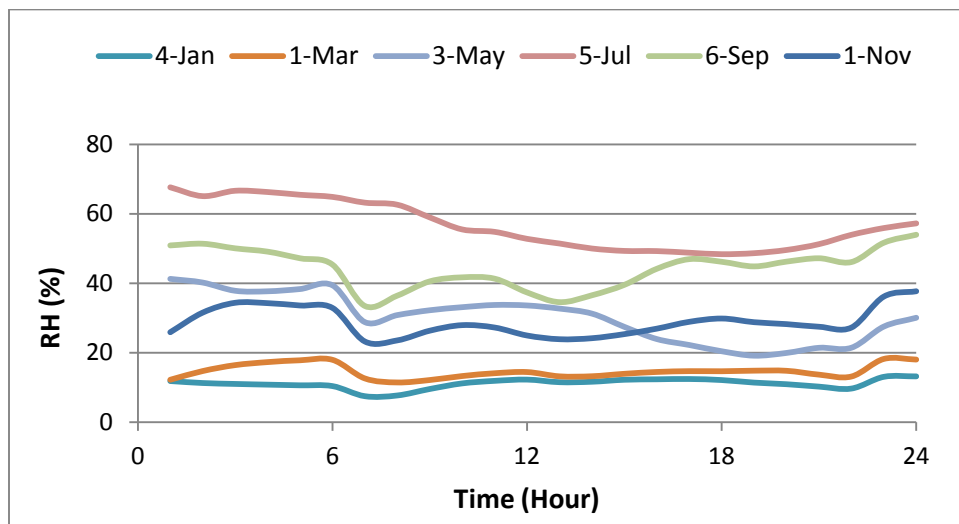
Figure 4-42 Hourly RH of West Zone for the selected days

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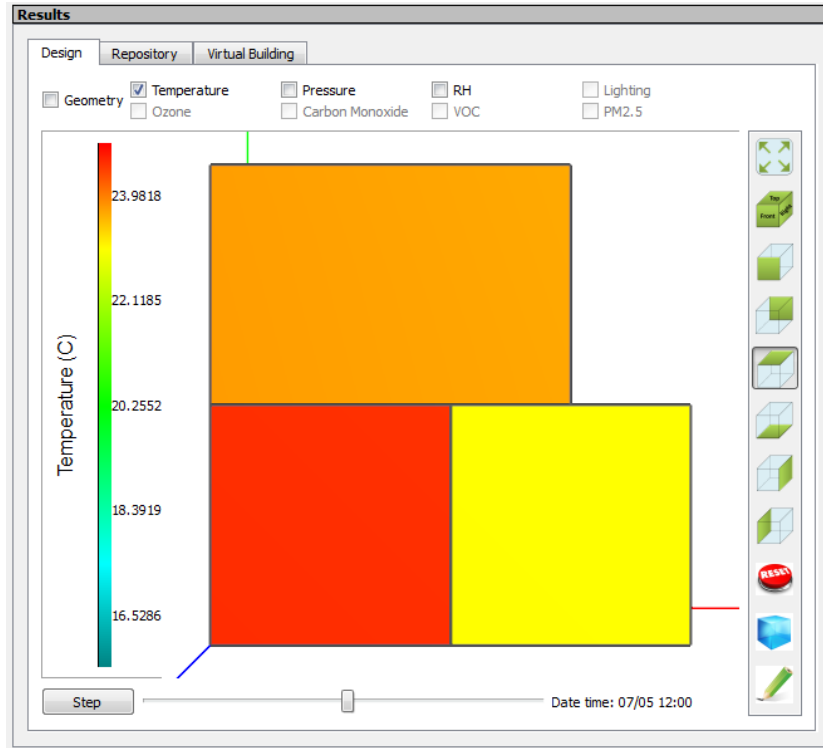
Figure 4-43 Dry-bulb temperature distribution at 12pm on July 5th
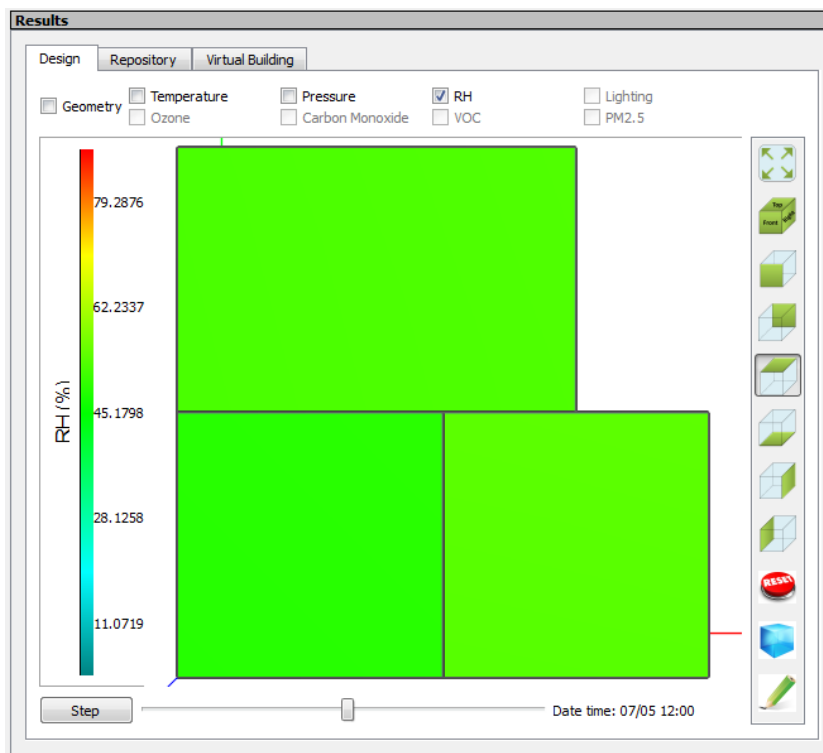
Figure 4-44 RH distribution at 12pm on July 5th

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.
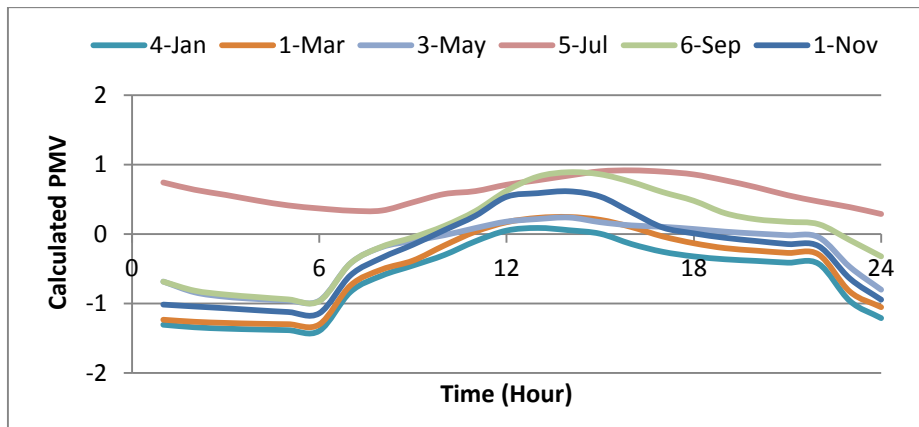
Figure 4-45 Hourly PMV of West Zone for the selected days
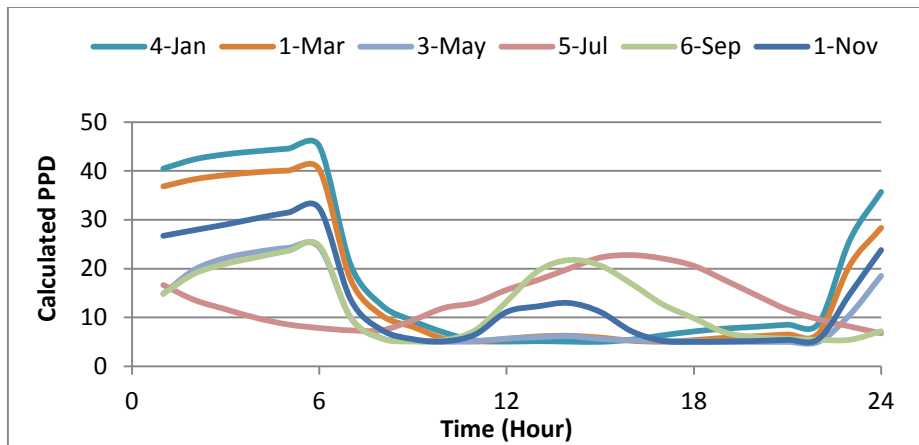
Figure 4-46 Hourly PPD of West Zone for the selected days

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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.
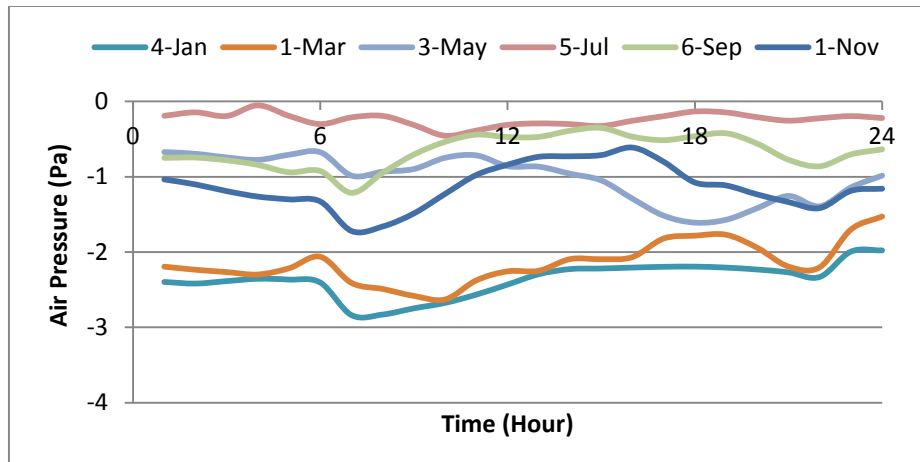
Figure 4-47 Hourly relative air pressure of West Zone for the selected days
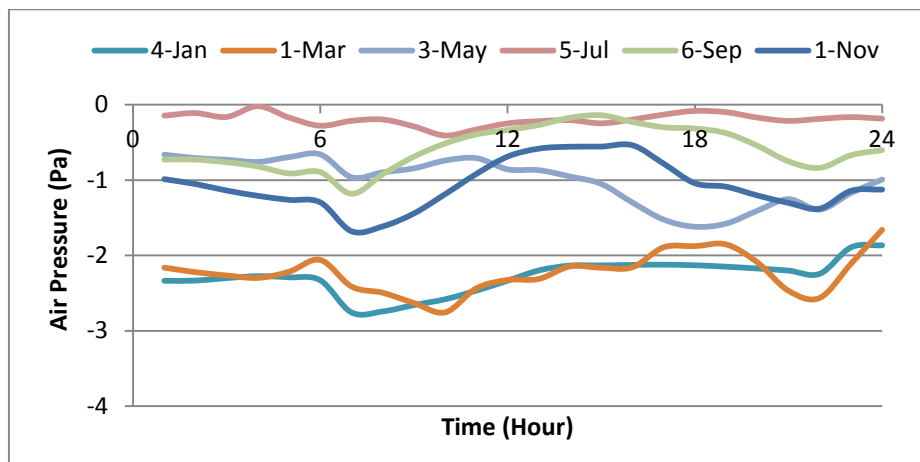
Figure 4-48 Hourly relative air pressure of East Zone for the selected days
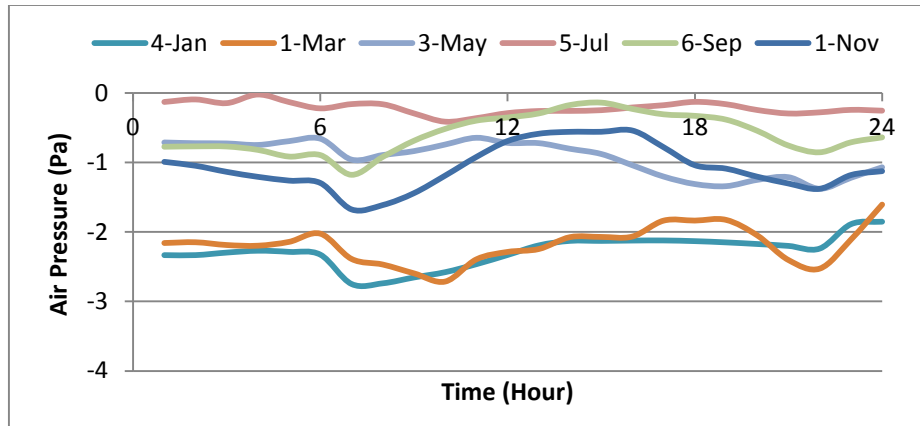
Figure 4-49 Hourly relative air pressure of North Zone for the selected days

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.
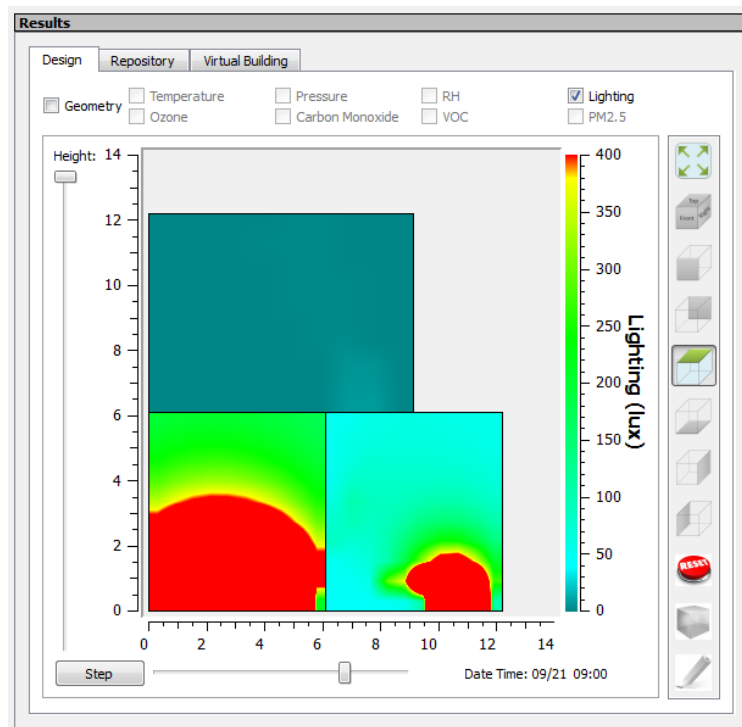
Figure 4-50 Daylighting distribution at 9am on Sep. 21st
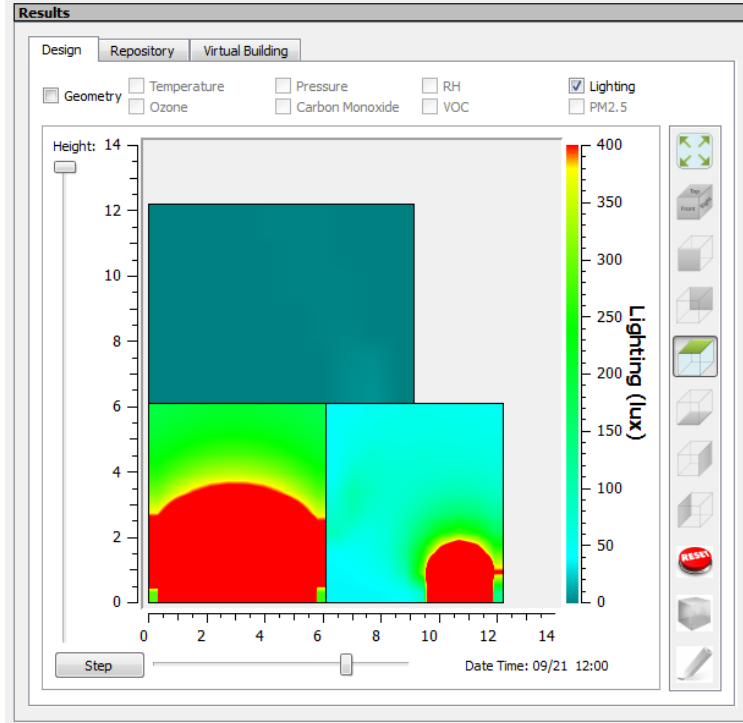
Figure 4-51 Daylighting distribution at 12pm on Sep. 21st
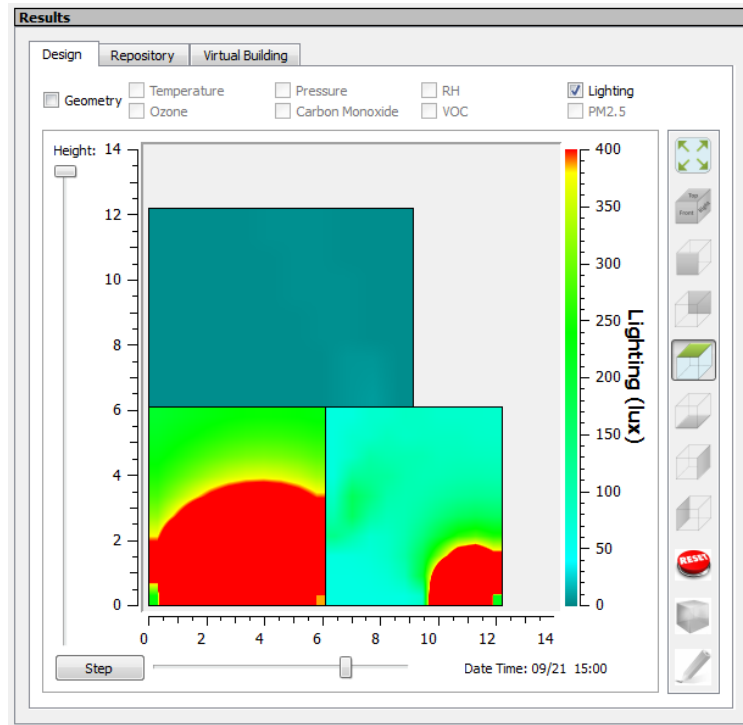
Figure 4-52 Daylighting distribution at 3pm on Sep. 21st

4.3.2. CHAMPS-WholeBuilding co-simulation

The 3-zone building is used to test and verify the CHAMPS-WholeBuilding co-simulation model. There are three cases simulated. Table 4-7 shows the VOC limits and the sources for these simulation cases.

Table 4-7 Simulation cases for testing and verification of co-simulation model

Cases	VOC Limit (mg/m^3)	VOC generation rate ($mg/m^2.h$)
Case 1	1	0.5
Case 2	1	5
Case 3	1	15

As shown in Table 4-7, three ceases are simulated for the 3-zone building. The results for July 19th are presented. Figure 4-53 shows the VOC concentration of West Zone; Figure 4-54 shows the air system outdoor air fraction; and Figure 4-55 shows the energy cost. For Case 1, the ventilation rate is under 20% as the VOC generation rate is low. For Case 2, the VOC generation rate is higher than Case 1, so the ventilation rate is increased to maintain the VOC concentration under the limit. For Case 3, although the ventilation rate is increased to 100% of the total supply air, the VOC concentration still exceeds the limit as the generation rate is too high. In these simulation cases, the ventilation rate requirements and VOC concentrations are calculated by the CHAMPS-Multizone model, and the calculated ventilation rate requirements, represented as outdoor air fraction are passed to EnergyPlus every time step (hourly) to calculate the energy and thermal comfort conditions, and zone supply and return air flow rates (which are then passed to CHAMPS-Multizone for calculating zone VOC concentration, and adjusting the outdoor air flow rate requirements.
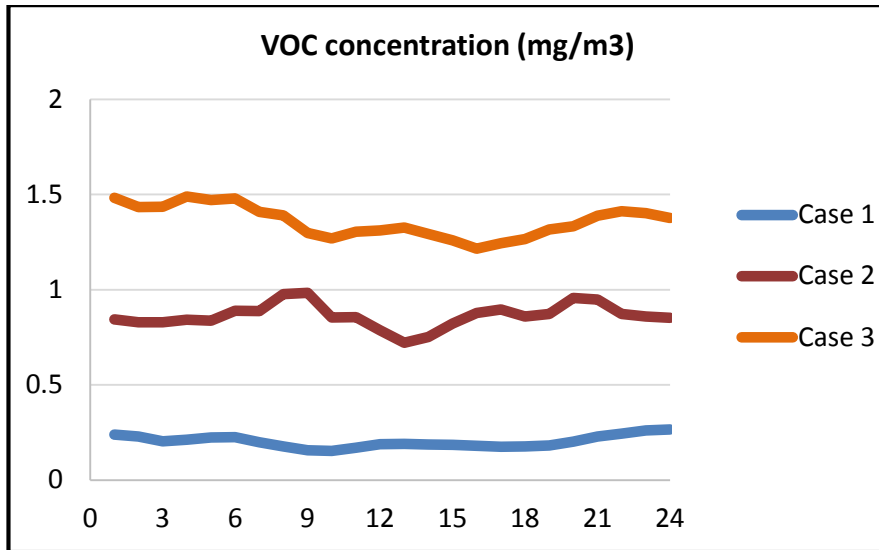
Figure 4-53 VOC concentration of West Zone on July 19th
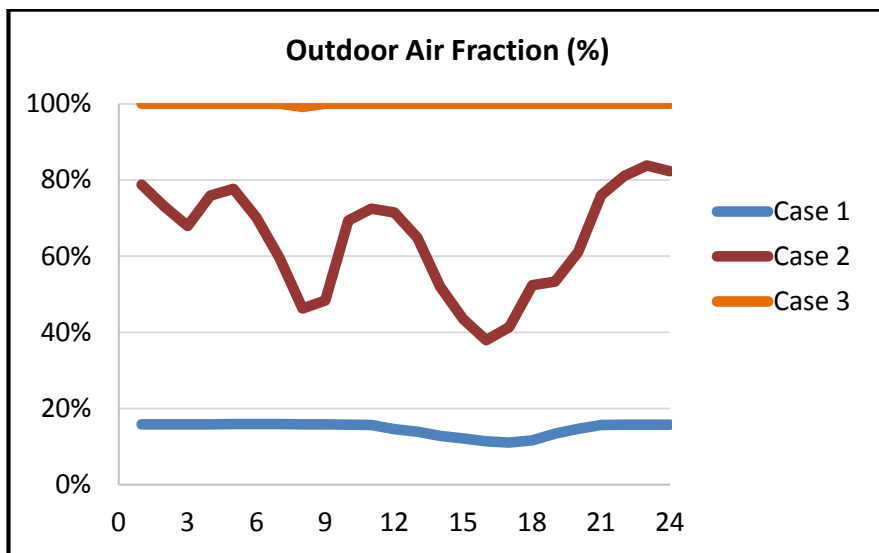
Figure 4-54 Air system outdoor air fraction of the 3-zone building on July 19th
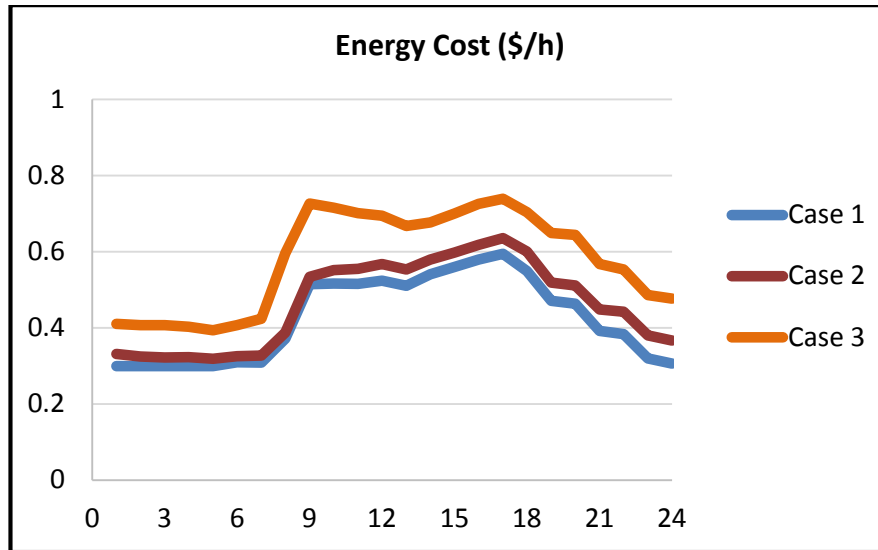
Figure 4-55 Energy cost of the 3-zone building on July 19th

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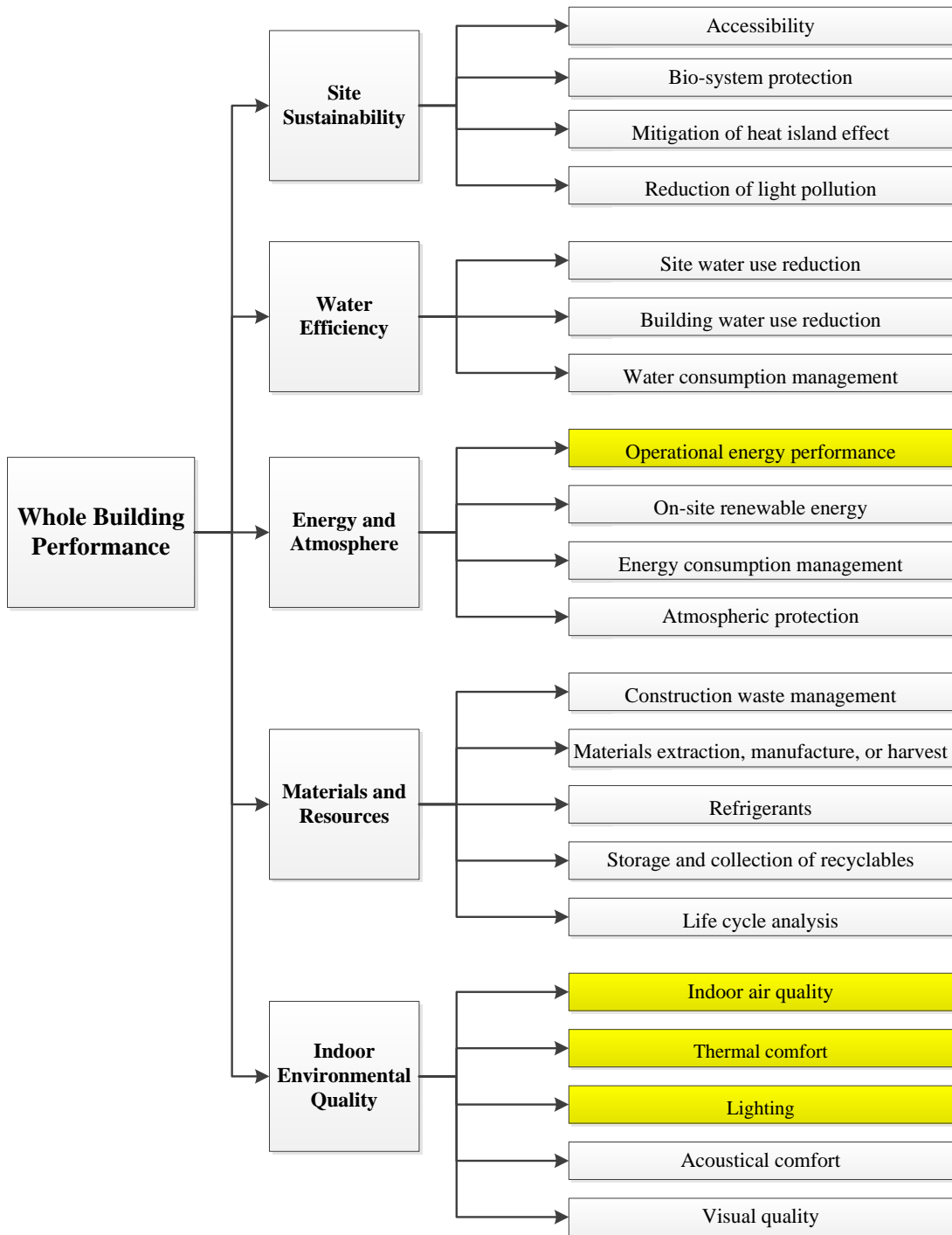
Figure 5-1: Systematic classification and hierarchical representation of green building performance aspects (highlighted sub-performance aspects have been implemented in the current VDS)

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

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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).

$$RP_p = \sum (\omega_{spi} \times RP_{spi})$$
<div align="right">Equation 5-3</div>

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).

$$RP_{wb} = \sum (\omega_{pi} \times RP_{pi})$$
<div align="right">Equation 5-4</div>

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.

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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

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.

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

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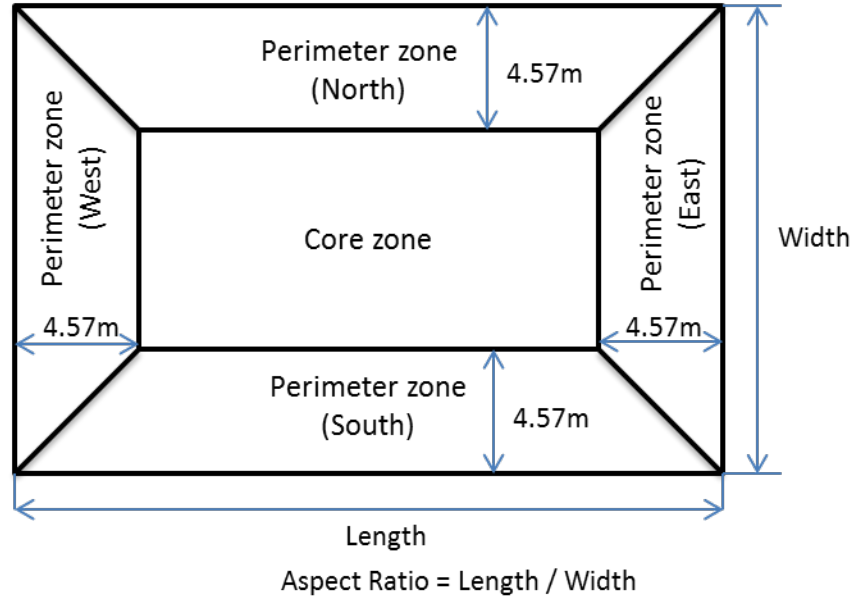
Figure 5-2 Floor plan of the VDS reference building for office buildings

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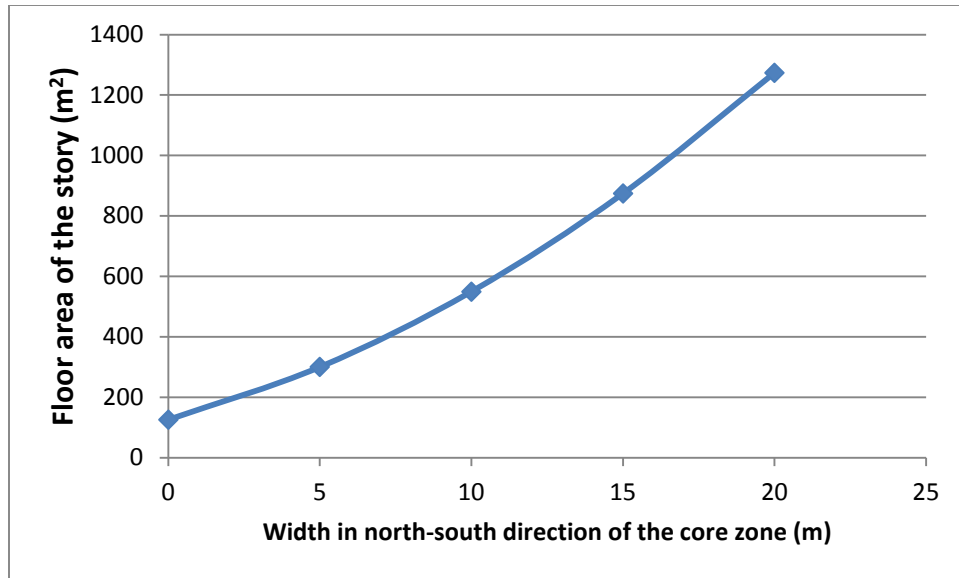
Figure 5-3 Relationship between the width of the core zone and the total floor area of the story

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

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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 SyracuseCoE 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

The 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.

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

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.

$$I_{zt} = \max(I_p)$$ 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).

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

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,

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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 5-8**).

$$DPI_t = \frac{CA_t}{TOA}$$

Equation 5-8

Where

DPI_t: The daylight performance index of time t

CA_t: The complied area of time t

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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.

$$WBDPI = \frac{\sum_{t=1}^{N_t}(DPI_t)}{N_t}$$

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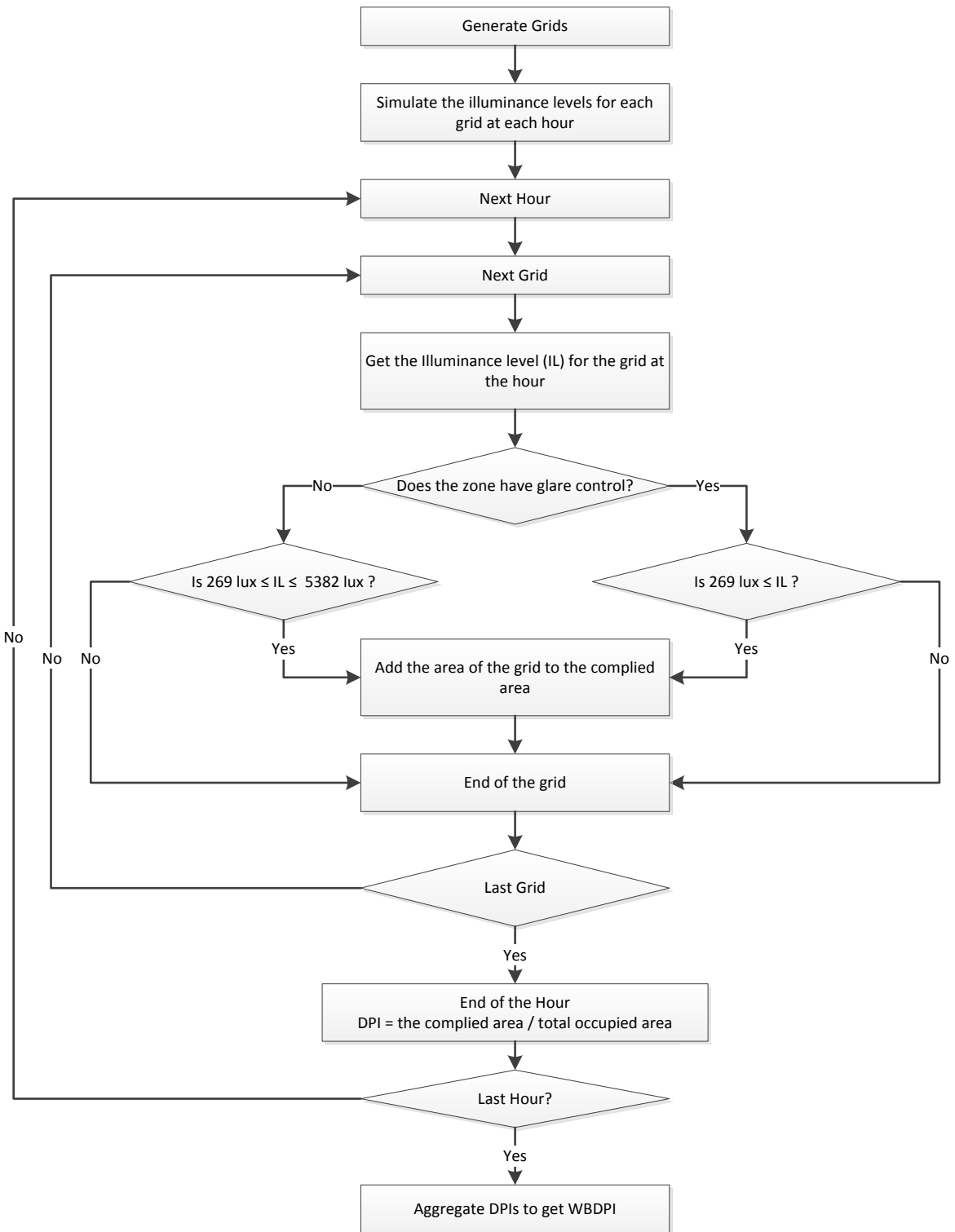
Figure 5-5 Procedures for calculating the whole building daylight performance index (WBDPI)

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.

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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.

$$RPC_f = \frac{PI_{pb} - PI_f}{PI_{rb}}$$
<div align="right">Equation 5-10</div>

$$RPC_f = \frac{PI_f - PI_{pb}}{PI_{rb}}$$
<div align="right">Equation 5-11</div>

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 SyracuseCoE 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
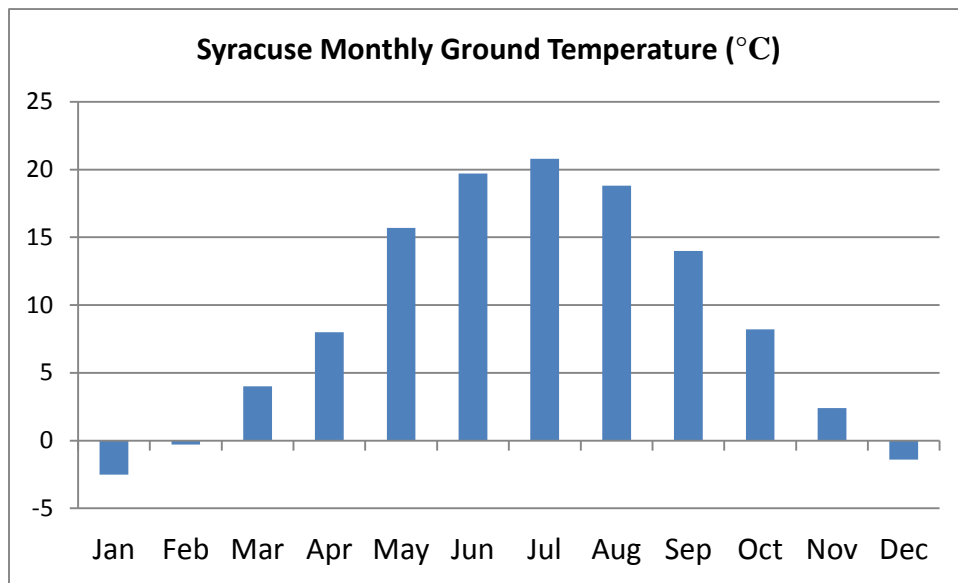
Figure 5-6 Syracuse monthly ground temperature

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.

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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, CO_2 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.
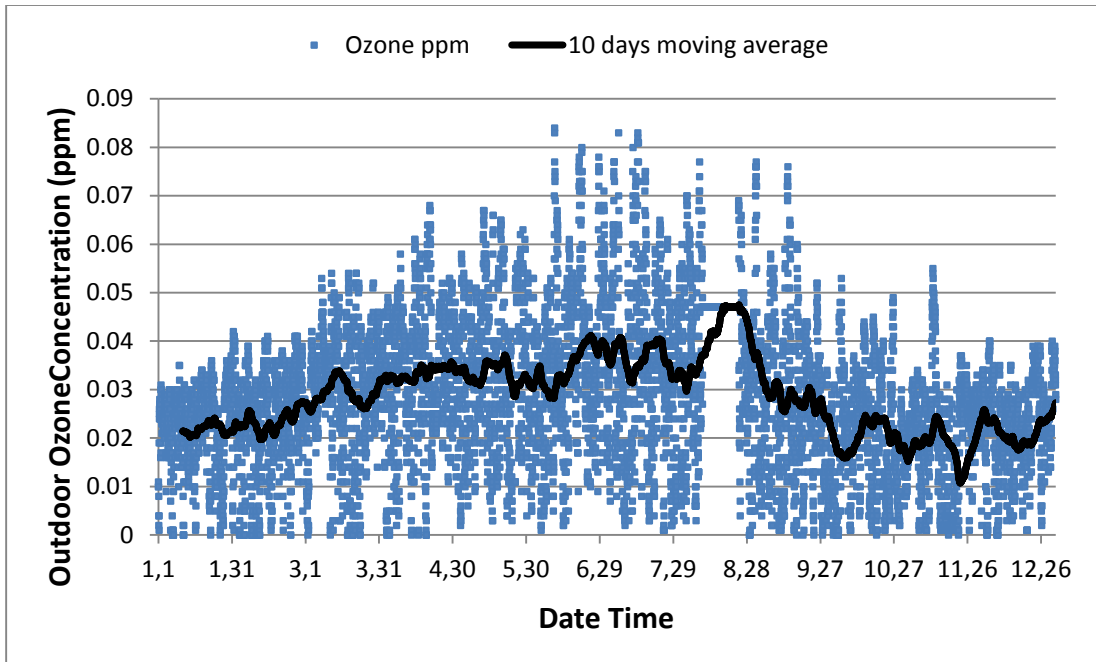
Figure 5-7 Hourly outdoor ozone concentration in East Syracuse, 2012

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 $6.80 \mu g/m^3$.
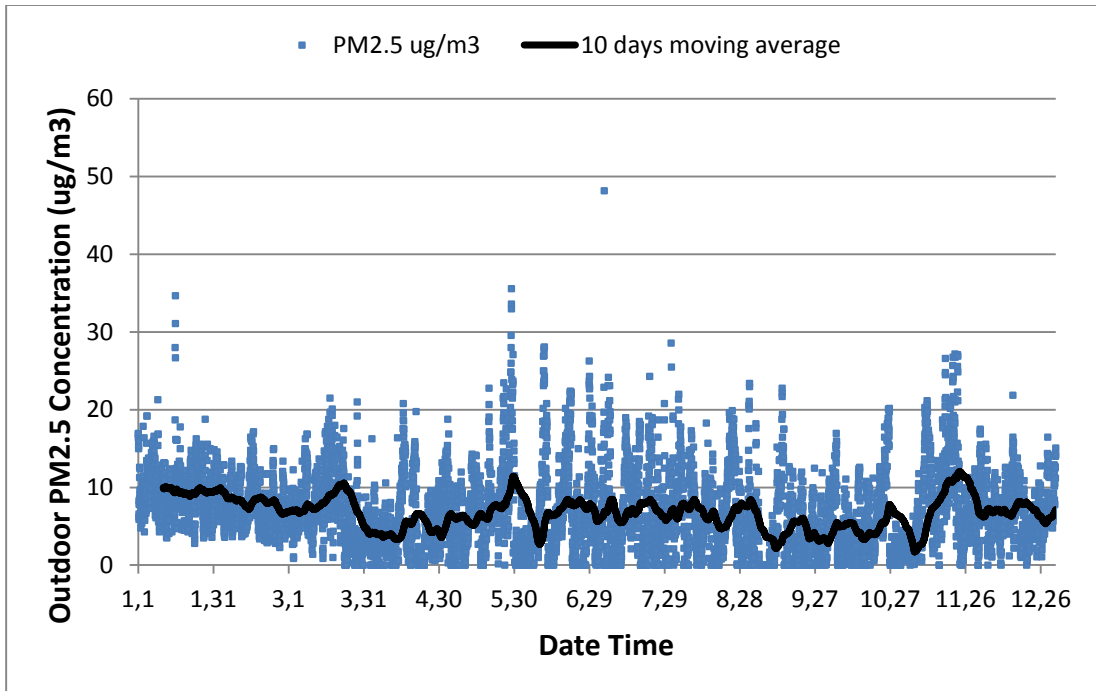
Figure 5-8 Hourly outdoor PM2.5 concentration in Rochester, 2012

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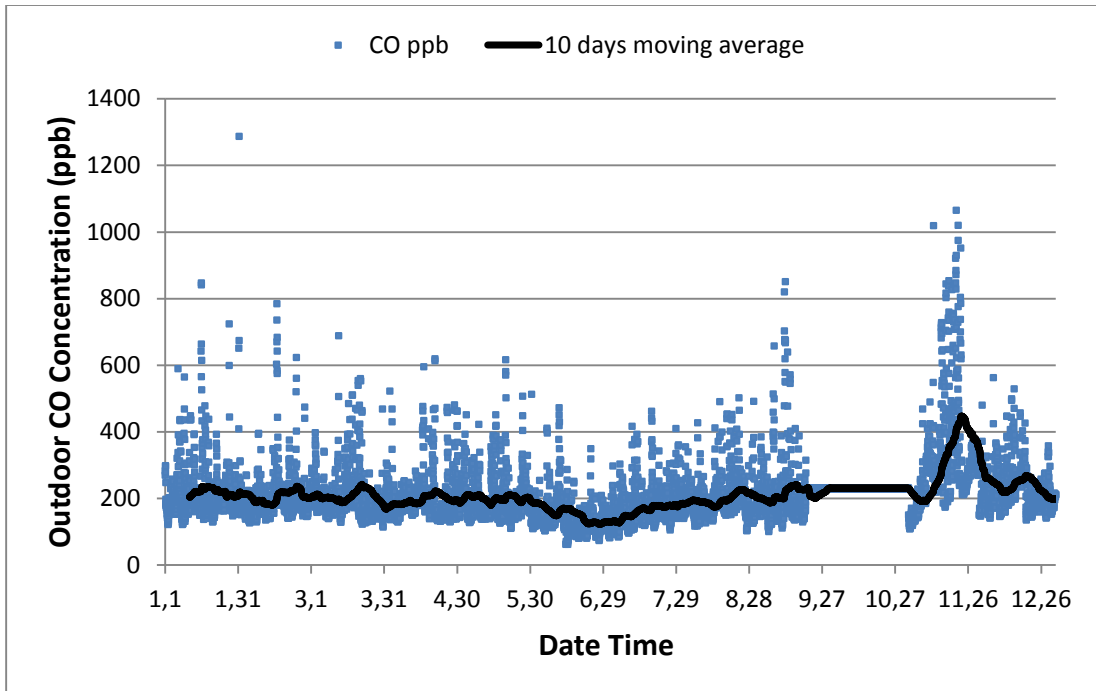
Figure 5-9 Hourly outdoor carbon monoxide concentration in Rochester, 2012

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 shows the shape and thermal 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

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	Average	1255.4	1255.4
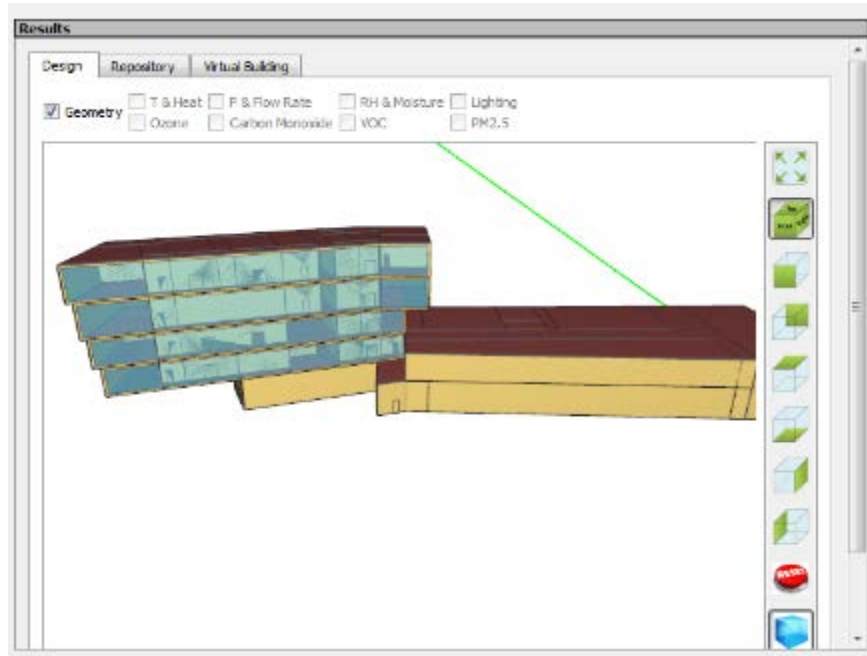
Figure 5-10 South view of the case building
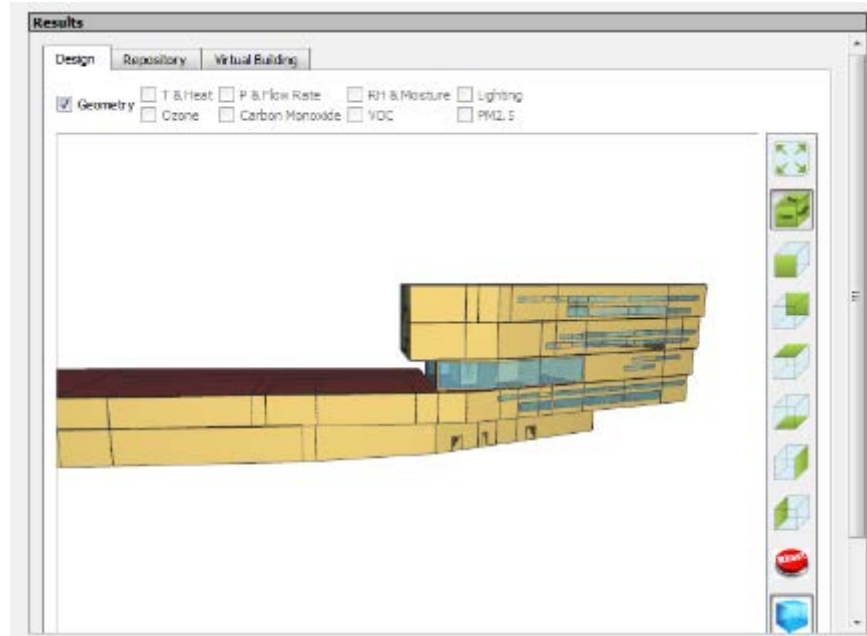
Figure 5-11 North view of the case building
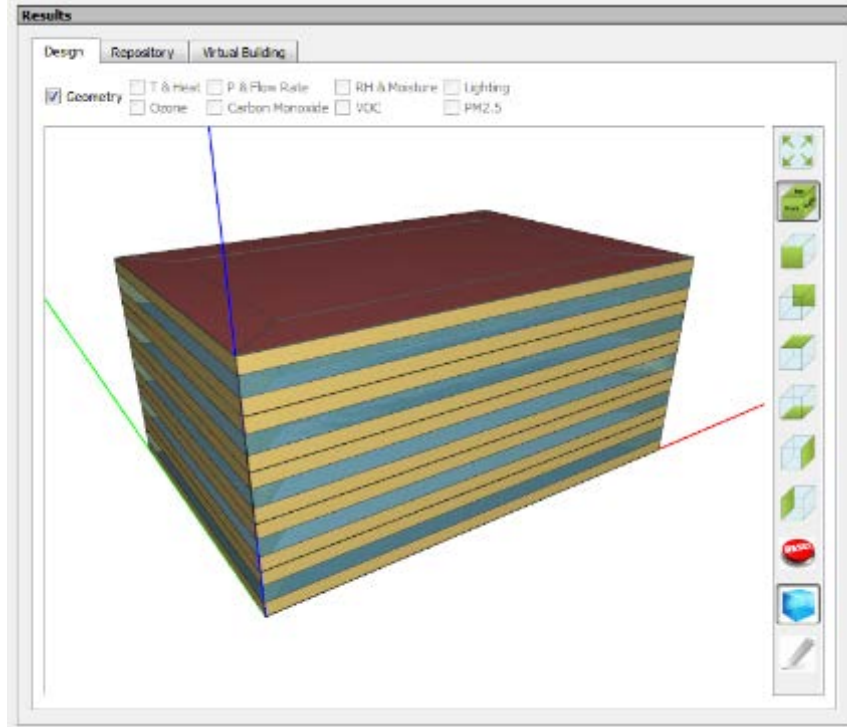
Figure 5-12 Shape of the VDS reference building
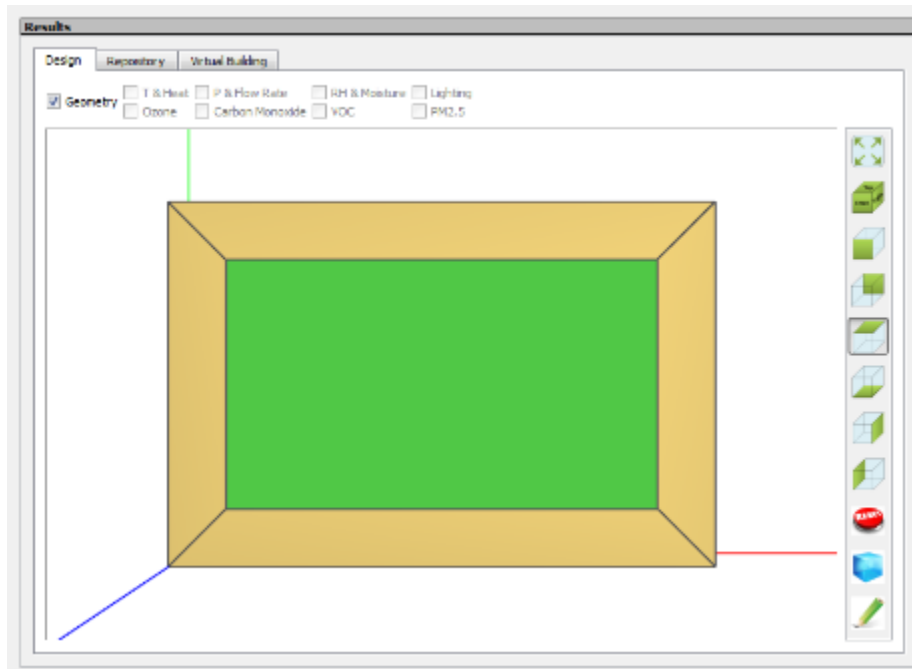
Figure 5-13 Thermal zoning of the VDS reference building

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 (200ft²/person), the total outdoor air rate is $0.085 cfm/ft^2$.

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

Start– End (Hour)		0-6	6-18	18-22	22-24
Heating Setpoint (°C)	Winter Design Day	21	21	21	21
	Weekdays	15.6	21	21	15.6
	Saturday	15.6	21	15.6	15.6
	Sunday & Summer design day	15.6	15.6	15.6	15.6
Cooling Setpoint (°C)	Weekdays & Summer Design Day	26.7	24	24	26.7
	Saturday	26.7	24	26.7	26.7
	Sunday & Winter Design Day	26.7	26.7	26.7	26.7

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 $0.7\ W/ft^2$ (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, the 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.
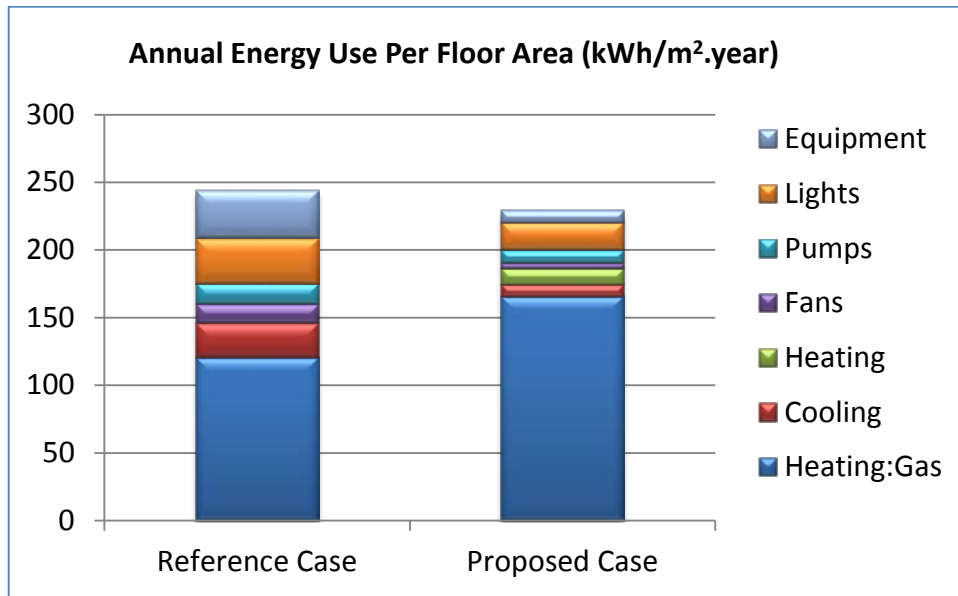
Figure 5-14 Annual energy consumption of cases 0 and 1

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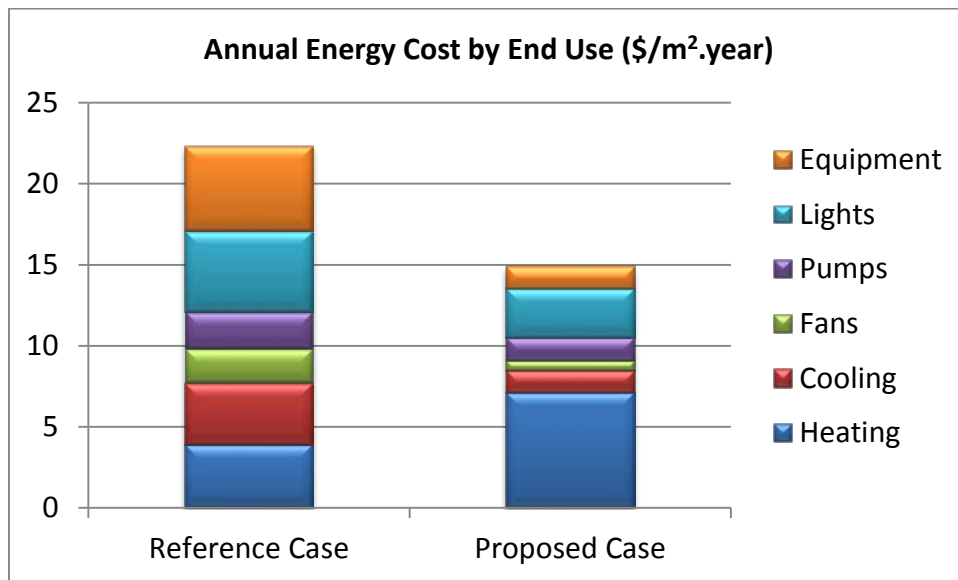
Figure 5-15 Annual energy cost of cases 0 and 1

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.

Annual Energy Use Per Floor Area (kWh/m².year)
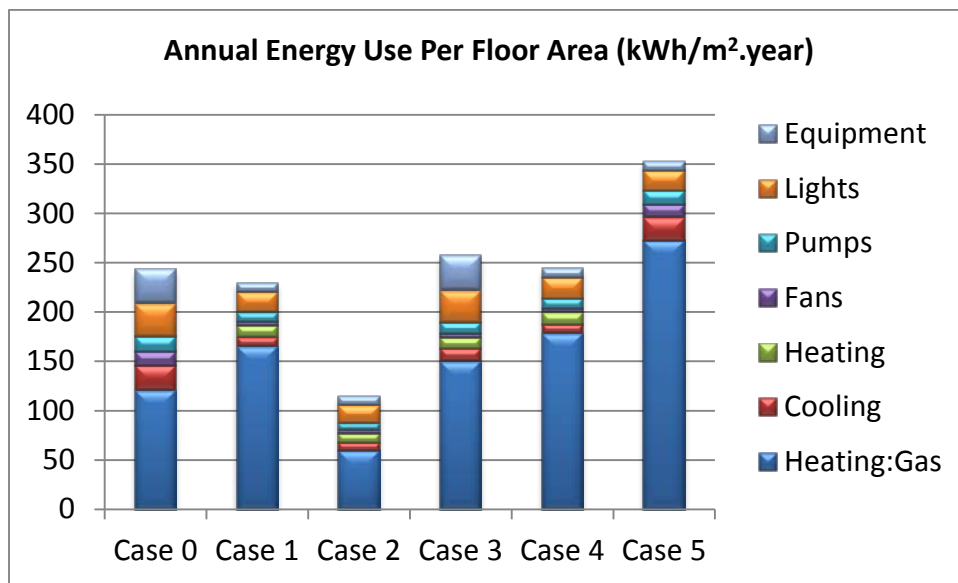
Figure 5-16 Annual energy consumption of cases 0, 1, 2, 3, 4, and 5

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 (m².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	10.20	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.

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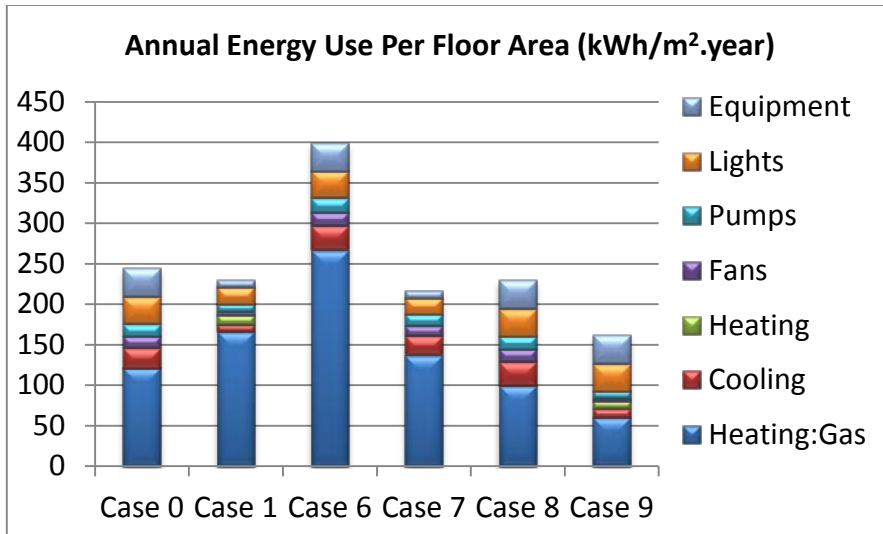
Figure 5-18 Annual energy consumption of cases 0, 1, 6, 7, 8, and 9

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.
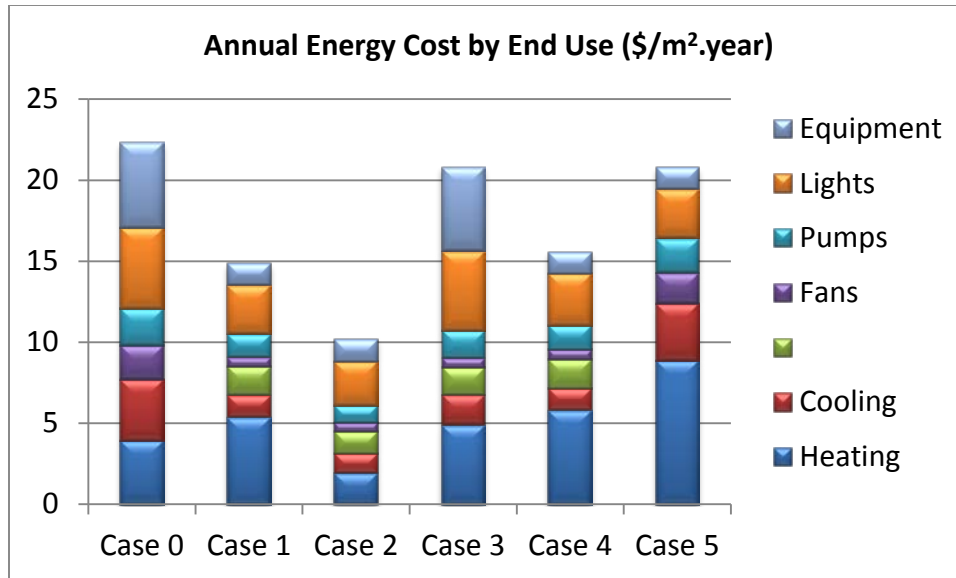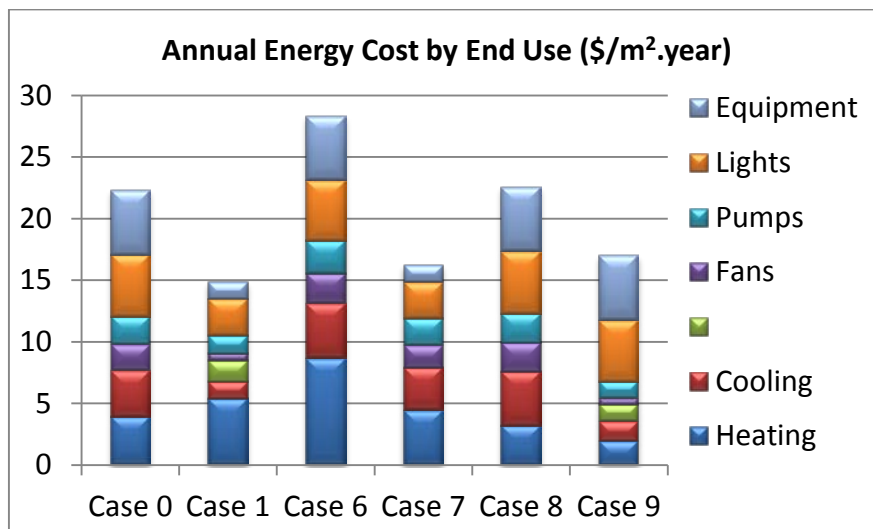

Figure 5-19 Annual energy cost of cases 0, 1, 6, 7, 8, and 9

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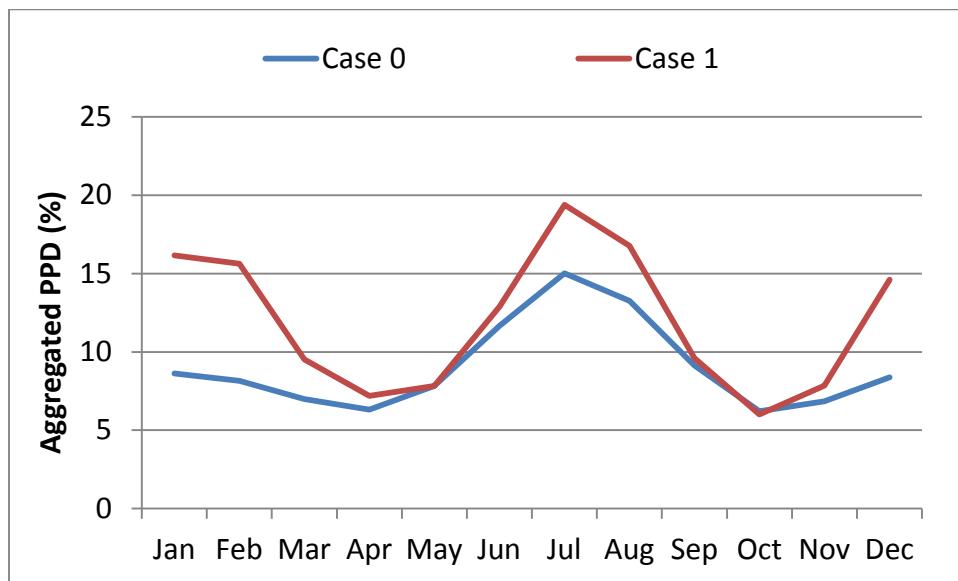
Figure 5-20 Monthly aggregated PPD of cases 0 and 1   `

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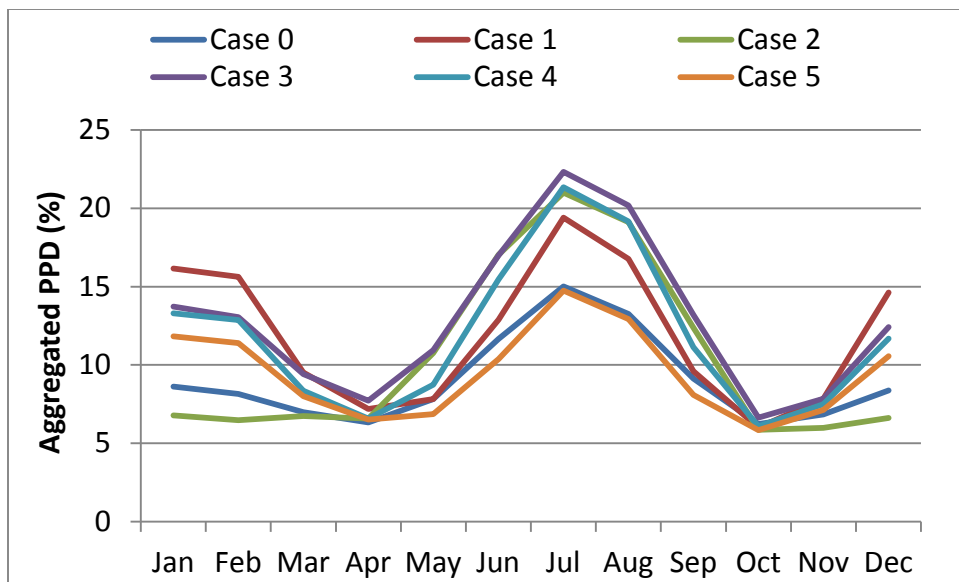
Figure 5-21 Monthly aggregated PPD of cases 0, 1, 2, 3, 4 and 5

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

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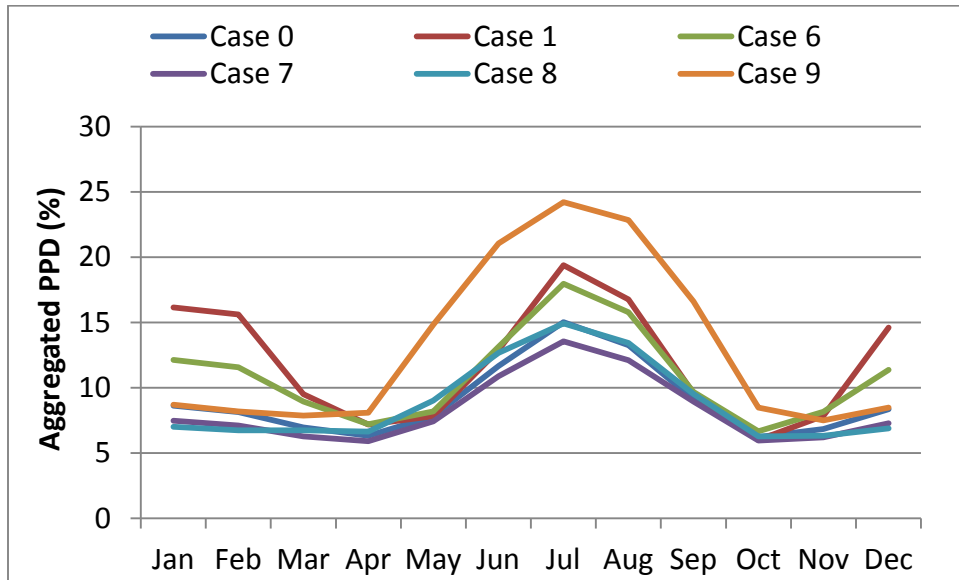
Figure 5-22 Monthly aggregated PPD of cases 0, 1, 6, 7, 8 and 9

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).
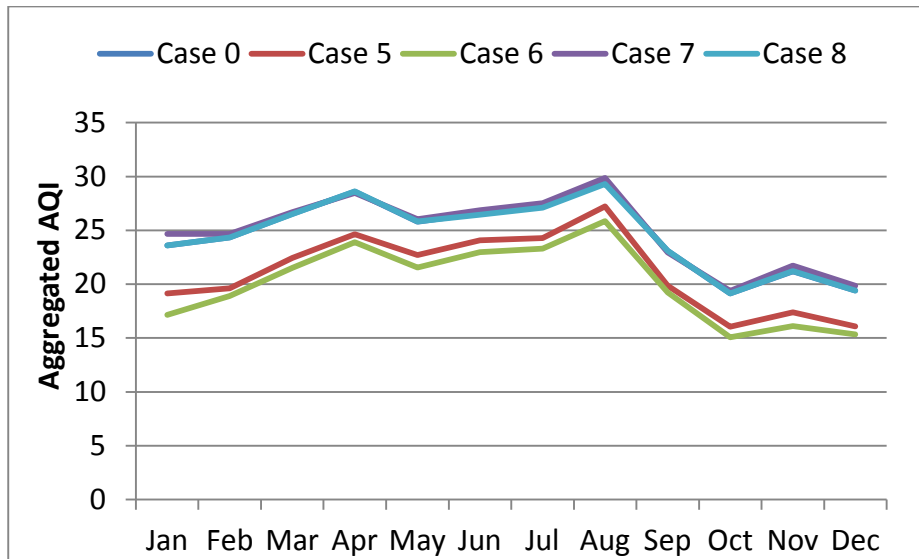
Figure 5-23 Monthly aggregated AQI of cases 0, 5, 6, 7, and 8
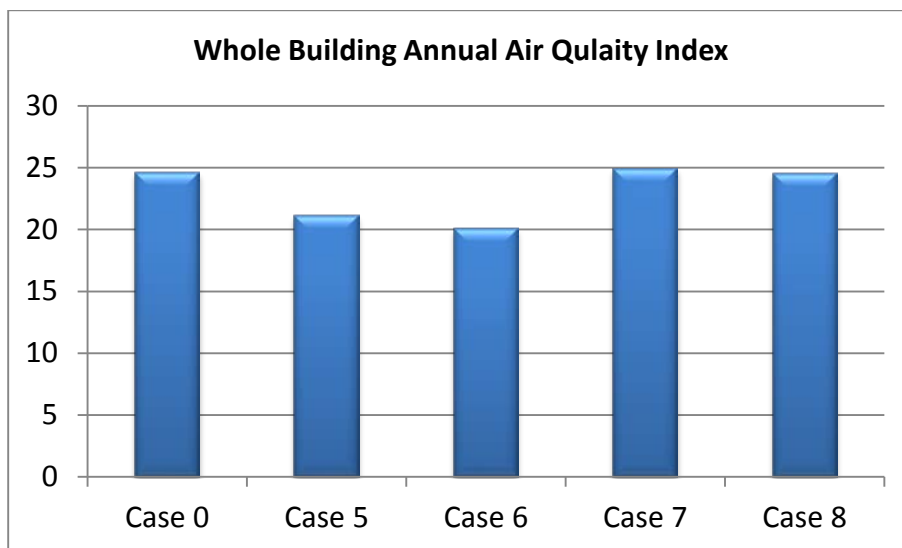
Figure 5-24 Whole building AQI of cases 0, 5, 6, 7, and 8

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.Conclusions and Recommendations

6.1.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 dissertation research, which is considered as one of the major contributions to the VDS development.

One of the original contribution of this dissertation 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 dissertation is the development of the performance evaluation model to analyze the overall performance of the proposed design, and the contribution and potential improvement of each design factors. The reference buildings are determined 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.

6.2. 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.

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