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8-2012

Champs-Multizone and Virtual Building for Integrated Building Systems Design and Performance Evaluation

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Recommended Citation

ABSTRACT

The ultimate goal of this research was to develop an integrated framework that facilitates performance-based multi-stage design of buildings and comparison between the performance predicted at the design stage and that monitored at operation stage. Such an integrated framework would not only enable design optimization, but also enable confirmation of design intent or diagnosis of performance deficiency, and thus provide feedbacks for future building design. This dissertation study represents the first step toward this ultimate goal, and had the following specific objectives: 1) developing a combined heat, air, moisture and pollutant transport model for whole building performance simulation; 2) developing a real-time building IEQ and energy performance monitoring system using a Virtual Building structure to facilitate fast comparison between design and monitored performance; 3) developing a methodology to use CHAMPS-Multizone for a green building design throughout its initial and final design stage. The CHAMPS-Multizone model consists of a building envelope model, a room model, a HVAC model and an airflow model, and has an efficient and accurate numeric solvers. The model is tested under different building cases including ASHRAE 140 standard test and a three zones building test and comparision with EnergyPlus calculation results. The Virtual Building is a digital representation of the physical building with a hierarchical data structure, containing both static data such as enclosure assemblies, internal layout, etc. and dynamic data such as occupant activity schedule, outdoor weather conditions, indoor environmental parameters, HVAC operation data and energy consumption data. The Virtual Building approach was

demonstrated in a LEED office building with its monitoring system. A multi-stage design process was formulated that considers the impact of climate and site, form and massing, external enclosure, internal configuration and environmental system on the whole building performance as simulated by CHAMPS-Multizone. Using the testbed building, the simulation results were also compared with the results monitored by the Virtual Building monitoring system. Future research includes refining CHAMPS-Multizone simulation capability and adding modules such as water loop calculation and integrating HVAC calculation with EnergyPlus.

CHAMPS-MULTIZONE AND VIRTUAL BUILDING FOR
INTEGRATED BUILDING SYSTEMS DESIGN AND
PERFORMANCE EVALUATION

by

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Dissertation
Submitted in partial fulfillment of the requirements for the degree of
Doctor of Philosophy in Mechanical and Aerospace Engineering
In the Graduate School of Syracuse University

August 2012

ACKNOWLEDGEMENTS

The path toward net zero energy building is a long way. To work in this area, one must understand the physics of building systems, equip with the knowledge of measuring building performance, be skillful of modeling in various simulation environment, and be good at developing models in computer languages. After working on all of these and looking back, I would like to give special thanks to Professor Jensen Zhang for the advisory he provided in this research. Thanks to Jingjing Wang for her help and encouragement. And also thanks my dissertation committee members and faculty in the Department of Mechanical and Aerospace Engineering. It is BEESL lab that teaches me a lot during my first stop of American journey, and I want to thank all the professors, engineers, researchers and my labmates I have worked with. It is all your efforts that make this research possible.

TABLE OF CONTENTS

LIST OF FIGURES

Figure

LIST OF TABLES

LIST OF ABBREVIATIONS

CHAPTER I

Introduction

1.1 Background and problem definition

Many building system and component design standards exist in which the core idea is to guide designers, engineers, builders and operators/managers to design, build and operate buildings to achieve desired indoor environmental quality in an energy efficient and sustainable manner. LEED standard, developed by US Green Building Council (USGBC), is one of the most comprehensive rating system on green building design in the industry that incorporates the concept of Sustainable Site, Water Efficiency, Energy & Atmosphere, Materials & Resources, Indoor Environment Quality (IEQ), Innovation & Design Process (*USGBC*, 2006). ASHRAE Standard 189.1 is one of the most comprehensive standards for green building design and operation, which covers the same performance aspects as LEED, but is a code-compliance standard as oppose to a guide or rating system *ASHRAE* (2009). Other studies also give similar definitions among which energy efficiency and indoor environment are core parts of green building design (*MOHURD*, 2005, 2006; *Hong*, 2009; *CASBEE*, 2010; *BREEAM*, 2011)

The comprehensive rating systems and standards raise a challenge for designers – since it currently does not provide guidance on the performance levels that can be

achieved through the practices, how to evaluate Green Building design through the entire architectural design process by taking all performance aspects into account. It is found that some aspects of LEED are difficult for evaluating building performance when combining with other aspects. For example, the design of Indoor Environment Quality Credit 2 states that, for mechanically ventilated spaces, it is recommended to "Increase breathing zone outdoor air ventilation rates to all occupied spaces by at least 30% above the minimum rates required by ASHRAE Standard 62.1-2004 as determined by EQ Prerequisite 1." However, the increase of outdoor ventilation rate, in some buildings, can impose heavy energy cost which seems to conflict with Energy & Atmosphere chapter, "Minimum Energy Performance" credit requirement. This conflict requires designer to evaluate their green building performance in comprehensive or sometimes trade-off manners. The missing of guidance on how to resolve the possible conflicts between energy efficiency and IEQ goals make it imperative to have building performance evaluation tools which can cover both Indoor Air Quality (IAQ) and building energy performance.

Building design is a very complex process having different stages from conceptual, schematic to detailed components design and involving various design parties: architects, structure, electrical and mechanical engineers. So, it is important to coordinate and evaluate different design activities through the entire design process. Especially in earlier design phases when project information is not well defined, design activities are mostly conceptual and experience-based. But decisions (such as building orientation, building shape etc.) made in these phases are crucial and have a big impact on building performance.

An effective way to evaluate building performance is to conduct simulations for design activities in different design stages. But 1) a combined metric for energy efficiency and IAQ rating does not exist, and is urgently needed to optimize the trade-off between the two; 2) the advanced building simulation tools such as NIST-CONTAM for IAQ

and DOE-EnergyPlus for energy are very useful for detailed as-built performance analyses, but very few research has been conducted for building performance at earlier conceptual phases to detailed stages.

To support design activities, simulation programs need to access building design data. The interoperability between design platforms and simulation programs can greatly enhance the design process and interaction between architects and engineers. Furthermore, to verify building performance simulation with realistic designs, real-time performance monitoring should be developed. Comparing monitored and predicted results will help identify weakness in construction. The monitoring system will measure real-time building performance, and record long-term performance data for comparison with design models. And all those results should be merged into one single platform for better comparisons and verifications.

1.2 Goals and objectives

The ultimate goal of this research is to develop a methodology and computer software platform for integrated building system design, which will help achieve both high IEQ and energy performance. Specific objectives are:

- Develop a combined heat, air moisture and pollutant transport model at building multizone level to evaluate whole building energy and IEQ performance

- Develop Virtual Building, a method and system for online monitoring of whole building performance in IEQ and energy

- Evaluate a real building performance through its design processes using developed CHAMPS-Multizone and Virtual Building tools

1.3 Scope and dissertation organization

A comprehensive literature review (Chapter II) is performed for current architectural design practice, design stages, and major design parameters which could affect building performance. The existing building performance simulation programs are also reviewed and their strength and weakness are compared. The numeric fundamentals used to solve building simulation models are introduced and finally the methodology of developing a real-time building performance monitoring system is described.

A program called Combined Heat Air Moisture and Pollutant Simulation (CHAMPS) – Multizone is introduced in Chapter III. The physical models of this program are stated for building envelope, air-flow, HVAC, and zone balance calculation.

The numeric methods of solving CHAMPS-Multizone models are introduced in Chapter IV. Different calculation solvers' integration methods are described to better illustrate how building physical properties are exchanged among solvers. The program is applied to simulate several cases to test its numeric integrity and accuracy. And the result is compared with existing simulation programs for energy and IAQ simulation.

Virtual Building system for real-time building performance measurement is introduced in Chapter V. The hierarchical structure of the system is formulated to maintain both static building information and dynamic building performance measurement data in a consistent structure. Measurement examples for a case building performance are extracted from Virtual Building system and discussed.

Finally, Chapter VI demonstrates how to assess building design parameters using modeling and simulation tools. One case building is selected for performance based building design. The case building evolves from conceptual, schematic and detailed design stage and we select its shape and massing, building envelope and fenestration systems, interior program, HVAC systems. Existing simulation programs as well as

CHAMPS-Multizone program developed in this study are used to support design parameter selection. The final designed model is compared with Virtual Building's measurement results to verify our case building's performance.

CHAPTER II

Literature Review

To understand building performance and performance based design, it is essential to conduct comprehensive studies on building design process, building performance analysis tools and the methods to measure and evaluate building's real performance. Simulation assisted design analysis is an effective to evaluate building performance even in building design stage. To conduct building performance simulation and assessment, several fundamental investigations are needed:

- The nature of building design practices, design parameters and parametric considerations in different design stages.

- The state of arts on building performance simulation programs to evaluate whole building's energy and IEQ performance.

- The fundamentals of simulation programs and their modeling capability on zone quantities balance, air flow model, building envelope systems, fenestration systems, HVAC systems, and solar radiation

- The methods to monitor whole building systems performance and store measurement information in a structure and organized way.

2.1 Building design process and design parameters

Building Design is a very complex process which involves different parties (manager/-clients, architects, structure engineers, mechanical engineers, electrical engineers) and the design period varies from project to project from a few weeks to months. Many design projects involve different stages and each stage has its own characteristics.

2.1.1 Building design stages

Several studies have been done on identifying building design stages and some simulation assisted design stages models have been developed to better describe and organize design activities (*Karhu*, 1997; *Mahdavi*, 1999; *De Wilde*, 2003; *Morbitzer*, 2003; *Hien*, 2003; *Ochoa*, 2009). *AIA* (2006) gives the macroscopic definition of building design, from architects point of view, that each construction and design project contains five phases:

- Phase 1: Originate

- Phase 2: Focus

- Phase 3: Design

- Phase 4: Build

- Phase 5: Occupy

The "Originate" phase involves discussions on new projects. This phase will address ideas of the new project and prepare for next stage design activities. The "Focus" stage defines the project's scope, features, purpose, and functionality. Agreement between clients and architects needs to make at this stage to initialize design activities. The intensive designs are carried on in "Design" phase when most of design decisions

are made. The "Build" phase describes how to implement designs during construction. Design changes and alternatives may happen during this stages when compared with actual construction implementation. The "Occupy" phase begins when the building construction is finished and starts to allow occupant to move in. The actual building's functionalities as well as its built environment and performance can be assessed by occupant.

Karhu (1997) developed IDEF0 model which describes building design from construction management point of view by using block diagram flow charts. IDEF0 describes design process as six sections - brief (conceptual) design, program startup, global design, detail design, design during construction, and tasks during use and maintenance. This model gives a very detailed definition of each design stage and the extent of different parties' involvements.

Another approach adopted by *Morbitzer* (2003), and *Ochoa* (2009) suggests three stages design model as outline design, scheme design and detailed design from building performance evaluation point of view. Each stage characteristics are stated and detailed important design parameters are listed. The advantages of this model are:

- it allows evaluation of relevant design parameters for each stage.

- it well connects with specific building energy simulation tools that help designers to evaluate the impact of design parameters.

However, *Morbitzer* (2003) and *Ochoa* (2009)'s studies missed the design implementation (construction) stage and building occupied stage and only focus on the narrow sense of designs which most of time focuses on models, drawings development and design alternative selections.

Among all the studies above, very few studies have been done by combining the actual building design process adopted by architects with building performance simulation

and analyzing each design stage's performance. The gaps between architectural definitions and performance evaluation requires more detailed understandings on design process by connecting the architectural practices with evaluations of building's performance simulation design stages.

The methodology of three design stages approach, "Conceptual Stage", "Scheme Stage" and "Detail Stage" is used and adopted for performance evaluation in design development periods. Conceptual Stage is the period during which a building is conceptualized in the mind of architect. The input information and constraints (e.g. requirement of building floor area, budget, and construction schedule etc.) of this stage mainly come from building owner. A rough and approximate picture about building geometry, shape, orientation etc. will be conceptually drawn in architects' mind however those parameters are unclear, and mostly qualitative. The preliminary design sketch can be available for architect's discussion, but design activities are mainly involved by architects. Engineers (structures, electrical, or mechanical etc.) are not really involved. Design parameters in this stage are mainly related to site climate consideration, building context and building geometry, and the definition of building itself. Building service designs are rarely considered. The building performance targets will be determined by choosing the optimal design alternatives based on available design considerations and existing design standards. The conceptual design stage is equal to IDF0 model's "Brief" and "Programmings". It also complies with "Originate" phase in AIA's definitions.

The second stage is "Scheme Stage". Architects, after Conceptual Stage, will have basic understandings and preliminary design on building geometry, site context and climate considerations. Design sketch is available and more concrete design activities will take place. Structure engineers will work closely with architects to validate and refine conceptual designs. The information input and constraints of this stage mainly come from project owner, previous stage sketch, and material suppliers. Preliminary

buildings facades design, envelope and window prototypes will be determined. The first version of architectural and structure drawings can be available at the end of Scheme Stage. However, building service design (equipments/HVAC) is only conceptual and preliminary. The involvement of mechanical and electrical engineering design is very limited. This stage is equal to IDF0 model's "Global Design" stage and it also complies with the "Focus" phase definitions of AIA.

The third stage is "Detail Stage". In this stage, architects will work closely with structure engineers and mechanical/electrical engineers. Architectural design will be finalized based on various parties input. Furthermore, building service equipments design will also come into shape and be finished. Building service equipment information is available. (For building energy and IEQ performance perspective, HVAC systems are our concern). Detailed drawings will be provided for biding and construction. These also include design changes made on site during construction. Detailed building performance targets are available based on building location, outside environmental conditions, building functionality and owner requirements. HVAC simulation as well as building envelope simulation can be conducted in detailed information input manners. This stage is equal to IDF0 model's "Detail Design" stage and AIA's "Design" phase.

Besides the three design stages, the "Construction" stage defined in IDF0 model (also referred as "Build" phase in AIA) describes the design implementations periods. The construction implementation will re-evaluate existing designs and compare with real construction situations. Should any conflict between designs and real construction implementation occurs, alternatives and modifications are needed for design models for better implementations. To Revisit building's performance is needed when changing the design models to as-built model. However, most modifications happen in this stage are considered as not-critical to building performance point of view. Important building performance related parameters like the geometry, facades, and HVAC

systems are considered not subjecting to major modifications.

After design implementation and construction, the building is delivered for occupation. This stage is described as "Take-over" stage in IDF0 model and "Occupy" phase in AIA. In this stage, the activity intended for the building is launched and the readiness for the use is monitored. The project ends with a series of inspections. For building performance point of view, the building's functionalities, Indoor Environments Qualities (IEQ) and energy performance can be assessed and measured by users at this stage. The actual performance data can be used to validate the previous stages design models. This stage is named as "Feedback Stage" in our studies as most of building performance is actually measured by the users and feedback to designers.

2.1.2 Building design parameters for performance evaluation

Design parameters are defined as certain building systems, components, equipments that affect the general shape, functionality or building performance. Thousands of design parameters may be used in one building's design project. From the perspective of their influence on building performance, *Ellis* (2001) states that building design parameters should be divided into those have small effects on building performance, big impact on building performance but only act independently, and parameters which have big impact on building performance and interconnect with other parameters. The impact of design parameters are evaluated in terms of sensitivity ratio which is defined as the percentage change of building performance (e.g. thermal load) divided by the change of design parameters. (e.g. the change of thermal load/the change of window area ratio is used to evaluate the sensitivity of design parameter "window area" in terms building energy performance).

Another way to define design parameters is to evaluate them through building design stages. Typical design parameters will be analyzed for each stage from building

performance point of view. This approach has been used in by *Macdonald* (2002); *Lam* (2002); *Morbitzer* (2003). The design parameters researches done by *Macdonald* (2002) are based on different stages' uncertainty analysis. He states that the uncertainty of design parameters will be introduced into building performance at different levels. *Morbitzer* (2003), based on his building design stages analysis, lists design parameters from energy performance considerations. *De Wilde* (2003) and *Ochoa* (2009) find parameters determined at earlier design stages (conceptual and scheme stage) have highest uncertainty but have key impacts on building performance and the selections of later stage design parameters. It is also found that building simulation tools are not used to support selection of building parameters (components) to optimize building performance but to verify actual building energy consumption. And simulations tools to support building parameters are not used until conceptual design has finished.

Based on the reviews of literature, key design parameter groups that affect building's energy and IEQ performance are as follows:

1. Climate conditions and urban context

2. Building shape and orientation

3. Zoning and internal configurations

4. Building envelope and fenestration systems

5. Building Environmental systems (HVAC, lighting)

6. Occupied performance verification

Each parameter group may represent one or more design parameters. And in different stages, design activities focus on different design parameter groups serving for different design purposes. Parameter groups, which are not intensively studied in

12

one design stage, will be considered to have certain default values defined by common project practices or standards. Based on the design process and stages studies in section 2.1.1, the parameter groups "Climate condition and urban context" and "Building shape and orientation" are usually intensively studied in the "Early design stage". Building's performance, usually qualitative, need to be evaluated before later stages design decisions are made. Parameter groups which will be addressed in later stages, for example "environmental systems", are not taken into major considerations in this stage, and certain default parameters will be chosen for better conducting whole building performance analysis. Parameter group 3 and 4 are mainly addressed in "Scheme Stage", when the urban context and the shape of building are well understood. The "Detail Stage" stage will focus on parameter group 5, however, parameters designed in earlier stages need to refine and finalize in this stage. After the building is constructed, its performance will be evaluated in "Feedback" stage by comparing the actual as-built performance with design models as parameter group 6 addresses.

2.2 Building performance simulation tools

Building simulation has the history of nearly 40 years and four generations of building simulation tools took in shapes during this period. At beginning stages, most simulations tools are designed to estimate building energy usage. The reduced complexity of model is preferred by simplifying system and use simplified boundary conditions (*Clarke*, 2001; *Morbitzer*, 2003). The 1st generation of building simulation tools are handbook oriented computer implementations and were developed towards simplicity. The full map of energy and mass flow in building systems are not represented and only building performance indications are provided to the user. The 2nd generation simulation tool introduced the actual building physical components, which are temporally constant (for example, the multiple layer construction assembly model). However, the limitations of technologies make it difficult to consider design stage and various design parameters into simulation program. The 3rd generation of building simulation program, originated from mid 1980s, started to assume that time and space are independent variable and other simulation variables in buildings are coupled with each other. The 4th generation program development started in the mid-1990s. At this stage, building simulation programs start to evolve to have more accessible user-interface, comprehensive HVAC simulations and controls. Data interoperability and building information modeling begin to play active role in simulation programs.

U.S. Department Of Energy (2010) lists more than 200 building simulation tools. For energy simulation tools, lots of researches have been done and hundreds pieces of software have been developed. *Crawley* (2008) compares over 20 most popular energy simulation software: BLAST, BSim, DeST, DOE-2.1E, ECOTECT, Ener-Win, Energy Express, Energy-10, EnergyPlus, eQUEST, ESP-r, IDA ICE, IES/VES, HAP, HEED, PowerDomus, SUNREL, Tas, TRACE and TRNSYS etc. Software's room balance calculation, building envelope model, infiltration/exfiltration model, HVAC

system model and economic evaluation model are compared in details. *Crawley* (2001) also reviewed EnergyPlus performance compared with ESP-r, BLAST, DOE2, SRES/SUN, SERIRES, S3PAS, TRNSYS and TASE. The structure and advantage of EnergyPlus are introduced. *Morbitzer* (2003) compares ESP-r with Energy-10, DTA and LT-Method and detailed ESP-r based building performance simulation is conducted.

Compared with energy simulation tools, the amount of multi-zone IAQ programs is relatively small. Tools such as CONTAM, COMIS, BREEZ and etc. (*Walton and Dols*, 2006) are popular tools for Indoor Air Quality simulation. In principle, those IAQ simulation tools are very similar. All those tools have detailed air flow element models, a customized high speed linear and non-linear solver for solving multi-zone air and contaminants flow. COMTAM is relatively easy to use with straight-forward Graphic User Interface (GUI) and simple but representative enough geometrical features. COMIS, developed by International Energy Agency (IEA) Annex program, has powerful but complex models. In summary, all those tools cover common building air/contaminants flow features, contaminant filtering, contaminants reactions and HVAC duct model etc. However, since those tools are specially designed for IAQ analysis, few building thermal effects are taken into consideration in IAQ analysis. And those tools are all developed for fully finished building and no interaction with building designs activities.

To better assist building design practices, some other design-based simulation tools are developed. Different from energy simulation tools and IEQ simulation tools developed for scientists and engineers, those tools are developed for building designers. Building Design Advisor - BDA (*Papamichael*, 1999) is a software tool developed by Lawrence Berkley National Lab (LBNL) targeted for building design analysis. This tool uses object-oriented design method to model building systems and simulate building energy and lighting performance. An overview of BDA is shown in Figure

[2.1](#). BDA can model building geometry based on building drawing sketches. It can read environmental condition files as well as integrate other detailed building energy (DOE2) and IAQ (COMIS) simulation tools for better building design analysis. The object-oriented model of this software provides a basic concept building component modeling however, since this software is designed in 1999, and no further development/upgrade has been made after that, detailed simulation model integration is very limited. Also, most emphasis of this software is based on energy and IAQ simulation, but energy and IAQ coupling effects are barely considered.
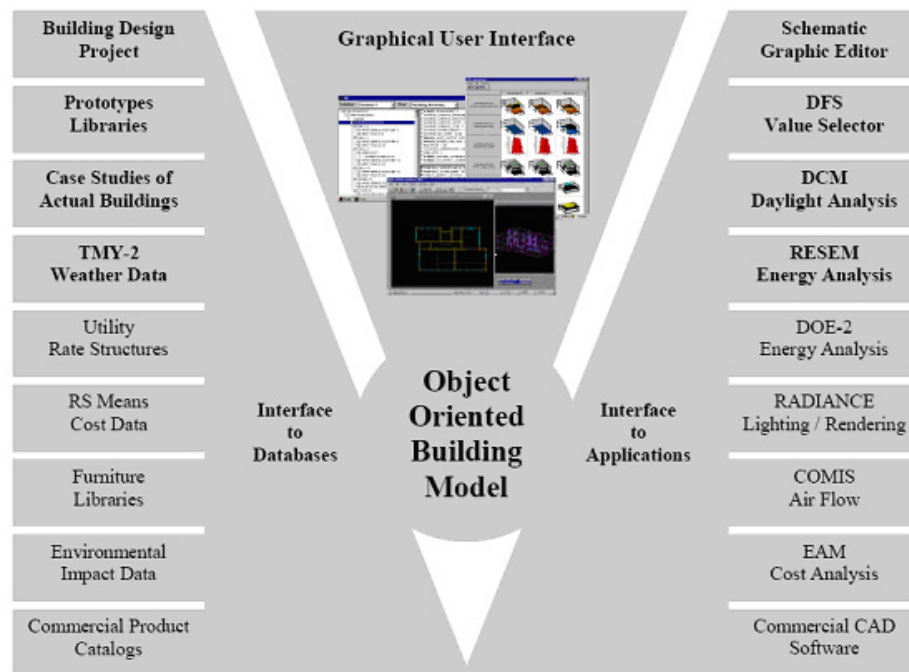
Figure 2.1: Building Design Advisor structure (*Papamichael*, 1999)

Another building design-assisted simulation tool is Green Building Studio (GBS) developed by *Autodesk* (2010). GBS is designed in the way that the tool can help architects, by inputting rough building information, evaluate building performance. GBS can associate with Ravit which use Building Information Modeling (BIM) concepts for detailed building geometry inputs as well as building energy usage user input and environmental conditions. GBS is very easy to use, but the web-based software

16

can only treat rough information input and could not performed detailed building simulation. Also, the energy simulation engine of GBS is DOE2 and the missing value of IAQ simulation makes it not unsuitable simulation tool of this research.

A more recent simulation tool for designers, Sketchup and its EnergyPlus plug-in, is developed (*Ellis*, 2007). Sketchup is an architectural design tool widely used by architects to sketch a building for their conceptual design and analysis. Compared with Ravit and its BIM method, Sketchup is easier to use and more user-friendly. The energy plug-in of Sketchup connects Sketchup' geometry input and its energy simulation engine provided by EnergyPlus can conduct building energy simulation regardless of HVAC systems. Since Sketchup is designed specially for architects use, the plug-in can simulate even if building information is rough. It is stated that the design decisions made in early stages are usually empirical but sometimes critical for later stage design and final building performances. Sketchup and its energy simulation plug-in is a very promising software tool for this research but it highly depends on EnergyPlus limits its application primarily for energy analysis as oppose to combined IEQ and energy analysis. And this user-interface is still in development stages, and the features of this program to support design process is very limited.

2.2.1 Building envelope model

For each whole building performance simulation tool, building envelope simulation is one of the most important components. A variety of building envelope models have been implemented in building performance simulation programs. However, most of them belong to two categories:

1. numerical method, primarily finite difference, to calculate discretized building envelope volumes Heat Air and Moisture (HAM) transport.

2. A response factor method to transform heat transfer differential equations to

algebraic Conduction Transfer Function (CTF).

The first method is adopted and developed by *Grunewald* (1997); *Nicolai* (2008) to solve building envelope heat, air, moisture and salt transport. The general governing equation of this approach is given by equation (2.1)

$$\frac{\partial \rho^E}{\partial t} = -\frac{\partial}{\partial x_k}\left(\sum_i j_{k,i}^E\right) + \sigma^E \tag{2.1}$$

Here, E represents a full set of conserved properties such as, energy, water vapor, air mass, and liquid water given by $E = U, m_v, m_a, m_w$ The change of conserved properties (also called extensive properties) is expressed in spacial derivative of the sum of extensive properties flux plus any extensive properties' source or sink term. The studies further give balance equations for energy and moisture. The governing equation for energy balance is given in equation (2.2a) and moisture mass balance equation is given in equation (2.2b):

$$\frac{\partial \rho^U}{\partial t} = -\frac{\partial}{\partial x_k}[j_k^Q + h_l j_{k,conv}^{m_l}$$

$$+ h_v\left(j_{k,diff}^{m_v} + j_{k,conv}^{m_v}\right) + h_a j_{k,conv}^{m_a}] \tag{2.2a}$$

$$\frac{\partial \rho_{m+v}^m}{\partial t} = \frac{\partial}{\partial x_k}\left(j_{k,conv}^{m_w} + j_{k,diff}^{m_w} + j_{k,conv}^{m_v} + j_{k,diff}^{m_v}\right) + \sigma^{m_{w+v}} \tag{2.2b}$$

The model describes the rate of energy change in a control volume is due to spatial variation of multiple energy fluxes, including heat conduction flux between volumes j_k^Q, convective liquid state water flux $j_{k,conv}^{m_l}$, water vapor diffusive mass flux $j_{k,diff}^{m_v}$ and convective mass flux $j_{k,conv}^{m_v}$, and convective air mass flux $j_{k,conv}^{m_a}$. The rate of moisture mass change in the control volume is balanced by the spatial derivatives convective liquid water mass flux $j_{k,conv}^{m_w}$, diffusive liquid water mass flux $j_{k,diff}^{m_w}$, convective water vapor mass flux $j_{k,conv}^{m_v}$ and diffusive water vapor flux $j_{k,diff}^{m_v}$ plus a local source or sink term $\sigma^{m_{w+v}}$.

Another method tries to avoid solving complex finite element heat and moisture transport phenomenon but model heat transfer through building envelope as a function of interior and exterior surface temperature and heat flux with a series of building envelope's response factor (*Myers and Ceylan*, 1980; *Seem*, 1987). This method, even though only calculate energy transport, greatly decreases the computation time of solving building envelope balance equation and thus has been widely adopted by many building energy simulation software. This method (also call Conduction Transfer Method) can calculate, for example, energy conduction term from exterior building envelope surface as equation (2.3):

$$j_{ko}\left(t\right) = \sum_{k=0}^{\infty} X_k T_{o,t-j\delta} - \sum_{k=0}^{\infty} Y_k T_{i,t-j\delta} \qquad (2.3)$$

Here, X and Y are response factors series and *Seem* (1987) gives detailed methods to calculate building envelope's response factor X and Y based on physical properties of individual material layers of the building envelope including density, thickness, conductivity and specific heat. The basic idea is to convert building envelope surface heat balance equation to a series of algebraic expressions, that heat conduction flux term can be calculated as a series of historical building envelope surface temperature multiplying its corresponding response factor. State Space conversion and Laplace Transform are two major approaches to derive those response factors.

2.2.2   Zone model

Two basic zone models are considered by most building performance simulation tools. The first one is well-mixed zone model which models one zone as a single node, and all different locations in that zone share the same properties. This is the simplest way to model and simulate one zone which requires the least computation power to solve zone's balance equations. However, the accuracy of this method is poor when solving

zones with large space volume or zones like atrium or warehouse whose ceiling is higher than others, or when detailed air flow influence in zones need to be considered (e.g. open window, or ventilation effects). Another method uses finite volume to perform balance calculation of each control volume by taking air flow, ventilation and air stratification into account. This method gives better accuracy in terms of room air distributions, but it consumes more computation resources and uses longer time. The second method has been further developed in the computational fluid dynamics (CFD) area which give more accurate resolutions for zone air distribution and temperature gradients.

The well mixed method is widely adopted by several major simulation programs (*EnergyPlus*, 2008; *CONTAM*, 2010). The zone quantities balance equation can be generalized as equation (2.4)

$$\frac{\partial \rho}{\partial t} = \sum j + \sum \sigma \tag{2.4}$$

where j represents the different type of fluxes interacting with the zone, and σ represents all local source or sink terms in the zone. Equation (2.4) has different expressions in terms of heat and mass (moisture, pollutants or any mass species) balance. The basic heat balance equation given by *EnergyPlus* (2008) shows:

$$C_p \rho_{air} \frac{dT}{dt} = j_{int,conv} + j_{airflow} + j_{sys} + \sum \sigma \tag{2.5}$$

Equation (2.5) states that the zone energy density change (expressed in terms of zone temperature change) is contributed by the convective heat transfer with building envelope interior surface $j_{int,conv}$, the airflow caused by infiltration, exfiltration and inter-zonal air flow $j_{airflow}$, and HVAC system heat delivery j_{sys} plus local heat source

or sink terms. Equation (2.5) can be further derived as

$$C_p \rho_{air} \frac{dT}{dt} = \sum_{i=1}^{N_{surf}} h_i A_i (T_{s,i} - T) + \sum_{i=1}^{N_{zone}} \dot{m}_i C_p (T_i - T)$$
$$+ \dot{m}_{inf} C_p (T_{out} - T) + \sum_{i=1}^{N_{source}} \sigma \qquad (2.6)$$

EnergyPlus further gives the method to solve equation (2.6) by expanding the *lhs* term in the form of first order Euler formula and can be further written in third order finite difference approximation:

$$\frac{dT}{dt} \approx (\delta t)^{-1} \left(T^t - T^{t-\delta t} \right) + O(\delta t)$$
$$\approx (\delta t)^{-1} \left(\frac{11}{6} T^t - 3T^{t-\delta t} + \frac{3}{2} T^{t-2\delta t} - \frac{1}{3} T^{t-3\delta t} \right) + O(\delta t^3) \qquad (2.7)$$

This approximation gives plausible accuracy when solving zone heat balance and also simplifies the way of solving ODEs by using its historical values and gives fast calculation. However, this method can be applied to solve only heat balance problems. When coupling between heat, moisture and pollutant transport in building envelope, this method may not be directly applied.

The way to model zone mass (moisture, pollutants ect.) balance can be achieved by deriving from equation (2.4). CONTAM gives the model that for any species α transport in zones, its mass balance equation in zone i can be written in equation (2.8)

$$\frac{dm_i^\alpha}{dt} = \sum_k^{N_{zone}} q_{k \to i} (1 - \eta_k^\alpha) \rho_k^\alpha - \sum_k^{N_{zone}} q_{i \to k} \rho_i^\alpha + G_i^\alpha - R_i^\alpha \rho_i^\alpha - m_i \sum_\beta^{N_{species}} \kappa^\alpha \beta C_i^\beta \qquad (2.8)$$

The change of species α mass is influenced by the air flow from zone k into zone i minus the air flow from zone i to zone k plus the local source generation term G_i^α minus local species α loss plus any possible chemical reaction to generate species α.

A customized solver called "skylight" is implemented to use fixed time step to solve equation (2.8). Fast and accurate results can be achieved by "skylight" solver.

2.2.3   HVAC model

To understand the coupling effects of pollutant distribution and building energy performance, it is important to develop the HVAC air loop to capture the interaction of zone air through ventilation system. Different HVAC air systems, such as constant air volume, variable air volume, and dedicated outdoor air system, can significantly affect building's energy use and pollutant redistribution in buildings. However, previous study (*Demetriou and Khalifa*, 2009) does not provide a good model for air distribution in different zones through various HVAC air systems, but relies on existing models from TRNSYS and CONTAM to calculate energy and IAQ respectively. To better characterize HVAC air system and its role on energy and pollutant transport, two typical methods are usually used to model the Air Handling Unit (AHU) and its related component such as duct and air filter. The first method considers each main supply and main return duct as a well-mixed zone that quantities conservation equations can be applied. This method can reduce the complex AHU components modeling to very simple "zone" based model where detailed AHU components (coils, fans, dampers, etc.) behavior is not the first priority of the simulation program (*Walton and Dols*, 2006). The other methods need to consider each component's characteristic and model the whole AHU by integrating air flow passing through each AHU equipment. This method is highly dependent on the specific configuration of AHU. Take VAV system for example, *ASHRAE* (2005) gives a common method to loop over AHU every equipment and calculate heat flow through each component. The algorithm can be summarized in Figure 2.2

The basic idea of this scheme is to use calculated zone heat load to trigger AHU
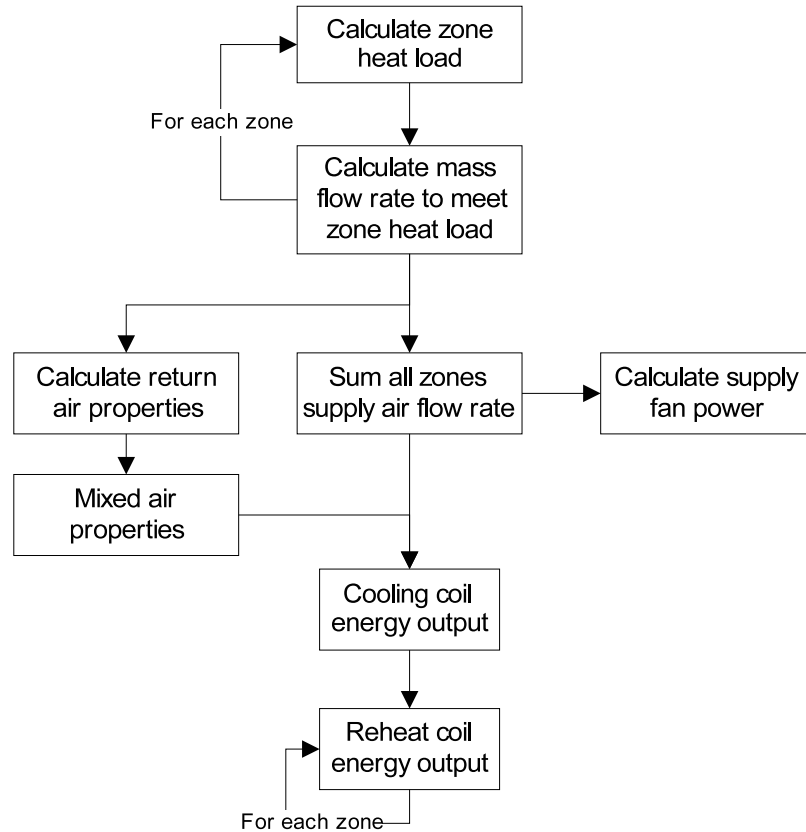
Figure 2.2: AHU calculation algorithm

air loop (also called "Secondary Systems") calculations. To balance the amount of heat load for each zone, each zone's supply air flow rate can be calculated for a given supply air temperature, and thus calculate the total supply air flow rate. The calculated flow rate is then used to calculate supply fan power, and with return air properties (calculated based on each zone's air properties), mixed air properties can be calculated by given outside air properties and air mixing ratio. Should mixed air temperature is too low, preheat coil is activated to heat the supply air temperature to certain point. Then we calculate the main cooling coil energy output. If supply air temperature after the cooling coil is lower than one zone's supply air temperature setpoint, the reheat coil of that zone is activated to heat the supply air temperature to the setpoint condition.

2.2.4 Multizone air flow model

To characterize room air flow is a complex process. The modern approach is to discretize zone volume into finite difference and use Computational Fluid Dynamics method to conduct transient air flow analysis. This method can give very good room air properties profile. However, this method requires lots of computation resources and it is difficult to apply to multiple zones. For multizone air flow, flow network model is usually adopted for whole building simulation. The network model does not reflect details of airflow in zones, but describes that each network zone is characterized as a single node containing air properties. Then the zone air density can be determined by ideal gas law given in equation (2.9)

$$
\rho_i = \frac{P_i}{R_{air} T_i}
$$
$$
m_i = \frac{P_i V_i}{R_{air} T_i} \tag{2.9}
$$

Zone temperature is related to the heat transfer and energy balance of the zone. So, the density of zone air is determined by both zone pressure P and zone temperature T, considering the transient behavior of zone air properties. The derivative of equation (2.9) gives (*CONTAM*, 2010):

$$
\frac{\partial m_i}{\partial t} = \rho_i \frac{\partial V_i}{\partial t} + V_i \frac{\partial \rho_i}{\partial t}
$$
$$
= \sum j_{i,k} + F_i \tag{2.10}
$$

The first term $\sum j_{i,k}$ in equation (2.9) represents the zone mass change related to pressure driven air flow. The second term F_i represents the zone air mass change because of internal density change (e.g. Temperature change). Studies found that the airflow between zones and zone pressure changes very fast speed (within seconds), much faster than the change of temperature and contaminant concentration in the

zone. so that the density change because of airflow happens almost simultaneously. Thus, airflows are typically calculated in quasi-steady state manner (i.e., the steady state of airflows are assumed at each time step for the mass conservation calculations) and mass conservation is applied to each zone. This method without giving too much details on zone resistance and momentum balance can be easily applied to not only multizone buildings but also air flow element like duct, fan etc. This method is applied in the popular multizone models such as CONTAM.

2.2.5 Model integration

To conduct combined heat, moisture, and pollutant calculation, it is necessary to integrate multiple models calculation and calculate the coupling effects among heat, moisture, and pollutant. Currently, extrinsic integration is a common approach as *Demetriou and Khalifa* (2009) demonstrated that to integrate Matlab code with CONTAM and TRNSYS for coupled heat and IAQ calculation. The extrinsic integration relies on communication "bridge" by which the calculation results of one program can be extracted and new calculation inputs can be passed into the program through communication protocols (e.g. *Demetriou and Khalifa* demonstrated using TCP/IP communication for fetch results between CONTAM and Matlab). Usually, the extrinsic method exchange integration information based on simulation program's time step. And, one needs to coordinate different time step between different simulation programs for combined heat and IAQ calculation. For heat and energy analysis, usually hourly or sub-hourly time step is sufficient, but for air-flow and IAQ analysis which is more dynamic compared with heat balance calculation, usually much smaller time steps (e.g. minutes or seconds) are needed.

To better manage time step and improve simulation accuracy, an intrinsic integration method is proposed in this study to exchange numeric solvers information more dy-

namic based on iteration steps (not simulation time steps). For building simulation program, one simulation time step is usually composed by several iteration steps to reach convergence at the end of that time step. Intrinsic integration allows solvers to couple at each iteration so that better convergence can reach at the end of one time step. The difference of model integration methods is illustrated in Figure 2.3.
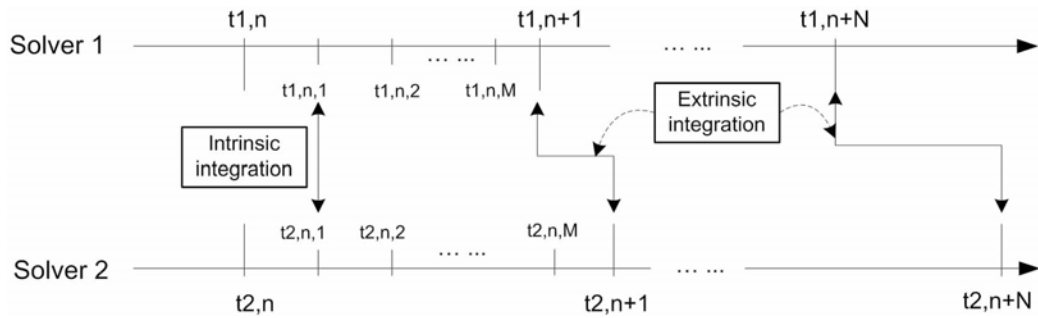
Figure 2.3: Extrinsic and intrinsic integration method

2.3 Numerical solution methods

To evaluate building's performance, the dynamic building heat air moisture transport process and whole building's response requires numerical solution methods. The use of simulation tools often involves multiple cases studies and multiple runs and comparison. Therefore, the numerical schemes used to construct simulation program engines become critical for the stabilities, convergence and accuracy of simulations. Different from CFD studies and building envelope HAM research, where 2D or 3D simulations are needed where simulation objects are discretized to finite volumes styles and equations for each Control Volume are often expressed in Partial Differential Equations (PDE) formats, whole building performance simulation programs usually solve multizone heat air moisture and pollutants transport in Ordinary Differential Equation (ODE) formats. Even though the 2D and 3D cases PDEs can be eventually transformed and reduced to ODEs through spatial discretization and numeric fundamentals of solving ODEs are somehow similar, different numeric methods and schemes are used in whole building performance simulation in order to improve the simulation speed. In this section, several numeric schemes and methods will be reviewed in terms of their roles and applications in building performance simulation. And common approaches which can be applied to multizone heat, air, moisture and pollutants simulation isare identified.

The first type of numeric scheme is customized scheme. This type of numeric schemes apply common numeric approaches and customize them for specific problems. This type of scheme usually has very good simulation speed and plausible accuracy. The examples of customized schemes are "Skylight" solver in CONTAM (2010), the customized Newton-Raphson method implemented by Nicolai (2008) for building envelope HAM transport analysis etc. However, this type of schemes has its special application fields to address certain kinds of problems, and it is difficult to utilize the

implemented scheme for general purposes applications.

The second type of numeric scheme is general purpose schemes. This type of of schemes allows users to implement their own models in an open platform and control simulations. Sometimes, post-processing modules, graphical user interface are included in the platform to enable one to manage simulation and control simulation sequence. The example of general purpose schemes are MATLAB, Dymola Modelica, Visual SPARK, SUNDAIL CVODE etc.

Several studies (*Mendes et al.*, 2003) show how to use MATLAB to solver whole building modeling problems. *Demetriou and Khalifa* (2009) developed a TC++ model for distributed demand control ventilation (DDCV) study. The model implements a simple and fast room heat balance model as well as HVAC heat pump energy calculation. The most recent applications of MATLAB in whole building multizone involves integrating Modelica and various building simulation programs to conduct building virtual control test bed (BCVTB) (*Wetter*, 2009). MATLAB, with its immediate availability of control libraries in SIMULINK, can apply a series of differential equation solver to calculate initial value problems (IVPs) table 2.1

In whole building multizone modeling, most equations we are going to solve are non-stiff IVPs. However, the solver given in table 2.1 are mostly explicit or semi-explicit solvers which require certain small time step to achieve convergence and system stability. MATLAB also provide fully implicit function "odel5i" to use backward differentiation formulas (BDFs) to achieve good convergence and stability. MATLAB also offers a couple of commands to modify the solvers settings (i.e. tolerance, minimum step) for different application purposes. The readily available post-processing module make possible that one can plot and analyze his system immediately after the systems are solved. However, MATLAB does not provide graphical user interface, and is not an object oriented programming platform, This makes MATLAB an idea

Table 2.1: MATLAB solver review

Solver	Type	Oder of Accuracy	Method	When to Use
ode45	Nonstiff	Medium	Runge-Kutta	The first solver to try.
ode23	Nonstiff	Low	Runge-Kutta	For problems with crude error tolerances or for solving moderately stiff problems.
ode113	Nonstiff	Low to high	Adams	For problems with stringent error tolerances or for solving computationally intensive problems.
ode15s	Stiff	Low to medium	NDFs (BDFs)	If ode45 is slow because the problem is stiff.
ode23s	Stiff	Low	Rosenbrock	If using crude error tolerances to solve stiff systems and the mass matrix is constant.
ode23t	Moderately Stiff	Low	Trapezoidal rule	For moderately stiff problems if you need a solution without numerical damping.
ode23tb	Stiff	Low	TR-BDF2	If using crude error tolerances to solve stiff systems.

environments for integrating other simulation programs and conduct research such as building control instead of whole building multizone performance modeling tools.

Modelica, originated from Europe, is an open standard, object-oriented equation based language to conveniently model complex physical systems. The language, first intensively developed and used by automobile industry, can be used for mechanical, electrical, electronic, hydraulic, control etc. process-oriented subcomponents. The object-oriented features of Modelica unifies classes which can be exported to C++ library and reused for integration and evolutions of models. Dymola is a user interface of Modelica language which provides Modelica translator to perform symbolic transformations for large systems modeling. Another advantage is it comes with several model libraries which can be easily used without reproducing by users. Dymola can

also project Modelica model into a MATLAB SIMULINK S-function C mex-file which can be simulated in SIMULINK as an input/output block. At the same time, each model will use its C integrator to solve ODEs. The advantage of Modelica is that it can model building systems in components and group components into libraries for different purpose use. This greatly improves building system model reusability. The easy integration between Dymola Modelica and MATLAB SIMULINK also gives the the modeling language flexibility especially for control purposes (*Wetter et al.*, 2008). However, for multizone modeling point of view, Modelica doesn't provide a comprehensive solution to model complex geometry and explain multizone combined heat air moisture and pollutants. It is a very promising tool for building systems modeling, but is not a good option for multizone modeling in this thesis.

Visual SPARK, developed by Lawrance Berkeley Lab, is the IDE of SPARK (Simulation Problem Analysis and Research Kernel). SPARK uses mathematical graph both to describe models of such systems and to solve the embodied differential-algebraic equation systems (DAEs) (*Sowell et al.*, 2004). It describes problems declaratively with atomic objects, modeled and generated by atomic classes, representing individual equations and macro objects, generated by marco classes, representing larger programming entities. Graph-theoretic methods are used in SPARK to represent the problems, in a preprocessing step, at the level of equation s and variables. Similar with Modelica, the object-oriented feature makes models and equations in SPARK easy to extend and assemble with other models. SPARK also employs "component decomposition" and "small cutset discovery" to reduce the complex of calculations and optimize the solver's performance. In the first stage,"Component decomposition", components are identified and classified as "strong" or "weak". Weak components are typical topologically sorted sequence of nodes while strong components mean the component is strongly connected in a graph-theoretic sense that the component is heavily related to other nodes or edges of the system. SPARK will then

process weak components sequentially and strong components iteratively. In the second stage, "small cutset discovery", SPARK identifies a small set of nodes that break all cycles within the strong components using contraction algorithm. Numerically, it constructs an integration vector by using the small set of nodes and then use this vector and equations in strong component to calculated necessary Jacobian matrix used for Newton-Raphson method. The small cutset discovery can optimize the Jacobian by significantly reducing its size and make it much small than that if computed by using original strong component. The two stages optimization will be processed by SPARK automatically. *Wetter et al.* (2008) uses SPARK and Dymola Modelica to conduct a VAV system simulation and compare SPARK and Dymola solver performance in terms computational speed and accuracy. It states that Dymola has its computational advantage because Modelica uses a symbolic processor to select the most appropriate inverse for complicated functions. While using SPARK, with atomic classes, a model builder routinely provides multiple inverses, and determines which inverse gets selected for use in the numerical stage. The two solvers' performance is similar. And integrating SPARK with OpenModelica is promising for open source modeling purposes.

Studies from Grunewald (1997) and Nicolai (2007; 2008) show how to use a generic solver scheme SUNDIAL CVODE to solver combined heat air moisture transport for building envelope analysis. The CVODE solver scheme can solve both stiff and nonstiff problems in C or Fortran. The CVODE integrator is a variable-order and variable-step multi-step method. The scheme itself adjusts the order and step size intelligently based on the problems convergence. The advantage of this CVODE is that it can be smoothly integrated with building simulation programs and exchange simulation results with user interface. Users can adjust solver's parameters to optimize its performance. The CVODE gives users, compared with other numeric schemes, greater flexibility to adjust and manage the actual integration process.

2.4 The living testbed – Building performance measurement

The living testbed is a real whole building test environment to demonstrate the performance of building's envelope, energy resources and equipments, lighting systems, intelligent control systems, and effectiveness of utilizing renewable energy. Several studies have been done in testbed design, development, system configuration and commissioning (*Davis and Szegeti*, 1999; *BREEAM*, 2003; *Morrissey et al.*, 2004; *O'Sullivan et al.*, 2004; *Xue*, 2005). The study of Morrissey show how to use building information modeling (BIM) method to characterize building systems performance. The study show how to combine static building information such as geometric data, equipments information with dynamic building inputs including building systems measurement and metering data, simulation data and climate conditions into one single BIM domain that life cycle analysis can be carried out as shown in Figure 2.4. Morrissey formulates that the static building information modeled by EnergyPlus and eventually converted to BIM industry foundation class IFC2x2. The imported static building information can be used to populate building static data for building performance monitoring and analyze rich performance history datasets. This method, first initialized by O'Sullivan (2004), describes how to use non-proprietary BIM method to exchange building information with various analysis tools as well as building management system (BMS).

However, the complexity of existing BIM standards usually limit the analysis of building performance monitoring to certain aspects, i.e. HVAC system performance in Morrissey's (2003) study. The needs of whole building performance monitoring require to use a common BIM structure to store and analyze building performance on, not only HVAC system, but also indoor environments qualities, climate conditions, building envelope system etc.

The research of Xue (2005) shows how to achieve low energy consumption building
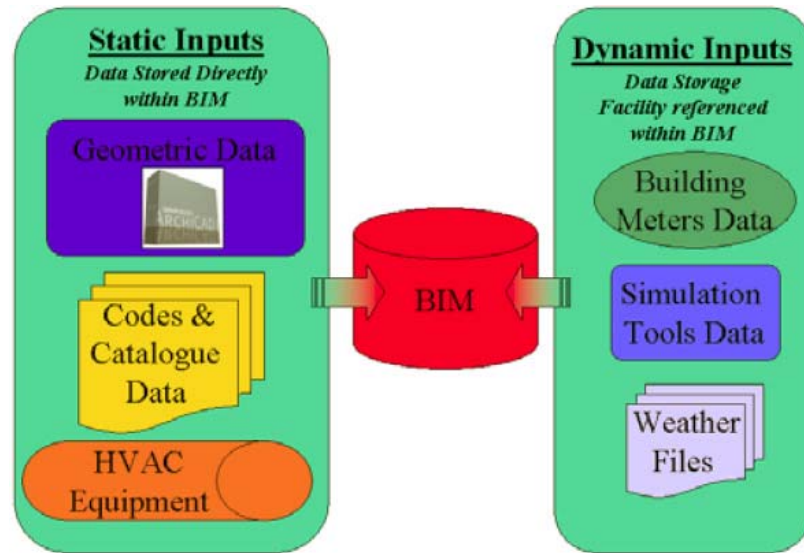
Figure 2.4: Building performance data storage using BIM method (*Morrissey et al.*, 2004)

designs. The study demonstrates advanced building systems used by a green testbed building in China. Advanced building envelope system, indoor thermal comfort controls and ventilation system, energy and power system are described. This study gives good guidelines on green building designs. However the missing merits of structural storage of building performance information and comparing design with real-time performance require the development of a virtual building platform which dynamically measures and stores various building systems performance.

In this study, the testbed concept is adopted and further developed to comprehensively store building performance data in a hierarchical structure called "Virtual Building". The stored building data can be used to verify building system performance, conduct fault detection and diagnostic analysis, and compare design with actual operation performance.

2.5 Summary of Literature Review

This chapter reviews the components to conduct building performance evaluation studies including understanding design process and design parameters, building simulation tools for combined energy and IEQ performance analysis, and the detailed simulation models and methods to store and validate building's real performance.

Traditional building design process is reviewed based on architectural structure and project management model of AIA's definition and IDEF0 model. AIA gives five stages description on building design process as: Originate, Focus, Design, Build, Occupy. The model of IDEF0 gives six stages design process from building design project management point of view: Brief, Programming, Scheme, Design, Construction, Take-over. Even though slightly different from AIA's description, the actual design practices involved in each stage are very similar. Based on the architectural definitions, several studies are conducted to qualify building design process from building performance evaluation point of view. Studies found that building performance is not usually evaluated in the early design stages. Design parameters which tightly related to the building performance are selected. And parameter groups are discussed in combination with design stages.

To conduct building performance evaluation in design, various performance simulation tools are reviewed. Two types of simulation tools: energy simulation tools and IAQ simulation tool are studied. The limitation of existing tools in supporting design process is stated and a missing combined energy and IAQ simulation tool is also discussed. Then, building envelope models, zone models, multizone air flow models, and HVAC models are reviewed in major simulation programs.

Two different numeric methods, customized solver scheme and general solver scheme, are commonly used to solve whole building multizone models. The customized solvers can solve specific building multizone simulation in efficient computation ways because

highly customized algorithms can either simplify ODEs problem or solve ODEs in step optimization methods. The customized solver schemes can be found in EnergyPlus, CONTAM, CHAMPS-BES etc simulation platforms. Nonetheless, the customized solver schemes are problem-specific designed that it is difficult to move a customized scheme from one platform to another, and thus its re-usability is very poor. Another solver scheme type is general solver environment. This type of scheme can be found at MATLAB, SPARK, Modelica (Dymola), SUNDAIL CVODE ect. The computational capacities of theses solver environments are reviewed and their advantages of simplifying problems and reducing computation time are discussed. It is summarized that SUNDAIL CVODE solver schemes provide full flexibility to adjust solver parameters and achieve efficient calculations. The availability of CVODE in C language also make it possible to integrate building multizone solvers with other C/C++ environments.

Finally, the approaches used for building performance monitoring are discussed to validate design performance. Previous studies are reviewed to extract building information modeling information and combine static building design data with dynamic building performance input data. Studies on different green building design and monitoring systems are also discussed. The current research is limited by the complexity of utilizing current BIM methods for whole building performance storage and analysis. A new approach to whole building modeling and dynamic performance monitoring will be discussed in following chapters.

In summary, the aforesaid literature review reveals that:

- A comprehensive energy and IEQ simulation tool is missing (not by customized combining multiple tools), and hence needs to be developed for building performance study.

- A suitable numerical tool is needed to enable the simultaneous solving combined energy and IEQ analysis questions by using intrinsic integration method to
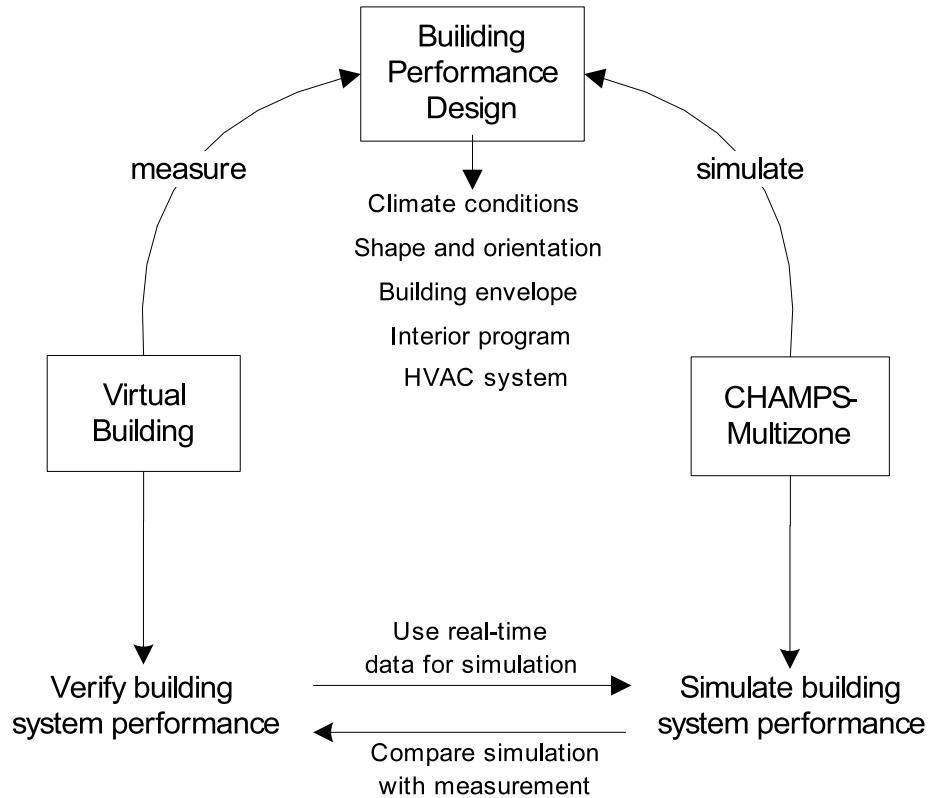
Figure 2.5: Integrated Building Performance Design Research Areas

provide better accuracy and coordinate simulation time step via different solvers (not combining different solvers and exchange variables via solver bridge).

- There is no existing method to measure building performance and store monitored data in a structured way that one can verify building performance predicted by simulation at the design stage.

- To evaluate building performance, it is important to understand each design stage, design parameters, and evaluate design parameters' impact on building performance.

Figure 2.5 illustrates the major research areas for integrated building performance design study. In order to better assess design parameters, a new combined heat, air, moisture and pollutant simulation model for multizone analysis (CHAMPS-

Multizone) is developed in this study. Chapter Three introduces the physical models of CHAMPS-Multizone, and Chapter Four explains the numeric methods to solve CHAMPS-Multizone and the model's calibration and testing case study. Only simulation is not sufficient for comprehensive building performance analysis. A hierarchical building performance monitoring system, Virtual Building, is developed to store real-time performance data and used to compare and verify building design performance. Chapter Five introduces the methodologies of Virtual Building development and its hierarchical structure. In this chapter, preliminary monitoring data is also collected to investigate the actual building systems performance. In Chapter Six, the developed CHAMPS-Multizone design tool and Virtual Building performance monitoring system is used in the whole building design process to evaluate the selection of design parameters. And, finally the simulated building performance is compared with measured as-built results for a case building.

CHAPTER III

CHAMPS-Multizone

This chapter introduces a new simulation program CHAMPS-Multizone for whole building combined heat, air, moisture and pollutant simulation analysis. Models implemented in CHAMPS-Multizone are introduced and the solving methods are discussed. The chapter is structured based on different simulation modules/solvers implemented in CHAMPS-MULTIZONE.

3.1 Overview

CHAMPS-Multizone includes several models and modules. From computer simulation program point of view, it is designed to have graphical user interface (GUI), numerical solvers, project data model, post-processing module etc. The GUI module interacts with user and transfer input variable values to project data model; the numerical solver module is the calculation engine with input from building information data and output of building performance prediction; project data module provides structural data modeling support for GUI, solver and other modules; the post-processing module plots simulation results and interacts with users.

From numerical modeling point of view, CHAMPS-Multizone includes the following major models:

- Climate condition and solar radiation calculation

- Building envelope model

- Zone quantities balance

- HVAC model

- Airflow model
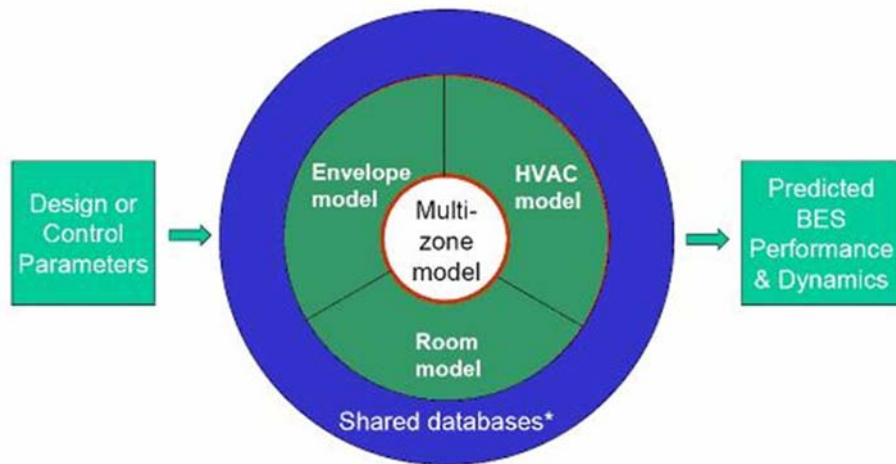
Figure 3.1: An overview of CHAMPS-Multizone Numerical modules

Firgure 3.1 gives an overview of CHAMPS-Multizone numerical modules. The climate condition and solar radiation model calculates building surrounding environmental conditions as well as direct and diffuse solar radiation incidental on building envelope exterior surfaces; building envelope model calculates quantity fluxes happening at interior and exterior surface of building envelope; the zone quantities balance model conducts heat, air, moisture and pollutant balance for each building zone; HVAC model gives the supply and return air conditions to each building zone and also calculates quantities balance inside HVAC air handlers. Air-flow model calculates air infiltration, exfiltration and inter-zonal air flow and quantities fluxes carried by air-flow.

To better explain the numerics of CHAMPS-Multizone program, certain notation conventions are introduced here. The notation is consistent with other CHAMPS program (*Nicolai*, 2007, 2008; *CHAMPS-BES*, 2004).

Mass and energy densities are commonly denoted by the symbol ρ. Mass and energy fluxes are commonly denoted by the symbol j. The superscript indicates whether energy, water vapor or pollutant is used. Typical superscripts used in CHAMPS-Multizone include:

- energy: U

- water vapor: wv

- pollutant(s): p

The subscript indicates which zone or air handling unit duct is modeled in CHAMPS-Multizone program.

In CHAMPS-Multizone, most calculation is conducted in terms of gas phase species. For detailed building envelope modeling which calculates building envelope heat moisture and pollutant transport effects, integration of CHAMPS-Multizone with CHAMPS-BES (BES) will extend the capabilities of CHAMPS-Multizone simulation. Liquid phase species, especially water, is calculated usually at CHAMPS-Multizone's HVAC quantity balance when taking condensation and latent heat load into consideration.

3.2 Solar Radiation Models

The solar radiation models are discussed in this section. Basic solar calculation equations are exhibited and the methods to calculate short wave and long wave radiation are given.

3.2.1 Short Wave Solar radiation and time calculation

To calculate solar radiation, firstly, the general geographical/geometrical information of solar radiation needs to be calculated

1) Calculate current date in the year: DOY.

2) Calculate Equation of time. First, a "spring angle" b $[rad]$ is calculated to represent the angular relation current date of year to spring time (*Duffie and Beckman*, 1991)

$$b = \frac{2\pi(DOY - 81)}{364} \tag{3.1}$$

Then, equation of time EOT $[hr]$ is calculated based on this "spring angle" (*Duffie and Beckman*, 1991) [1]

$$EOT = 9.87\sin(2b) - 7.53\cos(b) - 1.5\sin(b) \tag{3.2}$$

3) Calculate apparent solar time $[hr]$ (*ASHRAE*, 2005)

$$AST = LST + \frac{EOT}{60} + \frac{LSM - LON}{15} \tag{3.3}$$

where

[1]ASHRAE Hand Book 2005 calculates Equation of Time by using tabulated method.

AST = apparent Solar Time, current location's solar time $[hr]$

LST = local solar time $[hr]$

EOT = equation of time $[hr]$

LSM = local standard time Meridian $[deg]$, the mean solar time in local time zone

LON = location longitude $[deg]$

4) Calculate solar Declination angle DA $[rad]$ (*Spencer*, 1972)

$$DA = \frac{DOY - 1}{365} \cdot \frac{2\pi}{360} \tag{3.4}$$

Then, based on the declination angle DA, we calculate Declination Number $[rad]$

$$DN = 0.3963723 - 22.9132745cn + 4.0254304sn$$
$$- 0.387205c2n + 0.05196728s2n - 0.1545267c3n + 0.08479777s3n \tag{3.5}$$

where

$cn = \cos(DA)$

$sn = \sin(DA)$

$cn2 = \cos(2DA)$

$sn2 = \sin(2DA)$

$cn3 = \cos(3DA)$

$sn3 = \sin(3DA)$

5) Calculate Solar Time Angle H $[rad]$ (*ASHRAE*, 2005)

$$H = 15(AST - 12) \cdot \frac{2\pi}{360} \tag{3.6}$$

6) Calculate Solar Altitude Angle β [rad] (*ASHRAE*, 2005)

$$\sin\beta = \cos(LAT) \cdot \cos(DA) \cdot \cos(H) + \sin(LAT) \cdot \sin(DA) \qquad (3.7)$$

where

LAT = location latitude [rad]

DA = declination angle [rad]

H = solar time angle [rad]

7) Calculate Solar Azimuth Angle ϕ

$$\sin\phi = \frac{\sin\beta \cdot \sin(LAT) - \sin(DA)}{\cos\beta \cdot \cos(LAT)} \qquad (3.8)$$

where

ϕ = solar azimuth angle [rad]

LAT = location latitude [rad]

DA = is declination angle [rad]

3.2.2 ASHRAE Clear Sky Model

ASHRAE Clear Sky Model(*ASHRAE*, 2005) uses tabulated method to calculate Direct Normal Irradiance E_{DN}. ASHRAE Clear Sky Model is designed for cloudless sky condition and are generally used for summer design day calculation. For unclear sky, a sky correct number is multiplied to modify E_{DN}.

ASHRAE Handbook documents ASHRAE A, B, C values as:

where

A = apparent solar irradiation at air mass $m = 0$

B = atmosphere extinction coefficient

C = dimensionless diffuse radiation factor

Direct Normal Solar Irradiance is calculated as

$$E_{DN} = \frac{A}{B/\sin\beta} \cdot N_{clearness}$$ (3.9)

where β = solar altitude angle (rad) $N_{clearness}$ = Sky clearness number.

Once E_{DN} is calculated, the direct solar radiation can be calculated with incidental solar radiation angle θ. Incidental Solar Radiation Angle is calculated as

$$\cos\theta = \cos\beta\cos\alpha\sin\Sigma + \sin\beta\cos\Sigma$$ (3.10)

where

θ = incidental solar radiation angle $[rad]$

β = solar altitude angle $[rad]$

α = azimuth angle difference $[rad]$, which is defined as solar azimuth angle - surface azimuth angle

Σ = surface tile angle $[rad]$

Table 3.1: ASHRAE Clear Sky Model Coefficients

	I_0 [W/m^2]	Equation of Time [$minutes$]	Declination [$degree$]	A [W/m^2]	B [$--$]	C [$--$]
Jan	1416	-11.2	-20.0	1202	0.141	0.103
Feb	1401	-13.9	-10.8	1181	0.142	0.104
Mar	1381	-7.5	0.0	1164	0.149	0.109
Apr	1356	1.1	11.6	1130	0.164	0.120
May	1336	3.3	20.0	1106	0.177	0.130
Jun	1336	-1.4	23.45	1092	0.185	0.137
Jul	1336	-6.2	20.6	1093	0.186	0.138
Aug	1338	-2.4	12.3	1107	0.182	0.134
Sep	1359	7.5	0.0	1136	0.165	0.121
Oct	1380	15.4	-10.5	1166	0.152	0.111
Nov	1405	13.8	-19.8	1190	0.144	0.106
Dec	1417	1.6	-23.45	1204	0.141	0.103

Direct solar radiation E_D can be calculated

$$E_D = E_{DN} \cos \theta \qquad (3.11)$$

where

E_D = direct solar radiation $[W/m^2]$

θ = incidental solar radiation angle $[rad]$

Once direct radiation is calculated, diffuse solar radiation has two components: diffuse solar radiation from sky E_{sky}, and diffuse solar radiation from ground reflection E_{gnd}. ASHRAE Clear Sky model calculate sky short wave diffuse radiation as

$$E_{sky} = C \cdot E_{DN} Y \qquad (3.12)$$

where

E_{sky} = sky diffuse radiation $[W/m^2]$

C = ASHRAE Clear Sky diffuse coefficient $[rad]$

Y = incidental angle ratio

Y is given by

$$Y = 0.55 + 0.437 \cos \theta + 0.313 \cos^2 \theta \qquad \text{for} \ \cos \theta > 0.2 \qquad (3.13)$$

$$Y = 0.45 \qquad \text{for} \ \cos \theta \le 0.2 \qquad (3.14)$$

Ground reflected radiation (included both direct radiation part and diffuse radiation part) is given by

$$E_{gnd} = E_{DN}(C + \sin \beta) F_{ref} \frac{1 - \cos \Sigma}{2} \qquad (3.15)$$

where

45

E_{gnd} = ground radiation (with combination of diffuse and direct radiation) $[W/m^2]$

C = ASHRAE Clear Sky diffuse coefficient $[rad]$

β = solar altitude angle $[rad]$

F_{ref} = ground reflectance factor[2]

Σ = building surface tilt angle $[rad]$

The total solar radiation incidentally on a building surface is can be written as the sum of ground reflected radiation, sky diffuse radiation and solar direct radiation.

$$j_{sol} = E_{gnd} + E_{sky} + E_D \tag{3.16}$$

3.2.3 Diffuse Solar Radiation Model

The Diffuse Solar Radiation model uses real climate condition to calculate diffuse solar radiation. Since direct solar radiation can be get from weather file and calculation of incidental direct solar radiation is similar with ASHRAE Clear Sky model, only diffuse solar radiation is given here. This model is developed by *Perez* (1990) and eventually adopted by *EnergyPlus* (2008) as its diffuse solar radiation model. Here, only preliminary equations are given.

The core concept of the model states that diffuse solar radiation consists of three components: circumsolar diffuse radiation, sky dome diffuse radiation, and horizon diffuse radiation. The diffuse solar radiation is given by [3]

$$j_{dif} = I_{hoz} + I_{sky} + I_{cir} \tag{3.17}$$

where

---

[2]Ground reflectance factor has the value of 0.2 for normal ground condition and 0.6 for snow covered ground condition

[3]The documentation of *EnergyPlus* (2008) is a little bit misleading. Diffuse horizontal solar irradiance should be used as I_h, instead of total/global horizontal solar irradiance.

j_{dif} = diffuse solar radiation flux incidental on a surface $[W/m^2]$

I_{hoz} = horizon diffuse solar radiation $[W/m^2]$

I_{sky} = sky dome diffuse solar radiation $[W/m^2]$

I_{cir} = circumsolar diffuse solar radiation $[W/m^2]$

The detailed calculation of I_{hoz}, I_{sky}, I_{cir} can be found in reference and will not be stated in this study. [4]

3.2.4 Long Wave Radiation

Long wave radiation model calculates building construction surface long wave radiation heat exchange with exterior environments. Three environment components are considered in CHAMPS-Multizone: Sky, ground, and air and their temperature is represented as T_{sky}, T_{gnd}, and T_{air} respectively. And for each radiation format, its exchange radiation energy is governed by Stefan-Boltzmann long wave radiation law:

$$j_{lw} = \sigma(\Delta T)^4$$

where

$\sigma = 5.67 \times 10^{-8}\ [W/m^2 K^4]$ for Stefan-Boltzmann constant

If one construction exterior surface temperature is $T_{os}\ [K]$, and surface emmisivity is ϵ, the long wave radiation exchange on the surface is given by

$$j_{lw} = \epsilon\sigma(T_{os}^4 - T_{sky}^4) + \epsilon\sigma(T_{os}^4 - T_{gnd}^4) + \epsilon\sigma(T_{os}^4 - T_{air}^4) \tag{3.18}$$

Note that this equation requires to solve building envelope surface temperature and long wave radiation heat flux simultaneously. In most applications, ground surface temperature is treated to have same value as air temperature, while sky temperature

---

[4]Special attentions should be paid to CHAMPS climate condition direct solar radiation which is defined as the direct radiation received and measured at a horizon surface where most other weather files provide direct solar radiation as a flat surface normal to sun beam. $I_{dir,champs} = I_{dir,others} \cdot \sin\beta$

is related to altitude of the location.(*EnergyPlus*, 2008) [5] Another approach is to linearize this equation to a linear equation and use last time step's surface temperature to calculate current step's long wave radiation flux. This approach is introduced and adopted by *EnergyPlus* (2008).

3.2.5 Other CHAMPS Solar Radiation Models Implementation

Various solar radiation models have been implemented in other CHAMPS software, including *CHAMPS-BES* (2009)[6] and ThermalRoomModel[7]. Grunewald has summed up all the solar radiation models used in CHAMPS family (*Grunewald*, 2010).

In summary, solar radiation models have two types, one is to use tabulated solar radiation information to generate incidental solar radiation (e.g ASHRAE Clear Sky Model in section 3.2.2) and the other type is to use real weather file's direct and diffuse radiation data to calculate incidental solar radiation. The first type solar radiation model is generally used in "design day" simulation that one is trying to capture the "worst" case(or highest values in summer day) of solar radiation and its influence on built environment, while the second type is widely used for one year simulation in which one is trying to find the dynamic building energy performance throughout a "typical" year. CHAMPS-Multizone uses ASHRAE Clear Sky model for its summer design day simulation and use Perez diffuse sky model to calculate weather file based solar radiation.

There are different methods to calculate Equation of Time, Solar Declination Angle, solar altitude angle etc. All those methods have been summed up by *Grunewald* (2010). The future research will combine all short wave and long wave radiation

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[5]Iteration method is needed to solve this non-linear equation in combination with surface heat balance equation

[6]The model is developed by Syracuse University and Technical University of Dresden, Germany. And the German version of this model is called "Delphin"

[7]The model is developed by Technical University of Dresden, Germany

models into one software package which can be easily integrated in any simulation program of CHAMPS family. Users will have flexibility to choose models for specific simulation needs.

3.3 Building Envelope Systems

CHAMPS-Multizone has different forms of building envelope model. To conduct simple and fast simulation in which we are primarily interested in heat transfer through building envelope systems, heat balance based envelope systems are developed in CHAMP-Multizone. Alternatively, if the combined heat moisture and pollutant performance of one or more building envelope (wall/roof/slab..) and its/their impact on whole building performance is the research goal, integrating CHAMPS-BES building envelope into CHAMPS-Multizone can provide detailed building envelope Heat, Moisture, and Pollutant (HMP) calculation capacity. This documentation mainly focus on simplified building envelope systems models while CHAMPS-BES has detailed envelope model documented.

3.3.1 Surface heat balance

Surface heat balance is the basis for heat transfer simulation analysis regardless what conduction transfer method is used to solve heat transfer through building envelope or whether it is simplified with energy equation only or detailed HMP transport model. Surface heat balance also provides the interface between wall solver (solving building envelope and window in CHAMPS-Multizone) and zone solver(solving zone quantity balance equations).

In CHAMPS-Multizone implementation, a building wall/floor/ceiling assembly (also called "Construction Interface" – CI)[8] interior surface temperature is written as T_{s1} while exterior surface temperature of this Construction Interface is T_{s2} and its interior zone temperature is T_{z1}, exterior zone temperature is T_{z2}.[9] For a external

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[8]It can be internal construction or external construction

[9]The interior surface and exterior surface is mainly named for external building envelope. For an external wall, the interior surface means the side associated with the inside zone and exterior surface means another side exposed to ambient environment. However, we extend this definition to internal construction interface. For one physical internal construction interface A in the middle of $zone1$

Construction Interface, the heat balance equation of its exterior surface can be given as: (*ASHRAE*, 2005)

$$j^U_{sol} + j^U_{lw} + j^U_{conv} - j^U_{ko} = 0 \qquad (3.19)$$

where

j^U_{sol} = short wave solar radiation $[W]$

j^U_{lw} = long wave environmental radiation $[W]$

j^U_{conv} = convective heat transfer on exterior surface $[W]$

j^U_{ko} = heat conduction out of exterior surface $[W]$

The interior surface heat balance is

$$j^U_{sol} + j^U_{lwx} + j^U_{conv} + j^U_{ki} + j^U_{sws} + j^U_{lws} = 0 \qquad (3.20)$$

where

j^U_{sol} = short wave solar radiation $[W/m2]$

j^U_{lwx} = long wave radiation exchange with other interior surfaces $[W/m2]$

j^U_{conv} = convective heat transfer on interior surface $[W/m2]$

j^U_{ki} = heat conduction into interior surface $[W/m2]$

j^U_{sws} = short wave source radiation imposed on interior surface (lighting source) $[W/m2]$ [10]

j^U_{lws} = long wave source radiation imposed on interior surface (e.g. equipment, people..) $[W/m2]$

and *zone2*, there are two simulated construction interface objects a and a' created in CHAMPS-Multizone (and similarly in E+ and DesignBuilder). Here a is assigned to belong to *zone1* so a will have its interior surface connected to *zone1*(interior zone) and exterior surface connected to *zone2*(exterior zone) and vice versa for a'. This concept is very important and used in all building envelope simulation through CHAMPS-Multizone where interior construction interfaces exist.

[10]lighting equipments usually have convective heat gain part which directly contribute to zone air and diffuse short radiation and long wave radiation equally imposed on interior surface

3.3.2 Heat Conduction – Conduction Transfer Method(CTF)

Conduction transfer function (CTF) transforms a building wall assembly heat conduction equation into the fashion of response factors, and thus calculates conduction flux in a algebric ic equation instead of complicated differential equations. This method can significantly decrease calculation time and have very good accuracy.

The CTF equation on a exterior building assembly surface is given by

$$j_{ko}^{U}(t) = -Y_0 T_{i,t} - \sum_{l=1}^{ny} Y_j T_{i,t-l\delta} + X_0 T_{i,t} + \sum_{l=1}^{nx} X_j T_{o,t-l\delta} + \sum_{l=1}^{nj} \Phi_l j_{ko,t-l\delta}^{U} \qquad (3.21)$$

The interior surface CTF equation is given by

$$j_{ki}^{U}(t) = -Z_0 T_{i,t} - \sum_{l=1}^{nz} Z_j T_{i,t-l\delta} + Y_0 T_{i,t} + \sum_{l=1}^{ny} Y_j T_{o,t-l\delta} + \sum_{l=1}^{nj} \Phi_l j_{ki,t-l\delta}^{U} \qquad (3.22)$$

where

X_l = outside CTF coefficient, $l = 0, 1, ...n_x$

Y_l = cross CTF coefficient, $l = 0, 1, ...n_y$

Z_l = inside CTF coefficient, $l = 0, 1, ...n_z$

Φ_l = flux CTF coefficient, $l = 0, 1, ...n_\phi$

T_i = inside surface temperature, $[C^o]$

T_o = outside surface temperature, $[C^o]$

j_{ko}^{U} = conduction heat flux on outside surface, $[W/m^2]$

j_{ki}^{U} = conduction heat flux on inside surface, $[W/m^2]$

The CTF coefficients are pre-calculated based on the assembly configuration, and individual material layer's thickness, density, thermal conductivity and specific heat. The detailed method for CTF coefficients calculation is described in the study of *Hittle* (1979). This method is eventually adopted by ASHRAE and implemented in

ASHRAE (2002) Tool Kit. CHMAPS-Multizone can call a generated CTF coefficients file apply the coefficients for heat conduction calculation.

3.3.3 Heat Convection on construction air interface surface

Heat convection on construction interface surfaces is calculated by using certain convective heat transfer coefficient. The general heat convection calculation is given by

$$j_{conv}^{U} = h_{conv}(T_{surf} - T_{air}) \tag{3.23}$$

The equation can apply to both interior and exterior surface. CHAMPS-BES model convective heat transfer coefficient h_{conv} by using user-assigned number. However, customized convective heat transfer coefficient can cause trouble for users who are not familiar with building envelope heat transfer, and assign convective heat transfer coefficient to each construction interface is unrealistic considering the complexity of building geometry.

CHAMPS-Multizone adopts ASHRAE convective heat transfer coefficient calculation algorithm and use calculated convective heat transfer coefficient. Both ASHRAE-SIMPLE and ASHRAE-DETAILED convective heat transfer coefficient computation algorithm is implemented in CHAMPS-Multizone.

1) ASHRAE-SIMPLE algorithm for the exterior surface of external wall:(*ASHRAE*, 2005; *EnergyPlus*, 2008)

   ASHRAE-Simple algorithm calculates convective heat transfer coefficient according to exterior surface roughness and wind velocity coincided on the surface.

It gives the exterior surface convective heat transfer coefficient h_{ext} as:

$$h_{ext} = D + EV_z + FV_z^2 \qquad (3.24)$$

where

V_z = local wind speed calculated at the height above ground of the surface centroid.

D, E, F = material roughness coefficients defined by *ASHRAE* (2004a) given in table 3.2:

Table 3.2: Material Roughness Coefficients

Roughness Index	D	E	F	Example Material
1 (Very Rough)	11.58	5.894	0.0	Stucco
2 (Rough)	12.49	4.065	0.028	Brick
3 (Medium Rough)	10.79	4.192	0.0	Concrete
4 (Medium Smooth)	8.23	4.0	-0.057	Clear pine
5 (Smooth)	10.22	3.1	0.0	Smooth plaster
6 (Very Smooth)	8.23	3.33	-0.036	Glass

2) ASHRAE-SIMPLE algorithm for the interior surface:(*ASHRAE*, 2005; *EnergyPlus*, 2008)

For interior surface, ASHRAE-SIMPLE algorithm calculate convective heat transfer coefficient by simply given convective heat transfer coefficient number

based on surface convection type. [11]

$$h_{conv,int}(W/m^2 \cdot K) = \begin{cases} 3.076, & \text{vertical surfaces} \\ 0.948, & \text{horizontal surfaces with reduced convection} \\ 4.040, & \text{horizontal surfaces with enhanced convection} \\ 2.281, & \text{tilted surfaces with reduced convection} \\ 3.870, & \text{tilted surfaces with enhanced convection} \end{cases}$$

(3.25)

3) ASHRAE-DETAILED algorithm for exterior surface of external wall:(*ASHRAE*, 2005; *EnergyPlus*, 2008)

For exterior surface, ASHRAE-DETAILED algorithm calculate convective heat transfer coefficient by splitting convection coefficient into tow part: natural convection h_n, and forced convection h_f. The convective heat transfer coefficient is defined as

$$h_{conv,ext} = h_f + h_n$$

(3.26)

Forced convective term is given by

$$h_f = 2.537 W_f R_f \left(\frac{PV_z}{A} \right)^{1/2}$$

(3.27)

where

W_f = wind factor and equal 1.0 for windward surfaces and 0.5 for leeward surface

R_f = roughness multipliers defined by Table 3.3

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[11] For $\Delta T = T_{air} - T_{surf}$, the reduced convection is defined as upward facing surface with $\Delta T > 0.0$ or downward facing surface with $\Delta T < 0.0$. For $\Delta T = T_{air} - T_{surf}$, the enhanced convection is defined as upward facing surface with $\Delta T < 0.0$ or downward facing surface with $\Delta T > 0.0$. The definition in *EnergyPlus* (2008) is wrong.

P = perimeter of surface $[m]$

V_z = local wind speed calculated at the Height above ground of the surface centroid $[m/s]$

A = area of the surface $[m^2]$

Table 3.3: Material Roughness Multipliers R_f

Roughness Index	R_f	Example Material
1 (Very Rough)	2.17	Stucco
2 (Rough)	1.67	Brick
3 (Medium Rough)	1.52	Concrete
4 (Medium Smooth)	1.13	Clear pine
5 (Smooth)	1.11	Smooth plaster
6 (Very Smooth)	1.00	Glass

And natural convection term is given by [12]

$$
h_{conv,int} = \begin{cases} 1.31\,|\Delta T|^{\frac{1}{3}} & \text{vertical surfaces or no temperature difference} \\ \frac{9.482|\Delta T|^{\frac{1}{3}}}{7.283-|\cos(\Sigma)|} & \text{enhanced convection} \\ \frac{1.810|\Delta T|^{\frac{1}{3}}}{1.382+|\cos(\Sigma)|} & \text{reduced convection} \end{cases}
$$

$$(3.28)$$

where

Σ = surface tilt angle

$\Delta T = T_{air} - T_{surf}$ the temperature difference between air and surface

4) ASHRAE-DETAILED algorithm for interior surface of a wall:(*ASHRAE*, 2005; *EnergyPlus*, 2008) The interior surface convective heat transfer coefficient is calculated as natural convection. The equations are the same with the natural convection part for ASHRAE-DETAILED algorithm as equation 3.28 shows.

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[12]In CHAMPS-MULTIZONE, since surface temperature is related to convective heat transfer as shown in equation 3.28, this requires to solve surface temperature in combination with convective heat transfer coefficient. Iteration methods are needed to solve the non-linear equations in construction interface surface heat balance equations. EnergyPlus use previous time step approximation to calculate convective heat transfer coefficient. There are certain errors in this approach and detailed analysis is needed. But the approach is good for computation speed.

3.3.4 Interior surface long wave radiation exchange

The interior surface long wave heat exchange with other interior surfaces in the same zone is very important for interior surface heat balance. This has not been considered in CHAMPS-BES since it is only a single envelope model and can't take other interior surfaces in the same zone into account. Similar with ambient long wave radiation equation, the interior surface long wave radiation exchange is given by

$$j_{lwx,il}^{U} = \sigma A_i F_{i,l}(T_{surf,i}^4 - T_{surf,l}^4) \tag{3.29}$$

where

A_i = construction interface i surface area

$F_{i,l}$ = the "script F" viewing between construction interface i and l

The calculation of script F is a core issue here(*Hottel and Sarofim*, 1967; *EnergyPlus*, 2008). The determination of F is a complex process and this parameter is based on the view factors of two construction interfaces, the relative "view" area one surface can see another. CHAMPS-Multizone implements the method in a simplified way by using following assumptions:

- A surface can't see itself.

- A surface can only see other surfaces in the same zone.

- Approximate the direct view factor from surface i to surface j as the ratio of the area of surface j to the total area "seen" by surface i.

The view factor calculation method as well as its assumptions have been well established and implemented by several energy simulation program such as EnergyPlus, DOE2.

3.3.5 Effect of internal heat source on interior surface

The heat source in a zone can also directly affect interior surface heat balance. Since equipments and people can generate long wave radiation and lighting equipments can generate diffuse short wave radiation imposed on interior surface of a construction interface. Lighting equipments will have convective heat part directly contribute to zone air which is used in zone heat balance equation 3.42, long wave radiation heat and short wave diffuse radiation heat imposed on construction interface interior surfaces. Similarly Equipments and people will have convective heat part and long wave radiation heat part. Details will be discussed in section 3.4.3.

3.3.6 Initial Conditions

The initial condition of building envelope system is calculated through the "warm-up" algorithm. The warm-up algorithm basically runs simulation based on first day's weather condition and convergence is reached until surface's temperature (both interior and exterior) change is within a pre-setup threshold. This can greatly buildup building envelope initial temperature to a reasonable value instead of using arbitrarily user-specified value. The same method can be applied to both CTF conduction method and more complex numerical method as in CHAMPS-BES..

3.3.7 Building envelope heat conduction with moisture effects

The CTF heat conduction calculation method demonstrates a fast way to compute sensible heat transfer through building envelope. However, water vapor also plays an important role on building envelope especially on latent heat transfer. The general heat and moisture mass transport balance governing equation are shown in equation

3.30 and 3.31 respectively:

$$\rho C_p(T,\theta)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}[\lambda(T,\theta)\frac{\partial T}{\partial x}] - H(T)\frac{\partial}{\partial x}(j_v) \tag{3.30}$$

$$\frac{\partial \theta}{\partial t} = -\frac{\partial}{\partial x}(\frac{j_w}{\rho_w}) \tag{3.31}$$

where,

j_v = water vapor mass flux, $[kg/m^3 s]$

j_w = liquid water and vapor mass flux, $[kg/m^3 s]$

θ = material total moisture (liquid and vapor) volumetric content, $[m^3/m^3]$ Different from CTF method, the heat balance governing equation is not only expressed in the form of Fourier's Law but with an additional term due to moisture transport and latent heat. Furthermore, the mass transport of moisture can be expressed as

$$\frac{j_v}{\rho_w} = -D_{T,v}(T,\theta)\frac{\partial T}{\partial x} - D_{\theta,v}(T,\theta)\frac{\partial \theta}{\partial x} \tag{3.32}$$

for water vapor transport, and

$$\frac{j_w}{\rho_w} = -D_{T,w}(T,\theta)\frac{\partial T}{\partial x} - D_{\theta,w}(T,\theta)\frac{\partial \theta}{\partial x} \tag{3.33}$$

for liquid water transport.

Here,

$D_{T,v}$ = vapor transport coefficient associated with a temperature gradient $[m^2/sK]$

$D_{\theta,v}$ = vapor transport coefficient associated with a moisture content gradient $[m^2/s]$

$D_{T,w}$ = mass transport coefficient associated with a temperature gradient $[m^2/sK]$

$D_{\theta,w}$ = mass transport coefficient associated with a moisture content gradient $[m^2/s]$

Applying equation 3.32 to equation 3.30 gives the new building envelope heat balance

59

equation as

$$\rho C_p(T,\theta)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}[\lambda(T,\theta)\frac{\partial T}{\partial x}] + V_T + V_\theta \tag{3.34}$$

where,

$V_T = H\rho_{mv}\frac{\partial}{\partial x}[D_{T,v}(T,\theta)\frac{\partial T}{\partial x}]$, defined as latent specific heat associated with a temperature gradient

$V_\theta = H\rho_{mv}\frac{\partial}{\partial x}[D_{\theta,v}(T,\theta)\frac{\partial \theta}{\partial x}]$, defined as latent specific heat associated with a moisture gradient

The moisture mass transfer at building envelope boundary is given as equation 3.35 for exterior surface:

$$j_v = \beta_{v,o}(\theta_{ext} - \theta_{x=0}) \tag{3.35}$$

And the interior surface moisture mass transfer boundary condition can be also defined in similar way. In addition to the heat transfer boundary condition described in equation 3.23, the latent heat introduced by moisture transfer provides a new total (sensible + latent) heat flux at envelope exterior surface as:

$$j_{total} = h_o(T_{ext} - T_{x=0}) + H_{evap}j_v \tag{3.36}$$

The equations above basically summarize the heat and moisture transfer in building envelope as implemented in *CHAMPS-BES* (2009). The integration between CHAMPS-Multizone with CHAMPS-BES will make possible for CHAMPS-Multizone to evaluate sensible and latent heat transport and provide more accurate building heat load calculation. The detailed integration approach will be discussed in section 4.3.

3.3.8 Window Systems

Energy transports through window systems due to solar radiation j_{sol}^U and heat conduction/convection j_{cond}^U. Solar radiation incidental on window surface is calculated exactly like other construction interfaces. Equations in section 3.2 can still apply to window solar radiation. To calculate how much solar radiation transmitted through a window interface, its solar radiation transmittance characteristics need to be understand. The detailed modeling of solar energy transmittance through window requires:

- A very detailed window material database which contains: transmittance coefficients, light spectrum coefficients (related to window colors), radiation beam angular behavior, etc.

- Algorithm that calculates window transmittance based on transmittance coefficients, light spectrum coefficients and radiation incidental angle.

- Shading device material characteristics and shading calculation algorithms. (This will vary from interior shading, exterior shading to inside-pane shading)

While detailed simulation package is available from LBNL's simulation software "Window 5"(*WINDOW*, 2009). The core issue here is to calculate the transmittance coefficient or, defined by ASHRAE, called Solar Heat Gain Coefficient (SHGC). The definition is SHGC is given as(*ASHRAE*, 2005)

$$SHGC = \mathcal{T} + \sum \mathcal{N} \mathcal{A} \tag{3.37}$$

where

$\mathcal{T} = $ transmittant contribution coefficient $[W/m^2]$

$\mathcal{A} = $ solar absorptance

$\mathcal{N} = $ inward-flowing coefficient $[W/m^2]$

Most window simulation programs calculates SHGC in the simplified manners by considering each window pane's

- transmittance characteristics

- solar absorptance

- solar reflectance

This assumes that the a window is

- spectrum average (or spectrum/wave-length independent) for solar radiation (SHGC is equally applied to all spectrum/wavelength solar beams)

- solar radiation incidental angle independence. (SHGC is independent of incidental angle)

CHAMPS-Multizone calculates heat transfer passing through windows by splitting the coefficient into two part: transmittance part (with transmittance coefficient τ) and conduction/convection part (with thermal resistant γ $[m^2 K/W]$).The transmittance coefficient is calculated as

$$\tau = \prod_{i=1}^{N} T_i \qquad (3.38)$$

where

T_i = layer i solar radiation transmittance coefficient.

Equation 3.38 is generally true when we ignore the influence from each layer's reflection to solar transmittance.

Once τ and γ are calculated, the heat fluxes through a window interface can be calculated as [13]

$$j_{sol} = (j_{dir} \cos \theta + j_{dif}) \cdot \tau \cdot IAC \qquad (3.39)$$

where

j_{sol} = solar radiation passed through a window interface $[W]$

j_{dir} = direct solar radiation incidental on a window surface $[W]$

j_{dif} = diffuse solar radiation on a window surface $[W]$

IAC = Internal Attenuation Coefficient (the shading coefficient from internal curtain or blinds)

CHAMPS-Multizone assumes that zone air is transparent and does not absorb radiation energy, and the solar radiation passing through windows is distributed to floor surface and calculate as a flux term in floor heat balance.

The conduction/convection heat transfer is calculated as:

$$j_{conv} = \left(h_{ext} + \frac{1}{R_{win}} + h_{int} \right) (T_o - T_i) \qquad (3.40)$$

where

R_{win} = window assembly R value $[m^2 K/W]$

h_{ext} = exterior window surface convective heat transfer coefficient $[W/(m^2 K)]$ calculated in section 3.3.3

h_{int} = interior window surface convective heat transfer coefficient $[W/(m^2 K)]$ calculated in section 3.3.3

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[13]The direct heat flux from window interface will only be distributed the the connected zone's floor. Should direct radiation be distributed to specific parts of the floor or any wall interface, detailed 3D solar radiation algorithm are need to calculate natural lighting topology.

This is generally true, when assuming static state conduction, that window panes do not store heat. Should each layer heat storage capacity be consider, detailed heat balance equations should be written for each layer (*EnergyPlus*, 2008).

3.4   Zone Balance

The zone balance model calculates heat, air, moisture, and pollutant conservation in each building zone.

The general zone balance equation is given as

$$\frac{\partial \varrho^E}{\partial t} = \sum j^E + \sum \sigma^E \tag{3.41}$$

where

E is extensive properties consistent with CHAMPS-BES definitions

$E = U$ for energy

$E = wv$ for water vapor

$E = p$ for a pollutant species

ϱ^E = density of extensive properties, with

ϱ^U for energy density

ϱ^{wv} for water vapor density [14]

ϱ^p for a pollutant species density

σ^E = source/sink term of extensive properties, with

σ^U for energy source/sink

σ^{wv} for water source/sink

σ^p for a pollutant species source/sink

For energy balance, the equation is given as

$$\frac{\partial \varrho^U}{\partial t} = \sum j^U + \sigma^U \tag{3.42}$$

65

For water vapor balance, the equation is given as

$$\frac{\partial \varrho^{wv}}{\partial t} = \sum j^{wv} + \sigma^{wv} \tag{3.43}$$

For a pollutant species balance, the equation is given as

$$\frac{\partial \varrho^{p}}{\partial t} = \sum j^{p} + \sigma^{p} \tag{3.44}$$

3.4.1 Initial Conditions

Currently supported initial conditions of one zone are:

- Temperature T (base unit K)

- Relative Humidity RH (base Unit $-$)

- Contaminant Concentration ϱ^{p}_{init} (base Unit kg/m^3)

The initial conditions are defined by user inputs. Since certain warm-up algorithm will be triggered before the actual simulation starts, the initial conditions will be used as initial points for warm-up period. Once warm-up is finished, the envelope conditions get at the end of warm-up process will be used for the actual simulation.

The initial air internal energy density is given by

$$\rho^{U} = c_{p,air}\rho_{air}\left(T - T_{ref}\right) + \left[c_{p,mv}\left(T - T_{ref}\right) + h_{evap}\right]\rho_{mv} \tag{3.45}$$

where

T_{ref} is the reference temperature at $0\ [K]$

The initial water vapor density is given by

$$p_{sat} = P_{sat}(T)$$

$$p^{mv} = RH \cdot p_{sat} \tag{3.46}$$

$$\rho^{mv} = \frac{p^{mv}}{T \cdot R_{vapor}}$$

The initial pollutant(s) mass density ρ^p is user-specified.

The Conserved Quantity in CHAMPS-Multizone zone balance system are energy density ϱ^U, water vapor density ϱ^{wv}, and pollutant species density ϱ^p.

3.4.2 Heat flux calculation for energy balance equation

The summation term of heat fluxes $\sum j^U$ in equation 3.42 is calculated by

- Heat conduction/convection flux from all interfaces (walls, doors, windows) interior surface j_{conv}^U. Since section 3.3 has stated how to solve interior surface temperature, the heat flux from a surface can be calculated easily as

$$j_{conv}^U = h_i \left(T_{surf,int} - T_{zone} \right)$$

- Air-flow heat flux is introduced by infiltration/exfiltration and inter-zonal air flow j_{flow}^U:

$$j_{flow,i}^U = \sum j_{j \to i}^{air} C_p^{air} \left(T_{zone,i} - T_{ref} \right) - \sum j_{i \to j}^{air} C_p^{air} \left(T_{zone} - T_{ref} \right)$$

  The heat flux is defined as the net heat flow based on air flow in and out zone i. Detailed calculation on air flow heat flux will be explained in section 3.6

- HVAC net heat flux is calculated by

$$j^U_{hvac} = j^U_{sup} - j^U_{ret}$$

where,

$j^U_{sup} = Q_{sup} \cdot \rho_{sup} \cdot C^{air}_p \cdot (T_{sup,i} - T_{ref})$

is heat flow in zone i from HVAC supply duct,

$j^U_{ret} = Q_{ret} \cdot \rho_{ret} \cdot C^{air}_p \cdot (T_{zone,i} - T_{ref})$

is heat flow out of zone i to HVAC return duct.

Detailed calculation on HVAC supply and return air flux will be explained in section 3.5

3.4.3 Heat, moisture and pollutant source

Different heat source σ^U is given by

- lighting heat source

- equipment heat source

- occupants heat source

Usually, one heat source can have different parts. For instance, lighting heat source is consisted with short wave radiation part (visible light), long wave radiation part, and convective part. Only convective part of the heat source will be considered as zone heat source and contribute to zone heat gain, while other parts will contribute to construction interface interior surface heat balance calculation.[15]

Moisture source term is given as σ^{wv} and pollutant source term is given as σ^p.

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[15]This is a common assumption taken by most building simulation software. It assumes that zone air is transparent that long wave and short wave radiation will pass through zone air and diffuse on interior surface of building envelope, rather than absorbed by zone air.

3.4.4 Moisture mass flux calculation

Moisture flux come from following terms similar as heat flux situation

- air flow moisture flux(infiltration/exfiltration/inter-zonal air flow)

- HAVC supply air and return air moisture flux

- building envelope moisture flux (this flux is only calculated when run detailed building envelope simulation by using CHAMPS-BES building envelope model)

Air flow moisture flux and HVAC moisture flux are calculated in section 3.6 and section 3.5 respectively.

3.4.5 Pollutant mass flux calculation

Pollutant mass flux comes from following terms similar with moisture and pollutant case

- pollutant air flow flux(infiltration/exfiltration/inter-zonal air flow)

- HAVC supply air and return air pollutant flux

- building envelope pollutant flux (this flux is only calculated when run detailed building envelope simulation by using CHAMPS-BES building envelope model)

Pollutant air flow flux and HVAC pollutant flux are calculated in section 3.6 and section 3.5 respectively.

3.4.6 Decomposition algorithm

Calculation of intrinsic variables and potentials (i.e. temperature) from conserved quantities is done using the inverse form of equation 3.45. The decomposition equation

3.47 requires $\varrho_{air} c_T = const.$

$$T \approx \frac{\varrho^U - H_{evap} \rho_{mv}}{\rho_{air} c_{p,air} + \rho_{mv} c_{p,mv}} \tag{3.47}$$

where,

H_{evap} is latent heat density

Zone air ideal gas law is given by

$$\rho_{air} = \frac{p_{air}}{R_{air} T} \tag{3.48}$$

Saturation pressure is given by

$$p_{v,sat} = P_{v,sat}(T) \tag{3.49}$$

Relative humidity is given by

$$\phi = \rho_{mv} \frac{p_{v,sat}}{T R_{vapor}} \tag{3.50}$$

3.4.7   Condensation in zones

Condensation may happen in a zone if the relative humidity of that zone is over 100%. The water vapor in the zone air will be condensed to liquid water. Since liquid water is not a part of zone air, the zone water vapor balance calculation will not consider it in the next iteration. To determine whether condensation happens or not, it is necessary to calculate water vapor saturation pressure based on equation 3.49. Then a corresponding relative humidity level is calculated by equation 3.50. Should the calculated RH value is above 100%, condensation happens and the liquid water will be removed out of the zone air and zone air will achieve saturation point.

3.5 HVAC Systems

The HVAC system in current CHAMPS-Multizone contains air loop calculation only. The basic assumption for HVAC air handlers is that the supply air duct and return air duct are considered as two separated "zones" where zone balance equations (heat, moisture, and pollutants) can still apply[16]. A general schematic of HVAC air handler system is illustrated by figure 3.2.
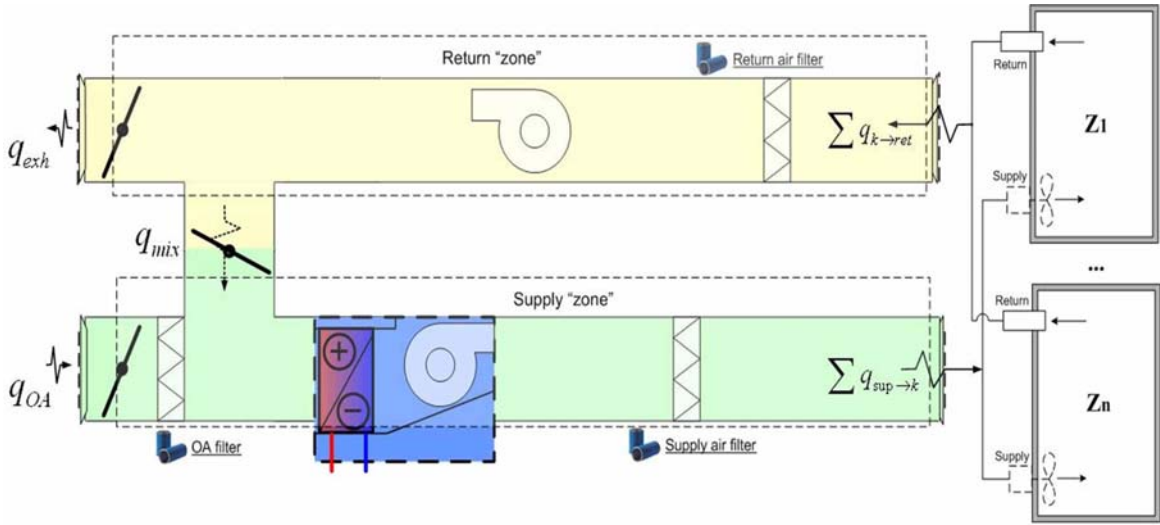
Figure 3.2: HVAC air handler schematic

Three filters are mounted in the air handler to filter Outside Air (OA), return air and supply air respectively. Three dampers locate at OA, exhaust, and mixed air branch. For a single HVAC air handler illustrated as figure 3.2, air mass balance criteria are satisfied to balance the amount of OA supply, exhaust and mixed air. The size/volume of mixed branch is neglected. Each zone will have its own supply and return air duct branch connected with HVAC air handler and CHAMPS-Multizone assumes that the size of these ducts is very small compared with air handler supply and return main ducts, and thus the volume of these branch is negligible. To heat/cool each zone, heating/cooling energy is added into duct at the end of each zone's supply

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[16]This model is still built under well-mixed assumption. The assumption applies to both supply and return duct.

duct branch. This assumes that the energy added in the branches will not directly contribute to supply and return duct energy change. The amount of energy added into each zone's supply branch (thus, directly flow into connected zone) is determined and controlled by that zone's heat load.

Similar with section 3.4, for a HVAC air handler duct i, balance equation is given as

$$V_i \frac{\partial \varrho_i^E}{\partial t} = \sum_k^N q_{k \to i}^E \left(1 - \eta_{in}^E\right) \varrho_k^E - \sum_k^M q_{i \to k}^E \varrho_i^E \tag{3.51}$$

where

E is extensive properties consistent with CHAMPS-BES definitions

$E = U$ for energy, ϱ^U for energy density

$E = wv$ for water vapor, ϱ^{wv} for water vapor density[17]

$E = p$ for a pollutant species, ϱ^p for a pollutant species density

k = any duct/zone connected with current duct i

$q_{k \to i}^E$ = extensive property E flow-in volumetric flow rate, from duct/zone k to current duct i $[m^3/s]$

$q_{i \to k}^E$ = extensive property E flow-out volumetric flow rate, from current duct i to duct/zone k $[m^3/s]$

η_{in}^E = filter efficiency for extensive property E applied to air flow in

3.5.1 Supply duct balance equation

From general duct balance equation 3.51, supply duct balance can be derived as

$$V_{sup} \frac{\partial \varrho_{sup}^E}{\partial t} = q_{OA} \left(1 - \eta_{OA}^E\right) \rho_{OA}^E + q_{mix} \varrho_{ret}^E - \sum_k^N q_{sup \to k} \varrho_{sup}^E \tag{3.52}$$

For supply duct, only OA and mixed air from return duct contribute to the air

flowing in. And only OA side has filter mounted, so the terms for air coming in can be simplified. The air flowing out is distributed to each zone k connected with this HVAC air handler. Further derivation of equation 3.52 can give three balance equations for energy, water vapor and contaminant respectively. All three equations will keep similar format and will not be given separately here. It is noticed that filters are only effective for certain contaminant and will not affect the amount of heat or moisture flow into the supply duct. So, when $E \neq p$ (pollutant), filter coefficients $\eta_{OA}^E, \eta_{out}^E = 0$.

3.5.2 Return duct balance equation

From general duct balance equation 3.51, return duct balance can be derived as

$$V_{ret}\frac{\partial \varrho_{ret}^E}{\partial t} = \sum_{k}^{N} q_{k \to ret} \left(1 - \eta_{ret}^E\right) \varrho_k^E - q_{exh}\varrho_{ret}^E - q_{mix}\varrho_{ret}^E \tag{3.53}$$

For return duct, only exhaust and mixed air will flow out of return duct. The air flowing in is distributed by each zone k connected with this HVAC air handler. Further derivation of equation 3.53 can give three balance equations for energy, water vapor and contaminant respectively. The return duct quantity balance and contaminant filtering calculation can be achieved similar as supply duct.

3.5.3 Supply and return duct air mass balance

Since HVAC air handler's both supply and return ducts are considered as a "zone", the mass balance of supply duct is given as

$$j_{sup}^{air} = j_{OA}^{air} + j_{mix}^{air} \tag{3.54}$$

where

j_{sup}^{air} = total supply air mass flow rate, from supply duct flowing into zones connected with current HVAC air handler unit [kg/s]

j_{OA}^{air} = HVAC air handler unit OA mass flow rate [kg/s]

j_{mix}^{air} = HVAC air handler unit mixed return air mass flow rate [kg/s]

Similarly, return duct mass balance is given as[18]

$$j_{ret}^{air} = j_{exh}^{air} + j_{mix}^{air} \tag{3.55}$$

where

j_{ret}^{air} = total return air mass flow rate (flow from zones connected with current HVAC air handler unit into return duct) [kg/s]

j_{exh}^{air} = HVAC air handler unit exhaust air mass flow rate [kg/s]

j_{mix}^{air} = HVAC air handler unit mixed return air mass flow rate (flow from return duct to supply duct) [kg/s]

It is necessary to know supply air mass flow rate out of supply air duct and return air mass flow rate into return duct in order to calculate the mass flow of OA, exhaust, and mixed air. For CAV system, the supply air return air flow rate is defined by user input. For VAV system, the supply and return flow is calculated based on zone heat balance by given user-defined supply air temperature. Once all those flow rates in equation 3.54, 3.55 are known, supply duct balance equation 3.52 and return duct balance equation 3.53 can be solved.

3.5.4 Different types of HVAC systems

Three different types of HVAC systems are considered in CHAMPS-Multizone,

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[18]Water vapor and pollutant(s) are treated as trace gas that they will not affect the mass quantity of air.

- Constant Air Volume (CAV) – variable supply air temperature

- Variable Air Volume (VAV) – constant supply air temperature

- Constant Air Volume and Constant Supply Air Temperature (CAVCSAT)

For CAV system, the supply air flow rate to individual zone is constant and specified by a user, and the supply air temperature is adjusted in order to make supply air energy added into the zone can balance zone's heat load. VAV system keeps supply air temperature constant value for heating and cooling respectively and vary supply air flow rate to balance zone air heat load. CAVCSAT system defines that the HVAC air handler only supply air without providing additional energy at terminal side. However, to balance zone heat load, extra heating/cooling must be added into the zone air. That has been done and controlled by an internal heating/cooling source. In this case, the internal heating/cooling source acts as a radiant panel or a split room unit in the zone to condition zone air temperature.

3.5.5 Zone supply air condition calculation – control issues

General zone heat balance equation given by equation 3.42 in section 3.4 can be further derived as

$$j_{sys}^{U} + \sum j_{conv}^{U} + \sum j_{src}^{U} + \sum j_{air\_flow}^{U} = 0 \qquad (3.56)$$

where
j_{sys}^{U} = HVAC system energy flow rate $[W]$
j_{conv}^{U} = zone convective heat gain from building envelope $[W]$
j_{src}^{U} = zone source heat gain $[W]$
$j_{air\_flow}^{U}$ = zone air flow (infiltration/exfiltration/inter-zonal air flow) heat gain $[W]$

To balance each zone's heat load, supply air energy j_{sys}^U should be calculated according to equation 3.56. The zone heat load can be written as

$$j_{load}^U = \sum j_{conv}^U + \sum j_{src}^U + \sum j_{air\_flow}^U \tag{3.57}$$

Thus, HVAC system supply energy can be written as

$$j_{sys}^U = -j_{load}^U$$
$$j_{sys}^U = j_{sys,ext}^U + j_{sys,int}^U \tag{3.58}$$

where

$j_{sys,int}^U =$ internal heating/cooling system gain (e.g. radiant panel) $[W]$

$j_{sys,ext}^U =$ external heating/cooling system supplied from HVAC system $[W]$

HVAC system has the same supply energy form as the summation of supply air energy and water vapor energy

$$j_{sys,ext}^U = j^{air} C_{p,air} \left(T_{sup} - T_{zone} \right) + j^{mv} C_{p,v} \left(T_{sup} - T_{zone} \right) \tag{3.59}$$

For CAV system, since supply air flow rate is user specified, and zone temperature T_{zone} is also known, supply air temperature T_{sup} can be calculated according to equation 3.58. Certain cooling and heating supply air temperature threshold are set to make sure supply air temperature is within a reasonable range. Should calculated temperature is out of this range, the supply air temperature is set to the closest threshold value. In this case, the system internal heating/cooling gain $j_{sys,int} = 0$ (which means all building load is compensated by external CAV HVAC system). The return air flow rate is user-specified[19] and the return air condition is exactly the same

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[19]the return air flow rate could be the same with supply air flow rate which means HVAC system won't pressurize/depressurize a zone. It can also be smaller/bigger than supply air flow rate which will make a zone pressurized/depressurized by HVAC system

with zone condition since CHAMPS-Multizone uses well-mixed assumption.

For VAV system, since supply air temperature (T_{sup}) is fixed, and zone temperature T_{zone} is also known, supply air flow rate (j^{air} and hereby j^{mv}) can be calculated. CHAMPS-Multizone also requires users to input min supply air flow rate to maintain the basic IAQ. Should calculated VAV system flow rate is lower than the min flow rate, the min flow rate will be reset to min flow rate. In this case, the building zone internal heating/cooling gain $j^U_{sys,int} = 0$ (which means all building load is compensated by external VAV HVAC system). VAV system return air flow rate is always the same with supply air flow rate.

For CAVCSAT system, since both supply air temperature (T_{sup}) and supply air flow rate (j^{air} and hereby j^{mv} can be calculated) are user-specified. The zone internal HVAC system heating/cooling energy

$$j^U_{sys,int} = -j^U_{load} - j^U_{sys,ext}$$

The control approach for CHAMPS-Multizone is to use the predictive method instead of feedback method because feedback method requires enough real-time sampling points and it is hard to achieve in simulation software (*EnergyPlus*, 2008). The important control issue is zone air temperature T_{zone}. CHAMPS-Multizone supports two control methods. First method is ideal control that zone temperature will be adjusted to setpoint instantaneously and zone temperature T_{zone} will always be controlled at $T_{control}$ that

$$T_{zone} = T_{control}$$

Another method allows zone temperature T_{zone} slightly change around setpoint $T_{control}$. In this method, the heat load in one time step may not be balanced instantaneously by HVAC system supply air condition. However, control algorithm will maintain that zone temperature T_{zone} will not deviate too far from control setpoint $T_{control}$. This

method is closer to realistic case of zone temperature control.

To balance zone heat load, both methods calculate the amount of energy delivered to each zone. And the energy delivered from supply duct will be used to calculated supply air conditions, supply duct heat balance.

3.5.6 OA, exhaust and mixed air flow rate calculation

From equations 3.54 and 3.55, since supply and return air conditions can be calculated in section 3.5.5, HVAC system OA, exhaust, and mixed air flow rate can be calculated subsequently.

For common case, the HVAC system total supply air and total return air flow is the same (the system is not pressurizing/depressurizing), and since system minimum OA is user-specified. In this case, the system will run HVAC air handler with minimum OA intake. Then mixed air flow rate can be solved as

$$j_{mix}^{air} = j_{sup}^{air} - j_{OA}^{air}$$

And exhaust air can be easily solved as

$$j_{exh}^{air} = j_{OA}^{air}$$

If the HVAC system is pressurizing or depressurizing zones, the difference between supply air flow rate and return air flow is calculated as

$$j_{dif}^{air} = j_{sup}^{air} - j_{ret}^{air}$$

Then a difference flow rate ratio is calculated and compared with min OA intake to

see if

$$\eta_{min,OA} < \frac{\dot{j}_{dif}^{air}}{\dot{j}_{sup}^{air}} \tag{3.60}$$

where

$\eta_{min,OA} = \dot{j}_{OA}^{air}/\dot{j}_{sup}^{air}$ is min OA flow ratio

If equation 3.60 is satisfied, this means min OA ratio can't compensate the entire system supply and return air difference and the system can't run at min OA ratio. In this case, the OA intake needs to adjust to the level that

$$\eta_{OA} = \frac{\dot{j}_{dif}^{air}}{\dot{j}_{sup}^{air}}$$

$$\dot{j}_{OA}^{air} = \eta_{OA} \cdot \dot{j}_{sup}^{air}$$

And since the system is running at supply air flow rate much higher than return air flow rate, return air will be fully utilized. That makes exhaust air flow rate become 0 and return duct air mass balance equation 3.55 becomes

$$\dot{j}_{mix}^{air} = \dot{j}_{ret}^{air} \tag{3.61}$$

If equation 3.60 is not met, this means the minimum OA ratio one sets is enough to support HVAC system flow rate and system OA, mixed, and exhaust air flow rate can be calculated as

$$\dot{j}_{OA}^{air} = \eta_{min,OA} \cdot \dot{j}_{sup}^{air}$$

$$\dot{j}_{mix}^{air} = \dot{j}_{sup}^{air} - \dot{j}_{OA}^{air}$$

$$\dot{j}_{exh}^{air} = \dot{j}_{ret}^{air} - \dot{j}_{mix}^{air} \tag{3.62}$$

79

3.5.7 Solving HVAC balance equations

Iteration methods are employed to solve HVAC balance equations. This is similar with solving zone balance equations since one HVAC air handler is considered to have one supply duct and one return duct and each of these is considered as a zone. Two solver architecture is considered in the implementation. The first option is to
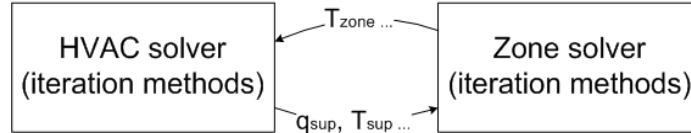
Figure 3.3: HVAC solver schematic

write HVAC solver separated with zone solver and each solver will managed its own iteration scheme and between these two, variables such as $T_{zone}, T_{sup}, q_{sup}, q_{ret}$ are exchanged as shown in Figure 3.3.

Another option is to implement zone and HVAC solver to calculate balance equations in the same iteration scheme. In this case HVAC ducts will be treated completely as zones and those variables will become internal variables easily known in the iterations.

The first option offers more flexible implementation and can split HVAC module apart from zone solver module. But the ways to exchange variables need further investigations in order to achieve system stability. The second option is much easier to implemented when HVAC system is not complicated enough and since all variables become internal, this can avoid stability issues. In CHAMPS-Multizone, the second option is adopted since its HVAC system calculation is simplified. Should further detailed HVAC model is needed, the code can be easily converted and restructured to the first option.

3.6 Air Flow Model

The basic assumption for air flow model is steady-state flow fields. This is general true for whole building application, since in inter-connected multi-zone application, a drastic change in air pressure of ambient air or one zone will yield very quick steady-state air flow fields across the entire building.[20].

3.6.1 Air Flow Equation

The steady state air flow model is given as

$$V_{zone,i}\frac{\partial \rho_i^{air}}{\partial t} = \sum_{j}^{N}(s_{i\to j}K_g\,|p_i - p_j|^{n_{i\to j}}) = 0 \tag{3.63}$$

where

p_i = zone i pressure field $[pa]$

p_l = zone l (connected with zone i) pressure field $[pa]$

$V_{zone,i}$ = zone i volume $[m^3]$

K_g = air flow coefficient $[kg \cdot m^3/pa^n]$

$n_{i\to l}$ = flow exponent from zone i to zone j

$s_{i\to l}$ = flow direct sign, 1 if $p_i < p_l$ and -1 if $p_i \geq p_l$

If HVAC air flow is considered as solving airflow network, equation 3.63 can be further derived as

$$V_{zone,i}\frac{\partial \rho_i^{air}}{\partial t} = \sum_{l}^{N}(s_{i\to l}K_g\,|p_i - p_l|^{n_{i\to l}}) + j_{sup}^{air} - j_{ret}^{air} = 0 \tag{3.64}$$

---

[20]The pressure built-up process has been simulated and verified in MATLAB that a zone of size $100m^3$ it will react to a $10p_a$ sudden wind pressure change and build up its own pressure field in accordance with wind pressure in $1s$. This has been done under standard building envelope crack/opening condition by applying air flow equations.

3.6.2   Solving Air Flow Equation

Solving pressure field equation requires to solve a non-linear equation as

$$[K_g] \cdot [P]^n = [A]$$

once $[P]$ is solved, the pressure filed for each zone is known, then the air mass flow rate across openings between zone i and zone j can be calculated as

$$\dot{m}_{i \to j}^{air} = s_{i \to j} K_g \left| p_i - p_j \right|^{n_{i \to j}} \tag{3.65}$$

where

$j_{i \to j}^{air}$ = air mass flow rate from zone i to zone j $[kg/s]$

And moisture, pollutant(s) mass flow rate across the opening can be calculated subsequently by using the mass fraction of that species in that zone.

CHAMPS-Multizone solves equation 3.63 by using non-linear iterations based on Krylov-Newton inexact guessing methods. The solver package used is called KINSOL (Krylov Inexact Newton SOLver) and implemented in SUNDIALS suit.

3.7 Summary of CHAMPS-Multizone models

The complexity of combined heat, air, moisture and pollutants transport model in whole building performance simulation introduced above involves a set of interconnected and coupled balance equations and physical models. Many important physical models are introduced, such as

- solar radiation model and incidental solar radiation calculation on a construction assembly interface,

- building envelope system including opaque building envelope simplified heat transfer calculation and fenestration systems,

- zone heat, moisture and pollutant governing balance equations

- HVAC air loop model for heat, air, moisture and pollutant balance calculations

- airflow model to capture whole building infiltration, exfiltration and interzonal airflow.

and others. The listed models comprise major components for whole building heat, air, moisture, and pollutants analysis. Solving all the models for a building provides a solid building performance predictions in terms of combined energy and IEQ.

Solution methods for models described in equations discussed above will be addressed in following chapter.

CHAPTER IV

Numeric methods of solving CHAMPS-Multizone models

Most CHAMPS-Multizone balance equations given in previous chapter can be described as ordinary differential equation (ODE), and its initial value problem (IVP) can be written as equation (4.1)

$$\frac{\partial \rho^E}{\partial t} = \sum j^E + \sum \sigma^E \tag{4.1}$$

Equation (4.1) is the same format of equation (3.41) which can be used for zone and HVAC duct properties balance calculation, where E represents the conserved quantities. In CHAMPS-Multizone, E can be used for energy, moisture, or pollutant(s).

This system ODE needs to be solved simutanenously for all conserved properties. For whole building simulation, the ODEs shown in equation (4.1) always exhibit in various formats because of complexity of boundary conditions, zone conditions ect. Hence, except for very simple cases (single zone) which require less information input and reductions of boundary conditions and building geometry, a numerical solution method is needed to address whole building solutions.

The numerical solution for calculating combined heat, air, moisture and pollutant transport in whole building scale should follow several important criteria:

1. The numeric solution for the system of ODEs should be stable and accurate, suitable for whole building performance analysis.

2. The computation code should be well structured by considering each model's input and output variables.

3. The integration of different models' solver should be robust to enable smooth variable exchange between solver schemes and assure system stability.

4. The numerical algorithms and code implementation should be efficient to achieve fast computation coupled properties.

In this chapter, based on the literature reviews of numerical methods for general computation needs, the numerical schemes to solve combined heat, air, moisture and pollutants in multizone scale are introduced. Then the specific numeric methods to address individual models are formulated. The various solver schemes are integrated by dynamically exchanging variables between multiple solver modules. Finally, integrated solver schemes are calibrated in contrast of calculation results of well-established simulation programs and examples are given for whole building combined energy and IEQ analysis.

4.1 Introduction of numerical solution methods

The method of solving ODEs as the basic format of numerical calculation, has been evolved for very long time. The literature reviews give two methods to solve ODEs:

- Custom implementation of a complete solver scheme, i.e. Newton-Raphson iteration and integration solver

- Use an existing generic automated integration library for solving generic system of ODEs

The first method, as implemented in Nicolai (2008), CONTAM (2006) etc. programs, shows highly efficient computation capabilities. This method, most of time, is specifically designed for complex geometry, boundary conditions and physical effects with special considerations for the numerical problems it is addressing. The second method, usually supported by numerical platform such as MATLAB, Dymola Modelica, SPARK ect., offer more generality and flexibility, simpler and quick implementation.

This research will focus on utilizing existing numerical platform SUNDIALS::CVODE library, as a typical general solver scheme. The CVODE integrator is a variable-order variable-step multi-step method. Before discussing the specific implementation details of the CVODE integrator in detail, an overview of the mathematical fundamentals on multistep methods is given. After this, introduction to multi-step methods and their implementation in the generic SUNDIALS::CVODE solver package are given. Then various important numerical aspects on applying the generic solver scheme to the coupled heat and moisture transport are discussed.

4.1.1 The basic formulation of ODEs

Assume the system equation we are going to solve can be written in the general form as equation (4.2):

$$\dot{y} = f\left(t, y(t)\right) \tag{4.2}$$

where y is the unknown. And the previous time step (t_{n-1}) solution of y is known and is denoted as y^{n-1}. The single step method can easily solve y^n based on y^{n-1} and the step length $h = t_n - t_{n-1}$. Comparing with single step method, we can solve equation (4.2) by stating that y^n can be solved by calculating previous time points $t = t_{n-1}, t_{n-2}, \cdots, t_{n-k}$ respectively to obtain a more accurate solution. Thus, instead of calculating one step from t_{n-1} to t_n, several steps are used to achieve better predictions.

Another numeric solution characteristic is the order of solution. The simplest method is first order solution which can be described as Euler method. The forward Euler method gives solution of equation 4.2 as shown in equation 4.3;

$$y^n = y^{n-1} + h \cdot f\left(t_{n-1}, y^{n-1}\right) \tag{4.3a}$$

The forward Euler method is also characterized as first order method that, from equation (4.3), a typical linear solution of y^n is calculated by linearly extrapolating from y^{n-1} (in the order of 1).

In contrast, the multi-order method, instead of extrapolating results linearly, predicts solution at time t_n based on polynomial expression of multiple previous steps. The multi-order method can avoid the high order truncation error usually exhibited in 1st order solution and reach more accurate solution. Combining with multi-step method, we can calculate solution of y^n by knowing all previous steps $t_{n-k}, t_{n-k+1}, \cdots, t_{n-1}$

calculation results $y^{n-k}, y^{n-k+1}, \cdots, y^{n-1}$ and their derivatives $\dot{y}^{n-k}, \dot{y}^{n-k+1}, \cdots, \dot{y}^{n-1}$. Using all or a subset of these values, the current step $y^n, \dot{y}^n$ can be obtained. This method is also called as multi-value method by *Gear* (1971) who summarizes a two-process method to solve this problem by step 1) prediction and step 2) correction. In the prediction stage, an approximate initial guess of unknown $\mathbf{y}^n = [y^n, \dot{y}^n]$ is made by a given known vector $\mathbf{y}^{n-1}$ (4.4):

$$\mathbf{y}^{n-1} = \left[y^{n-1}, y^{n-2}, \cdots, y^{n-k}, \dot{y}^{n-1}, \dot{y}^{n-2}, \cdots, \dot{y}^{n-k}\right]^T \tag{4.4}$$

The prediction of initial approximate solution of $\mathbf{y}^{n,(0)}$ can be obtained by equation (4.5)

$$\mathbf{y}^{n,(0)} = \mathbf{B}\mathbf{y}^{n-1} \tag{4.5}$$

where $\mathbf{B}$ can be further written in equation (4.6)

$$
\begin{bmatrix} y^{n,(0)} \\ y^{n-1} \\ \vdots \\ y^{n-k+1} \\ h\dot{y}^{n,(0)} \\ h\dot{y}^{n-1} \\ \vdots \\ h\dot{y}^{n-k+1} \end{bmatrix}
=
\left[\begin{array}{cccccc|cccc}
\alpha_1 & \alpha_2 & \cdots & & \alpha_k & \beta_1 & \beta_2 & \cdots & & \beta_k \\
1 & 0 & \cdots & 0 & 0 & 0 & \cdots & \cdots & & 0 \\
\vdots & \ddots & & \vdots & \vdots & \vdots & \ddots & & & \vdots \\
0 & \cdots & 0 & 1 & 0 & 0 & \cdots & \cdots & & 0 \\ \hline
\gamma_1 & \gamma_2 & \cdots & & \gamma_k & \delta_1 & \delta_2 & \cdots & & \delta_k \\
0 & \cdots & \cdots & & 0 & 1 & 0 & \cdots & 0 & 0 \\
\vdots & \ddots & & & \vdots & \vdots & \ddots & & \vdots & \vdots \\
0 & \cdots & \cdots & & 0 & 0 & \cdots & 0 & 1 & 0
\end{array}\right]
\begin{bmatrix} y^{n-1} \\ y^{n-2} \\ \vdots \\ y^{n-k} \\ h\dot{y}^{n-1} \\ h\dot{y}^{n-2} \\ \vdots \\ h\dot{y}^{n-k} \end{bmatrix}
\tag{4.6}
$$

here α_i, β_i, γ_i, and δ_i are constants. And the approximation of initial guessing at

time $t = n$ can be further summerized as follow:

$$y^{n,(0)} = \sum_{i=i}^{k} \left(\alpha_i y^{n-i} + h_n \beta_i \dot{y}^{n-i} \right)$$

$$h_n \dot{y}^{n,(0)} = \sum_{i=i}^{k} \left(\gamma_i y^{n-i} + h_n \delta_i \dot{y}^{n-i} \right)$$

(4.7)

Equation (4.7) shows that the initial guessing of unknown is an summation of multiple steps' known conditions. A simplest version of equation (4.7) gives, when $k = 1$, $\gamma_i = \delta_i = 0$, $\alpha_1 = \beta_1 = 1$, that a single step initial guessing can be reached:

$$y^{n,(0)} = y^{n-1} + h_n \dot{y}^{n-1}$$

(4.8)

Equation (4.8) exhibits the same meaning as equation (4.3) as explicit Euler method. If the prediction process does not give exact solution of our differential equation system at time $t = n$, a correction process is needed to follow prediction process to tune the approximate guessing so that desired solutions can be found. The accuracy of prediction results can be evaluated by rearranging differential equation (4.2) and plugging in the prediction result $y^{n,(0)}$ as follows:

$$G(\mathbf{y}^n) = -\dot{y}^{n,(0)} + f(y^{n,(0)})$$

(4.9)

Should accurate prediction is made, equation (4.9) will yeild $= 0$. However, most of time when $G(\mathbf{y}^n) = 0$ is not satified, corrections are made to multiply a scaler c to $G(\mathbf{y}^n)$ and another round correction approximation can be made by:

$$\mathbf{y}^{n,(1)} = \mathbf{y}^{n,(0)} + cG(\mathbf{y}^{n,(0)})$$

(4.10)

This iterative correction process can continue by:

$$\mathbf{y}^{n,(m+1)} = \mathbf{y}^{n,(m)} + cG(\mathbf{y}^{n,(m)}) \qquad m = 1, 2, \cdots \qquad (4.11)$$

for a fixed number of iteration or until no further change of $\mathbf{y}^{n,(m)}$ is observed (based on error tolerance) at iteration M. At this point, the system is called to reach convergence.

The order of the method and whether it is explicit or implicit method is determined by the points of k, the coefficients in matrix $\mathbf{B}$ and the form of the vector $\mathbf{c}$. Most multizone building performance modeling problems are stiff problems which require implicit methods to solve. The Gear equations described above are recognized to be the one of the best implicit multi-step method, which has been explained in detailed by *Press et al.* (2007). The actual implementation of Gear type functions requires detailed understanding of numeric principles. However, existing research make a number of tools available with numeric flexibility and implementation convenience. The SUNDIALS::CVODE (*LLNL*, 2009) is the most recent solver package with complete numeric structure, developed based on Gear type equations. Instead of developing customized solver schemes, this research is going to focus on utilizing the existing CVODE solver for whole building performance modeling.

4.1.2   Introduction of SUNDIALS::CVODE Integrator

CVODE, developed based on Gear type formulas, solves ODE initial value problems (IVPs). It uses variable-order and variable-step methods developed based on Gear's equation (4.7) and gives general numeric expression as equation (4.12):

$$\sum_{i=0}^{K_1} \alpha_{n,i} y^{n-i} + h_n \sum_{i=0}^{K_2} \beta_{n,i} \dot{y}^{n-i} = 0 \qquad (4.12)$$

When normalization $\alpha_{n,0} = -1$ is used, equation (4.12) will exhibit in the same way of Gear's equation (4.7) as:

$$y^n = \sum_{i=1}^{K_1} \alpha_{n,i} y^{n-i} + h_n \sum_{i=0}^{K_2} \beta_{n,i} \dot{y}^{n-i}$$

For stiff problems, CVODE employs the Backward Differentiation Formulas (BDFs) by giving a so-call fixed-leading coefficient form that specifies $K_1 = q$ and $K_2 = 0$. The equation reduces to:

$$y^n = \sum_{i=1}^{K_1} \alpha_{n,i} y^{n-i} + h_n \beta_{n,0} \dot{y}^n \tag{4.13}$$

where K_1 represent the numeric system order and usually varies between 1 and 5.

For nonestiff problems, COVDE includes the Adams-Moulton formulas, which specifies $K_1 = 1$ and $K_2 = q$, and the order of q varies between 1 and 12. The nonestiff problems are not common in whole building performance modeling area, and it is not the topic of this research.

CVODE also implements intelligent calculation schemes which can determine the coefficients in equation (4.13) by recent calculation historiy of the step sizes and method order. The method order will be changed based on system convergence history, the current and past time steps and total solver's work.

To rearrange equation (4.12) can give similar expression as equation (4.9) has for CVODE solver:

$$G(y^n) = y^n - h_n \beta_{n,0} f(t_n, y^n) - a_n = 0 \tag{4.14}$$

where a_n is defined as:

$$a_n = \sum_{i=1}^{K} \left(\alpha_{n,i} y^{n-i} + h_n \beta_{n,0} \dot{y}^n \right) \qquad (4.15)$$

for stiff systems, equation (4.15) can be further reduced to:

$$a_n = \sum_{i=1}^{K} \alpha_{n,i} y^{n-i} \qquad (4.16)$$

The non-linear equation (4.14) must be solved approximately for each integration step. Various Newton integrations methods are used in CVODE. Equation (4.14) can be solved by calculating linear systems:

$$(\mathbf{I} - h_n \beta_{n,0} \mathbf{J}) \left[y^{n(m+1)} - y^{n(m)} \right] = -G \left(y^{n,(m)} \right) \qquad (4.17)$$

where $\mathbf{J}$ is Jacobian matrix determined by $\mathbf{J} = \partial f / \partial y$.

SUNDIALS::CVODE provides six methods for its solver, and for multizone modeling, the relative simple direct linear solver can satisfy the problems without diving into more sophisticated methods. CVODE is available in both Fortune and C language which can be integrated by various development platforms. The default solver settings can provide excellent numeric performance by given problem convergence conditions. The detail implementation of the solver for multizone modeling will be explained in next section.

4.2 Implementation of CVODE for multizone modeling

CHAMPS-Multizone solver is implemented based on SUNDAIL::CVODE numeric scheme. To implement the solver, various factors areneed to consider for better solver performance accuracy of solution. Among these, we mainly discuss following aspects:

- Selection of unknown variables in CHAMPS-Multizone

- Numeric convergence criteria and settings

- Construction of Jacobian matrix in CVODE

- Numeric solver order and time step adjustment control

4.2.1 Selection of the solution variables

The selection of solution variables will greatly affect the implementation of numerical schemes and solutions of physical problems in whole building simulation. Some unknowns, with proper selection, can be solved in an analytic way while others may require numeric iterations methods, which, compared with analytic method, require more computational power and potentially decrease calculation speed.

The first unknown we need to consider is solution variable for building energy balance calculation. The building has its basic cells – zones. The whole building's energy performance can be expressed by the summation of all its zone energy. Two approaches are considered for zone energy balance calculation and variable selection. The first one, which is used by EnergyPlus (2008), directly relates zone temperature fluctuation to zone heat load and HVAC system heat transfer. This method, since it only considers heat load balance, gives fast calculation for zone temperature solution because it avoids calculating zone air state coupling with moisture. Another method states that zone temperature is related to zone air internal energy quantity, which

is determined in combination of dry air property and water vapor in zones. This method takes the moisture influence on zone energy balance into account, also known as latent heat, and gives more accurate zone energy calculation. While both methods use zone temperature as unknown variable of zone energy calculation, the internal energy method provides more information for zone energy balance calculation, and thus is adopted for CHAMPS-Multizone zone energy calculation. Once the internal energy is solved at certain time step, the zone temperature can be easily retrieved by apply ideal gas law (4.18):

$$T = \frac{\rho^U - H_{evap}\rho^{m_v}}{C_p^{air}\rho^{air} + C_p^v\rho^{m_v}} \tag{4.18}$$

Water vapor density is used as a solution variable in CHAMPS-Multizone mainly because most of multizone building performance simulation only considers water vapor in air. Vapor to liquid water state change will happen in CHAMPS-Multizone HVAC air loop calculation especially at cooling coiling position. The amount of moisture removal is calculated by cooling effects and the amount latent heat removal is also considered.

Pollutant mass density is also selected as a solution variable. Although not directly coupled with zone energy and moisture variables, the zone pollutant density is affected by the infiltration, exfiltration or internal zonal airflow as well as supply and return air condition. The operations of HVAC systems for cooling and heating needs will affect the AHU supply and return flow rate, and thus contribute to zone pollutant mass balance.

The set of solution variables selected for CHAMPS-Multizone calculation can be summarized as the solution vector $y = \{\rho^U, \rho^{m_v}, \rho^p\}$. The coupling effects among variables can be found in section 3.4. The zone internal energy density and water vapor density is coupled via zone temperature. Zone temperature is first solved by

equation 4.18. Then, the solved zone temperature is used to calculate water vapor saturation pressure $P_{v,sat} = f(T_{zone})$. Then zone water vapor mass density can be calculated as

$\rho_{zone,i}^{mv} = \frac{P_{v,sat}}{T_{zone,i} \cdot R_v}$. The coupling effects of pollutant with water vapor and internal energy is represented at airflow and HVAC supply and return air calculation.

4.2.2 Definition of convergence criteria

SUNDAIL::CVODE convergence criteria is built based on weighing the root-mean-square norm $\|\mathbf{W}\|$ defined as :

$$\mathbf{W} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left(\left(y_i^{n,m+1} - y_i^{n,m} \right) W_i \right)^2} \tag{4.19}$$

where $1/W_i$ represents a tolerance for componment y_i defined as

$$W_i = \frac{1}{Tol_{rel} \cdot |y_i| + Tol_{abs}} \tag{4.20}$$

where Tol_{rel} is the relative tolerance defined for each type of unknown (i.e. ρ^U, ρ^{mv} etc.) , and Tol_{abs} is absolute tolerance applied for all the unknown in CVODE solution vector, and y_i is the unknown in the ith position of CVODE solution vector.

The convergence of solution is evaluated by the norm of vector $\mathbf{W}$.

4.2.3 Construction of Jacobian Matrix

The Jacobian matrix in CVODE is constructed by using system roundoff error which can be expressed in partial derivatives:

$$J_{i,j} = \frac{\partial f_i}{\partial y_i} = \frac{f_i(t, y + \sigma_j e_j) - f_i(t, y)}{\sigma_i} \tag{4.21}$$

The increments σ_i is determined by system roundoff error given by:

$$\delta_j = \max\{\sqrt{U}|y_j|, \sigma_0/W_j\} \tag{4.22}$$

where U is the unit roundoff determined by machine accuracy, σ_0 is a dimensionless value, and W_j is the error weight for unknown y_j defined in equation (4.20)

For most of multizone quantities balance problems, a direct CVODE dense solver is used. A Modified Newton iteration method is used that the iteration Jacobian matrix **J** is updated infrequently as possible to balance the high costs of matrix operations. The Jacobian matrix update occurs when:

- start the integration of the problem,

- more than 20 steps have been taken since the last update,

- The step size change (either increase of decrease) by more than 30%

- a non-fatal convergence failure just occurred, or

- an error test failure just occurred.

Usually, in CHAMPS-Multzione solution, very few CVODE Jacobian matrix update is observed.

4.2.4 Order and time step adjustment

CVODE manages the solver's order and time step automatically based on the performance of the solver. The determination of stopping test for the Newton iteration is defined by checking its local error. This is to satisfies that the final computed value $y^{n(m)}$ can meet that $\|y^{n(m)} - y^{n(0)}\| \le \epsilon$ where $y^{n(0)}$ represent the exact solution at step n. This is to make sure that iteration error is relative small especially less

than 0.1ϵ in default CVODE settings (adjustable by user). When local test fails, the current step iteration is redone by, most of time, reducing the time step. The step size adjustment is usually done by based on the asymptotic behavior of the local error. Detailed step size adjustment algorithm can be found in literature (*Brown et al.*, 1989; *Byrne*, 1989; *Hindmarsh et al.*, 2005; *A.C. and R.*, 2006). Should local error test fails for consecutive three times, the order of solver is reset to 1. After seven failures, CVODE returns to the user with a give-up message.

The adjustment of solver order is been done by CVODE periodically, with the goal to maximizing step size. Most of time, the system integration will start from order 1 and varies the order based on solver's performance. Generally, when the system is complex and large gradients is found, a higher order solver with small time steps is usually observed; when system is running smoothly, the solver will run at lower order with time step closed to maximum allowed step size.

4.3 Solver Integration

In this section, the overall CHAMPS-multizone integration and methods to combine CHAMPS-BES with CHAMPS-Multizone are discussed. For each integration scheme, the interface variables exchanged during integration are given.

4.3.1 Integration with CHAMPS-BES

Section 3.3.7 introduces the fundamentals of buiding envelope heat and moisture transfer. The governing equations and numeric schemes to solve discritized finite difference are already discussed and implemented in *CHAMPS-BES* (2009). Integration of CHAMPS-BES with CHAMPS-Multizone requires two simulation program can dynamic exchange boundary conditions. For combind heat, moisture and pollutant analysis, the boundary conditions we are interested for CHAMPS-BES are buidling envelope interior surface temperature T_{int}, moisture density θ_{int} and VOC density $\rho_{p,int}$. Under well-mixed zone assumption, the zone conditions are given as T_z for zome temperature, θ_z for zone moisture density and $\rho_{p,z}$ for zone pollutant (VOC) density. The properties transfer coefficients are h_{int} for convective heat transfer coefficient at interior surface, β_v for moisture mass transfer coefficient, and γ_p for pullutant mass transfer coefficient.

Two integration methods are proposed to combine CHAMPS-BES with CHAMPS-Multizone simulation together. The first approach is ping-pong integration illustrated as Figure 4.1. For building envelope interior surface variables T_{int}, θ_{int}, $\rho_{voc,int}$ calculated by CHAMPS-BES at any arbitary time step T_1. The heat, moisture and

pollutant mass tranfer are calculated by CHAMPS-Multizone as:

$$j_{U,int} = h_{int}(T_{int} - T_z) \tag{4.23}$$

$$j_{v,int} = \beta_v(\theta_{int} - \theta_z) \tag{4.24}$$

$$j_{p,int} = \gamma_p(\rho_{p,int} - \rho_{p,z}) \tag{4.25}$$

The calculated energy and mass fluxes will be used by CHAMPS-Multizone for zone quantities integration. After solving zone variables T_z, θ_z, and $\rho_{p,z}$ at time step T_1, solved zome temperature, moisture and pollutant densities will be passed to CHAMPS-BES as its boundary conditions for next time step calculation. In some
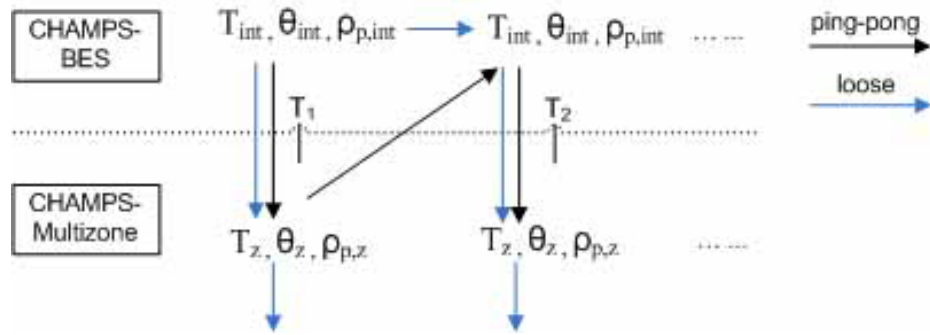
Figure 4.1: CHAMPS-Multizone and CHAMPS-BES Integration Methods

building applications, where HVAC system is available so that zone conditions, especially temperature and RH, are controllled at relative constant level, a relative loose integration can be developed to achieve similiar computation accuracy. This integration method has been demonstrated by *Demetriou and Khalifa* (2009) using TRNSYS to pre-calculate building envelope heat transfer fluxes and integrate them into a distributed environmental control model called "TC++". The integration method is also illustrated in Figure 4.1. The data flow is shown in blue arrow where CHAMPS-BES feeds building envelope interior surface conditions to CHAMPS-Multizone but it does not require CHAMP-Multizone to feedback the zone conditions. The loose integration method can further speed up the integration calculation compared with

Ping-pong approach, and its accuracy is generally good considering, for heat and moisture analysis, zone conditions are relative constant and does not vary significantly with time.

4.3.2 Overall solver integration

Once solvers are implemented in CHAMPS-Mutlzione simulation environment, to integrate multiple solvers into a system that each solver can maintain its own model's accuracy as well as exchange variables between different solver schemes. The solver schemes include climate and solar radiation solver, building envelope solver, zone and HVAC solver, and air-flow solver. A "Ping-Pong" solver integration scheme is implemented in CHAMPS-Multizone to exchange solver variables between different schemes as Figure 4.2 illustrated. The solar and climate solver will first solve solar
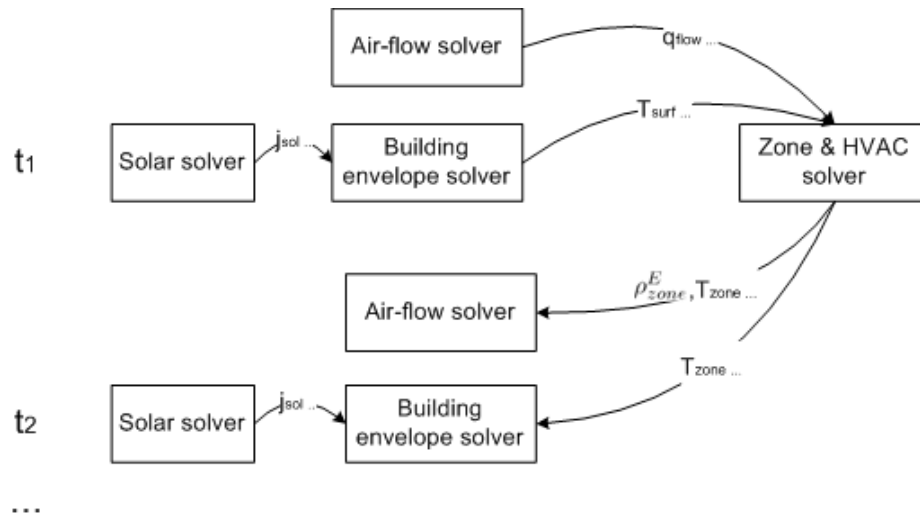
Figure 4.2: CHAMPS-Multizone solver structure

radiation conditions as well as necessary climate conditions. Then air-flow module will solve pressure fields in all zones, and then calculate the air-flow rates between zones. Building envelope module will utilize the calculated solar radiation and climate conditions to calculate heat, moisture and pollutant transport through building envelope and thus get construction interior surface temperature, moisture concentra-

tion, and pollutant(s) concentration. CHAMPS-Multizone uses construction interior surface temperature to calculate heat flux transfer to its adjacent zone. This offers better stability compared with directly using construction surface heat flux (*Nicolai*, 2010). Then the solved air-flow quantity and interior construction surface properties will be used by zone solver to conduct multi-zone calculation. After zone solver finishes zone extensive properties balance calculation, the zone extensive properties will be used for next step's air-flow, and building envelope solver calculations.

4.4 Simulation validations and case study

To assess CHAMPS-Multizone's simulation capabilities and compare the simulation results with other well established energy and IAQ simulation programs, a set of simulations are conducted and results are discussed in the section. A two floors, three zones building is setup with a centralized Air Handling Unit (AHU). Each zone is configured with doors, windows and cracks (openings). A schematic of zone geometry is illustrated by Figure 4.3.
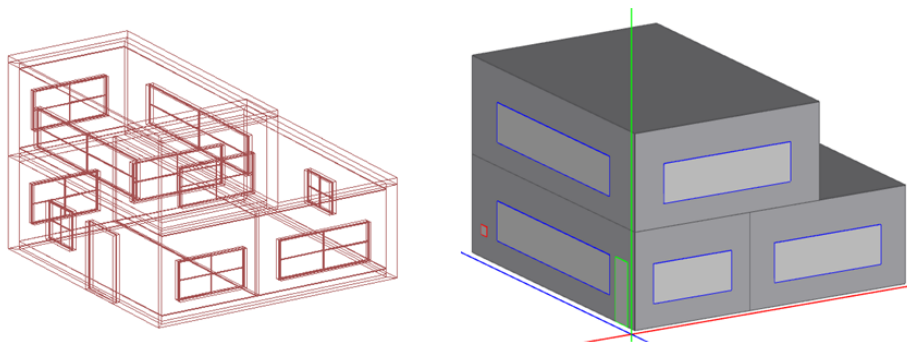
Figure 4.3: CHAMPS-Multizone simulation case building

4.4.1 Energy simulations and benchmarking

The building is simulated at Syracuse, NY weather conditions and one summer day's simulation results for the West zone of the case building is selected and compared with the same building simulated by EnergyPlus. Typical light weight construction is used as building envelope model. The simulation results are plotted in figure 4.4 and very good match is found between CHAMPS-Multizone results and EnergyPlus. The small error at low heat load in morning time is potentially caused by: 1) the variant from solar radiation model output between CHAMPS-Multizone and EnergyPlus; 2) the different solving methods CHAMPS-Multizone and EnergyPlus use to solve long wave radiation as section 3.2.4 indicated.
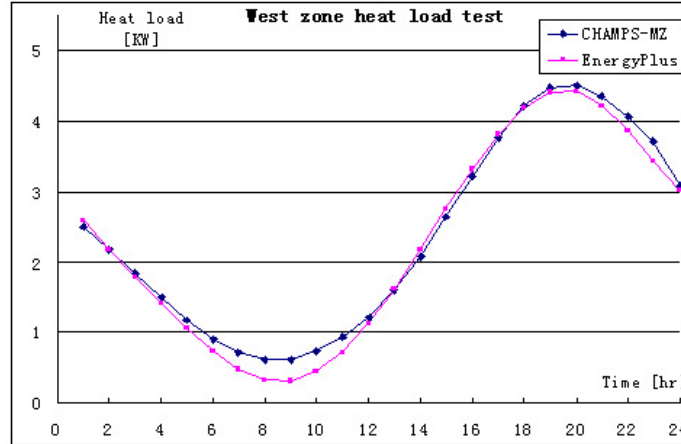
Figure 4.4: CHAMPS-Multizone and EnergyPlus Heat load simulation results

To compare long-term dynamics of building energy performance, an one-year simulation is conducted by using the same building building model. The zone on the 2nd floor as illustrated in Figure 4.3 is selected and its heat load is simulated in CHAMPS-Multizone and EnergyPlus. To better compare the simulation results, one month (July) is selected from one year simulation results. Since CHAMPS-Multizone and EnergyPlus use different weather file formats, to convert and create one single weather file for both program is needed to eliminate errors from climate conditions. Figure 4.5 shows different climate conditions between CHAMPS-Multizone and EnergyPlus's weather files. Since CHAMPS-Multizone doesn't provide weather file conversion tool, an approach to convert CHAMPS-Multizone climate files to EnergyPlus is developed. The general weather file conversion work flow path is given in Figure 4.6. Both path 1 and 2 can achieve to convert CHAMPS-Multizone climate files (*.ccd format) to EnergyPlus weather file (*.epw format). For middle layer weather file format conversions, NREL TMY3/TMY2 weather file conversion tool (*NREL*, 2010a) and EnergyPlus weather file conversion tool is widely used.

The heat load simulation result comparison between CHAMPS-Multizone and EnergyPlus is shown in Figure 4.7 and Figure 4.8. We notice that certain errors exist

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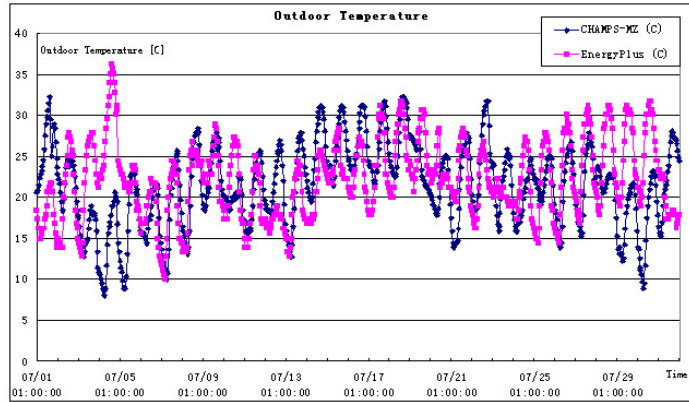
(a) temperature
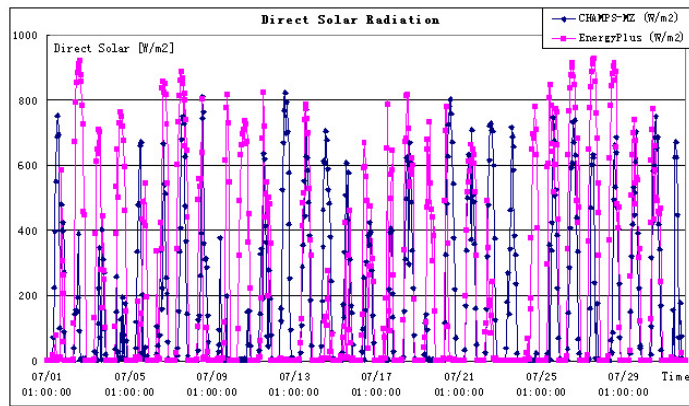
(b) direct solar radiation
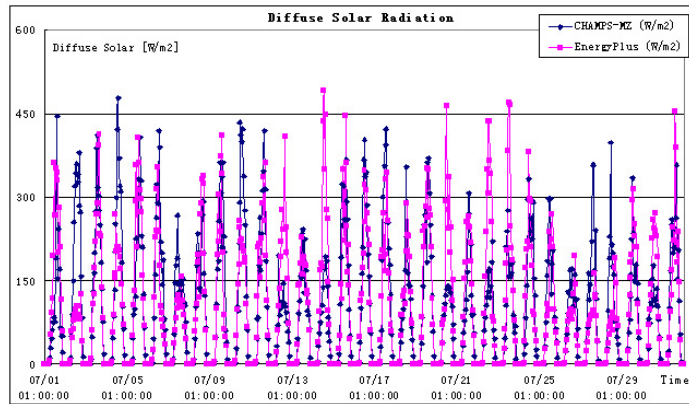
(c) diffuse solar radiation

Figure 4.5: Climate conditions comparisons between CHAMPS and EnergyPlus
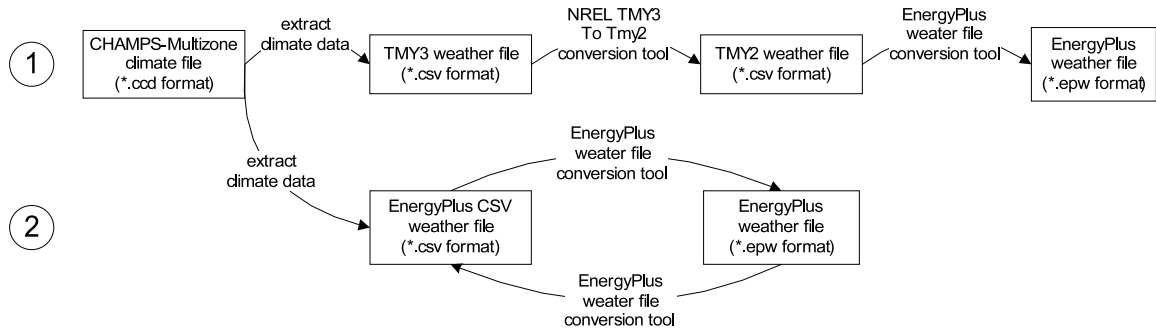
Figure 4.6: Weather file conversion work flow path

between CHAMPS-Multizone and EnergyPlus simulation heat load calculations especially on peak heat load prediction. The difference are mainly caused by the heat balance method when taking window solar radiation calculation into account. In general, two simulation programs predict similar heat load trend where the maximum zone heat load is around 5.6kW. Another potential reason of causing the difference is that CHAMPS-Multizone uses slightly different way to treat convective heat transfer coefficient calculation compared with EnergyPlust. This difference has been discussed in Figure 4.4 for one day simulation results.
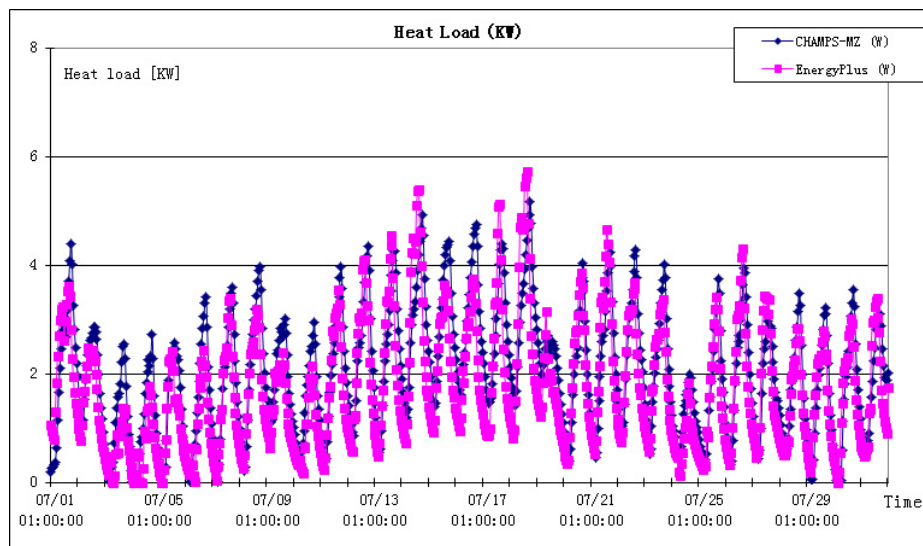
Figure 4.7: One month heat load simulation
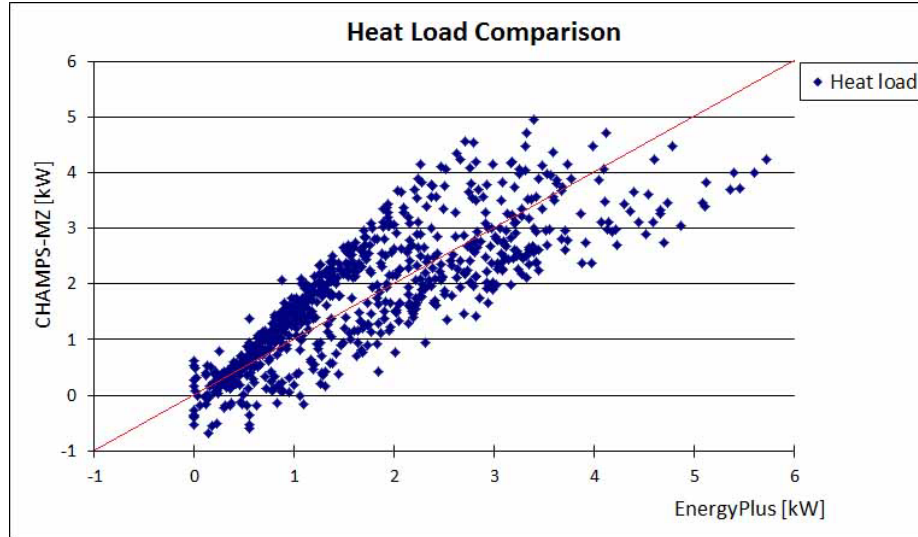
Figure 4.8: One month heat load comparison

In order to further validate CHAMPS-Multizone model and diagnose model's difference with other well-established building energy simulation programs, we perform ASHRAE 140-2007 standard case test and compare CHAMPS-Multizone results with EnergyPlus. Since CHAMPS-Multizone has a simple HVAC air loop model, the validation study is only made by applying ASHRAE 140-2007 building envelope cases especially Case 600 for low mass envelope building and Case 900 for high mass envelope building. The validation simulation cases are listed in Table 4.1.

Table 4.1: CHAMPS-Multizone ASHRAE 140-2007 Test Cases

Case name	Descriptions
600 w/o window	low mass envelope w/o windows on South side wall
600 South windows	low mass envelope w/ windows on South side wall
620 East & West windows	low mass envelope w/ windows on East & West walls
900 w/o window	high mass envelope w/o windows on South side wall
900 South windows	high mass envelope w/ windows on South side wall
920 East & West windows	high mass envelope w/ windows on East & West walls
600FF w/o window	low mass envelope w/o windows free floating temperature
600FF South windows	low mass envelope w/ windows free floating temperature
900FF w/o window	high mass envelope w/o windows free floating temperature
900FF South windows	high mass envelope w/ windows free floating temperature

To accommodate CHAMPS-Multizone simulation needs, all cases room thermostat temperature setpoint is 22^oC for the whole year. And to evaluate window's influence, for each 600 and 900 series case, another without window case is created by keeping case's other parameters the same. For free floating room temperature cases, we use the same building geometry as Case 600 and Case 900 have for conditioned space test. Since CHAMPS-Multizone does not provide weather file converter, a Central NY weather file is created by converting CHAMPS-Multizone weather file format to EnergyPlus weather file (EPW) following weather file conversion work flow path given in Figure 4.6. All other case settings are exactly same with ASHRAE 140-2007 standard.

Basically, ASHRAE 140-2007 gives two type of validation methods. The first one is conditioned space testing, by comparing different programs' cooling and heating energy. Another is unconditioned space testing, where air conditioning systems are not available for testing rooms or building, and rooms temperature are allowed to fluctuate (also called Free Floating, "FF"). In conditioned space cases, annual cooling and heating energy, as well as peak cooling and heating rate are compared; while in free floating cases, zone maximum and minimum temperature are compared. *ANSI/ASHRAE* (2007) gives detailed descriptions on testing cases and their setups. Figure 4.9 gives conditioned energy cases results comparison between CHAMPS-Multizone and EnergyPlus. And Figure 4.10 gives free floating cases maximum and minimum temperature comparison.

From the comparison, it is found that, CHAMPS-Multizone gives very similar annual heating, cooling energy and peak heating, cooling rate compared with EnergyPlus. The results match better at w/o window cases. In with windows cases, CHAMPS-Multizone tends to give slightly higher prediction of energy consumption compared with EnergyPlus. Similar results can be found in free floating temperature test cases. The main reason is that CHAMPS-Multizone models windows in different ways from

(a) Annual heating energy comparison

(b) Annual cooling energy comparison

(c) Peak heating energy comparison

(d) Peak cooling energy comparison
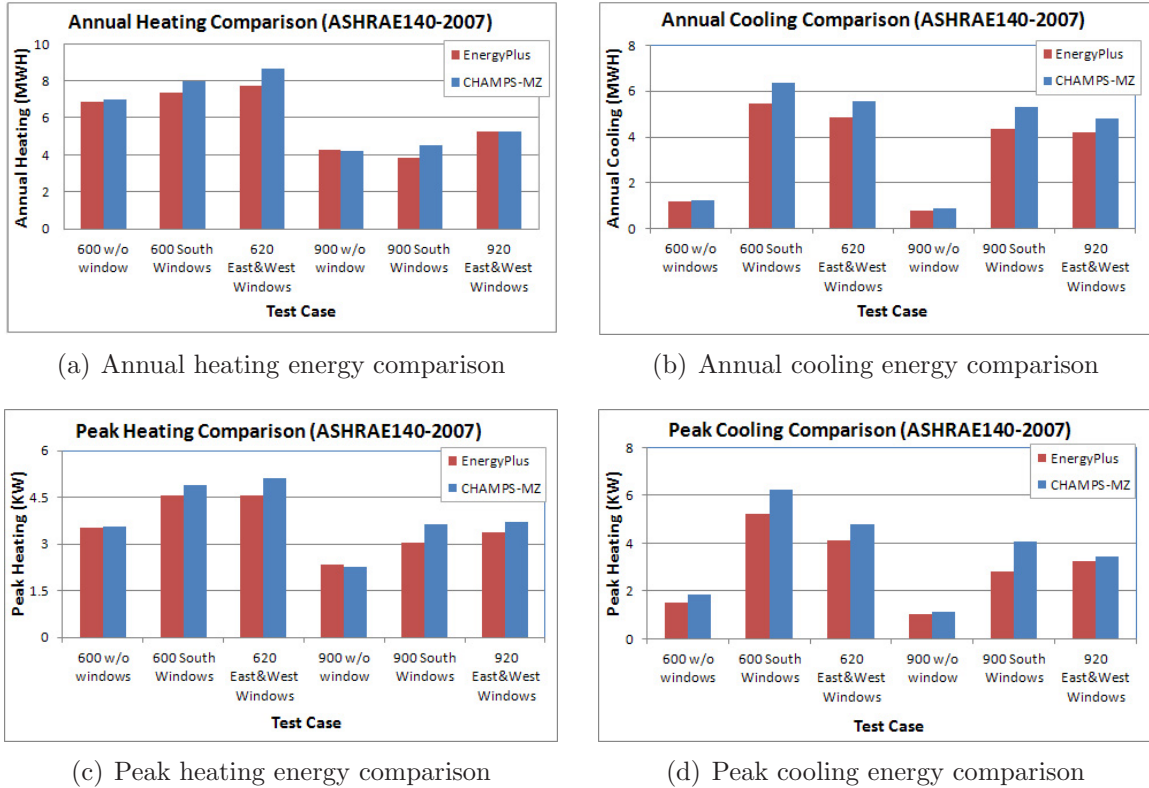
Figure 4.9: ASHRAE 140-2007 Conditioned Energy Comparison

EnergyPlus. CHAMPS-Multizone adopts the empirical window model which gives the conduction heat loss/gain through window as a temperature driven phenomenon by multiplying the indoor and outdoor temperature difference by window's U value; while the radiation heat gain is calculated by applying window system's SHGC. The total window system heat gain is given by Equation (3.39) Where U is window's U value, Aof is window projection area; is incidental solar irradiance. On the contrast, EnergyPlus uses detailed window pane balance method (EnergyPlus development team 2010). However, the difference is within the acceptable range (the maximum difference between CHAMPS-Multizone and EnergyPlus is 12% for peak load cases, and 3 ^oC for free floating temperature case) when contrasting EnergyPlus with other simulation software ASHRAE 140-2007 test results, in which the maximum difference between the other models and EnergyPlus is 15% of peak load and 5 ^oC for free
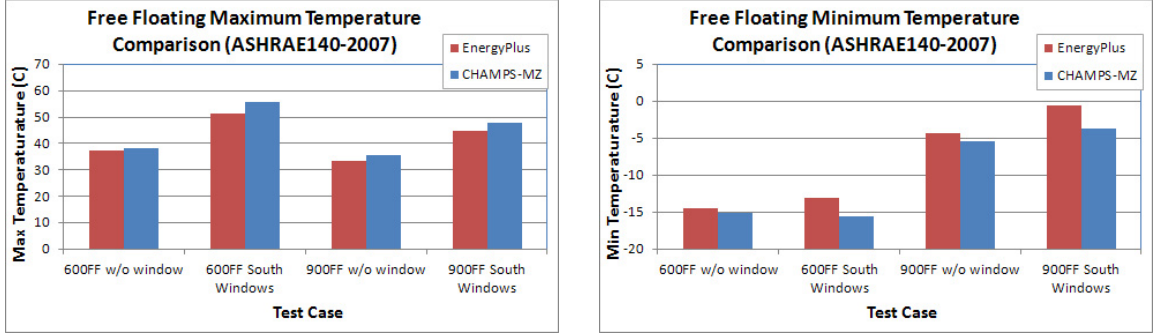
(a) Maximum free floating zone temperature (b) Minimum free floating zone temperature

Figure 4.10: ASHRAE 140-2007 Free Floating Zone Temperature Comparison

floating cases (*Henninger and Witte*, 2010).

4.4.2 Moisture transfer through building and latent heat load

To evaluate the moisture transport through building envelope and its impact on building latent load, a test case is built in CHAMPS-Multizone integrated with CHAMPS-BES. The test case building is a single zone 100 m^2 building. The building envelope is a single layer 0.1 m thick brick wall, and its material property is shown in Table 4.2. The building has concrete slab and roof with moisture insulation material and only heat transfer through building roof and slab is simulated in this case. The building's internal heat load is 3 W/m^2 for lighting and 5 W/m^2 for internal plug load. The convective heat transfer coefficient is 25 W/m^2 for the exterior surface and 3 W/m^2 for the interior surface. The moisture mass transfer coefficient at building envelope exterior and interior surface are 0.01 and 0.00306 m/s respectively. And we use Central NY climate conditions, and the room conditions controlled at 23 ^oC and RH of 50%. To simplify our calculation, the solar radiation is turned off in CHAMPS-Multizone and CHMAPS-BES. In this study, we use the loose integration method described in section 4.3.1 to calculate heat and moisture transfer through building envelope and sensible and latent heat load in CHAMPS-Multizone. The room's sensible and latent

Table 4.2: Brick wall material properties in a dry-basis condition

Property	Brick wall
$\rho[kg/m^3]$	1900
$\lambda[W/mK]$	1.11
$C_p[J/kgK]$	920
Open porosity	0.29

heat load is shown in Figure 4.11. Since the building envelope is a single layer brick
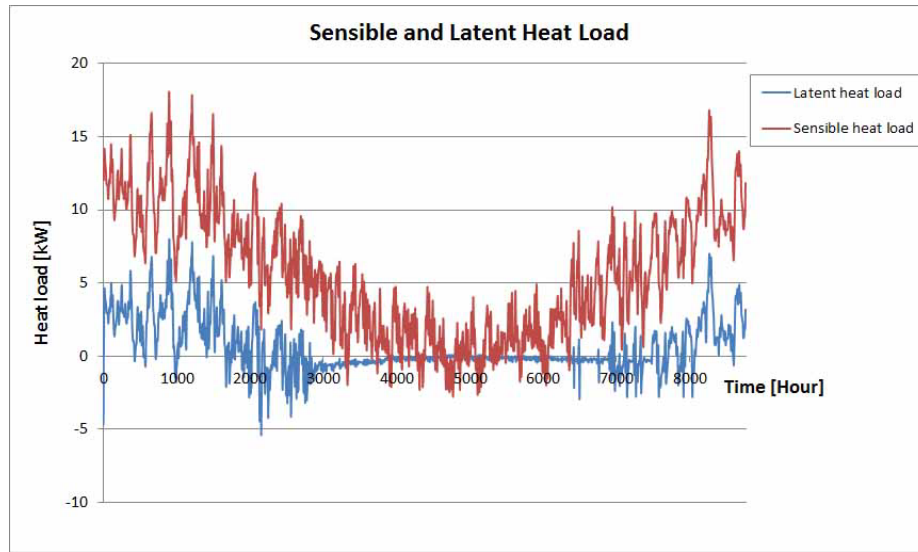
Figure 4.11: A Case Building Sensible and Latent Heat Load

wall, the low ambient temperature in winter causes large heat loss through building envelope and condensation happens at the wall's interior surface. Thus, large latent heat load and moisture removal is observed in winter time. During the summer season, the sensible and latent cooling load is relative small compared with heating load. It is noticed that the latent heat load can reach as high as about 30% of the total heat load.

Because CHAMPS-BES and CHAMPS-Multizone both can calculate heat transfer through building envelope, but using different methods, another test is conducted to use the same case building model and calculate building's sensible heat load.

Figure 4.11 shows the relationship between integrated CHAMPS-BES method and CHAMPS-Multizone CTF method calculation results. Two methods generally agree with each other. The difference between the two methods is mainly caused by long wave radiation energy exchange and view factor among different interior surfaces. When integrating CHAMPS-BES, it is difficult to have all BES walls to calculate long wave energy exchange simultaneously.
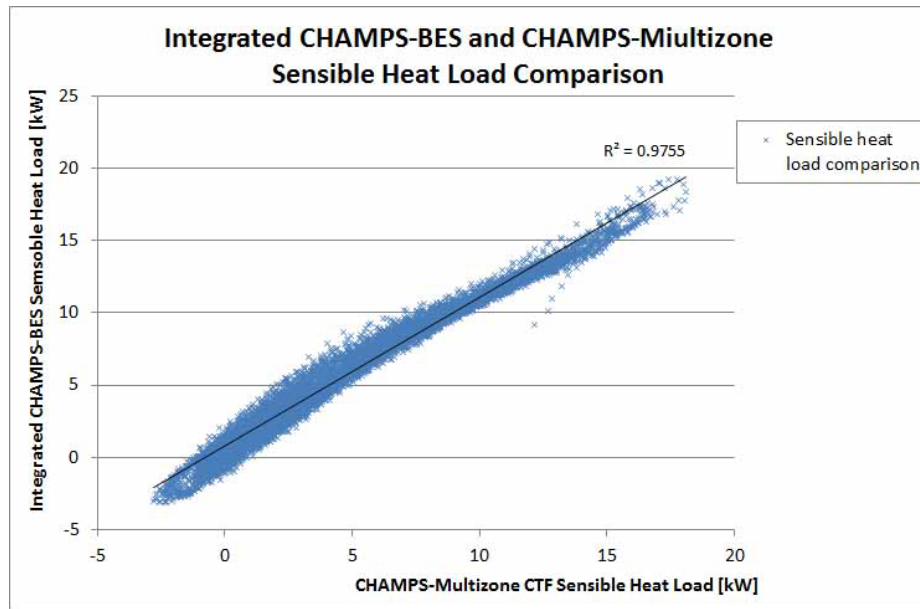
Figure 4.12: Sensible Heat Load Comparison

4.4.3 Combined Heat and IAQ simulation

To evaluate CHAMPS-Multizone's capability to conduct combined heat and IAQ simulation, the case building is setup to have the zone at 2nd floor emit VOC pollutant (e.g. from Carpet or furniture) at the rate of 1mg/s. Since all three zone are conditioned by one air handling unit. The return air of 2nd floor zone, mixed with Outdoor Air (OA) will be redistributed to zones in the 1st floor through the centralized AHU. The AHU is configured as Variable Air Volume (VAV) system which change the supply air volume to compensate the zone's heat load. The OA intake of the AHU is

111

clean air and does not have TVOC contaminant. The building is simulated in one summer day with 20% OA supply and each zone's energy and TVOC concentration is plotted in Figure 4.13 It is found that the lowest heat load of building happened

(a) zone energy simulation results

(b) zone IAQ simulation results
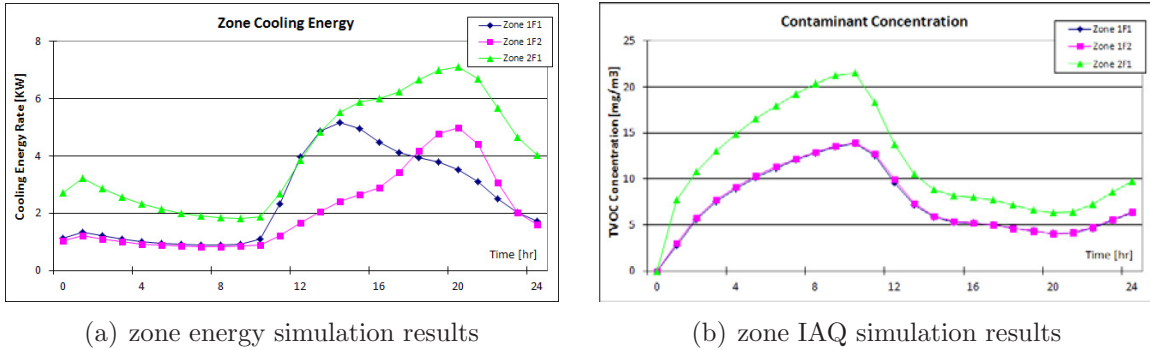
Figure 4.13: Case building's energy and IAQ performance with 20% OA

(a) 2nd floor room energy simulation results

(b) 2nd floor room IAQ simulation results
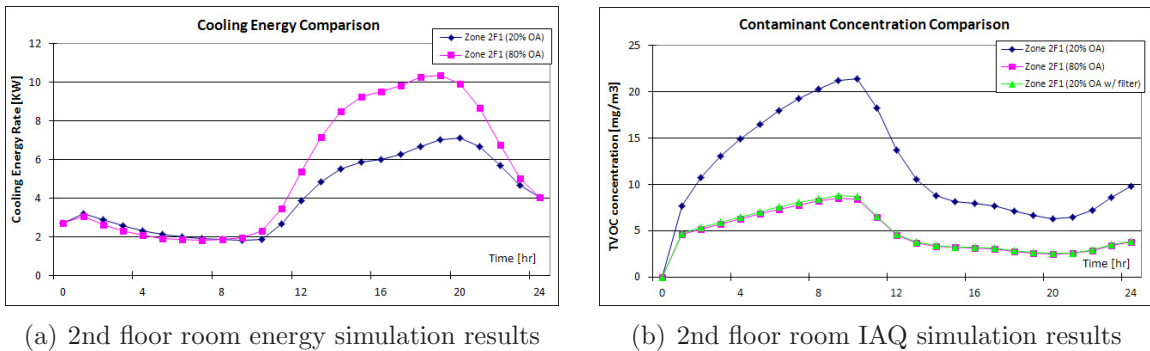
Figure 4.14: Case building's energy and IAQ performance with different OA ratio

around 9:00am in the summer day morning. And the AHU runs at very small supply air flow rate. The dilution effect is very small at this time which means contaminant removal effect is also very small and TVOC keeps accumulating in zones. And that is the reason high TVOC concentration is observed at early morning time. After that time, the building heat load increases, more air conditioning energy is needed to input to zones and AHU supply air flow increase. The contaminant concentration dilution effects increase and a decreasing TVOC concentration is observed at three zones. It is also found that the zones in the 1st floor TVOC concentration is changing with

112

similar pattern of 2nd floor zone but have relative lower concentration values. This is because the contaminant is redistributed, through the AHU, from the zone at 2nd floor to zones at the first floor.

To improve the building's IAQ performance, a simple way is to increase the OA ratio and thus increase the contaminant dilution effect. Another simulation is conducted by changing OA ratio to 80% (return air ratio is 20%). The building is simulated at the same summer day and results on the zone at 2nd floor are shown in Figure 4.14. Compared with the 20% OA case, 80% OA case provides more fresh air and thus improve the IAQ by diluting the TVOC concentration in the zone. However, higher energy consumption is observed caused by conditioning high volume of hot air. A better solution to improve IAQ is to install air filter at AHU's supply duct. In this case, a filter with TVOC removal efficiency of 70% is mounted and the simulation results show significant improvement of IAQ which decreases the TVOC concentration to the similar level of using 20% OA ratio. On the other hand, there is less energy penalty imposed by using filter.

Another heat and pollutant coupling application study is to investigate the relationship between solar radiation gain or heat transfer triggered a interior construction surface temperature increase and relevant construction surface material VOC emission (e.g. carpet). The emission of VOC is related to material temperature. The proper control approach, for example to use window shading device to control direct solar radiation penetrating through exterior window and imposing on the interior surface of floor carpet, of interior surface heat gain and temperature rise can not only reduce indoor pollutant emission and improve building IEQ, but also decrease building's heat load and reduce the amount of energy for air conditioning as well as ventilation due to indoor air quality improvement.

4.5 Summary of Numerical solution of CHAMPS-Mutlzione

The numerical methods to solve CHAMPS-Mutlzione models are discussed in this chapter. The basic Gear-type formulas are given and the solution algorithm is described by following a "prediction and correction" process. The SUNDIALS::CVODE is a numeric solver package implemented based on Gear-type formulas. CHAMPS-Multzione numeric solution is achieved by applying the SUNDIALS::CVODE solver package. To implement the CHAMPS-Mutlzione solvers, various numeric aspects are considered through the implementation. In this study, the selection of solution variables, convergence criteria, the construction of Jacobian matrix and adjustment of solver order and time step is particularly discussed.

The whole building solution is achieved by integrating multiple solvers together effectively and efficiently and exchanging solution variables dynamically. A "Ping-Pong" style integration method is formulated by specifying variables interfacing among building envelope (CTF model), zone, HVAC and airflow solver schemes and take energy, moisture and pollutants properties into account simultaneously. Finally, case simulations are conducted, and CHAMPS-Multizone its capacities, in terms of energy and IAQ simulation, are calibrated and compared with EnergyPlus and CONTAM respectively. CHAMPS-Multizone generally produces good simulation results when compared with EnergyPlus under ASHRAE 140 test cases. To demonstrate combined heat and IAQ simulation, a two-floor three-zone case is setup by using different HVAC supply outdoor air ratio. It is observed that low outdoor air ratio (20%) will cause high indoor contaminant concentration because of lack of air change; while high outdoor air ratio (80%) can improve indoor air quality but produce high energy penalty by conditioning outdoor air. An good solution is to apply air filtering technology to filter indoor pollutants and at the same use low outdoor air ratio to achieve high performance on building's both energy and IAQ.

CHAPTER V

Virtual Building, a new BIM method for whole building modeling and performance monitoring

Virtual Building (VB) is a digital representation of building information that includes building geometry, building materials and envelope, building equipments, and real-time building performance.

5.1 Virtual Building Concept

The term "Virtual Building" originally comes from Graphisoft, a Hungarian company, who used this technology in its software ArchiCAD. The original idea of VB is to design a way for building information representation and thus facilitate architectural design and engineering. The concept of Virtual Building for simulation and monitoring is originated by *Kato et al.* (2008) and initially used for building fire security simulation. It uses Object-Oriented Database (OOD) to store building information digitally in hierarchy structure. Later, this approach is extended to the development of a real-time indoor and urban environmental monitoring system, including a new and expanded primary database structure implemented in a web-base database program, interaction modules between the main database to sub-databases that directly obtain data from various type of sensors sensor network, or from the building energy

management system (*Feng and Zhang*, 2009). At each level of the primary database structure, different building indoor and outdoor monitoring parameters are defined and categorized. The Virtual Building concept can be summarized as Figure 5.1 shows. The static building information (e.g. materials, geometry) can be transfered
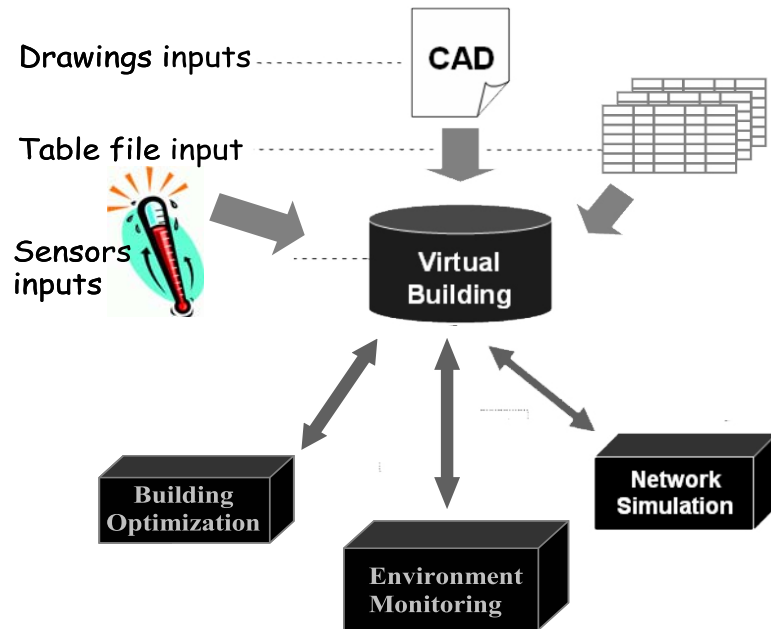
Figure 5.1: Virtual building data transfer schematic

via CAD files or data tables definitions to central Virtual Building database. The static data will provide the general frameworks of the building which provide information such as the geometrical description and shape of the building, the construction materials used in the building, the environmental systems and equipments in the building and so on. Dynamic sensor measurement data can also feed into Virtual Building central database, and reside within the frameworks of static building structure. The dynamic data will record building's real-time indoor environmental quality, outdoor conditions, environmental systems, equipments operation and performance and so on. The real-time measurement data from Virtual Building platform can be used for building performance monitoring and diagnostics. Both static and dynamic

data can be transfered to simulation programs to conduct server-based simulation and compare simulation results with building's real performance. It can also be used for building design and operation optimization study.

5.2 Virtual Building Modeling Structure

To model a whole building's information and then measure its performance, a well-organized modeling structure is needed to keep various building information in proper order. The study of Building Information Modeling (BIM) came into place in efforts to create a collaborating and integrated information management and data interoperability system. The original purposes of BIM research is to facilitate data exchange among, civil, structural, architectural, mechanical, and electrical design team and maintain the coordinations in building construction. Several BIM standards (*Eastman*, 1999; *Eastman et al.*, 2008) are developed to enhance building data interoperability. However, most of the applications of existing BIM technologies are served for building designs and construction management purposes. The increasing needs of building performance analysis and simulation and building performance monitoring require to use BIM method to boarder aspects that not only capable of represent the static design information (e.g. geometry, materials) but also to

- provide a common structure used for building performance simulation programs (CHAMPS-Multizone) and exchange data with other simulation platforms and design tools

- store long-term building performance in hierarchical structure and represent building's real-time performance

- enable comparison between monitoring data and predicted performance at the design stage or expected performance to identify possible reasons for discrepancy

Virtual Building is a new BIM method to model whole building's information used for performance simulation and real-time building performance monitoring. The initial data structure is further modified into a hierarchical structure (*Feng and Zhang*, 2009) to accommodate not only the needs of simulation programs to store a whole building's

data, but also capture and audit the temporal building behaviors after building's occupancy.

5.2.1 Virtual Building Hierarchical Structure

The Virtual Building structure for whole building modeling is given as Figure 5.2. The hierarchical structure is represented in different levels. The idea is to map a
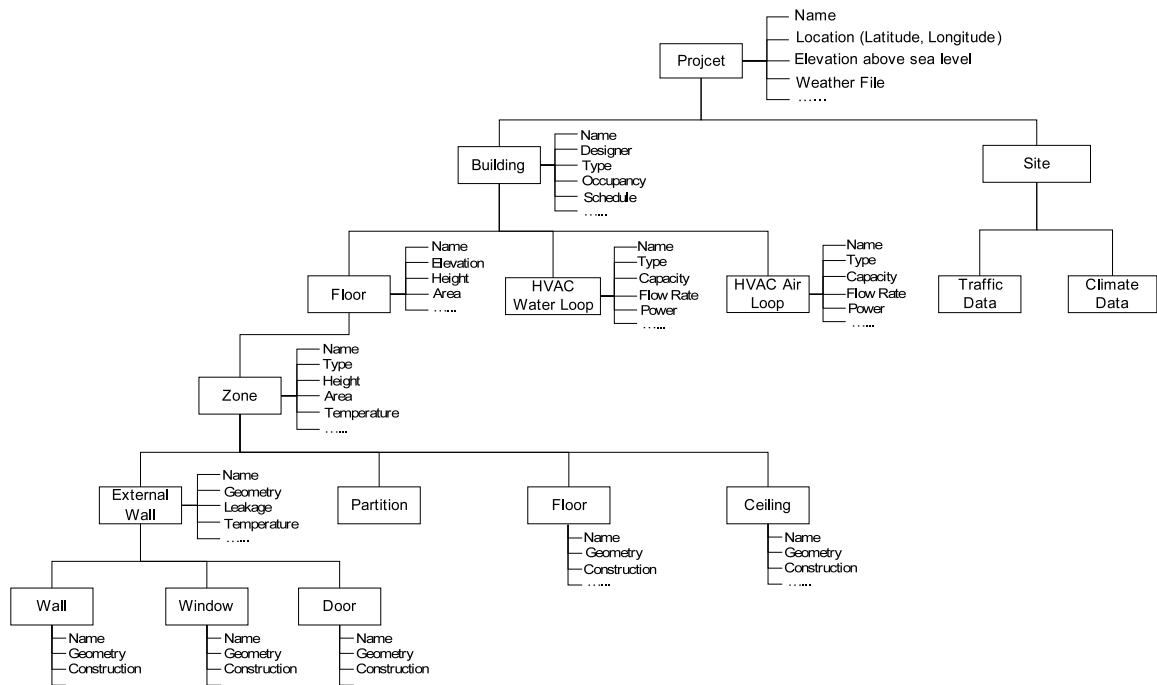
Figure 5.2: Virtual Building Data Structure

common structure to an Object-Oriented Design that can be easily implemented through software engineering approaches and create software models. Each level has corresponding classes with certain properties which could generate project objects to represent certain building components information. Two basic data types are considered in virtual building data structure:

- Static (time-independent) data including object name, type, floor areas etc. are used to identify different object at different level.

119

- Dynamic (time-dependent) data are data for specific monitoring purposes and represent building temporal behaviors.

Project level holds information with detailed project description. Information in this level will be useful to associate with specific weather files used for simulation or monitoring benchmarking. In this level, most of data we store are static data for project description.

Site level is designed to describe building outdoor environment and ambient conditions. The objects created in this level contain traffic description, the activities of neighborhood etc.

Several dynamic sub-levels classes are created under Site level. "Climate Data" is the class that holds urban monitoring information. Real-time outdoor data like temperature, RH, wind direction, wind speed, solar radiation, precipitation etc. are stored as objects in this class. Data are transferred from case building's weather climate monitoring system to virtual building central database through a real-time transfer bridge. Traffic level is used to describe traffic information as well as pollutants transportation phenomena. Since most of buildings in urban area are very close to highways, to study the relationship between highway traffic activities and building performance, traffic data is worth of storing in virtual building. In this case highway traffic volume, traffic speed and traffic (automobile) type are monitored in real time basis. Similarly, real-time data transfer bridge is developed to transfer data from traffic database to virtual building database (as to be discussed for the case building in this study).

Building level represents building object(s) in current project site. Static Data are associated with certain building(s) to describe building(s) information. We further split Building intro several sub-levels. Floor level represents floors in a building. Geometrical static data can be useful when generating building model for energy/environmental simulation. HVAC level is added especially for this study purpose to

consider dynamic data of HVAC system of the building. Here, we are more interested in the air side of HVAC system (particularly Air-Handling Unit) to see how urban (outdoor) environments interact with built (indoor) environments through AHUs. Therefore, parameters related to this indoor-outdoor interaction need to be measured to catch the dynamic interaction. These parameters include AHUs' inlet temperature, RH, pollutants (CO_2, particles etc.) concentrations. Several dynamic data points related to AHU's performance are captured by accessing the Building Management System (BMS) database. These parameters include system fresh air flow rate, supply/return/exhaust air ratio, and the air state properties when passing through each air conditioning equipment (e.g. coils, fans). BMS data is transferred and stored in Testbed database in accordance with the same sampling interval of air quality sensors' data.

HVAC water loop systems are also modeled in virtual building structure. The "HVAC water loop" class contains the model of different water loop systems including chilled water loop, heating water loop, condensing water loop etc. Static data is used to describe water loop's design features such as, design supply water temperature, return water temperature, design supply water flow rate. The static information can be transfered to performance simulation programs. The measured dynamic data is also collected for HVAC water loop systems. Typical measured data includes systems' heating/cooling rate, supply water temperature, return water temperature, energy consumption etc. Specific water loop equipment such as heat pumps, boilers ect are also modeled and considered as a sub-level of one water loop system. Equipments' static data and measured dynamic data are also collected similarly as "HVAC water loop" class is modeled. Figure 5.3 shows the part of the structure and some modeling properties for HVAC water loops and equipments. Dynamic data is shown in highlighted blocks while static data is shown at the right side of each class.
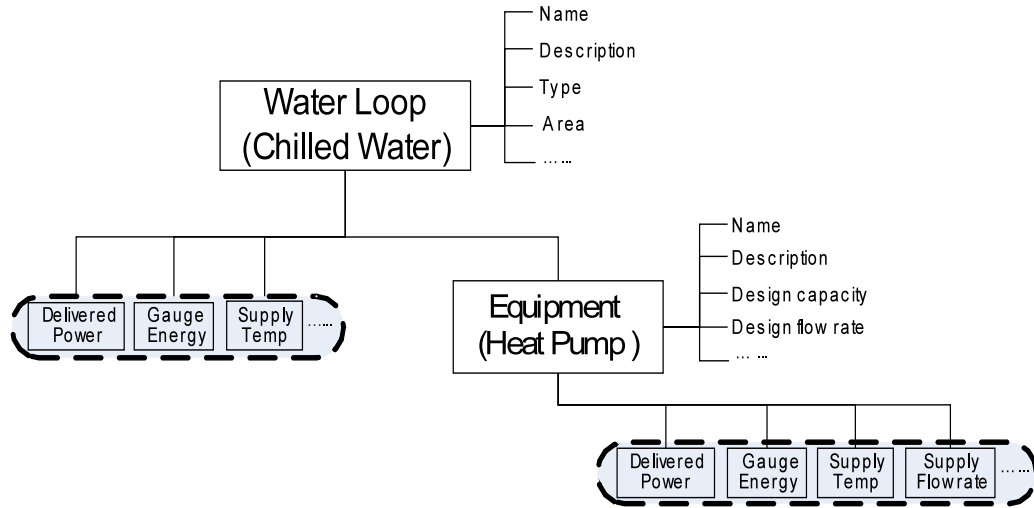
Figure 5.3: Virtual building water loop modeling schematic

Zone (or Room) level is a level below the Floor level. From simulation point of view, zone is a basic cell in one building, which hold unique built environment information. Certain static data is needed to describe Zone information, such as area, volume, designed maximum occupancy level etc. Measurement dynamic data is also configured to be associated with zones to represent zone conditions such as temperature, RH, CO_2, TVOC, etc. The data can be obtained from object building's BMS system or can be measured by using various sensors and transfer data to virtual building central database.

Building construction assemblies are modeled to associate with Zone level. Construction assemblies carry the geometry information which represents the shape and layers of materials of the construction assembly. The association of all construction assemblies with a zone will give the zone's geometry. Similarly, the floor and building's geometry can be determined through object association relationship. Construction assemblies also refer to one or multiple materials and the aggregation of one or more materials create one construction assembly. The physical properties of each material is utilized by one construction assembly through the reference. And hence, the physical transfer (e.g. heat transfer) properties of one construction assembly can be

easily obtained by calculating the combined effects of all reference materials. Dynamic data measuring construction assemblies performance can also be associated under construction assembly level. The data includes one constriction assembly's surface temperature, RH, cross wall assembly pressure difference etc.

5.2.2 Implementation of Virtual Building structure

The virtual building structure introduced in section 5.2.1 is translated into an Object Oriented Design structure and further defined in Unified Modeling Language (UML) and implemented in an OOD environment. An object-oriented database called "Cache" (*Intersystems*, 2010) is chosen as the centralized database to host projects information. Cache maintains each class defined in virtual building framework in a table way that standard SQL commands can be use to query data in very efficient manners. When implementing virtual building system, it is necessary to keep its structure consistent with CHAMPS-Multizone simulation program structure to make future data transfer between virtual building platform and CHAMPS-Mlutizone possible. This can also enable virtual building system to share software modules CHAMPS-Multizone and facilitate development.

Static building geometry, materials and various information are fed into virtual building system through a special data transfer bridge implemented in C++. The data transfer bridge can read results from building modeling programs (such as Design-Builder, Google SketchUp) and import the static information. Dynamic data is obtained through different sources as illustrated in Figure 5.4.

The first path is Building Management System (BMS) which collects data measured by sensors installed on different building systems. Virtual building can "talk" to BMS either through network communication, database dialog or data file transfer method. Wireless sensor network is widely used in this research to collect room and
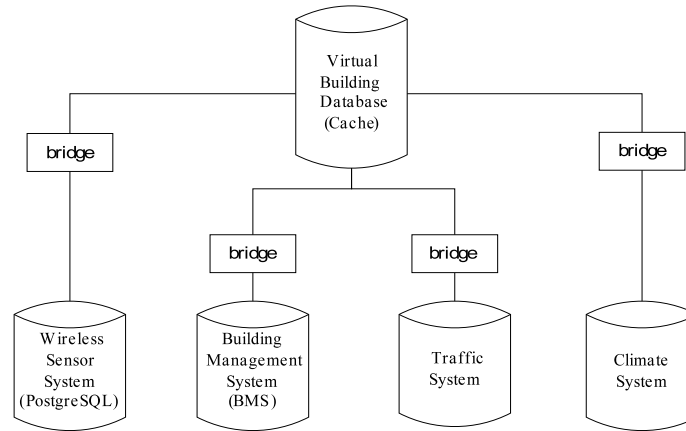
Figure 5.4: Virtual building data transfer schematic

building envelope information. The wireless sensor which is also called "Mote" can be easily integrated with other sensors and deploy in the case building. Section 5.3 will introduce wireless sensor integration methods. Other possible data sources such as traffic, ambient pollutants, information can also be integrated into virtual building database through respective "bridges".

5.2.3 Graphical User Interface (GUI) development

To help users to access Virtual Building central monitoring system, a web-based user interface is developed to

- provide a web-based user interface for browsing building's performance in different categories

- give users the ability to download the selected data set for their different research purposes

- administrate and maintain the Virtual Building to assure data's integrity and users' privilege and accessibility to the database.

124

Since a web-based user interface is needed, Java language and development platform is selected because of its flexibility to embed applications in webpages. A Java project is structured in NetBeans IDE (*NetBeans*, 2010). The communication principles between Virtual Building Cache database engine and Java is illustrated in Figure 5.5 where Cache will generate a set of Java classes called "Proxy class" and these classes can maintain communication and exchanging data with Cache database during system run time. The design of Virtual Building user interface is achieved by separating the
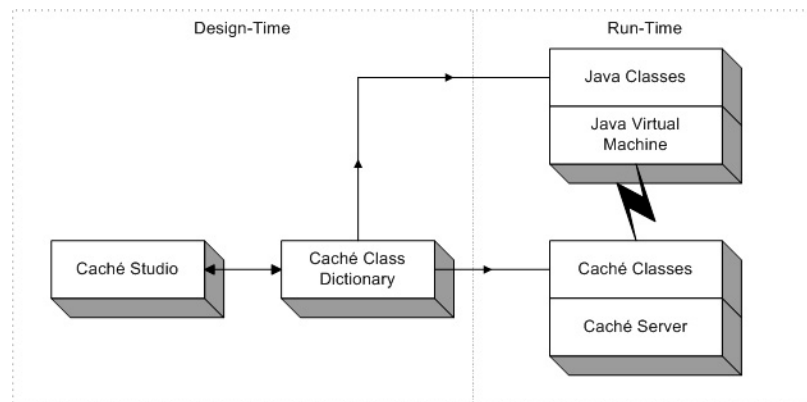
Figure 5.5: Cache Java binding schematic (*Intersystems*, 2010)

Java user interface into three modules:

- Cache proxy classes

- Cache query classes

- Java graphical user interface classes

Each of these three modules maintains its own function and interacts with other modules or platforms as Figure 5.6 illustrated. The proxy classes which are mainly generated by Cache itself contain the basic communication methods which enable Java programs to connect with Cache database and exchange data; the Cache query classes contains commands to query Virtual Building Cache database engine, through the proxy classes; the queried data will be eventually passed back to the graphical

user interface classes for users' display and download purposes. On the other hand, users' commands will be sent from the user interface classes and then trigger query classes. The query class will execute the query commands and get data from Cache database.
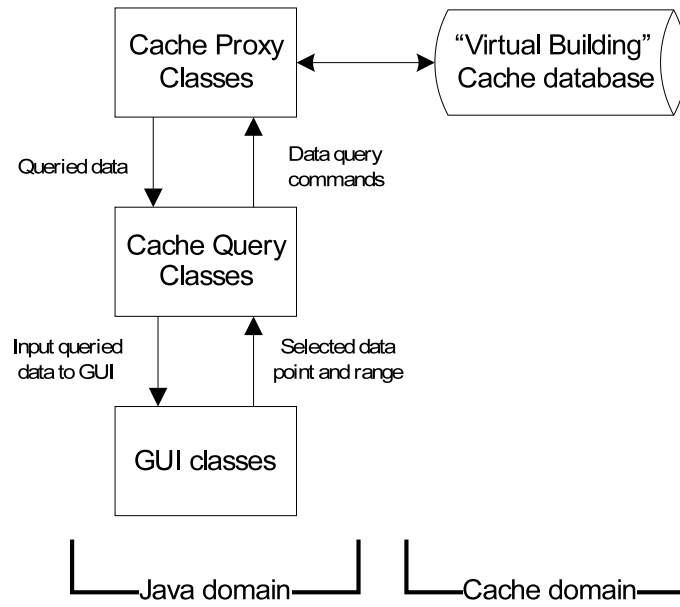
Figure 5.6: Virtual Building Java user interface modules

To map Virtual Building's hierarchical structure into visible user interface, the proxy generated proxy classes in Java domain must keep the same hierarchy as Virtual Building itself defined in Cache database. This will enable the Java user interface module to display the hierarchical structure as the way Virtual Building has. The hierarchical structure is implemented in Java tree structure and an monitoring example is given as Figure 5.7 illustrates. The user interface tree structure represents Virtual Building's hierarchical structure and display building's information in a tree view. One can easily expand the tree branches and browse each building components information. When clicking on certain building monitoring point node, the corresponding building performance curve will be plotted on the left hand side chart viewer region. The user interface menu provides the function that one can download or save plotted

data. The control buttons in the bottom can help users better manage the plotted chart and organize different building performance variables. Figure 5.7 shows an monitoring example of climate outdoor air temperature verse one room indoor air temperature.
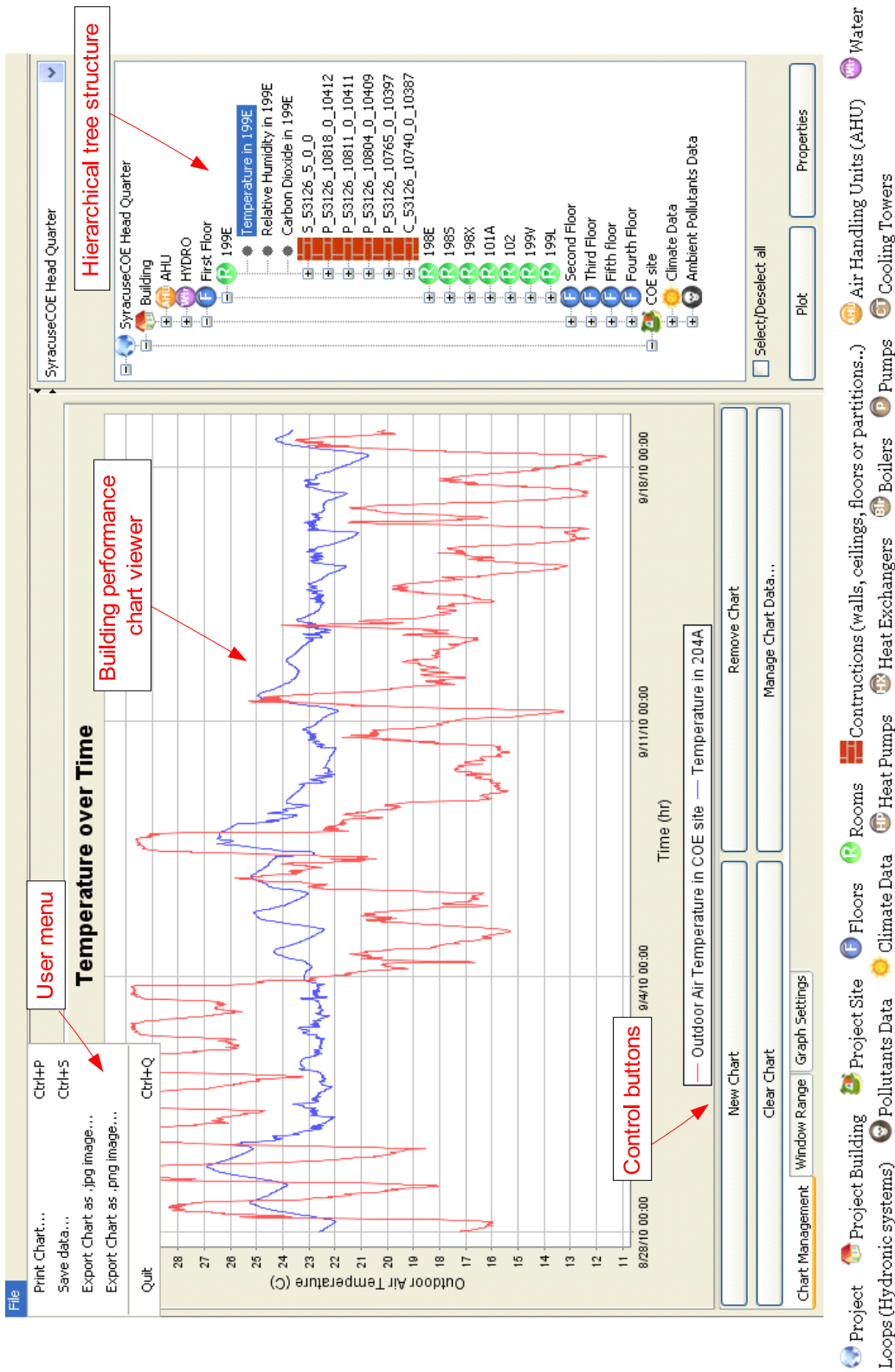
Figure 5.7: Virtual Building user interface

5.3 Wireless sensor monitoring system

To measure the whole building's performance, various sensors need to be deployed in different building locations and collect real-time building performance data. The sensors include, but not limit to

- Room(zone) based dynamic performance such as temperature, RH, CO2, TVOC or individual VOCs etc.;

- HVAC air loop systems and equipment performance such as supply/return air temperature, RH, flow rate before and after different air loop equipments (fan, coil, filter, damper etc.), air loop equipment operation and energy consumptions.

- HVAC water loop systems and equipment performance such as supply/return water temperature, flow rate before and after different water loop equipments (pump, coil, chiller, heat pump etc.), water loop equipment operation and energy consumptions, and overall delivered system (cooling/heating) delivered energy.

- Climate conditions such as outdoor temperature, RH, wind speed, wind direction, solar radiation etc.

- Building envelope performance such as boundary surface temperature, RH, cross building envelope pressure difference etc.

- Building ambient pollutants conditions

- Building ambient traffic conditions

Various systems are involved in collecting sensor measurement data as Figure 5.4 illustrated. While some sensors are already included in Building Management Systems, other sensors can be customized and deployed for research purposes. It is found that

wireless sensors and sensor network can greatly decrease equipment deployment time and labor cost by cutting down the work involved in data logger installation, sensor cabling etc.. The wireless sensor network also has the flexibility for removing and relocating sensors when necessary.

The wireless sensor "Mote" is selected as the basic node of wireless sensor network (*Koni et al.*, 2009). The IRIS "Mote" sensor can communicate within the band of 2400 MHz to 2483.5 MHz and is IEEE 802.15.4 compliant. It can also inter-relay to each other and all sensors' wireless signal can be transfered to wireless sensor database (Postgre SQL) through a local gateway. The wireless sensor monitoring network is illustrated in Figure 5.8. Environmental sensor boards which can measure
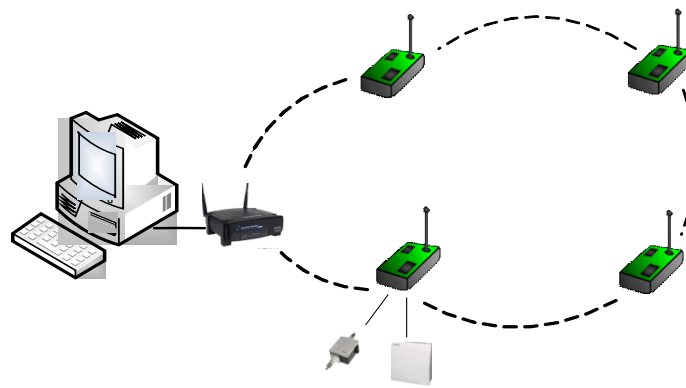
Figure 5.8: Wireless sensor network schematic

temperature, RH can be connected to the "Mote" with default interface. The "Mote" also provides additional interface that users can connect external sensor signal to the measurement board and thus, send the signal through wireless network. In this study, to measure indoor environment variables, one SIEMENS CO2, TVOC sensor and one differential air pressure sensor are integrated with one "Mote". Since CO2 sensor outputs wired signal between 0 to 10 vdc, and differential pressure sensor outputs wired signal between 0 to 5 vdc, and "Mote" sensor board can only accept input signal between 0 to 2.5 vdc, signal conversion circuit is needed to transmit the wired signal within the current range. A wireless sensor package is made by integrating various

sensors together and providing power supply for each of them. A sensor package wire diagram is shown in Figure 5.9. The developed sensor package is deployed to one case building. The sensor measurement location is shown as Figure 5.10
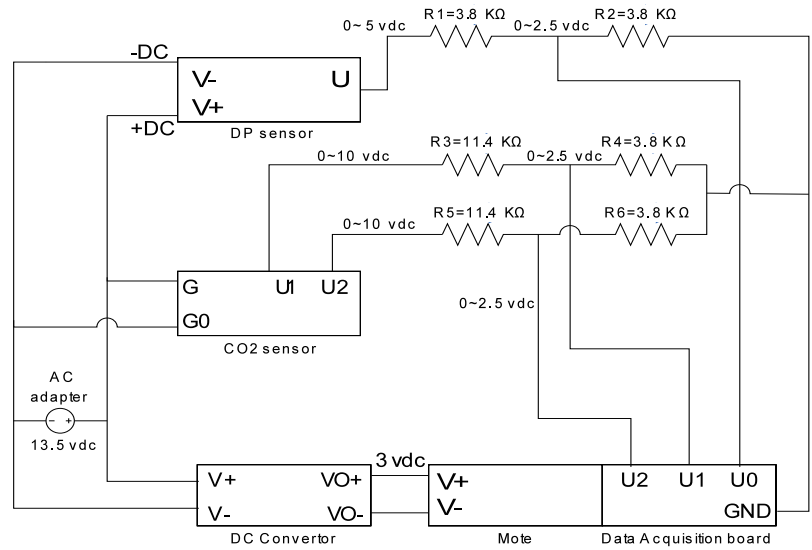
Figure 5.9: Wireless sensor package wiring diagram
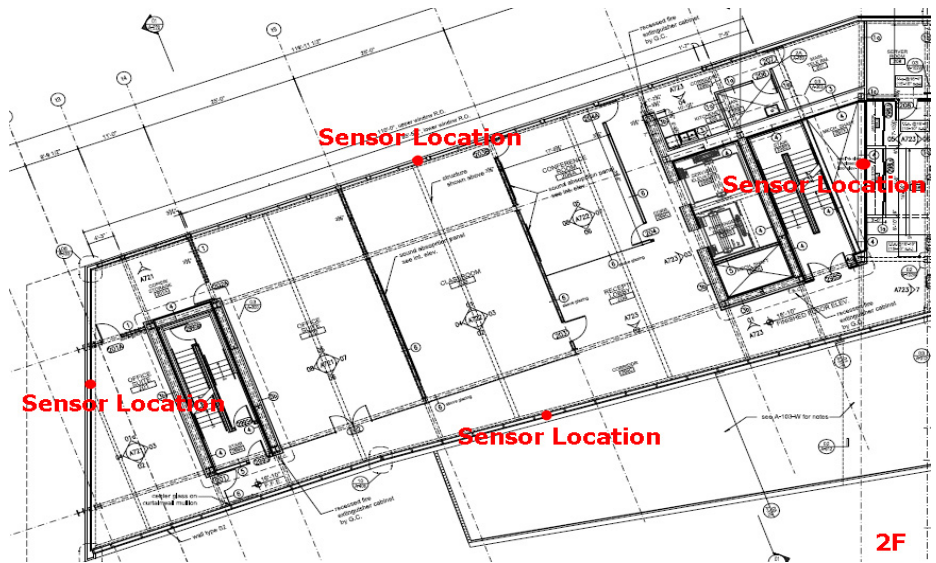
Figure 5.10: Wireless sensor deployment locations

5.4 Building performance monitoring

An online web-based Virtual Building monitoring platform is built by using Cache database and Cache CSP for web service (*Wei Feng*, 2010). One can select the monitoring point he/she is interested and browse building's performance. One office building located at Central New York climate conditions is selected as our monitoring building. This section will demonstrate different building systems monitoring results and analyze building's performance and indoor environments.

5.4.1 Air handling unit heat recovery performance

The office area of our monitoring building uses Dedicated Outdoor Air (DOA) system which is depicted as a typical "two-wheel" Air Handling Unit (AHU) as Figure 5.11 shown. The first heat recovery wheel is called enthalpy recovery wheel. When operating at heating mode, heat is absorbed as air passes through the matrix in the exhaust air stream, during one half rotation, and released during the second half rotation into the supply air stream in a continuous process. And vice versa for cooling operation. The second wheel, which is called desiccant wheel, provide latent heat removal or recovery for supply air. The preheat/precool coil uses ground water to precondition the Outdoor Air (OA) and the main cooling and heating coil will condition supply air by using cooling and heating water supplied by the building's water loop.

To demonstrate our case building's AHU performance. One summer week's monitoring results are selected and the supply air conditions are plotted in Figure 5.13. One time point of supply air states are selected as indicated in Figure 5.13(a). The supply air is first conditioned by the pre-cool coil from 29°C at state 1 (the OA is monitored to have RH 60%) to 27°C at state 2. After passing through the enthalpy recovery wheel, the supply air with high enthalpy is conditioned to around 23.5°C to state 3 (assuming no moisture exchange) which is only a little bit higher than room
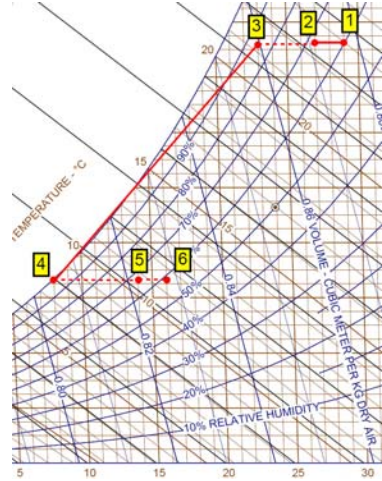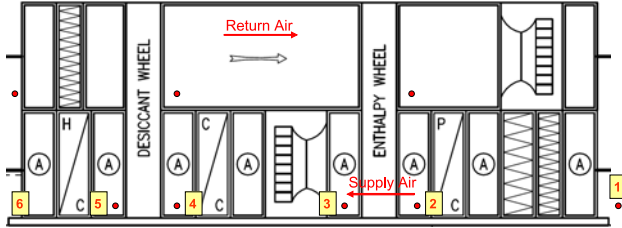
Figure 5.11: Building AHU monitoring schematic

Figure 5.12: Air state change conditioned by AHU

temperature 22.5°C. Then cooling coil further cools down the supply air by removing the sensible and latent heat to reach around 8°C at state 4 (the air is at saturation state). To reheat the supply air, the desiccant wheel further recover energy, gathered from exhaust air, and then heat supply air to 14°C at state 5 (assuming no moisture exchange). The supply air is further reheated by the heating coil to supply air setpoint 16°C at state 6 (this point is not monitored) and then deliver to the building. The entire air state change in supply air duct is shown a Psychrometric chart in Figure 5.12

At given supply air flow rate $Q_{sup} = 5.7m^3/s$ shown in Figure 5.13(b), the estimated sensible heat recovery rate by enthalpy recovery wheel can be calculated as (eqn. 5.1, "-" means cooling):

$$j_{erw}^U = Q_{sup}\rho_{air}C_{air}\left(T_{out} - T_{in}\right) + Q_{sup}\rho_v C_v \left(T_{out} - T_{in}\right)$$
$$= -13.03 - 0.4 \tag{5.1}$$
$$= -13.43 \quad (kW)$$
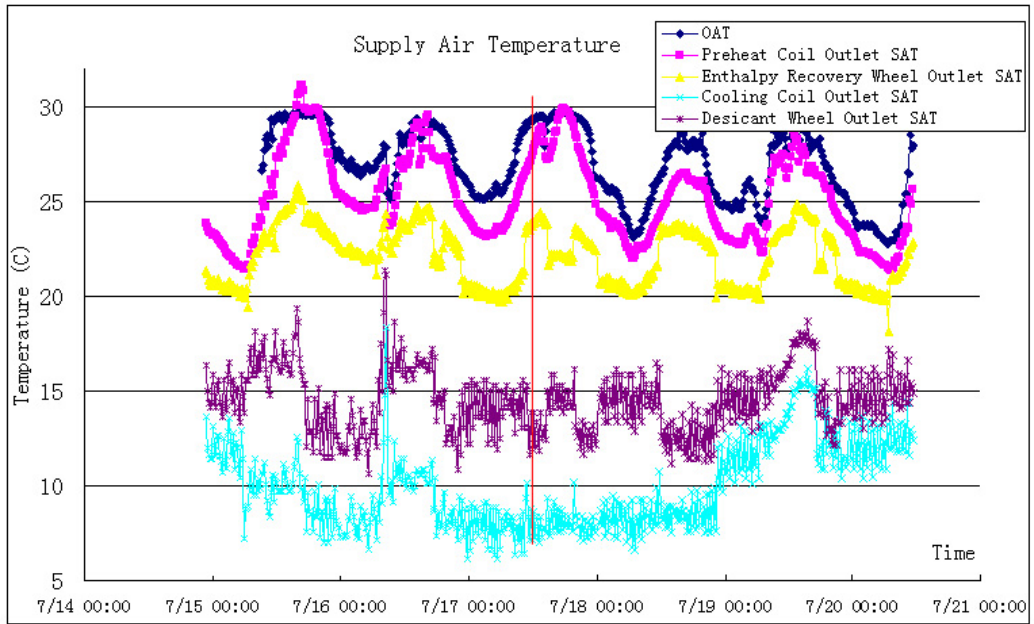
(a) AHU supply air temperature
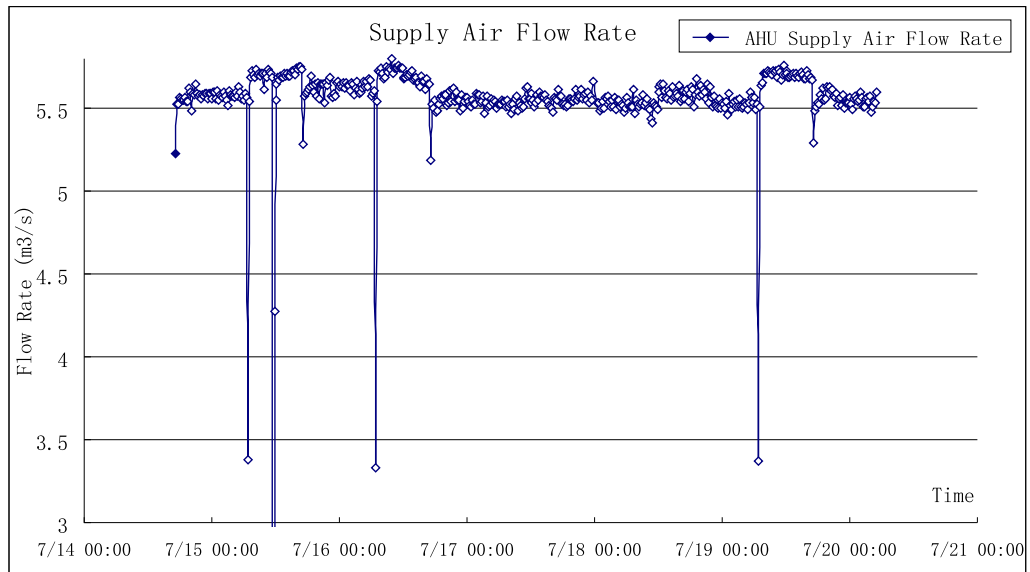
(b) AHU supply air flow rate

Figure 5.13: AHU supply air condition monitoring

134

The latent heat reconvery can also be calculated

$$j^U_{erw,latent} = H_{evap}Q_{sup}(\rho_{v,in} - \rho_{v,out}) \tag{5.2}$$

Unfortunately, the case building's AHU system does not measure the moisture or RH at each air state point. The actual enthalpy recovery rate should include both sensible and latent heat recovery.

where

j^U_{erw} is enthalpy recovery wheel sensible heat recovery rate $[kw]$

$j^U_{erw,latent}$ is enthalpy recovery wheel latent heat recovery rate $[kw]$

j^U_{dw} is desiccant wheel heat recovery rate $[kw]$

ρ_{air} is air density $[kg/m^3]$

C_{air} is dry air specific heat $[kJ/(kgK)]$

C_v is water vapor specific heat $[kJ/(kgK)]$

ρ_v is water vapor density $[kg/m^3]$

H_{evap} is the latent constant, $2445[kJ/kg]$

Q_{sup} is the supply air flow rate $[m^3/s]$

5.4.2   Ground source heat pump energy utilization analysis

The water system of case building is composed of seven Ground Source Heat Pumps (GSHP) which can be operated in both heating and cooling condition. Should additional heat is needed, two boilers, which can also be operated to supply domestic hot water, are connected to heating water loop. Each GSHP, when operating at cooling mode, has design cooling capacity $250kBtu/h (\approx 73kW)$ and can reject heat $350kBtu/h$ ($\approx 102kW$). The GSHP has design min Energy Efficiency Ratio (EER) value 14.1 when operating in cooling mode (equivalent to COP value 4.1). While operating in heating mode, the GSHP has design heating capacity of $250kBtu/h$

($\approx 73kW$) and can extract heat $170.6kBtu/h$ ($\approx 50kW$). The GSHP heating model has design min COP value 3.0.

The system is monitored continuously during the summer time. It is found that, to meet the demand of building's cooling load, about three (3) to four (4) GSHPs are needed. The Virtual Building system monitors the cooling energy outputted by the GSHP system, and the amount of heat rejected to the ground water loop to identify the building's actual energy COP. Figure 5.14 shows the cooling energy rate delivered by GSHPs and the heat rejected to the ground water loop. Cooling energy rates are analyzed at two time points. At point 1, it is found that four (4) GSHPs are running, and the system is producing $210kW$ cooling energy delivered to the building while rejecting $275kW$ heat to the ground water loop. The cycling equipment COP can be calculated by using equation 5.3 (*Henderson et al.*, 2000)

$$COP_{cycl} = COP_{cont}\left(1 - C_d(1 - PLR)\right) \tag{5.3}$$

where,

COP_{cycl} is cycling equipment COP value

COP_{cont} is equipment continuous COP value

C_d is the degradation coefficient, and here take the value 0.25

PLR is system partial load ratio defined as the actual load divided by system capacity

To obtain the system COP value during continuous operation condition, on common approach taken by building simulation community is to use the polynomial equipment performance curve to calculate at certain condenser and evaporator water temperature, the equipment COP value. However, the case building's GSHP equipment performance curve is not available. We use the data specification of the commercial HP model 50PSW360 (*Carrier*, 2009) to calculate the equipment COP value at contin-

uous running. By checking Virtual Building measured condenser side entering water temperature and flow rate, and evaporator side return and supply water temperature and supply water flow rate, the HP system continuous operation EER is estimated at 15.1 and 17.2 which is equal to COP value of 4.4 and 5.0 at stage 1 and 2 respectively in Figure 5.14. Thus, the system cycling COP_{cycl} is 4.1 and 4.8 respectively.
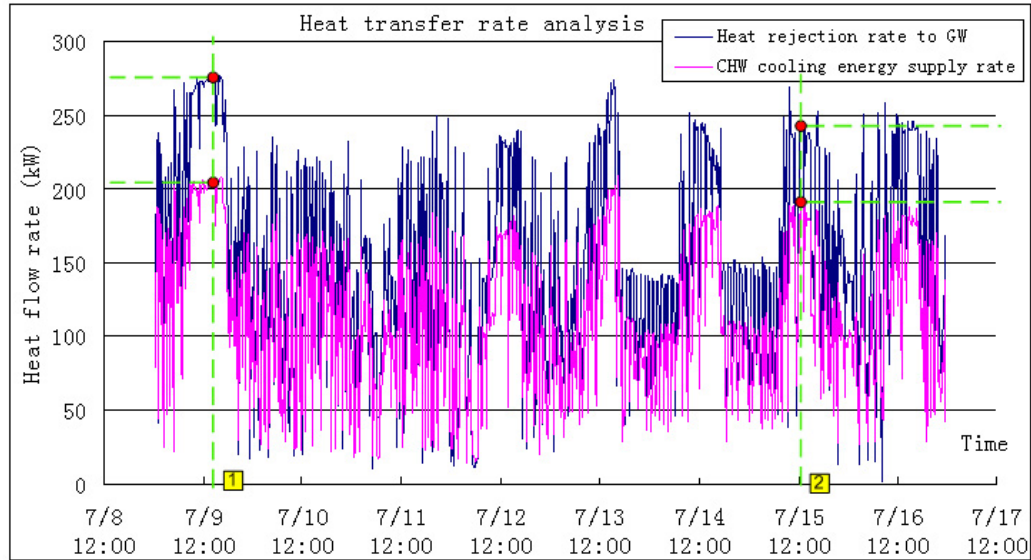
Figure 5.14: Ground source heat pumps heat flow rate

5.5 Summary

Virtual Building is a new Building Information Modeling method to model a whole building's information and store dynamic performance. The structure of Virtual Building is initially designed for CHAMPS-Multizone simulation program to store simulation model's data. Then, the structure is further expanded to include time-dependent building performance data and record long term built environments information. The Virtual Building hierarchical structure well represents a building static structure and its different systems. The structure is constructed with Object Oriented Design methodology, so it can be easily implemented in either object oriented environments (e.g. CHAMPS-Multzione C++) for simulation purposes or in object oriented database engine for performance storage purposes. Building's geometry, material etc. information can be modeled in third party design programs (e.g. *GOOGLE SketchUp* (2010)) and the static design data can be transfered into Virtual Building through data via a BIM compatible data transfer bridge. An object oriented database called "Cache" is selected as the central database engine of Virtual Building.

Since buildings usually have different measurement systems, it is important for Virtual Building to interact with them to collect various information. In our case building, Virtual Building is configured to communicate with the Building Management System (BMS) to transfer data periodically. Another wireless sensor network system is also developed to collect indoor environmental measurements wireless signals and then transfer the data into Virtual Building database. The wireless sensor measurement package is developed by integrating $CO2$, TVOC, and differential air pressure sensor into one wireless sensor "Mote".

To monitor and verify building's performance by using Virtual Building system, one case building's HVAC system air loop (AHU) and water loop (GSHP system) are analyzed. The supply air conditions are monitored at different air conditioning com-

ponents and the energy recovery rate is calculated by using heat recovery wheels. The GSHP system is monitored for cooling energy production rate and heat rejection rate to ground water. The system's COP is estimated at different operation conditions. The performance monitoring system establishes a framework to understand building system performance (i.e. commercial GSHP system) in Central NY climate region.

Virtual Building is proved to be an effective method to model building systems and store and analyze buildings' performance. It provides a structural way to measure building system performance and monitor its operations. The role of Virtual Building in understanding design and verifying building performance will be demonstrated in later chapter. The Virtual Building monitored data will be used to verify building's performance and compare real performance with simulation results. The Virtual Building also provides a comprehensive platform for researchers to understand the building's operation conditions.

CHAPTER VI

Building Design Parameters and Design-oriented Simulations

Building design is a very complex process involving many parties and design aspects. To study design process and its impact on building energy and IEQ performance, a design parameter hierarchy is developed based on the study of *Karhu* (1997) *Morbitzer* (2003) to address design activities' impact on building performance. Early, Scheme and Detail design stage are selected as typical design stages

Early design stage will address basic building geographical climate conditions and how the climate conditions, through interacting with local urban context, influence on building performance. Basic building shape and geometry will be developed and variation of shapes can significantly affects building performance and later Scheme and Detail stage parameters selections. Building performance evaluation can be performed at Early stage by using general or default building envelope and environmental service systems. Optimal building shape and geometry under given climate conditions and urban context can be developed for later stage analysis.

Scheme stage, with the designed building parameters from Early stage, will first address how program will be designed in terms of different choices of structure systems and customer needs. Building envelope can then be developed based on established

program by design opaque facade and fenestration systems. The variation of opaque facade selections as well as fenestration systems design can also significantly affect building performance. The determination of building envelope type can be achieved through performance based simulation with established zoning concepts and building geometry. However, to re-consider the impact of building shape and zoning designs, additional simulations are needed to achieve better performance. So, the refine of upper level design parameters are necessary to optimize building performance at Scheme stage.

In detailed design stage, the major design parameter is building environmental systems. This includes the design and selection of HVAC air system and water system. Combined energy and IEQ analysis is needed for HVAC system design to comprehensively evaluate building performance. By comparing simulated building's performance under different HVAC systems, the selection of HVAC system can be optimized.

The design stage and parameters studied in this chapter are illustrated in figure 6.1, including:

Figure 6.1: Building design parameters

- climate condition and building urban context

- building form, massing and orientation

- building envelope system and fenestration system

- interior program and zoning

- HVAC systems

- building performance verification

From building performance analysis, the design parameters discussed above are inter-connected. For example, the design of building form and orientation can affect later fenestration system designs, and the design of building form, envelope systems will also impact the design of HVAC systems. Moreover, when study building performance at early design stages, we need to provide some default parameter setting for later stages. Also, at later design stages, the early design stage parameter may also need small change and adjustment. The inter-connection of different design parameters require iterative design studies to optimize building performance in various design stages.

In this chapter, we analyze each design parameter and its impact on building performance by modeling a case building in CHAMPS-Multizone and EnergyPlus. Then, CHAMPS-Multizone is applied to demonstrate its ability in design analysis for same case building, and how the predicted results compare with those monitored by the Virtual Building system to demonstrate the current capability of the integrated platform developed for both design and monitoring. The limitations of the current platform is also identified, pointing the direction for future development.

6.1 Climate condition and site planning

Climate condition is the first design parameter to consider in early design stage. The importance of climate condition is that the selections of other design parameters studied in later stages are highly dependent on climate conditions.

6.1.1 Macroscopic climate consideration

Climate conditions can be further separated into two categories. One is macroscopic climate conditions which describes the global or continental general climate patterns. Macroscopic climate condition is formed by the regional geographical profile, solar radiation and also affected by ocean water circulation and some other climatological phenomena. Figure 6.2 gives the world macroscopic climate zone division based on solar radiation intensity. Four(4) climate zones – polar zone, temperate zone, subtropical zone and tropical zone, are defined in terms of the solar radiation intensity received on the earth surface. Macroscopic climate conditions can directly affect
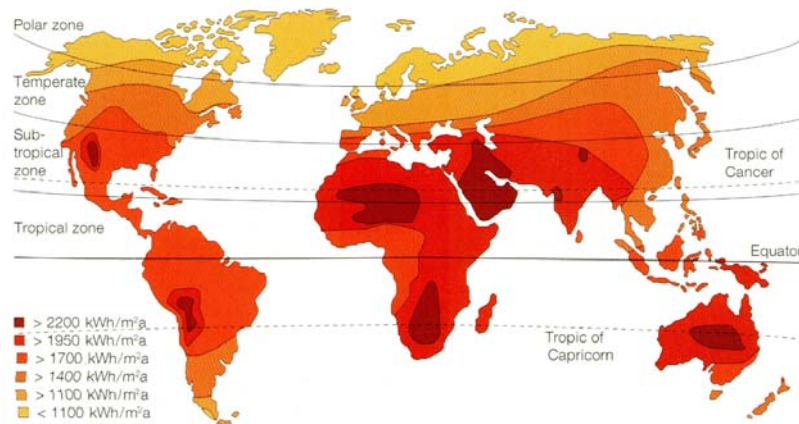
Figure 6.2: World climate zone division based on solar radiation (*Hegger and Liese*, 2008)

architectural design and thereby building's performance. In order to better describe climate zones under US climate conditions and especially take macroscopic climate

conditions influence into account for building performance, ASHRAE further defines climate zones as eight(8) regions in US as Figure 6.3 illustrated (*ASHRAE*, 2004b). Several building design features and parameters selection are affected by climate zone
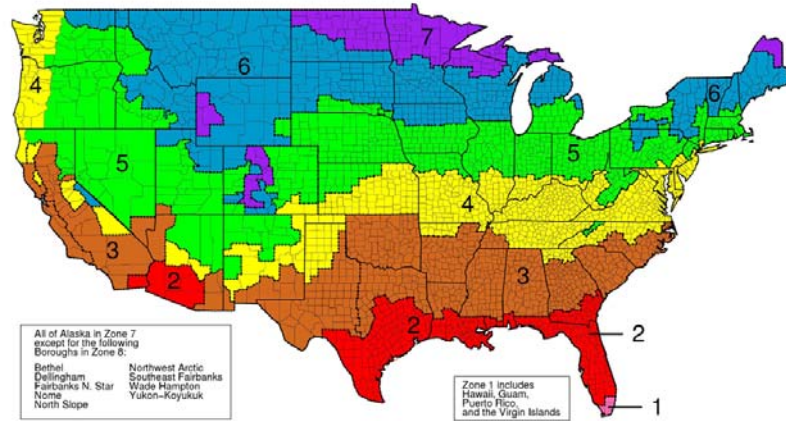
Figure 6.3: ASHRAE Climate Zone Map

definition. Also, design criteria are given in terms of climate zone consideration. Here some most common design parameters affected by climate zone definitions are listed:

- Building's massing and orientation,

- Building envelope systems,

- Building fenestration systems, and making use of daylight

- Air conditioning and other built environment service components.

To understand how climate zones impact on building's performance, an office building benchmarked case studied by DOE is shown here. The building has the similar floor area with our case building in this research. The benchmarking building is illustrated in Figure 6.4(a), with window to wall ratio 33%. And the building is configured with VAV system with Chillers and Boilers serving for heating and cooling plants. The building's site energy consumption is simulated in different US climate zones

144

and results are shown in Figure 6.4(b). It is noticed that some energy consumption components, such as lighting, equipment etc., are not affected by climate conditions and thus tend to be constant over different climate zone simulation. However, other energy consumption components, such as cooling, heating, fan, pump etc. are directly related to building's climate zone and we are particularly interested in those energy consumption in this study.
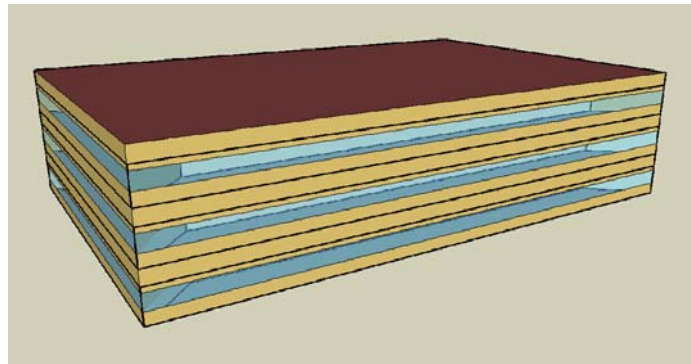
(a) building geometry
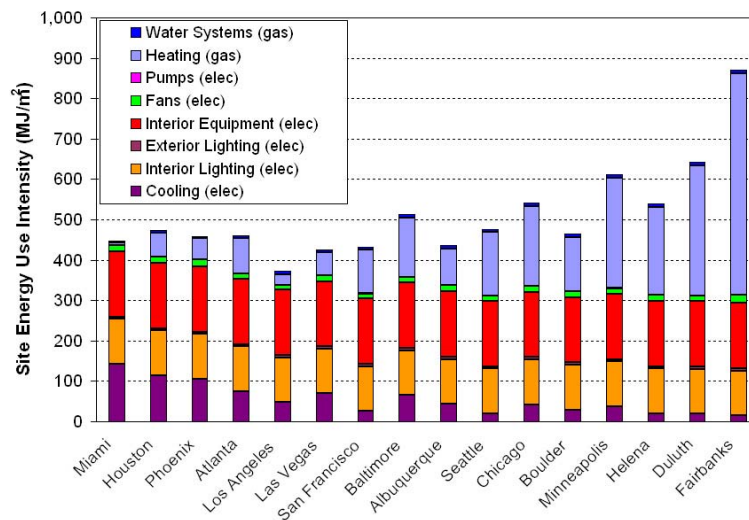
(b) energy performance

Figure 6.4: A benchmarking office building energy performance (*Deru et al.*, 2011)

6.1.2 Local climate consideration

The urban context of one building is often studied as microscopic and local climate conditions. Even in the same macroscopic climate condition, the local urban context can significantly change the object building's urban environment at:

- change the solar radiation by shading shadows shredded on object building.

- change the surrounding wind profile and thus affect the pressure distribution around the building and infiltration and exfiltration effects

- form the acoustic environment around the object building

To study the effects of urban context on buildings' performance especially energy consumptions. An urban context model, illustrated in Figure 6.5, is created with our object building in the middle of urban map and surrounding buildings around. Here, we are particularly interested in surrounding building's height, width, length and distance to object building. A couple of simulation scenarios are created based on context building's relationship with object building as Figure 6.6 shown.
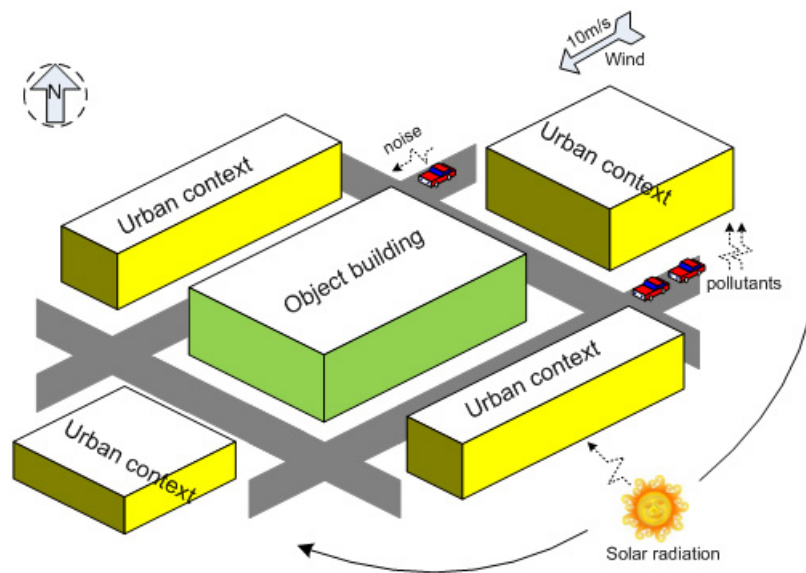
Figure 6.5: Urban context model

The baseline model's urban context is crated based on typical urban profiles where the context building has about 28 meters distance to object building (four traffic lanes plus two sidewalks), the context building has the same dimension as well as height in baseline building. We setup buildings to have a square shape with the same width and length for simple comparison by maintaining the same floor area, while detailed building form and massing comparison can be done in later design stage analysis. Our object building is a five-floor office building with floor area of $3700m^2$. And it has 20% of its facade area covered by glazing systems (20% window to wall ratio – WWR). The lighting systems of the object building are setup to control the building floor luminance level at 500lx by step dimming. Thus, variable lighting energy consumption can be observed under different urban context. Since in early design stage, HVAC system designs have not come into place, we simply use purchased (also called "district") heating and cooling for heating and cooling energy calculations and the building is controlled at 23 C. The study uses Syracuse, Central New York climate conditions for simulation. We simulate object building's one year heating, cooling and lighting energy consumption based on different urban context cases.
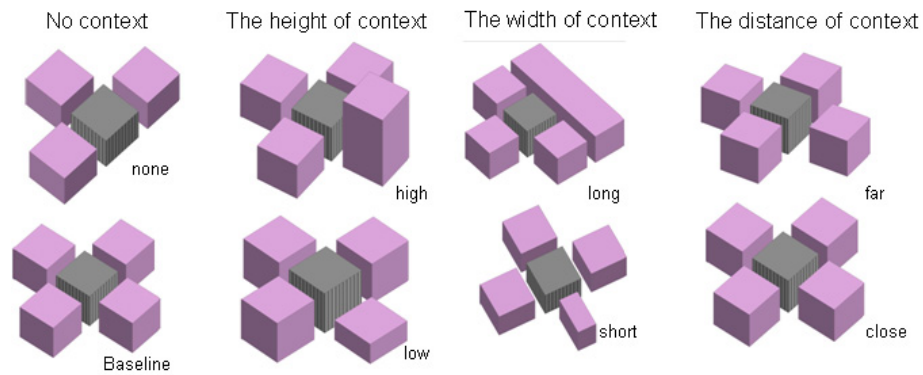
Figure 6.6: Urban context scenarios

The urban context is studied by comparing neighborhood building's *height, length, distance* to object building at *North, South, West* and *East* side of the object building.

Thus, multiple cases are generated based on the combination of context building's properties (height, length etc.) and which side the context building is located at (North, South, West, East). All cases are compared with a baseline urban context case and a case where there is no context at all at four sides of the object building. The object building's lighting, heating and cooling energy are simulated in different scenarios and the total building one year's energy consumption is summarized.[1] The results of urban context energy performance simulation are shown in Figure 6.7

(a) lighting energy

(b) heating energy

(c) cooling energy

(d) total energy
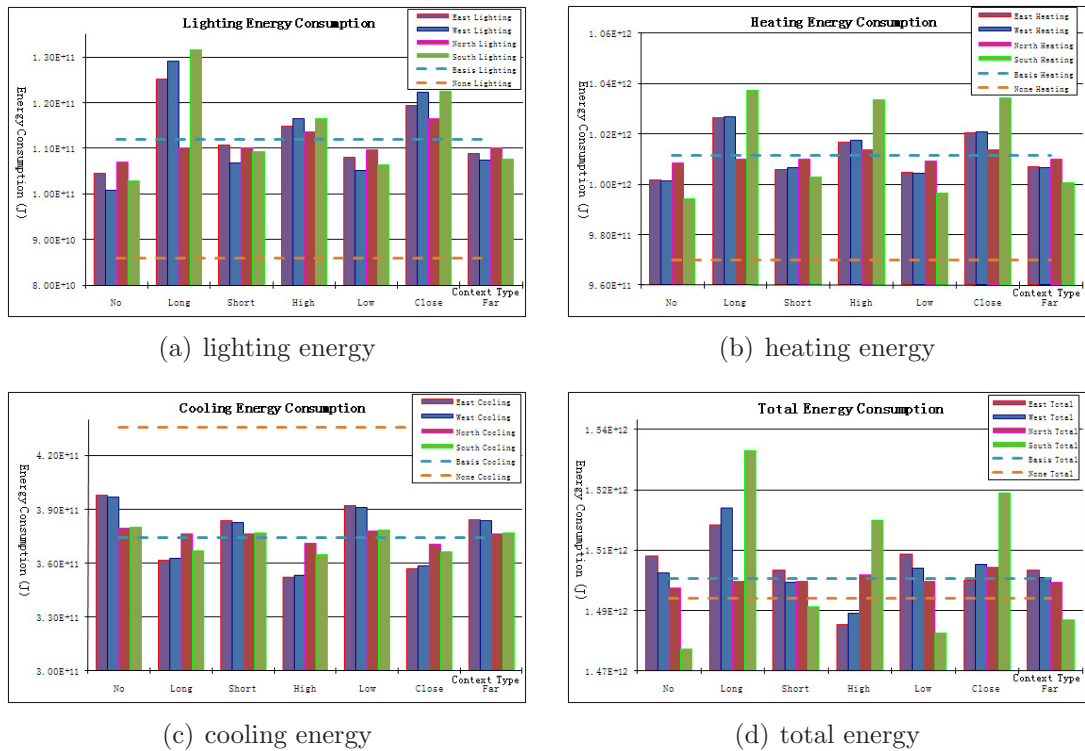
Figure 6.7: Urban context and building energy performance simulation results

The results show North side urban context building doesn't have much impact in terms of object building's lighting, heating and cooling energy performance. This is typically true for North hemisphere high latitude location where direct solar radiation generally does not project on the north side of building.

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[1]Since heating, cooling and lighting energy consumption exist in different forms, attentions should be paid to the total primary energy consumption. However, in early design stage, for qualitative building performance analysis, a simple summation provides an easy indication of whole building's energy performance.

The East and West side context building property changes show similar impact on object building's energy performance, while the object building energy consumption is slightly "sensitive" to West side urban context changes. This is because, for object building, the West facade tends to transfer more heat flux compared to East facade and the change of West side urban context will result in different amount of solar radiation projected on the West facade and thus produce more significant impacts on building's energy consumption. The total effects of East and West side context building's impacts on object building's energy performance are complex phenomena and require more in depth study on lighting, heating and cooling energy consumption. However, it is generally true that when object building is located at high latitude (i.e climate zone 6, 7), to have a relative loose urban context (i.e. no context buildings, short context building side and longer distance between context building and object building) on object building's East and West sides can allow more solar radiation energy received by the object building and thus decrease building's heating and increase cooling demands unless proper shading method is applied demands; while in low altitude (i.e climate zone 1, 2 ect.), an relative dense urban context on the East and West side can make object building operate more energy efficiently. In this case, a high urban context building on the East and West side of our object building give better energy performance simply because of reduction of solar radiation and therefore heat flux on object building's roof.

It is also observed that the object building is very sensitive to the South side urban context building's property change. And low energy demands are observed when we have loose urban context on South side or even no context at all. While a dense South context will lead to more energy consumption due to increase of artificial lighting energy use caused by lack of daylight penetration into building, and increase of heating energy use by reduction of winter solar gain.

149

Combining all four sides context building, under climate zone 6 for central NY climate condition, one building tends to have better energy performance when it is located at open context at its South side and loose urban context at its East and West sides. The significance of context buildings' influence on object building's energy performance is dependent on the model setup and especially the distance between the object building to the context buildings. A more close and dense urban context setup will yield more drastic impacts on object building's energy performance, in terms of context building's different shapes and properties. However, qualitatively, the trend of the impacts should be similar to the test case discussed above.

The actual building we are studying has very loose urban context where the context buildings' impacts on object building, in terms of shading solar radiation, are very small. In this case, we generally consider our research building is located in an open urban context (no context building on each side) and this local urban profile is adopted for selections of later design parameters.

6.2 Form, massing and orientation

The form and massing refer to the actual building shape design. The building's shape will determine how much area of the building is exposed to exterior environments and thus influence building's performance. Also, building's form and massing play important roles in building's envelope design, internal configuration designs, and the selections of many other design parameters. The actual choice of building form and massing is a very complex process which is usually constrained by external factors such as land availability of construction site, budget and clients preference. However, it is found that building performance is rarely simulated and analyzed in form and massing design.

6.2.1 A general case on building form, massing and orientation designs

In this study, the case building we used in climate conditions analysis section will also be used for this analysis by adopting the open urban context scenario. Instead of using square shape object building, the dimensions of our case building become research parameters to be determined. To maintain the building's function, the total building floor area is controlled at 3700 m^2 and the average floor height is about 4.6 m (15 ft). The idea of varying building's dimension is illustrated in Figure 6.8. Multiple building dimension (L:W)[2] combinations are considered in this case by maintaining total floor area the same as given in Table 6.1.

The building is setup to have 5 floors. The building envelope prototype is chosen as light weight construction assembly and 20% WWR with double glazing window system. To evaluate how much daylight can be utilized by the case building, lighting is controlled by step dimming and the indoor luminance level is controlled at 500 lux.

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[2]we denote that "Length" (L) is used to describe the distance between building's West and East point (parallel with the Earth latitude line).

Table 6.1: Building dimension design table

No.	Length (m)	Width (m)	Stretching Factor (L:W)
1	27.2	27.2	1:1
2	38.48	19.24	2:1
3	47.1	15.7	3:1
4	54.4	13.6	4:1
5	60.83	12.17	5:1
6	..	..	..
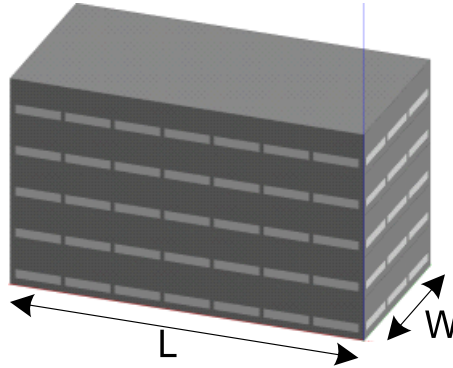
Figure 6.8: Building form and orientation

HVAC systems are not designed and we continue to use purchased (district) heating and cooling for simple analysis. At the same time, we are particularly interested in how building's orientation affects building's form and massing design. Thus, the case building is rotated from 0° to 180° with every 30° of building orientation increment. (The case building we have is axis symmetric. 180° rotation is sufficient to cover all possible scenarios for performance analysis). The case building's orientation and aspect ratio is setup as input variables and its lighting, cooling and heating energy is simulated and total energy consumption is summed up. One year building energy performance simulation is conducted and the building's energy consumptions are given in Figure 6.9.

The x axis of the results is case building's aspect ratio denoted by L:W. The y axis is building's orientation where 0 means building is oriented as L represents its length of South and North sides and W represents its width of West and East side. To orient
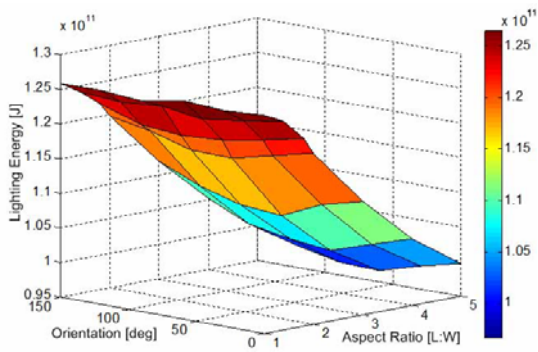
(a) lighting energy
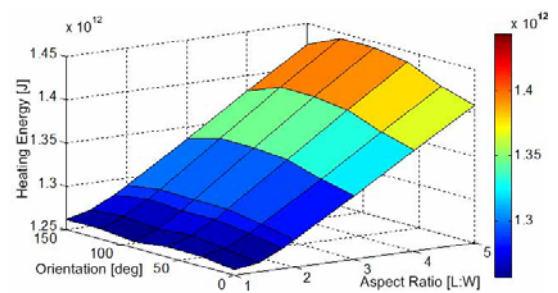
(b) heating energy
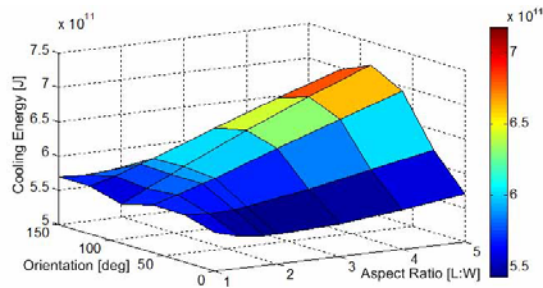
(c) cooling energy
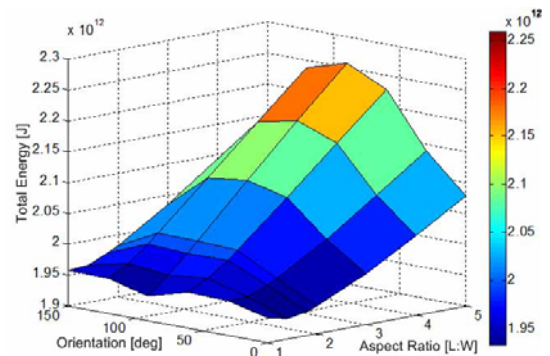
(d) total energy

Figure 6.9: Building performance simulation for form, massing and orientation

building 90º, for example, the L represents building's width of West and East and W represents represents its length of South and North sides. The z axis is building energy for lighting, cooling, heating and total energy use.

It is shown in the results that the case building's lighting energy keeps decreasing with the increase of aspect ratio under certain orientation. We take building's orientation at 0º for example. The increase of building's aspect ratio from 1:1 to higher value will increase case building's surface areas. Especially in 0º orientation, our case building South facade's area will increase with the increase of aspect ratio and thus allow more daylight to come into the building, which on the other hand, decreases the needs of artificial lighting. The increase of building aspect ratio also results in the decrease of building width W and thus allow daylight to penetrate "deeper" inside of our building from South side. The lighting energy does not change much with the building orientation.

The heating energy consumption exhibits a different behavior compared with lighting energy consumption. Increase of building's aspect ratio leads to the increase of building heating energy consumption simply because of more surface areas exposed to ambient environment and thus introduce more heat loss through building envelope.

Cooling energy is very sensitive to building's orientation especially when building is stretched in high aspect ratio. When building is oriented by 90º and its aspect ratio is over 3 (which means building has its long side:L facing West and East and has its short side:W facing South and North direction), the cooling energy consumption increases dramatically. This is not only because of the increase of building surface area, but also the West-East facing direction can introduce significant amount of solar radiation and heat load in summer time and thus requires more cooling energy. However, when building's orientation is 0º (building is in South-North direction), the cooling energy also increase with respect to aspect ratio increase mainly because of

building surface area increase. However, the magnitude of cooling energy demand is much less than 90° orientation case.

Another finding is that, under 0° orientation, with the increase of building's aspect ratio (also increase of building total surface area), the case building's cooling energy consumption decrease first, then increase. This is slightly different from common architectural design experience that energy consumption always increases with building total surface area that an optimal building form and massing design always happens at minimum surface-to-volume ratio. In this case, we find that the minimum cooling energy usage happen at aspect ratio value between 2 to 3. However, there is no exclusive conclusions that what aspect ratio value gives the best energy performance building design. The building's performance varies from case to case, and the selection of building form and massing alway relates to other building design parameters.

6.2.2   The as-built model form, massing and orientation designs

As Figure 6.8 shows, the case building's form, massing and orientation design is analyzed under certain building envelope designs that WWR value is 20% and is equally applied to case building four facades. However, it is also noticed that other design parameters, such as building envelope, can significantly affect building form massing and orientation selections. In this case, we are particularly interested in how the selections of later design stage's parameters can affect form and massing design.

The case building's envelope as-built design is considered here. Different from the case we have in section 6.2.1, the major difference of as-built model envelope is that it use 100% WWR on the South facade of the building. To understand how this building envelope design feature affect the selection of form and massing, we setup a new simulation model with 100% WWR on the South facade and maintain the same building envelope designs at all other sides as we have in previous case. Building's

orientation is also evaluated. However, in this case, we orient the case building from 0° to 360° since the building is not axis symmetric any more. Other design conditions and parameters are kept the same as compared with previous case.

To quantify building's total energy performance, we use total energy cost instead of summing up lighting, cooling, and heating energy. Since detailed HVAC designs are not involved in early stage, the calculation of building HVAC system performance is preliminary for early stage design parameter analysis. Detailed HVAC system performance design and analysis can be found in later sections. We assume that the case building uses ground sourced heat pump (GSHP) for heating and cooling and boilers for additional heating. The detailed primary (water loop) and secondary system (air loop) equipments and ducting designs are not evaluated in this section. Systems' coefficient of performance (COP) are given for early stage energy cost calculation. The GSHP system has cooling COP of 4.5 and heating COP of 3.6. The COP value for heating and cooling is obtained from Virtual Building's monitoring system as shown in section 5.4.2 by combining monitored water temperature and flow GSHP manufacturer data (*Carrier*, 2009) and an annualized average COP is obtained. And the natural gas boiler system efficiency is 90%. The GSHP systems will run for both cooling and heating conditions. When additional energy is needed in heating season, boilers will be turned on to provide additional heating energy. Based on Virtual Building observerance, it is estimated that the boilers will provide 20% heating energy while GSHP system provides the rest 80%. The energy source of GSHP is electricity and boilers consume natural gas. The electricity annual average rate at central New York location is 0.14\$/KWH and the natural gas average rate is 12\$/$MBtu$ (*EIA*, 2010; *NYSERDA*, 2010). At early design stage, a simple total building energy cost

156

estimation equation is given as (6.1)

$$Cost = Q_{lighting}R_{electric} + R_{electric}\left(Q_{cooling}/COP_{cooling}\right) \qquad (6.1)$$

$$+ R_{gas} \cdot 20\%Q_{heating}/\eta_{boiler} + R_{electric} \cdot 80\%Q_{heating}/COP_{heating}$$

where,

$Q_{lighting}$ = total lighting energy demand $[kWh]$

$Q_{cooling}$ = total cooling energy demand $[J]$

$Q_{heating}$ = total heating energy demand $[J]$

$R_{electric}$ = electricity rate $[\$/kWh]$

R_{gas} = natural gas rate $[\$/J]$

$COP_{cooling}$ = GSHP cooling system coefficient of performance

$COP_{heating}$ = GSHP heating system coefficient of performance

η_{boiler} = Boiler system heating efficiency

The case building's energy performance simulations are conducted by changing building's aspect ratio with different orientation angle and results are collected in terms of lighting, cooling and heating and total energy cost. The one year's simulation results are shown in Figure 6.10. Compared with our previous case with 20% WWR, this case's results show similar building performance. [3].

For lighting energy, the general trend is that lighting energy decreases with the increase of aspect ratio, and this agrees with 20% WWR case. However, the impacts of orientation on lighting energy performance is more significant than 20% WWR case because the big window area will make building's energy performance more volunable to the amount of daylight received by the object building. It is found that, at

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[3]It is noticed that since 20% WWR case only simulates building orientation from 0° to 180°, while in this case orientation is simulated from 0° to 360°, the performance contours we got in 20% case may only comparable with one half part of contours in 100% WWR case – 0° to 180°

(a) lighting energy

(b) heating energy

(c) cooling energy

(d) total energy
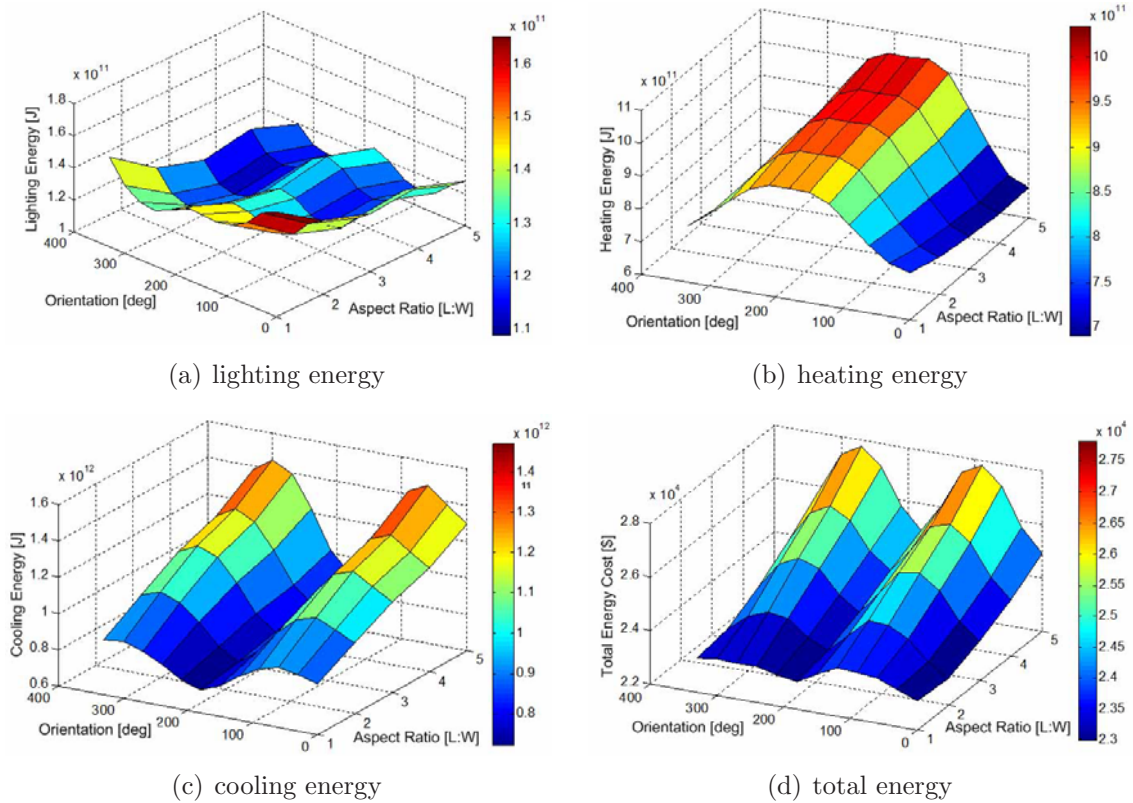
Figure 6.10: Building performance simulation for form, massing and orientation

certain aspect ratio, building's lighting energy consumption tends to be higher when it is oriented 180º (the 100% WWR South facade is oriented 180º to North direction) because of the lack of daylight coming into building when it is facing North.

For building's heating energy, when it (the 100% WWR facade) is mainly facing South, its heat gain increases due to solar radiation with the increase of its aspect ratio. However, when building is oriented to North direction, the increase of aspect ratio won't help building to receive more solar radiation energy but, on the other hand, leads to the increase of building's surface area and thus aggravates the effect of heat loss through building envelope. Under certain aspect ratio, building's heating energy performance reaches lowest level at South orientation, and reaches to maximum when it is oriented to North because building's orientation changes its capability to receive solar heat gain.

The cooling energy consumption tends to be lower at North orientation and higher at East, West orientation. Except North orientation, building's cooling demands increases with its aspect ratio. Also, the increase of aspect ratio will cause building to have bigger facade area, especially with 100% WWR facade, and allow more radiation heat penetrates through building envelope and increase building's cooling load.

When summing up all lighting, heating, and cooling energy and convert to whole building systems energy cost, the total energy cost profile is given in Figure 6.10(d). The case building is observed to have lower total energy cost at South orientation with small aspect ratio number, because of its capacity to utilize daylight and absorb solar radiation in the winter time. Building also shows lower energy cost at North orientation because of avoiding intensive solar radiation in the summer time. West and East orientations produce higher energy cost at different aspect ratio. However, the South orientation is better appreciated in this case since the potentials of using shading and other technologies to avoid intensive solar radiation in the summer time and this can essentially reduce cooling energy cost and thus building total energy cost. Psychologically, South orientation will allow more daylight to get into the building and are likely preferred by building's occupants. It is also found that, under South orientation, the optimal energy performance happen around aspect ratio value of 2 to 3. This also confirms with our previous 20% WWR case conclusions that the building optimal energy performance form and massing design does not always happen at minimum surface-to-volume number where aspect ratio is 1.

This section demonstrate methods to select different design options for building shape and orientation. The optimal building energy performance is found by selecting parameters whose final building energy usage is lowest. When selecting parameters in early design stage, parameters such as building envelope system, HVAC system which will be decided in later stages are hold at constant values. After evaluating the whole building's energy performance, the case building is selected to have aspect ratio of 3.

And building is designed to have South orientation.

6.3 Building envelope designs

After determining the building's form, massing and orientation, the design of building envelope become critical for building performance analysis. Building envelope designs relates to a broad scope of design parameters, ranging from opaque exterior walls, roof, slab-on-grade floor and fenestration systems. ASHRAE gives very detailed description on the parameters of building envelope regarding different climate zones *ASHRAE* (2004b). A comprehensive evaluation method has been established in terms of prescriptive energy performance criteria, energy trade-off method and energy budget method. Should one building fails to follow prescriptive method, either energy trade-off method or energy budget method needs to be used for building's energy performance. In this section, we are going to use the designed building form and orientation determined in previous section and conduct investigations on how envelope design affects building's energy performance. Building envelope study is consisted of two part: 1), opaque building envelope, 2), fenestration system.

6.3.1 Opaque building envelope

The majority of opaque building envelope is made up of exterior walls through which built environments interact with outdoor environment. The design of exterior walls will affect building heat, moisture, and airflow exchange with outdoor environment and therefore significantly influence building's energy, moisture and indoor air quality performance. Since building envelope plays very important roles in connecting indoor environments and outdoor climate conditions, the design of building envelope should meet certain climate zone requirements discussed in previous sections. ASHRAE defines the prescriptive building envelope in terms of its maximum U value or minimum R value in accordance with building's climate zones. For our case building, ASHRAE gives commercial building envelope (exterior walls) U value and R value in table 6.2

Table 6.2: Climate Zone 6 Opaque Building Envelope Assembly U, R value

Construction Type	Max U value $[W/m^2 \cdot K]$	Min R value $[W/m^2 \cdot K]$
Mass	0.592	1.7
Metal Building	0.642	2.3
Steel Framed	0.479	2.3
Wood Framed and Others	0.504	2.3

For our steel framed case building, the Max U value defined by ASHRAE is 0.642 $W/(m^2 \cdot K)$. The lower U value can buffer the heat transfer between indoor and outdoor environment and thus reduce the cooling or heating energy consumption. To understand different building's envelope designs and their impact on building energy consumption, a series of different building envelope designs are considered in this section. The building envelope types simulated include typical light, medium, and heavy weight constructions and a light weight construction design given by the case building design team. The light weight construction wall assembly is composed of exterior cladding, insulation material, air gap and gypsum wall board; the medium weight construction wall assembly has brick, insulation material, air gap and gypsum wall board; the heavy weight construction assembly includes brick, cast concrete, insulation material, air gap and gypsum wall board; the wall assembly of the case building includes exterior cladding, air gap, insulation material, fiberboard, air gap, gypsum wall board. Figure 6.11 shows building assembly layer schematics (the top layer connected to exterior environment and the bottom layer linked to indoor environment).

The U value of three *ASHRAE* (2005) wall assemblies as well as designed wall is calculated and given in Table 6.3.

To quantify different wall assemblies and their impact on building energy performance, we apply the wall assemblies to the case building by keeping the designed shape and using Central NY climate condition. Window to wall ratio is set as 20%

(a) Heavy Weight

(b) Medium Weight

(c) Light Weight

(d) Case Building Design

Figure 6.11: Case Building Envelope Design Prototypes

equally applied to each facade and double pane window is selected for the simulation model. (detailed window and fenestration design will be considered in later section.) Simple ideal HVAV system is configured and only input heating and cooling energy is calculated to quantify building's performance. The one year building heating and cooling energy consumption under different wall assembly configuration is given in Figure 6.12.

It is found that case building's heating and cooling energy consumption is directly related to the wall assembly U value. The higher U value of building wall assembly will give higher energy demands case building has in cooling and heating. The case building exterior wall design exhibits the best whole building energy performance among all the simulated exterior wall cases. And eventually it is selected as our case

Table 6.3: Building Wall Assembly U Value Comparison

Wall name	U value ($W/K \cdot m^2$)
Light Weight Construction	0.649
Medium Weight Construction	0.557
Heavy Weight Construction	0.472
Case Building Design	0.23
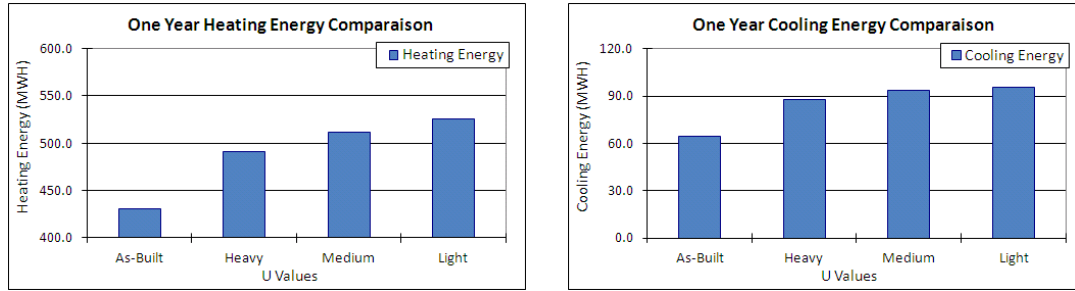
(a) Heating Energy

(b) Cooling energy

Figure 6.12: Case Building Envelope Designs and Energy Performance Comparison

building exterior wall assembly design and used for following building parameters and components selections.

6.3.2 Fenestration Systems

The fenestration system, different from opaque building envelope, can more dynamically influence building performance because of its capacity to introduce solar radiation and daylight into buildings. Moreover, building fenestration systems have relatively higher U value compared with opaque building envelope which makes fenestration systems more vulnerable to outdoor climate changes. Another important fact is that the more area for building envelope is designed as glazing systems, for example curtain walls, the less area opaque envelope becomes. Thus, the ratio of total window area to the total building envelope area (summation of both opaque and transparent parts) is defined as window to wall ratio (WWR). WWR becomes a very important design parameter not only it determines windows' influence on building performance but also constrains opaque building envelope's impacts on whole

building energy performance. *ASHRAE* (2005) gives an empirical window model in Equation (6.2) to explain how energy transfer through windows and influence building energy performance

$$j_{window} = U A_{pf} \left(T_{out} - T_{in} \right) + \left(SHGC \right) A_{pf} E_t \qquad (6.2)$$

where,

j_{window} is total heat flux transfer through window

T_{out} is outdoor temperature

T_{in} is indoor temperature

$SHGC$ is window's Solar Heat Gain Coefficient

A_{pf} is window solar projection area

E_t is incidental solar radiation received on window

The model states that energy transfer through window by conduction, affected by window's U value, and solar radiation, determined by using window's SHGC. So, Window's U value and SHGC become key fenestration system parameters for optimal building performance.

6.3.2.1 Window Type Design

A more detailed look at one window example is given in Figure 6.13(a) and its energy flow schematic is shown in Figure 6.13(b). Based on how much solar radiation transfered, reflected, and absorbed through window, windows can be further defined as four major types – clear, absorptive, reflective, and Low-E. The "'clear"' window type transfer most solar radiation (around 80%) into buildings. "'Absorptive"' window can absorb relatively more solar radiation and the solar heat gain can increase window's temperature, then energy is transfered via convective heat flow. "'Reflective"' window, compared with clear window type, can refelct more solar radiation

back to exterior and thus decrease the amount of radiation energy get into buildings. ”‘Low-E”’ window usually applies low emmissivity material on one or more window pane surfaces, the low emmissivy materials can significantly decrease the long wave radiation energy exchange between indoor and outdoor environment, and thus stop especially heat loss in winter time. *WINDOW* (2009) introduces details window types descriptions and their energy flow characteristics.

(a) An window example

(b) Window energy flow example
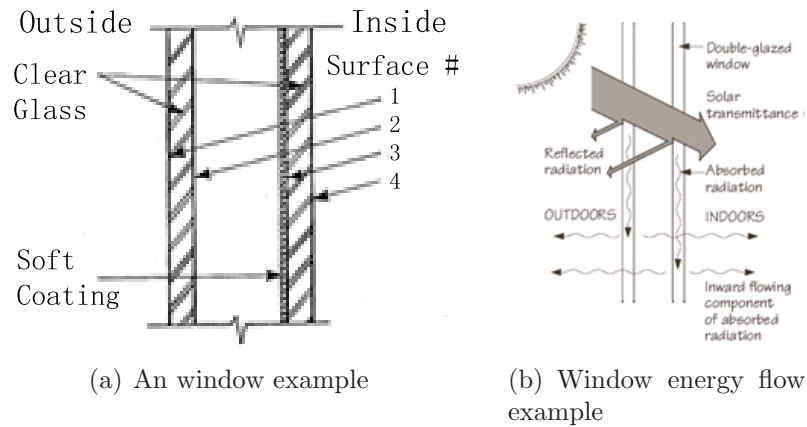
Figure 6.13: An Window Example and Energy Flow (*WINDOW*, 2009)

To understand what type of window system is suitable for our case building, ”‘Clear”’, ”‘Reflecting”’, ”‘Absorbing”’, and ”‘Low-E”’ four different window types are studied in our case building. Also, the U value of each window type can significantly affect building's energy performance and is another important performance parameter for study. Moreover, the selection of window type and U value need to combine with building's WWR and then contribute whole building's energy performance. By considering window type, U value and WWR those three parameters, a series of simulation studies are conducted by populating different window types, U value, and WWR.

In this study, Central New York Climate conditions is applied to the case building. The building's form and massing is maintained the same as designed in Section 6.2. The opaque building envelope determined in Section 6.3.1 is adopted for opaque

building envelope model. Conceptual HVAC system is configured to evaluate the heating, cooling energy. Since the design of building WWR is directly related to building lighting energy consumption, for lighting study needs, the whole building is assumed to have dimming control with floor illuminance level controlled at 500 lux. Double pane window configuration is applied to all simulation cases. The case building's energy performance is simulated under multiple window configurations and results are shown in Figure 6.14.

(a) Cooling Energy

(b) Heating Energy

(c) Lighting Energy
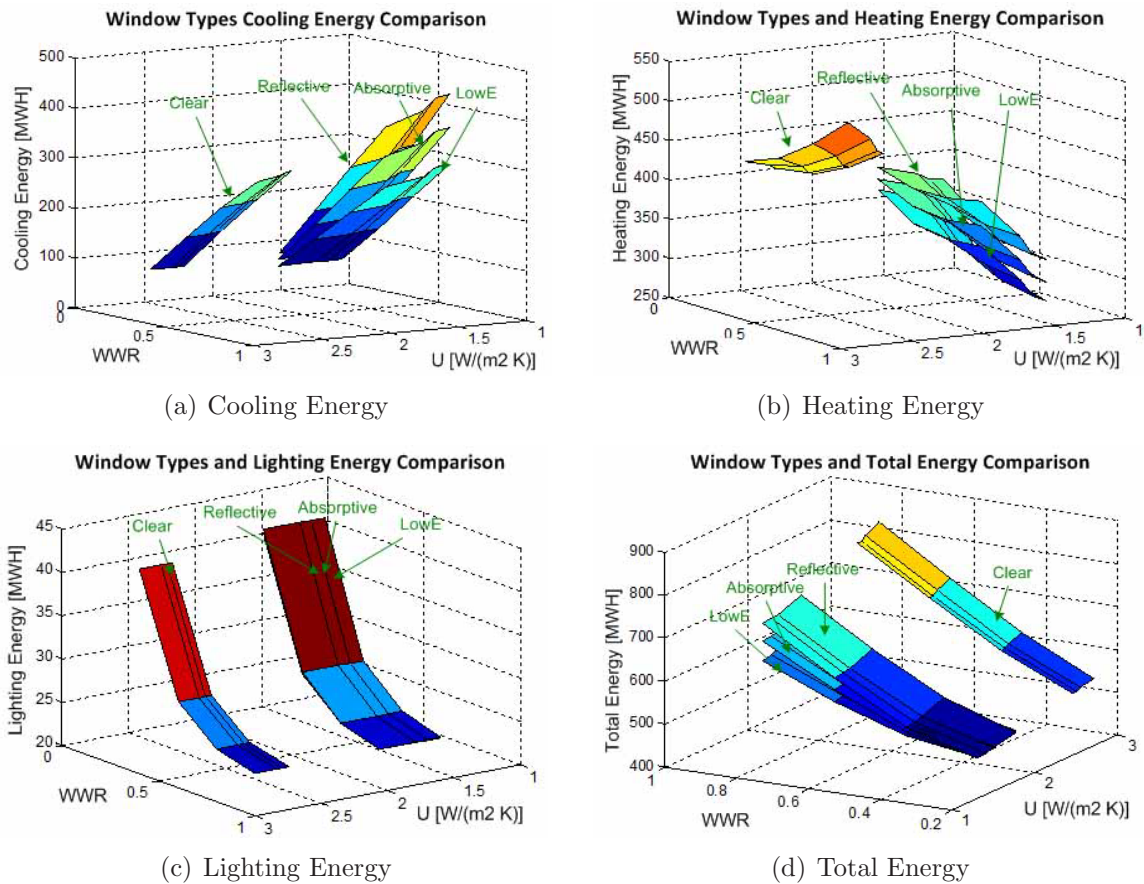
(d) Total Energy

Figure 6.14: Effects of Window Types on Building Energy Consumption

The cooling, heating, lighting and total building energy consumption is simulated under "Clear", "Reflective", "Absorptive" and "LowE" four different window types. "Clear" type window exhibits the highest U value in all four window types. Both "Clear" and "LowE" window type give the lowest cooling energy consumption under

different U value and WWR configurations. And the increase of WWR will always result in the increase of cooling energy because large window area will introduce more solar radiation into building and thus increase building's cooling load. (Here shading systems are not considered in the design yet.)

For heating energy, "Clear" window cases' heating energy increases with WWR because the high U value of "'Clear"' window makes that the increase of solar gain of building can not compensate the heat loss through windows in winter. However, the heating energy for "Reflective", "Absorptive", and "LowE" window cases decreases with WWR because the low U value enables the building to gain more radiation heat compared with the heat loss through window conduction. Also, under certain WWR value, the decrease of window's U value (e.g. use inert gas in window's air gap) can further decrease heating energy consumptions by reducing heat conduction. Among these window types, "LowE" window shows the best heating energy reduction performance.

Window's U value has no influence on building's lighting energy consumption. And all four window types exhibit the similar lighting energy consumption profiles. Increase of WWR allows more natural lights to enter building and thus reduce the artificial lighting demands.

For building's total energy performance, "LowE" type window with low U value (argon filling gas) gives the best results. The actual selection of WWR needs detailed investigations on each facade's WWR value and shading systems. However, it can be found that, without shading systems, the building's total energy consumption is only 20% higher at 80% WWR compared with that of 20% WWR. The increase in energy consumption can be significantly reduced by applying shading technology. In the case building of this study, motorized blinds are installed in the cavity of the glazed curtain wall. Another important advantage of large WWR is to give occupants more

visibility to exterior environments and thus improve occupants psychological feelings and productivity.

6.3.2.2 Window To Wall Ratio Design

Window to wall ratio affects building energy profile not only because it affects the area of window and thus contribute to building energy performance through solar radiation, natural lighting, and heat conduction through windows, but also affects opaque building envelope area and thus relates to the designs of opaque building envelope.

To demonstrate how WWR relates to opaque building envelope designs, we simulate building's total energy performance based on WWR designs and building opaque envelope selections (U value). Building's climate conditions, shape and orientation are kept the same as simulated in previous cases. Opaque building envelope prototypes can be found in section 6.3.1. The case building's total annual energy consumption is simulated under opaque envelope design (U value) and building's total WWR. The results of WWR's impact on opaque building envelope design and building energy performance is shown in Figure 6.15.
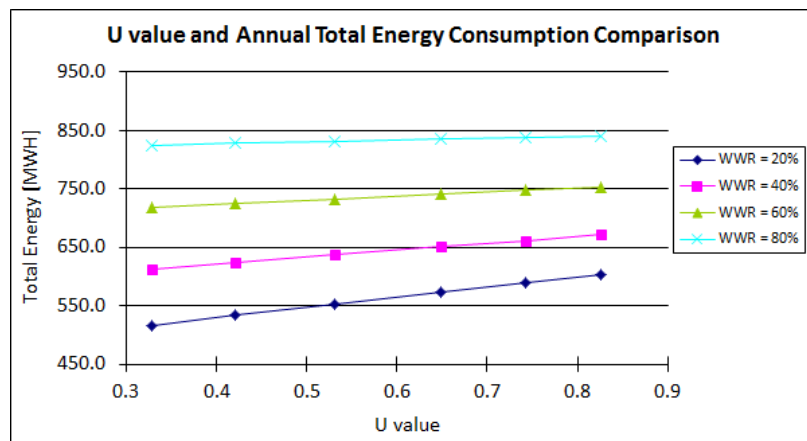
Figure 6.15: WWR and Opaque Envelope U on Building Energy Performance

It can be found that the influence of U value on building's energy performance is almost linear. And with the increase of WWR, the change of opaque envelope's U value becomes less influential to building total energy consumptions simply because the area of opaque envelope decreases with the increase of WWR.

However, the characteristics of WWR in building performance not only relate to changing building's opaque wall to window area ratio but also connects with window system designs. Here, according to previous window type design simulation, the "LowE" window type exhibits the best energy performance and is adopted in this case. The U value of "LowE" window is also selected by using Argon filling gas. All other simulation conditions are kept the same as previous window types simulations. Here, we are especially interested in how to select WWR value on our case building's each facade, and how WWR relates to the availability of window shading. All cases are simulated under "without shading" and "with shading" conditions. For "with shading" scenarios, window blinds are controlled to turn on during summer season (May 1st – Oct. 31st) to block solar radiation passing through windows, and turn off during winter season (Nov. 1st – Apr. 30th) to allow radiation energy come into building and reduce building's heating energy demands. The case building's South, North, West and East facades WWR designs are simulated. The results are given in Figure 6.16, 6.17, 6.18, 6.19 respectively.

(a) Cooling Energy   (b) Heating Energy

(c) Lighting Energy   (d) Total Energy
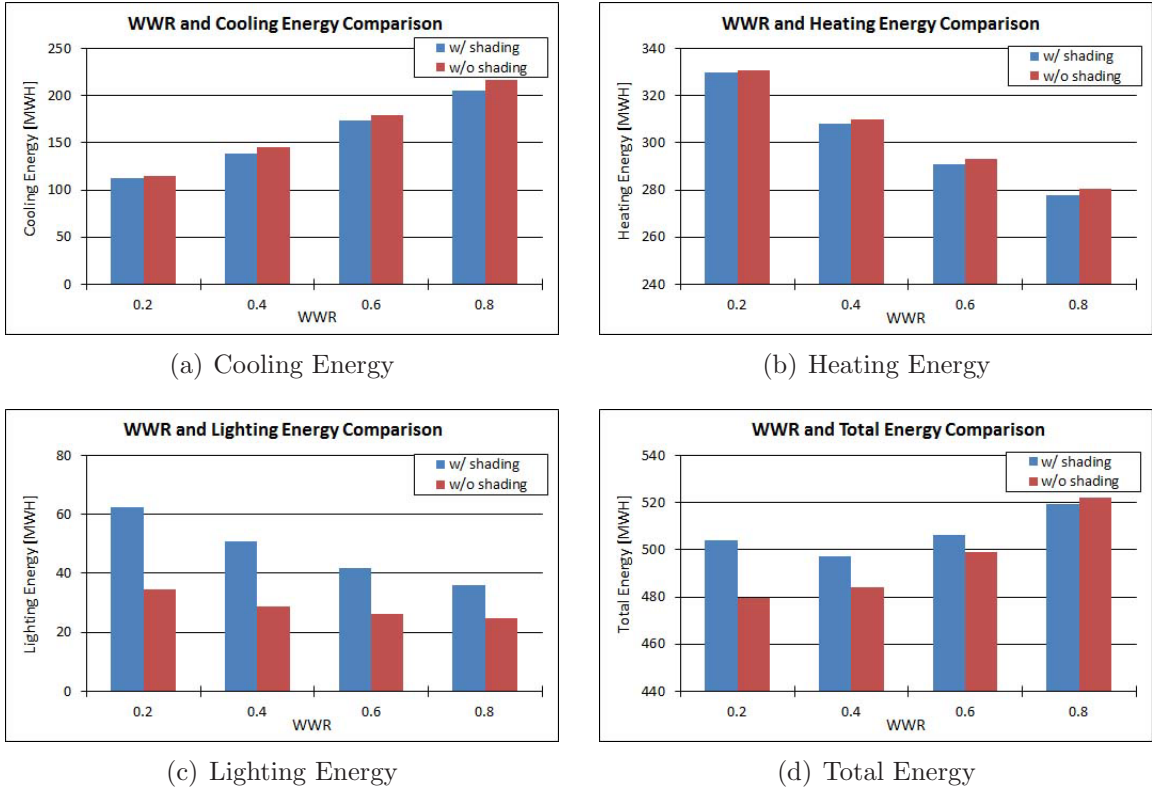
Figure 6.16: South Facade WWR and Building Energy Comparison

Figure 6.16 shows the design of South facade WWR and building's energy performance. The building's cooling energy increases with the increase of WWR value on the South facade. However, with shading control, it can reduce certain amount of building's cooling energy demand by reflecting solar ray and blocking radiation energy. For heating energy, WWR plays a positive role in reducing heating demands by making use of solar energy. Higher WWR value on the South facade also utilize daylight and decreases lighting energy consumption. Overall, the building's total energy performance at high WWR value is very close to that at low WWR value. Thus, from building performance point of view, to have relative high WWR value is acceptable for energy consideration. Moreover, to have large window area at building's South side can enhance building's visibility viewed from both inside and outside of building as well as building's aesthetic value. The simulation results also suggest that window blind or screen shading is recommended in summer season. Shading device should be

turned off during the day in winter time to increase building's solar heat gain .

(a) Cooling Energy

(b) Heating Energy

(c) Lighting Energy

(d) Total Energy
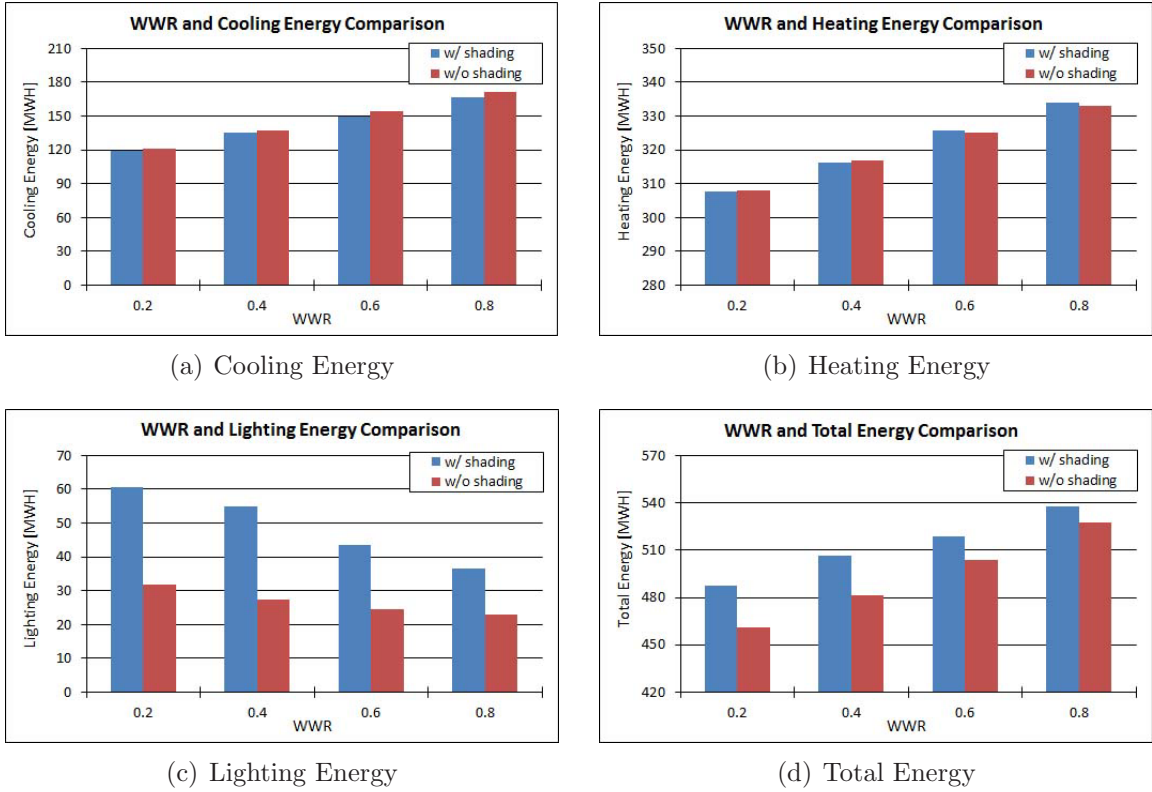
Figure 6.17: North Facade WWR and Building Energy Comparison

To have high WWR value at building's North facade will increase building's heating and cooling energy even though it is good for daylight. Since the building is located at relative high North latitude, large window area can not bring extra radiation energy into building but, on the other hand, makes the building more sensitive to window conduction heat gain/loss. So, according to simulation results, it is generally not recommended to have large window area in the North facade.
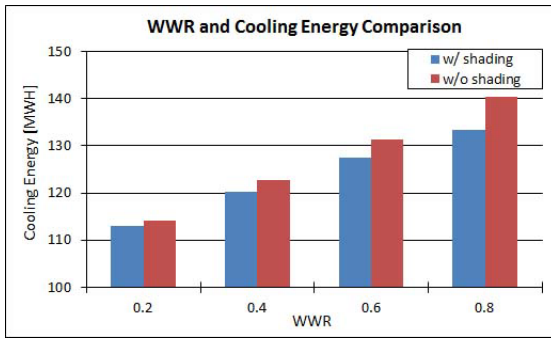
(a) Cooling Energy
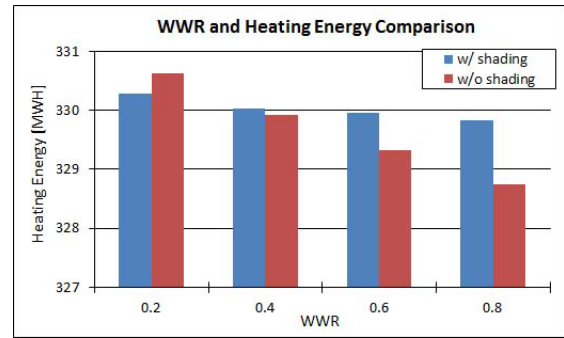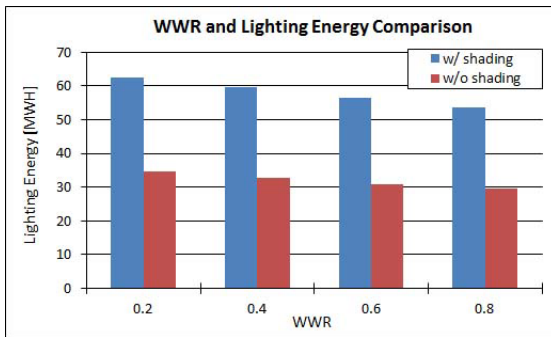
(b) Heating Energy

(c) Lighting Energy
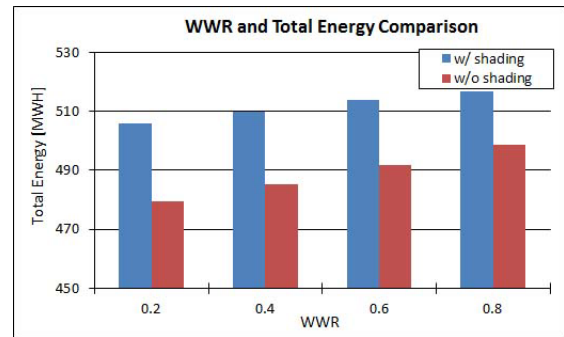
(d) Total Energy

Figure 6.18: West Facade WWR and Building Energy Comparison

Large window area on the West side is generally not a good practice because of large cooling energy demands. Large WWR has relatively small effects in reducing artificial lighting energy because the existing building shape gives small West facade area and it is very difficult for daylight to penetrate the building from its West side. WWR influence cooling and heating energy in the similar way as demonstrated in South facade case.
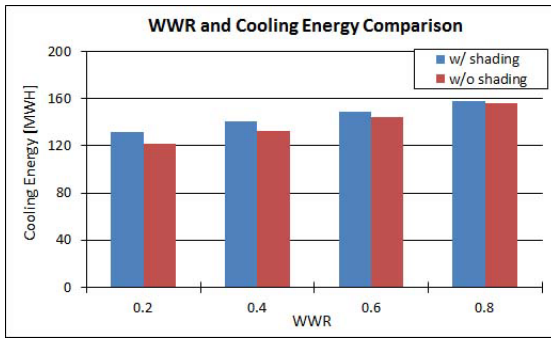
(a) Cooling Energy
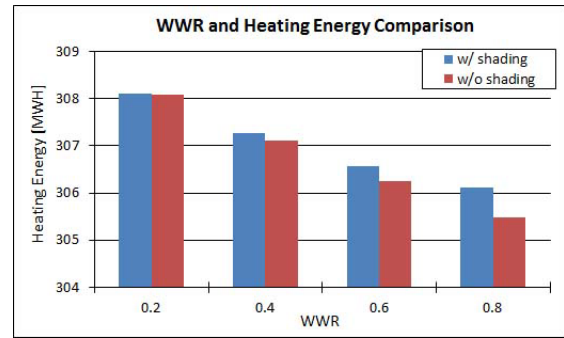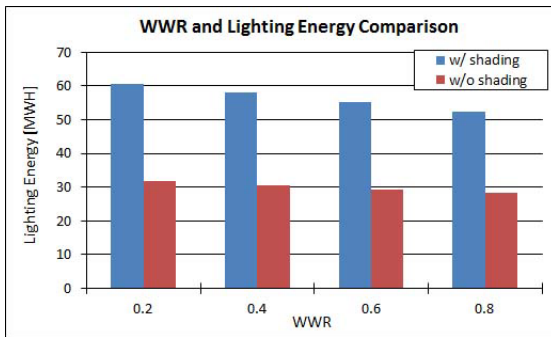
(b) Heating Energy

(c) Lighting Energy
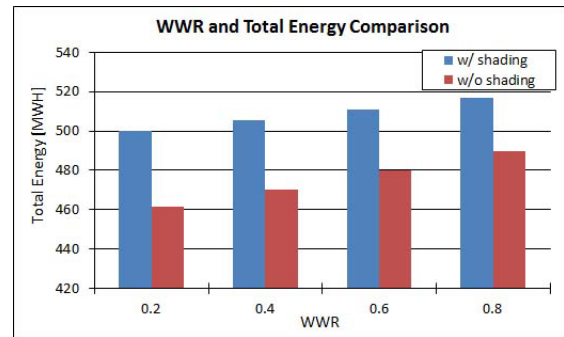
(d) Total Energy

Figure 6.19: East Facade WWR and Building Energy Comparison

On the East facade, large WWR value is acceptable according to energy simulation results. And the results pattern is very similar as West facade WWR design case shown in Figure 6.18.

Based on the results of each facade's WWR and shading design study. It is concluded that large WWR value (i.e. curtain wall, WWR > 80%) is recommended on the South facade, small window area or no window is suggested at North side building envelope. On the East and West side large window area is acceptable and is optional for design considerations. Finally, the fenestration system is designed to use "LowE" window type with argon gas filling, curtain wall at building's South side (WWR > 90%), 30% WWR at North side facade, 80% WWR on the east side and 0% at building's West side. Combined with the opaque building envlope design, the case building's envelope designs are well studied and will be used for following sections on building systems design studies.

6.4 Building zoning and interior program design

Building interior program design is to develop interior room/zone programs and functional spaces to meet with building's function. The interior program design is often called "zoning" by architects. The division of building interior space will affect, from building energy performance point of view, space's area, daylight penetration depth, setpoint and controls, thermal comfort requirements, and conditioned or unconditioned zone requirements.

For commercial office building, like our case building, the major task of interior program design is to divide each floor area into multiple functional spaces. The case building is 100% conditioned, and the main fucntional space types in this building are office/meeting room and corridor. Thus, the arrangement of these two functional space types become the core of interior program design. One floor of the case building is taken to evaluate interior design program. Two zoning strategy is evaluated here, the first one, which is also called "external circulation design", is to put corridors close to building envelope and office rooms in the middle of the floor. And the second design method is to have corridors in the middle of the floor but have offices and conference rooms close to building envelope. The two zoning strategies are illustrated in Figure 6.20. Furthermore, the interior partition type is also related to the program design. Two partition designs are considered in this study. The first one is traditional gypsum wall board partition and the second one is to use glass wall to create transparent partition which is often seen in modern interior space design. Compared with traditional gypsum wall board partition, it is estimated that the glass wall has potentials to distribute daylights into rooms and thus reduce lighting energy demand. However, the possibilities of energy savings need to be verified through performance simulation.

The simulation case is built by applying the known building shape and orientation,
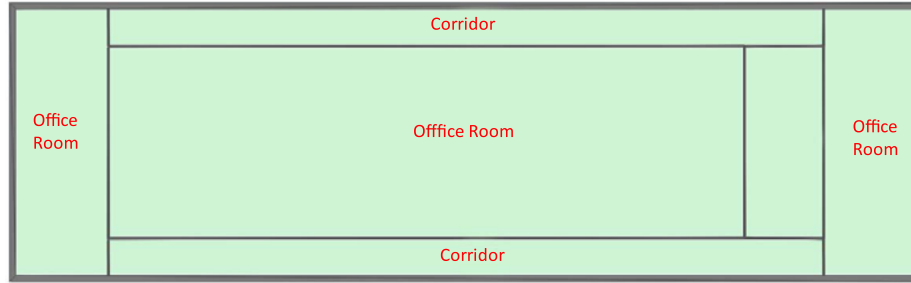
(a) External Circulation Design
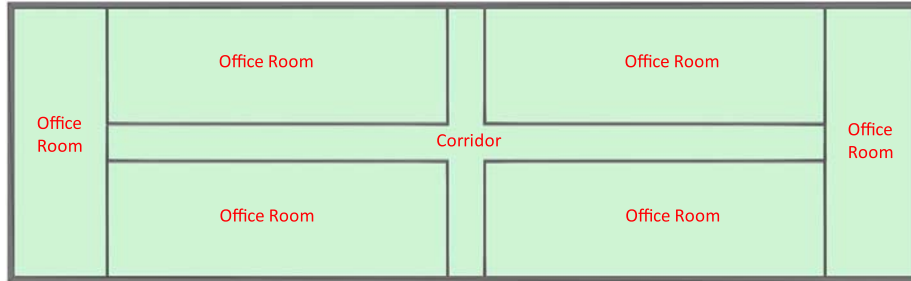
(b) Internal Circulation Design

Figure 6.20: Interior Program Design Methods

climate conditions, opaque and fenestration designed and determined in previous sections. The only variation is interior program design and partition wall type. We control corridor zones $2\ ^oC$ higher for cooling season and $2\ ^oC$ lower in heating season when compared with ordinary office zones. Because corridors are not frequently occupied, this control difference of control setpoint can achieve energy saving for corridors and, at the same time, maintain building's thermal comfort needs. All four interior program design cases for the case building's third floor are listed in Table 6.4.

The whole building's energy performance is simulated, and the third floor's results are given. The third floor energy simulation result is given in Figure 6.21. It can be found from the simulation results that the cases with glass partition wall exhibit to have lower lighting energy consumption and therefore total energy consumption. That is because the glass partitions allow daylight, mainly entering from the building's South facade curtain wall, to penetrate through corridors and office rooms and diffuse to

178

Table 6.4: Interior Program Design Cases

No.	Case Name	Description
1	Interior Circulation with opaque partition	Interior corridor with gypsum wall board partition
2	Interior Circulation with window partition	Interior corridor with glass wall partition
3	Exterior Circulation with opaque partition	Exterior corridor with gypsum wall board partition
4	Exterior Circulation with window partition	Exterior corridor with glass wall partition
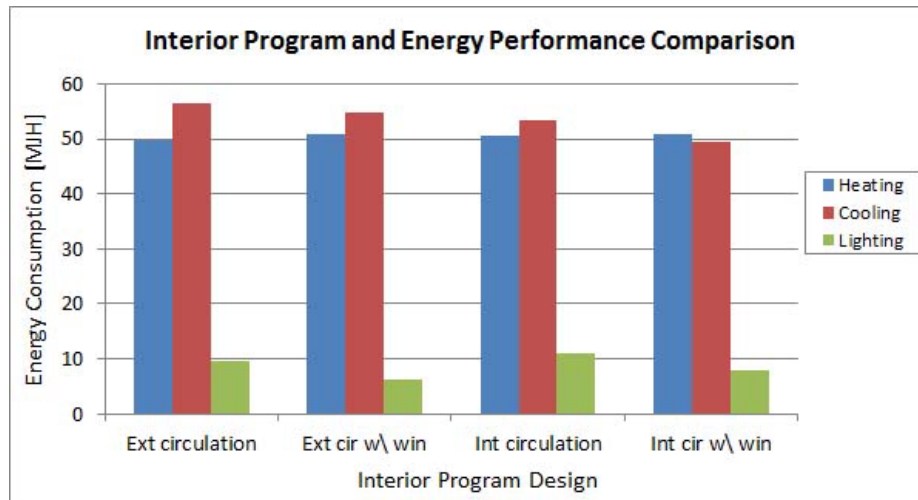
Figure 6.21: Interior Program Design Results

cover more floor areas compared with opaque partition wall.

However, the result does not give strong preference on which interior design strategy is better for building's energy performance. The total energy for interior circulation design and exterior circulation design demonstrate similar energy performance with glass partition wall. The main reason of this result is because the change of corridor and room space configuration does not pose significant change on building's whole cooling and heating load. Since the corridor and office space areas are the same in different cases (to maintain building's functional needs), the heat transfer between office rooms and corridors are relatively constant. Even though, for each corridor and office room, energy demand could be different, the whole floor's total energy

179

consumption shows similar patten.

6.5 HVAC System Designs

The previous sections have intensively discussed the architectural building design aspects regarding building environment, building form and orientation, building envelope and fenestration system, and interior program designs. After several design cases studies and simulation model validation, it is found that for given open urban context at Climate Zone 6 (Central New York Area), the building exhibits the best energy performance under aspect ratio of 3:1 (West-East : North-South). And the designed opaque building envelope has its U value of 0.328 $W/(m^2K)$. The fenestration system is designed to use double pane Low-E window type, and with curtain wall at building's South Facade, no window at West facade, and 30% window conver ratio on the North facade. Shading control is needed especially for building's South facade to block radiation energy come into the building and reduce cooling energy demand in the summer time.

In the detailed design stage, since most of architectural features have been determined, the design emphasis is shifted from architectural design to building service systems design. Preliminary Especially for energy and indoor environment quality consideration, heating, ventilation and air conditioning (HVAC) system designs become critically important for this stage.

For medium size commercial office building, like our case, the major role of HVAC systems is to maintain building's thermal comfort and indoor environmental qualities. The HVAC systems mainly serve for the office area, corridors and lobby (the case building has a one floor attached warehouse, but it is not the design object in this study.) Two parts of HVAC are considered here, the first part is also called as "Water Loop" which is HVAC systems central plants including equipments like chillers, heat pumps, boilers etc. which generate heating and cooling water for terminal equipments needs. Axillary equipments like pumps, cooling tower etc. are also included in this

part. The terminal parts of water loop system refer to cooling, heating coils, radiant panels, reheat coils and so on. The second part is called as "air loop" system which, most of time, distributes the heating and cooling energy to condition room space of the building as well as provides necessary fresh air for ventilation and indoor air quality needs. The design of primary system and secondary system is performed separately in following section, and the final design of the whole building HVAC system can be an integration of those two systems. However, sometimes the integrated consideration of water loop and air loop is needed.

6.5.1 Air System Design

The air system can have various forms in HVAC design. For our case building study, we consider the most common applications in office buildings such as constant air volume system, variable air volume system and dedicated outside air with radiant panel system.

6.5.1.1 Air System Design Alternatives

The terminal side of most air system in conventional office building usually uses all air system which often refers to hydronic variable air volume (VAV) system. For some old building, air and water mixed system such as fan coil unit (FCU) is also common. To maintain building's ventilation and thermal comfort needs, all systems are designed to operate within a daytime dead band of 21° - 24^oC. The minimum ventilation requirement is specified as per prescriptions of *ASHRAE* (2004a). For VAV system, the terminal box is configured to have the flow fraction of 0.3 as per typical VAV design for office environments. The VAV box reheats the supply air that the hot water flow rate through reheat coil ramps up with minimum air flow rate until the maximum hot water flow is reached. Then the air damper is gradually

opened from its minimum stop position to further increase heating capacity. For FCU system, each room is configured to condition with FCU. For each FCU, a three speed fan with heating and cooling coils is typical FCU equipment configuration used in office building.

For air system primary loop, air handling unit is the main design equipment. For most of commercial building, a minimum total outside air fraction of 0.25 is used. This configuration is also adopted for our air system design as combined with VAV and CAV-FCU. *ASHRAE* (2004a) also specifies office building's different space ventilation. The mappings between space type and standard and the resulting ventilation rates are presented in table 6.5. For our case, majority of building floor area is office and conference room. The sum of total building area gives the required flow rate for the whole building which is used for AHU design and fan sizing. The coiling coil and heating coil is installed in AHU and the size of the coils is determined and sized based on building's cooling and heating load.

Table 6.5: Office Building Ventilation Rate

Space Type	ASHRAE 62.1-2004 Space	Ventilation per Person $[L/s \cdot person]$	Ventilation per Area $[L/s \cdot m^2]$
Office	Office::Office Space	2.36	0.30
Conference	Office::Conference/Meeting	2.36	0.30
Restroom	Office::Office Space	0.00	5.28
Star	Office::Office Space	0.00	0.00

To use fresh OA to condition indoor environment, air side economizer is often used in office building AHU. *ASHRAE* (2004a), Section 6.5.1 states that an economizer is required in climate zones 2B, 3B, 3C, 4B, 4C, 5A, 5B, 6A, 6B, 7 and 8 for systems with cooling capacities larger than 40 kW. Most of office building's economizers are controlled according to air enthalpy.

The traditional office building HVAC air system is described above. VAV or FCU is

designed for its terminal air system and AHU with economizer and mixed air system for primary air loop. However, for better energy and indoor air quality consideration, one alternative HVAC design is considered. In this design, instead of using all-air system (VAV system) or air-water mixed system (FCU) at building's terminal side, all-water system – radiant panel is considered. The advantages of applying radiant panel system compared with other terminal systems are:

- the use of radiant heat exchange between panels and occupants can significant reduce the amount of energy used for ventilation to balance building heat load.

- the control and operation of radiant panel system can achieve better energy saving compared with traditional VAV or FCU systems

- since radiant panel system removes or supply heat to the space via radiant heat exchange, the total supply air to each space can be significantly reduced to the level of required outside air supply. The need of OA is achieved by applying dedicated outside air (DOAS). The DOAS in combination with radiant can produce effective energy saving as well as good indoor environmental qualities.

With radiant panel, office rooms heating and cooling temperature is set at 21 ^{o}C and 24 ^{o}C respectively measured in operative temperature. Building's heating or cooling load is neutralized via radiant and convective heat transfer without additional fan energy consumption as FCU system does. The heating and cooling capacity radiant panel provides, without introducing extra air flow into office rooms, can significantly reduce the AHU's fan size and thus decrease main supply fan energy consumption.

Moreover, radiant panel system is controlled at operative temperature instead of dry bulb air temperature. The comparison between radiant panel system and traditional VAV system control temperature is given in Table 6.6. It can be found that under the same thermal comfort (PMV) condition, radiant panel system tends to condi-

tion building space with lower room air dry bulb temperature for heating and higher room air dry bulb temperature for cooling. This is because the radiant heat exchange happended between the radiant panel and occupants does not require directly conditioning room air mass compared with traditional VAV or FCU system and thus reduces heating and cooling energy demands.

Table 6.6: Radiant Panel, VAV system comparison (*NREL*, 2010b)

Control Type	VAV System			Radiant Panel System		
	Air Temperature [^oC]	MRT [^oC]	PMV	Air Temperature [^oC]	MRT [^oC]	PMV
Heating	21.1	21.1	-0.17	20.0	22.8	-0.17
Cooling	23.9	23.9	0.12	25.6	21.1	0.12

Another advantage of radiant panel system is the advantage of combination with dedicated outside air system. Since radiant panel does not bring fresh air or contribute to office rooms air change, dedicated outside air system can compensate building's needs on air change by dedicatedly bring in OA and refresh room air. The DOAS is usually operated under 100% OA, so, quite often, energy recovery in a DOAS is needed. For our case building, located in Climate Zone 6, both sensible and latent heat recovery are considered. And one enthalpy recovery wheel is designed to operate between exhaust and supply air duct. The DOAS' fan size is determined by building's ventilation needes specified in Table 6.5. Because DOAS' fan is only designed for ventilation needs and most of building cooling/heating load is conditioned by radiant panel (radiant floor), the fan size of DOAS could be greatedly reduced when compared with VAV or CAV/FCU system. Furthermore, for indoor air quality consideration, the 100% OA has the potential of improving office room air quality because DOAS fully exhausts indoor pollutants without recirculating and mixing with OA. Another advantage of radiant panel and DOAS is that the HVAC duct size is reduced signifcantly and more space is available for the building.

6.5.1.2 Air System Design Simulation

In the aforesaid section, three air system designs are proposed: VAV system with AHU of mixed OA box, FCU with AHU of mixed OA box, and radiant panel system with DOAS. The advantages and disadvantages of each system is stated. In this part, we are going to model each of these systems and simulate building's performance to quantify three design alternatives.

For VAV and FCU system, the room dry-bulb temperature is our control target. The indoor temperature is controlled at 21 ^oC for heating and 24 ^oC for cooling. The AHU fan size is determined by building's ventilation needs. 25% OA is applied to the OA mixing box. And the size of cooling and heating coil in the AHU is determined by building's cooling and heating load under the supply air control temperature of 13 ^oC for heating and cooling. The rest of heating and cooling energy is delivered by terminal VAV box to meet room control conditions. Also each terminal VAV box and FCU is sized automatically to meet each room's heating or cooling load.

For radiant panel system, as given in Table 6.6, room operative temperature is our control object. The radiant panel is operated with water coil 100% open when the room operative temperature is lower than 21 ^oC for heating, and higher than 24 ^oC for cooling. Control dead band exists between 22-23 ^oC. Radiant panel is operated in propotional ramp control between 21-22 ^oC for heating and 23-24 ^oC for cooling. The dedicated outside air system is applied with enthalpy recovery wheel and 100% OA supply air. The fan size is determied by case building's OA ventilation needs. For energy recovery, an enthalpy recovery wheel is normally operated at sensible effectiveness of 60% and latent effectivess of 50% with pressure drop of 175 Pa. Since both supply air and exhaust air pass through the enthalpy recovery wheel, an overall 350 Pa pressure drop is applied to the enthalpy recovery wheel.

For all three system, the water loop are identical by application chillers and cooling
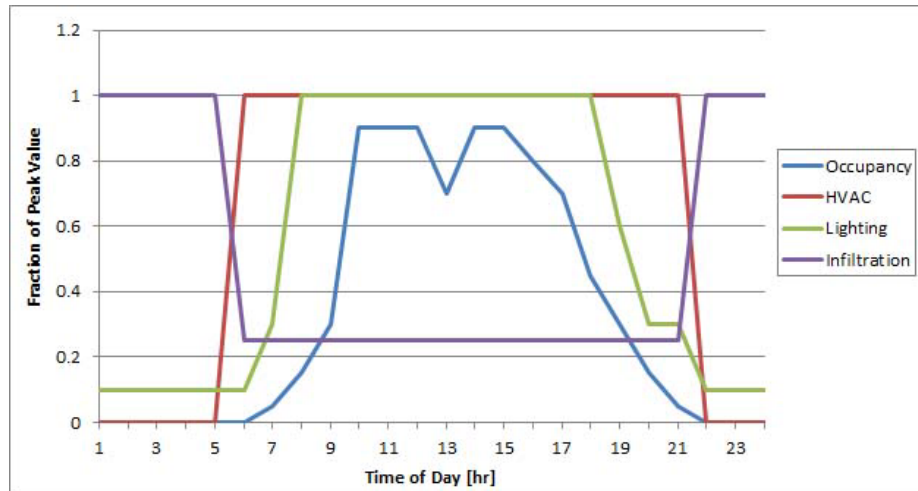
Figure 6.22: Building operation schedules

towers for cooling and boilers for heating. The chiller COP value of 5.2 and boiler efficiency of 80% are assumed. All other pumps, cooling tower sizes are calculated automatically.

All systems are operated under the similar schedules illustrated in Figure 6.22. The occupancy, infiltration, lighting control patterns are kept the same. HVAC is turned on at 6:00am in the morning and turned off at 10:00pm.

The room temperature is controlled as shown in Figure 6.23. Here, for VAV and FCU system, room dry-bulb air temperature is control object, while for radiant panel system, the control temperature indicates room operative temperature.

We simulate the VAV, CAV/FCU and radiant panel with DOAS three different systems. All three cases share the same climate conditions, building form and orientation, envelope and fenestration system, interior configurations as designed in previous sections. The simulated results are shown in Figure 6.24. It is found that FCU system, compared with VAV system, exhibits more fan energy consumptions. VAV system, has slightly higher heating energy consumption, because of the use of reheat coil at VAV box terminal side. However, the amount is not very significant. The variable frequency drive (VFD) used to control AHU's fan can produce about 20-30% fan

187
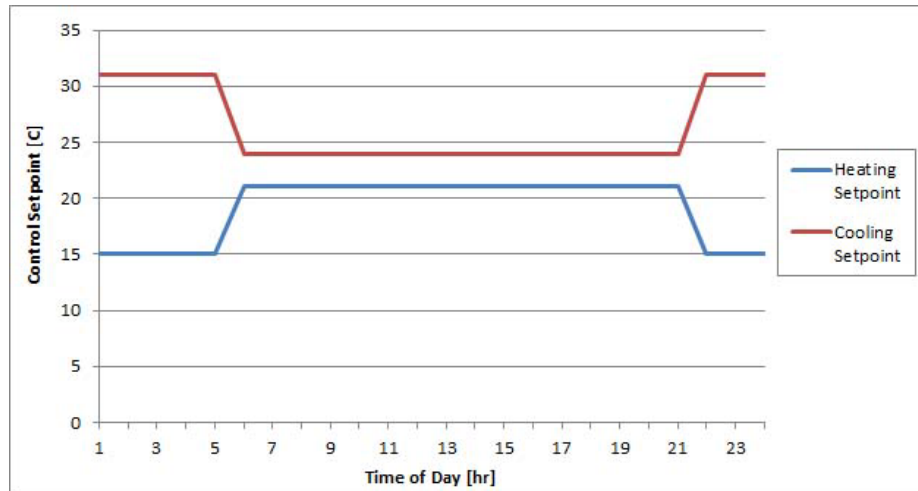
Figure 6.23: Building control setpoints
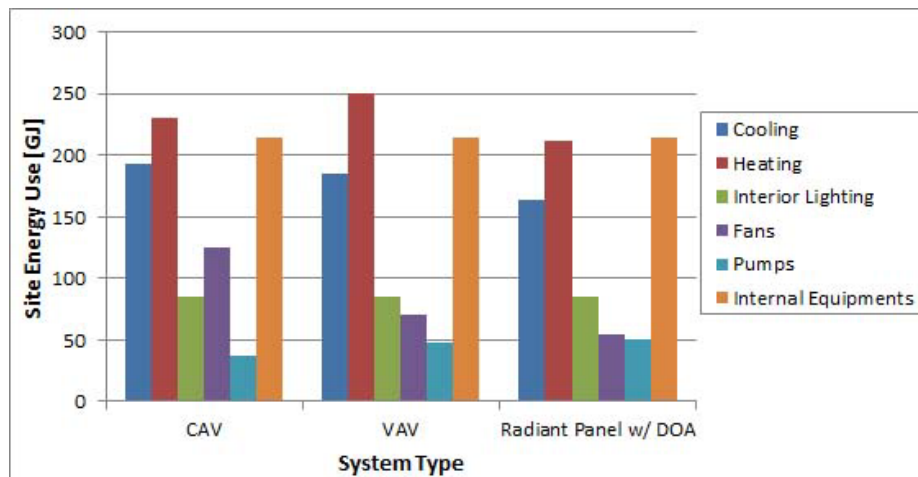
Figure 6.24: HVAC Terminal System

energy saving compared with FCU system without VFD control. Radiant panel system with DOAS exhibits the best energy performance among all three systems. The energy savings of radiant panel and DOAS mainly come from the operative temperature control which allows broader band of room dry-bulb temperture and fan energy savings by using smaller size AHU fan.

For building total energy performance, the radiant panel and DOAS shows site energy use of 780.02 GJ, VAV system 851.95 GJ and FCU system 887 GJ. The potential saving of applying radiant panel and DOAS is about 10% compared with VAV system.

Because of the energy efficiency advantage, radiant panel with dedicated outside air system are selected as the terminal side heating and cooling system, and air system.

6.5.2 Water System Design – Plant Room Systems

Once the terminal and air system is decided, the design tasks shift to central plant systems. The main purpose of plant room systems is to generate heating and cooling water used by air and terminal systems. The central plant system is also where energy like electricity and natural gas get converted to water source based energy. We are going to analyze the design of heating and cooling system in this section and compare a couple of design alternatives.

6.5.2.1 Traditional Water System Design

First of all, the design of the heating system is studied. Most traditional heating system uses boiler as central plant equipment. The boiled hot water is circulated by a heating water pump to the heating coils and terminal equipments for conditioning the whole building. However, most of traditional boiler has combustion efficiency around 75% to 85%. ASHRAE 90.1-2004 (Table 6.8.1F) requires natural gas-fired, water boilers with size less than 88 kW has minimum efficiency of 80% and with size less than 733 kW but bigger than 88 kW has minimum efficiency of 75%. The boiler's effiency depends on its load and inlet water temperature. For traditional office building boilers, an effiency curve, with maximum value of 83% of its combustion efficiency at 50% boiler part load and minimun 79% efficiency at 15% part load, is often produced for energy performance modeling. And this configuration is used for our traditional heating plant system design (*NREL*, 2010b).

The traditional design of cooling plant system consists of chilled water (CHW) system and condensing water (CW) system. Chillers are the main equipment in CHW

loop, which absorbs heat from its evaporator and dump heat through its condenser. Four typical chillers can be found in the market according to its different compressor types, reciprocating compression, scroll compression, screw-driven and centrifugal compression. Different types of chillers produce their cooling effect via the "reverse-Rankine" cycle, also known as "vapor-compression". With evaporative cooling heat rejection, their rated reference coefficients-of-performance (COP) is typically more than 4.0 (this is not operation COP). Air source heat pump is not considered in this case since our building located at Climate Zone 6, and severe cold winter will make it impossible to operate for heating.

The rejected heat from chiller, circulated by condensing water pump, passes through cooling tower, and eventually rejected to environment. Most cooling towers are operated through evaporation of water to remove heat, and the evaporation process is usually accelerated by blowing fan. Various fan configuration can be found ranging from constant speed, three speeds, and variable speed driven by VFD and fan speed is controlled to maintain certain condensing water temperature.

The heating and cooling water pumps are designed that each has 40 ft (12.2 m) of water head and variable speed pump motors with efficiencies of 87.5% and 90.0% for heating and chilled water loops. Pump part load ratio (PLR) curves are cubic to accurately account for reduced power consumption at low PLRs.

6.5.2.2   Ground Source Heat Pump System Design

The aforesaid part described the traditional designs of CHW, CW and HW systems. Besides traditional system design, an alternative design strategy is to use ground source heat pump (GSHP) to replace chillers and boilers for both cooling and heating. The potential advantages of GSHP system:

- GSHP system can operate for heating and cooling mode, which, instead of using

190

chiller and boiler for two systems, reduce the complexity of system and initial equipment investment.

- GSHP system can make use of relative constant ground soil or water temperature and operate at relatively higher COP compared with other HP system.

Under cooling mode, GSHP system extracts heat from building and rejects it into ground soil or water. For the plant system, the entire process only involves major equipments like GSHPs, chilled water pumps (CHWP), and condenser water pumps (CWP). Compared with traditional chilled water system discussed above, GSHP system reduces the initial investment of cooling towers and some other components. During the winter time, GSHP system can switch from cooling to heating mode. Thus, GSHP system can replace traditional boiler system.

Another advantage of GSHP system is that it can operate under relative low ground soil or water temperature for cooling, and high ground soil or water temperature for heating. The upper 3 m of Earth's surface, depending on latitude, maintains a nearly constant temperature between 10 and 16 ^oC (*DOE*, 2011). And compared with air-sourced heat pump, the relative low condenser side temperature for cooling and high evaporator side temperature in heating can give GSHP to operate under COP usually range between 3 and 6. [4] In this study, Virtual Building monitoring system confirms that in Central NY climate region, the annual heating COP for GSHP can reach value of 3.6 or higher for a GSHP equipment with rated reference heating COP of 3.0 (*Carrier*, 2009). This is much more efficient than boilers operated around 80% for heating condition. From energy utilization and carbon foot print point of view, GSHP is also much more efficient and produce less green house gas.

To compare GSHP with traditional chiller-boiler water system configuration and their corresponding building's energy performance, a GSHP water loop model is built in

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[4]The COP for air source heat pump ranges from 2.6 to 3.8 rated by NRC (*Wikipedia*, 2011)

EnergyPlus to connect with air system, and terminal radiant panel. To meet with building's cooling and heating load with certain safety factor, Seven (7) GSHP is designed with each load side heating and cooling capacity of 73 KW. The source (ground) water side has heat extraction capacity of 50 KW under heating mode, and heat rejection capacity of 90.8 KW for cooling. The heating system has designed supply water flow rate of 0.0221 m^3/s and cooling system design supply water flow rate 0.0157 m^3/s. Should additional heating energy is needed for the case building in severe cold winter condition, two boilers are designed to provide additional heating and connect with heating water system. *ASHLEY McGRAW* gives detailed GSHP water loop design for our case building.

6.5.2.3   Ground Source Heat Pump Performance Simulation

The case building energy performance simulation result is given in figure 6.25 with GSHP and chiller-boiler plant system. The simulation results suggest that GSHP (*Carrier*, 2009) has higher cooling energy consumption compared with centrifugal chiller plant system. This is mainly because most centrifugal chiller can reach slightly higher COP value compared with GSHP. The GSHP machine we design for our case building has min reference COP value of 4.15 (EER 14.1). One simple approach suggests the GSHP actual operation COP is related to ground soil or water temperature which can be determined in empirical polynomial format in Equation 6.3 (*MNRC*, 2001-2005).

$$COP_{act} = COP_{std} \left(k_0 + k_1 T_{ewt} + k_2 T_{ewt}^2 + ... \right) \tag{6.3}$$

where,

COP_{act} is actual GSHP COP

COP_{std} is standard system COP value read from equipment manual. (e.g. measured
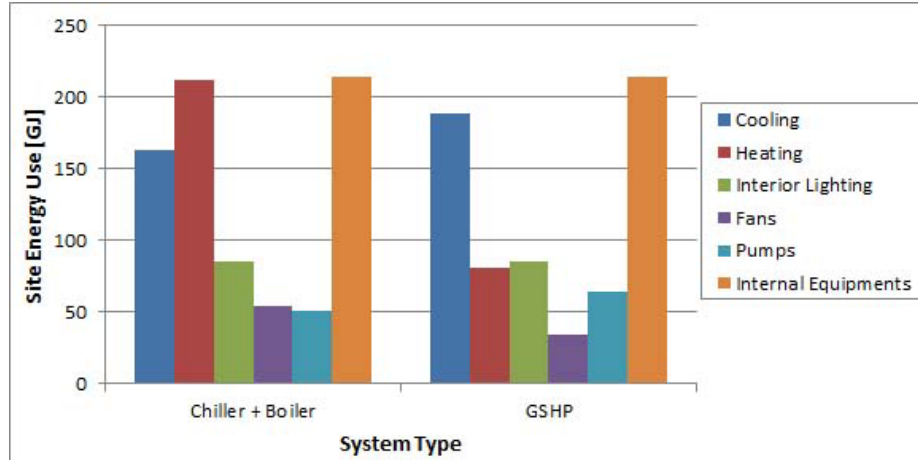
Figure 6.25: GSHP and Traditional Plant System Energy Performance Comparison

at standard rating conditions, 0 ^oC for heating and 25 ^oC for cooling)

k_0, k_1 are empirical polynomial coefficients

Once the actual GSHP COP is determined, the system operation cycling COP_{cycl} can be calculated by equation 5.3 by using the same degradation coefficient. The system partial load ratio can be calculate by assessing the system actual cooling energy production and the GSHP rated capacity.

GSHP system also requires more pumping energy to circulate ground side water, especially under heating mode when compared with boiler system. However, in cooling mode, since condenser water is cooled by ground soil instead of cooling towers, GSHP system does not use cooling tower energy. Another performance difference comes from heating energy. Most heating water is supplied by GSHP (about 80%) and the rest of it comes from boilers and the operation COP value of our GSHP during heating mode is around 3.6 on annual average. So, compared with boiler's efficiency of 0.8, this makes GSHP can save significant amount of heating site energy (if we used source energy for comparison, then the results will be slightly different). The total site energy of GSHP system is 668 GJ, while the boiler and chiller system

is 780 GJ.

After comparing GSHP and boiler-chiller systems' energy performance, the GSHP design is chosen for our water loop system. And, we will further discuss the effectiveness of GSHP system in the next section. Up to this point, we have finished all design alternative study and compare their impacts to building performance. The determined building massing, envelope systems, interior programs, HVAC air system and water system can eventually be implemented into our design model. The next step is to combine all design parameters together to study their interaction and how to design the optimal building performance and select all design parameters.

6.6 Multiple parameters design and performance optimization

In the whole building design process, the design parameters discussed in aforhead sections are inter-related to each other. So, the complex design practice, not only consider one or two parameters in one stage, but need to take multiple parameters and their interactions into consideration. For example, building envelope design and WWR selection are related to the design of building shape and orientation. There are some parameters, like HVAC system for example, even though their detail design is not considered in in early design stage, it is necessary to determine the general system types to better study building performance. From parametric study point of view, the interactions between multiple parameters requires one to select the best combination of parameter to meet the design goals.

6.6.1 Multi-parameter optimization

In this study, the design parameters evaluated in previous section will be combined together and optimization search is applied to find the best parameter selections for all parameter. Design objectives are setup, so the optimization engine can iterate with various parametric selections and drive design performance to meet with the objectives. Should one iteration does not reduce the "distance" between objectives and simulated performance, the optimization engine will intelligently select another set of parameter to minimize the distance. The optimization program used in this research is called "GenOpt", and its general structure is given in Figure 6.26. And simulation engine of this study is EnergyPlus.

This study use optimization engine "Hooke-Jeeves Generalized Pattern Search (GPS) Algorithm" in GenOpt. The GPS algorithms are derivative free optimization algo-

rithms, where the objective function (or called "cost function") $f()$ can not be evaluated exactly, but can be achieved in approximate methods. The GPS algorithms will apply search rules to find proper variables in the discretized space of dimension n (n is variable numbers), and if no decrease of cost function is obtained on the discretized n dimension space around current iteration, then the algorithm will reduce distance between the descritized points, and iteration is repeated. The Hooke-Jeeves algorithm is one type of GPS, and *Hooke and Jeeves* (1961) and *LBNL* (2009) give its detailed optimization algorithm.

The parameters for this case building performance optimization study and their parameter range are given below:

- building shape, aspect ratio (0.2, 5)

- orientation (0°, 360°)

- building envelope exterior color and solar absorptance (0.3, 0.9)

- South Facade WWR (0, 100%)

- window interior blind slat angle (0°, 85°)

- internal lighting density (7 W/m^2, 16 W/m^2)

- internal lighting illuminance level (300 lux, 600 lux)

- indoor room temperature setpoint, cooling (23 C, 26.5C)

- indoor room temperature setpoint, heating (18 C, 23C)

- HVAC system (VAV w/ chillers and boilers, GSHP w/ radiant panel)

The parameter's range is selected based on different design stage. For example, in early design stage, those parameters such as building shape, orientation, aspect ratio

will have broad range, while the HVAC system and control parameters can have a small range of selection or fixed default choice.

Each design parameter influence certain end use building energy performance, and hence design parameters interact with each other on whole building performance. For instance, the design of building's shape and orientation tightly connect with building WWR, and all of the parameters influence building heating, cooling and lighting energy consumption. Table 6.7 gives design parameters and their impacts on building performance. Here, C is cooling, H for heating, and L for lighting.

Table 6.7: Design parameter and their building energy impacts

Parameter	Impact
shape	C, H, L
orientation	C, H, L
envelope ext. color	C, H
South facade WWR	C, H, L
blind slat angle	C, H, L
lighting density	C, H, L
illuminance level	C, H, L
cooling setpoint	C
heating setpoint	H

The complexity inter-relation of design parameters to building performance requires to use optimization approach to select the most appropriate design parameters at the same time and calculate the optimal building performance.Thus, several design optimization objectives can be used to control the optimization program to achieve optimal performance. The objectives include minimize results of:

- site energy use

- energy cost

- primary energy use

- CO_2 generation from building energy use

197

Site energy optimization will calculate building's total annual energy consumption and the optimization program will minimize the total building site energy use. Energy cost optimization will calculate building's annual energy cost by multiplying different types of energy consumption with the energy tariff. Primary energy optimization will use primary energy converion factor to convert site energy to primary energy and minimize building's primary energy use. And CO2 generation minimization will reduce building energy consumption related CO2 emission. To do so, the grid and fossil fuel CO2 emission factor is obtained for NY state (*EPA*, 2006). All these optimization objectives share a common simulation scheme which calculate whole building energy site use for each energy type. Once one simulation scheme is calculated in an iteration, the optimization calculation scheme will read simulation results and determine if the results meet with the defined objectives. The optimization scheme will drive the parameters towards the set objectives until the optimization convergence is reached. [5]

Other objectives also include, to maximize building indoor environmental quality and to provide the optimal combined energy and IEQ performance, to optimize building life cycle cost (LCC) and so on. The combined energy and IEQ optimization study requires to develop methodology to evaluate combined energy and IEQ study together. This research only focuses on site energy, energy cost and primary energy use optimization.

The study of early design stage is conducted to have a default HVAC system, and vary other parameters to achieve optimal building performance. We apply VAV system with chillers and boilers and GSHP with radiant panel HVAC system separately to our case building. The building's geometry, envelope, fenestration and other systems described in previous sections are still applicable to this study. The objectives are

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[5] convergence is usually achieved when either the max iteration step is reached or the iteration is no longer observed significant objective results change.

defined to minimize its total site energy, energy cost and primary energy respectively. The total site energy is a "thermal" summation of building's electricity and natural gas energy use. Energy cost are calculated in $[kUSD]$ by applying commercial building energy tariff at case building's location. The total primary energy is converted from site energy by multiplying conversion factor of 3.167 for electricity and 1.084 for natural gas. The optimization process is shown in Figure 6.28, 6.29 for VAV system with chiller and boiler, and figure 6.30 6.31 for GSHP system with radiant panel.

6.6.2   Optimization results and discussion

The optimization process shows potential for significant reduction of building energy use as well as acceptable indoor environment quality, in terms of indoor temperature and illuminance level. The optimizations reach convergence after more than 200 iterations. To achieve the best total thermal energy, energy cost or primary energy performance, the performance of each system is traded off with each other so the total energy objectives can reach minimum value. The simulated optimal performance of thermal energy, energy cost, and primary energy are summarized in table 6.8 for VAV with boiler and chiller system, and table 6.9 for GSHP with radiant panel system.

Table 6.8:   Building performance optimization summary results – VAV w/ chiller and boiler

Case	lighting	internal equipment	cooling	fan	pump	cooling tower	heating [6]	total
energy [mWh]	20.34	71.01	41.57	13.24	10.48	1.24	35.52	193.42
cost [k USD]	3.686	11.362	6.23	1.98	1.59	0.19	1.36	26.36
primary [GJ]	261.5	809.6	446.8	141.7	114.0	13.4	146.3	1933.3

It is found that, under the optimal building performance, the GSHP with radiant panel system can reduce building total thermal energy, but the effect of energy cost and primary energy reduction is not significant. It is also noticed that, GSHP system

Figure 6.26: GenOpt Program Structure (*LBNL*, 2010)
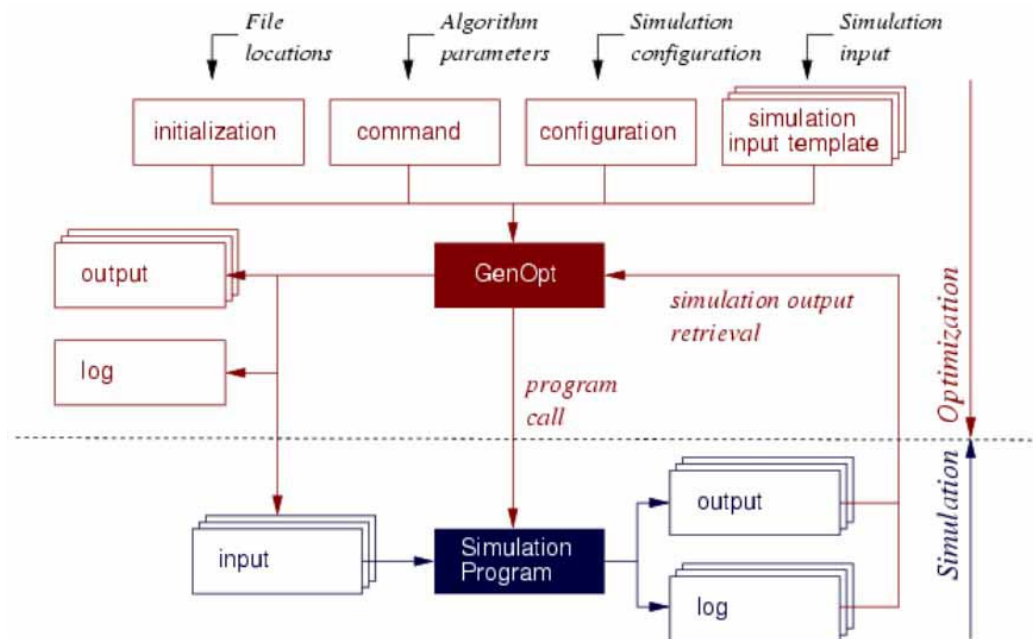
Table 6.9: Building performance optimization summary results – GSHP w/ radiant panel

Case	lighting	internal equipment	GSHP	fan	pump	total
energy [mWh]	21.43	71.01	41.57	7.96	11.41	154.83
cost [k USD]	3.43	11.362	6.88	1.27	1.83	24.78
primary [GJ]	245	809.6	491.9	91	130.5	1768

can increase pump energy because ground water loop has more resistance and require extra group water pump capacity. The radiant panel with DOAS is effective in reducing fan energy compared with VAV system. The GSHP system, compared with traditional chiller and boiler system, can use less thermal energy, since GSHP has COP value around 3.6 for heating which is more efficient than natural gas boiler whose efficiency is around 0.8.

Table 6.10: NY statewide monthly average energy price for commercial consumers

Month	electricity [$/kWh]	natural gas [$/k ft3]
Jan	0.152	10.85
Feb	0.152	10.57
Mar	0.148	10.78
Apr	0.15	10.04
May	0.163	9.46
Jun	0.173	9.28
Jul	0.179	8.86
Aug	0.168	8.82
Sep	0.159	9.18
Oct	0.158	9.60
Nov	0.157	9.48
Dec	0.156	9.69

However, when the optimization objective becomes cost, the advantage of GSHP is not obvious. Table 6.10 is a summary of NY state monthly avarge electricity and natural gas price for commercial consumers provided by *NYSERDA* (2010) for year 2010. The annual average price is about 0.16 [$/kWh] for electricity and 10$/GJ for natural gas[7]. The equivalent electricity price is equal to 44 [$/GJ]. The comparatively cheap natural gas price and expensive electricity price requires the ratio of GSHP annulized average operation COP vs boiler efficiency is larger than 4.4, so as to make GSHP cost-effective in building energy efficiency. But, it is noticed that the change of energy price can significantly affect the energy cost optimization and building parameter selections, and the effectiveness will vary with different heating energy

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[7]1 $[kft^3]$ natural gas has energy content around 1 $[MMBTU]$ which is about 1.055 $[GJ]$

types (oil, electricity heating). Figure 6.27 shows GSHP heating cost-effectiveness in different countries based on their energy price. The chart is developed based on annual heating load of 80 [GJ] under residential energy price. But, if we apply the commercial energy price given above, we can find that the GSHP saving is small.
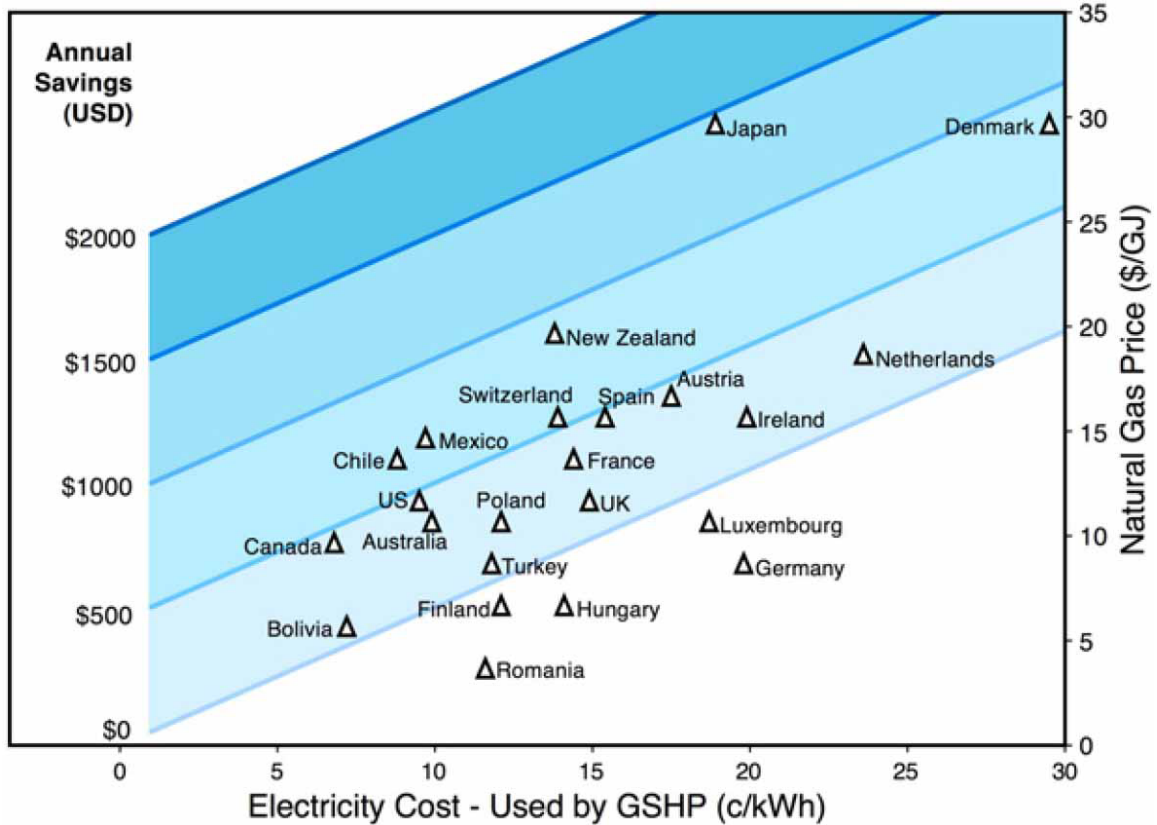
Figure 6.27: GSHP heating cost effectiveness study (*Hanova and Dowlatabadi*, 2007)

On the cooling design, the optimization case choose GSHP average operation COP value of 4.6 which is a little bit smaller than a e.g. screw chiller COP 4.8 (*Carrier*, 2011). But, the radiant panel with DOAS can save large amount of energy, and compensate the cooling energy use of GSHP system.

The primary energy optimization shows GSHP with radiant panel system achieves about 10% primary energy saving compared with VAV with boiler and chiller system. The saving is slightly higher than cost optimization results but less than thermal energy optimization.

In general, the saving of GSHP for heating is related to the heating system efficiency ratio defined as GSHP's annual average operation COP / boiler's efficiency and the ratio of electricity price to natural price for cost optimization, or the ratio of electricity primary energy conversion factor to natural gas conversion factor for primary energy optimization. The saving for cooling is determined by the factor of GSHP annual average cooling operation COP / chiller annual average COP.

Table 6.11: Building performance optimization parameter results

Case	orient-ation [deg]	aspect ratio	South facade WWR	lighting illumin-ance [lux]	lighting power density [w/m2]	blind slat angle [deg]	window glass transmit-tance	ext. wall absorp-tance	room clg stp [C]	room htg stp [C]
VAV energy	0	2.8	44%	300	7	85	0.9	0.3	26.5	18
VAV cost	-3.75	2.9	31%	300	7	85	0.9	0.3	26.5	18
VAV primary	-1.25	2.85	31%	300	7	85	0.9	0.3	26.5	18
GSHP energy	1.875	2.85	39%	300	7	85	0.9	0.3	26.5	18
GSHP cost	1.875	2.85	39%	300	7	85	0.9	0.3	26.5	18
GSHP primary	1.875	2.85	39%	300	7	85	0.9	0.3	26.5	18

After discussing the energy results, the optimized parameters are shown in table 6.11. Under different optimization objectives, some design parameters tend to be driven to the same optimal results, while some vary based on optimization objectives. The selection of parameters: lighting illuminance level, lighting power density, blind slat angle, window glass transmittance, exterior wall absorptance value, room cooling set-point and room heating setpoint converge at the same value in different optimization objectives. This is because these parameters either have simple influence on building energy performance, like cooling and heating setpoints, or they don't have strong and complex coupling effects with other parameters. Parameters like building orientation, aspect ratio, South facade WWR have strong coupling effects with other parameters and different energy use types, and their optimization results will vary based on different objectives. The variation is especially big for window WWR value. Under thermal energy optimization, the program selects a large WWR value compared with cost and primary energy optimization. This is because, thermal energy optimization

203

treats1J of electricity equal as 1J natural gas. The comparative "cheap" feature of electricity makes the program select large window ratio. In this scenario, cooling is comparatively less important than heating, the benefit of large window area can to make use of solar gain in winter overwhelms the increase of cooling energy use with large window area in summer. However, in cost and primary energy cases, the ratio of electricity to natural gas discussed above is much higher than 1 which makes the program gives more importance to cooling and thus, reduce the window area to decrease cooling energy demand.
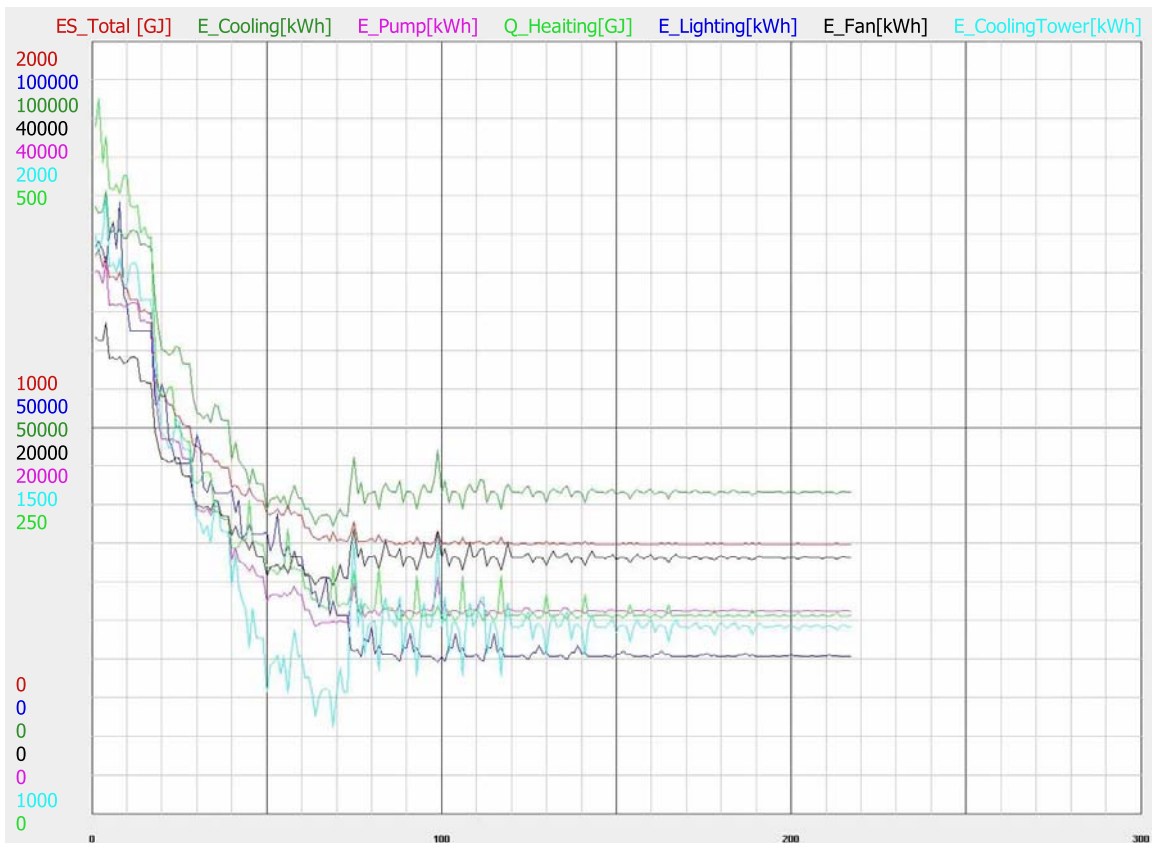

Figure 6.28:

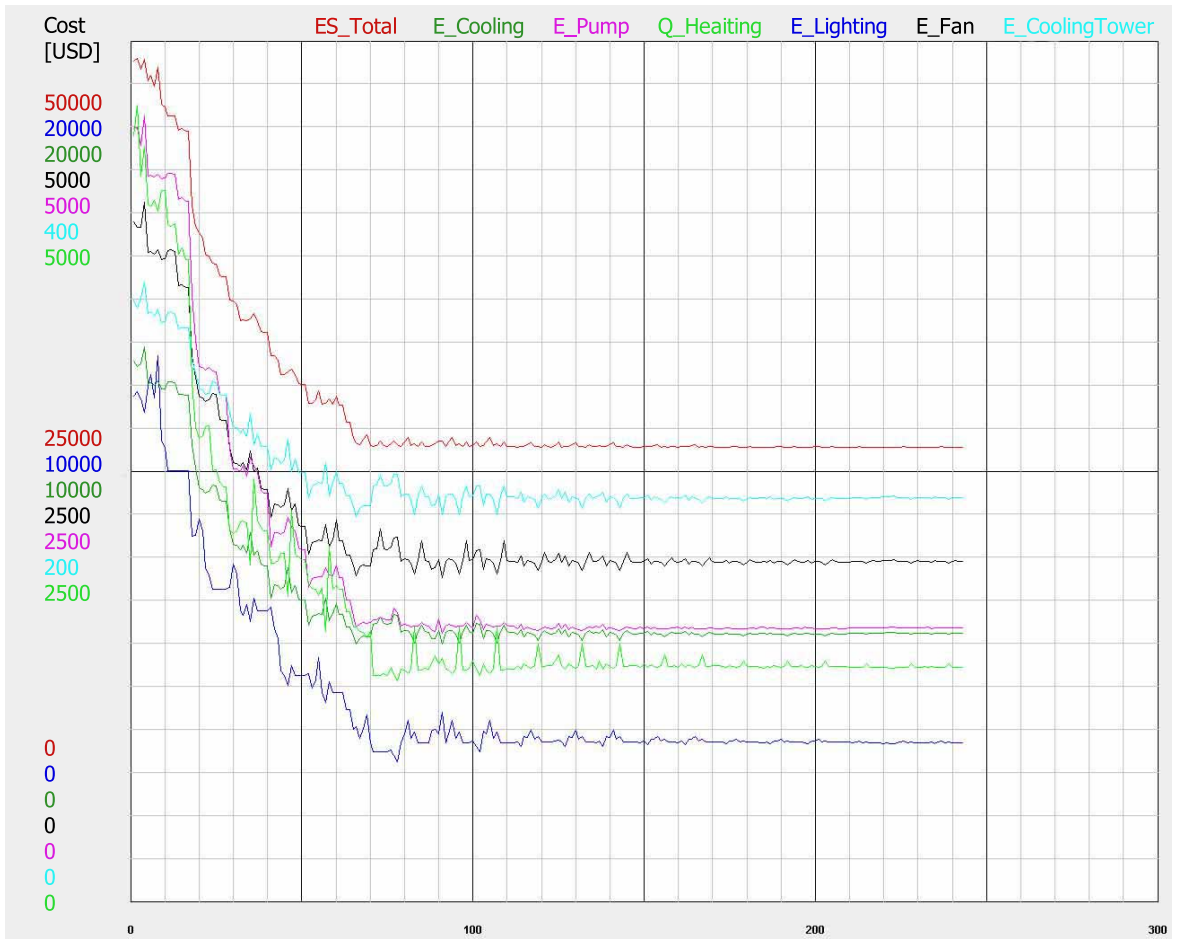Building performance optimization with VAV chiller and boiler system – energy

Figure 6.29: Building performance optimization with VAV chiller and boiler system – energy cost
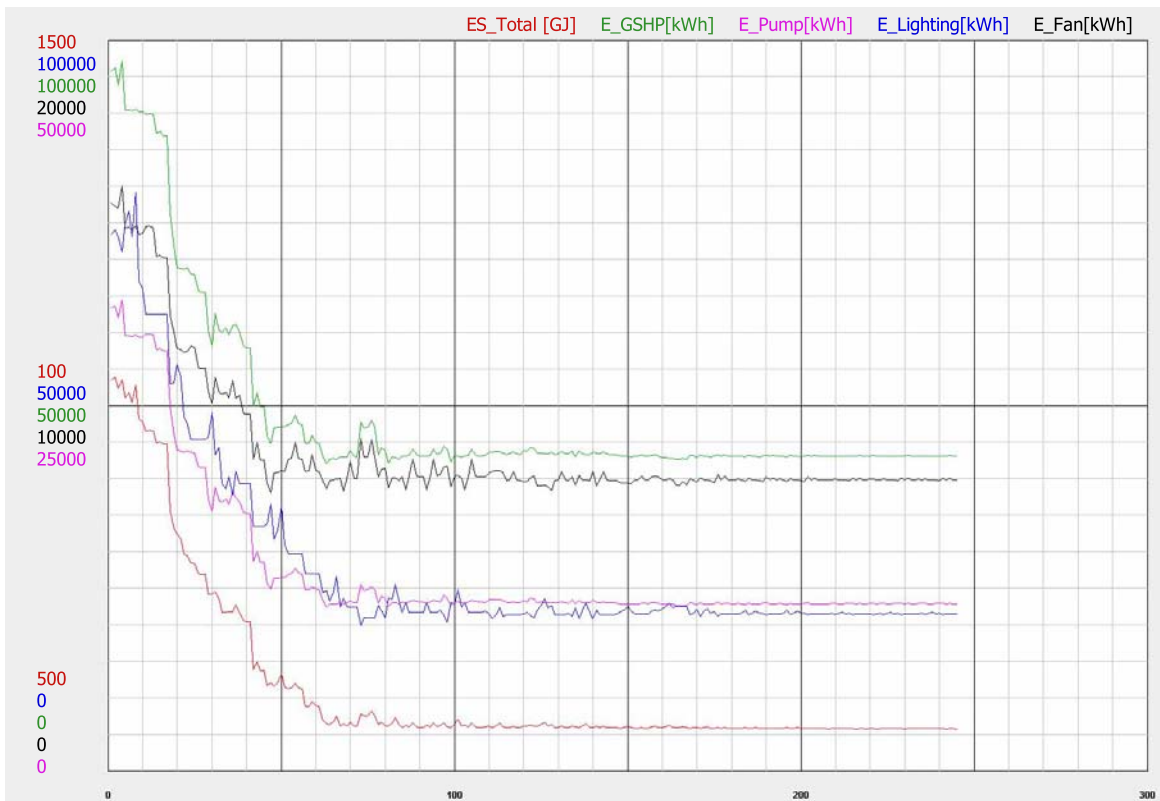
Figure 6.30: Building performance optimization with GSHP and radiant panel system – energy
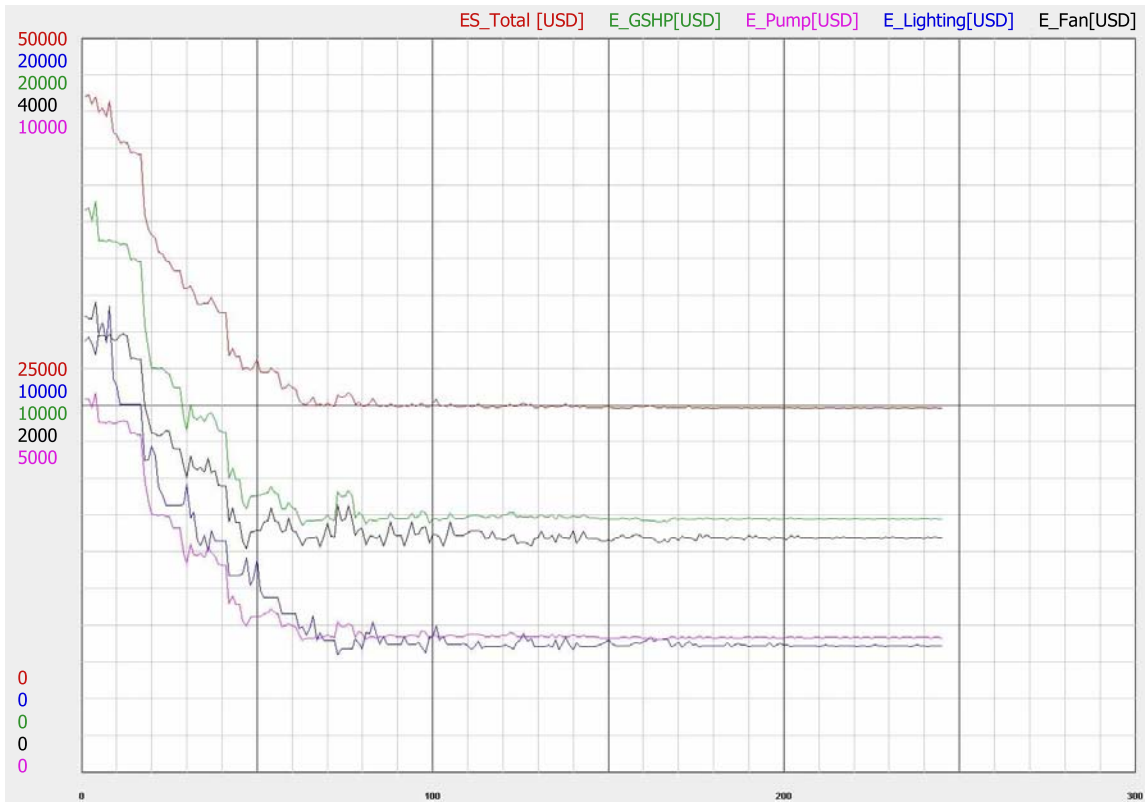
Figure 6.31: Building performance optimization with GSHP and radiant panel system – energy cost

6.7 Building Performance Confirmation

The integrated platform provides both simulation and measurement methods to evaluate building performance. The design alternatives described in aforesaid section are assessed by CHAMPS-Multizone to quantitatively explain building's performance. Once the simulated design performance is obtained, we can immediately verify it by comparing the actual measured data through Virtual Building system. Take building orientation design for example. Section 6.2, has demonstrated how to select building orientation and shape to achieve best overall energy performance. Here, we apply the integrated design approach to further verify building performance by contrasting with Virtual Building monitoring results.

Figure 6.32 shows the same case building winter month heat load measurement results collected by Virtual Building system. It is observed that the peak heat load is around 260kW. The peak heat load for different building orientation design at 0 (South facing), 45, 90, 135, 180, 225, 270 and 315 degree are simulated by CHAMPS-Multizone as shown in Figure 6.33. The different orientation design results are compared with Virtual building measurement data (green line), and it is found that South orientation (0 deg) design matches well with building's actual performance.

Some existing studies also have shown the measured building performance and its relationship with modeling results. *NBI* (2008) investigates 121 LEED New Construction (NC) buildings and their energy performance. The study compares LEED building energy use intensity, EUI in $kBtu/(ft^2 \cdot year)$ with various national building stock. National EUI is recorded from commercial building energy consumption survey (CBECS) and the results is given in Figure 6.34.

The medium measured EUI for LEED building was 69 $kBtu/ft^2$ (217 KWH/m^2) which is lower than CBECS mean value of 91 $kBtu/ft^2$ (287 KWH/m^2). For the investigated case green building, the measured performance is also compared with
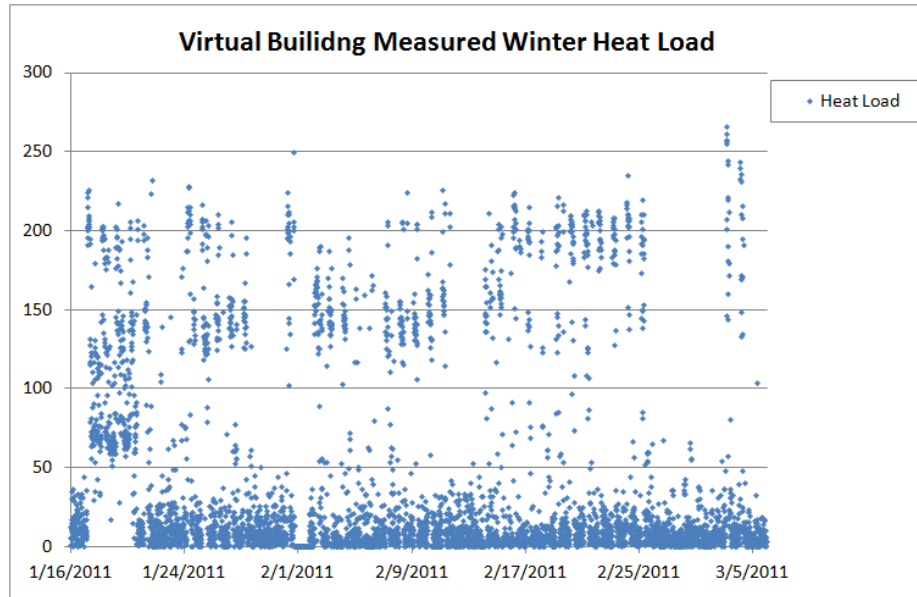
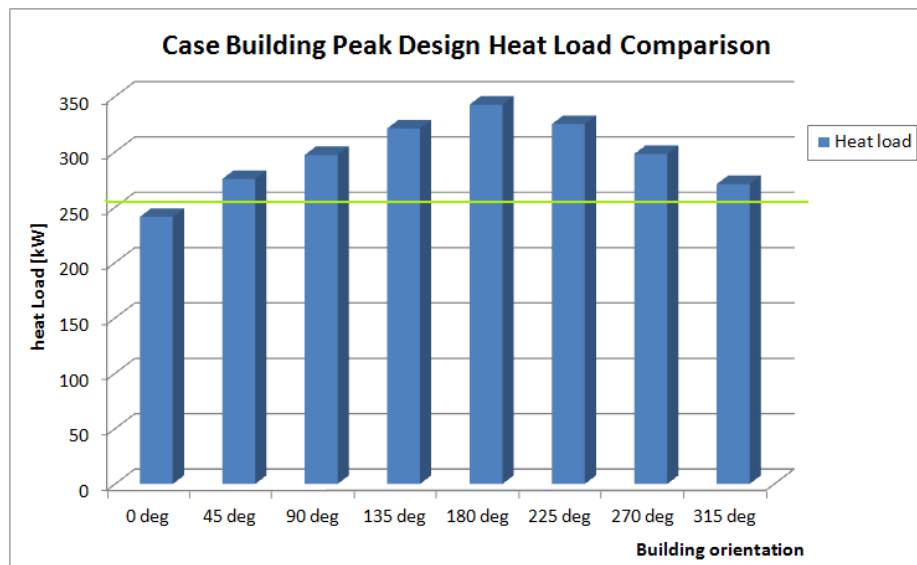Figure 6.32: A Case Builidng Heat Load Measurement by Virtual Building

Figure 6.33: A Case Builidng Orientation Design and Heat Load Comparison

209

modeling results and the result is shown in Figure 6.35.

The ideal comparison between measured and simulation results should line with the dash line as shown in Figure 6.35. However, most buildings' measurement and simulation data does not agree with each other. The points below the 45° dash line indicate that simulation over-predict buildings' energy performance, and the points above the 45° dash line means that the building operation energy performance is higher than predicted one.

There are several aspects which influence the predicted energy performance. We summarize those aspects in Table 6.12. The real building measurement data is collected based on the as-built building systems compared with the simulation results which are modeled based on design drawings. The operation and controls of actual building is subjected to various dynamics and issues while the simulation model assumes ideal controls without faults and not too much dynamics. The human behavior in actual is quite complex and can affects other aspects regarding building systems operations, internal loads and so on. But for simulated model, the human occupancy is assumed to be simple and most of time modeled in schedules. The real building equipments is operated with certain faults, but the modeled case always equipments are operated under equipment design conditions without errors. Weather data is another major aspect influence building real and modeled building performance. The real building climate conditions is measured by local weather tower and include various dynamics. However, simulation cases use certain types of weather files, such as TMY2/TMY3 which use more than ten years climate data and produces a typical one year clime file. The building's internal load is subjected to the actual needs, functions of the building and occupant behavior, while simulation most of time predict building's internal load based on building's occupation schedules. Last but not least, there is very little modeling guidance and quality control procedure for developing simulation models which makes difficult to evaluate the quality the building performance modeling.
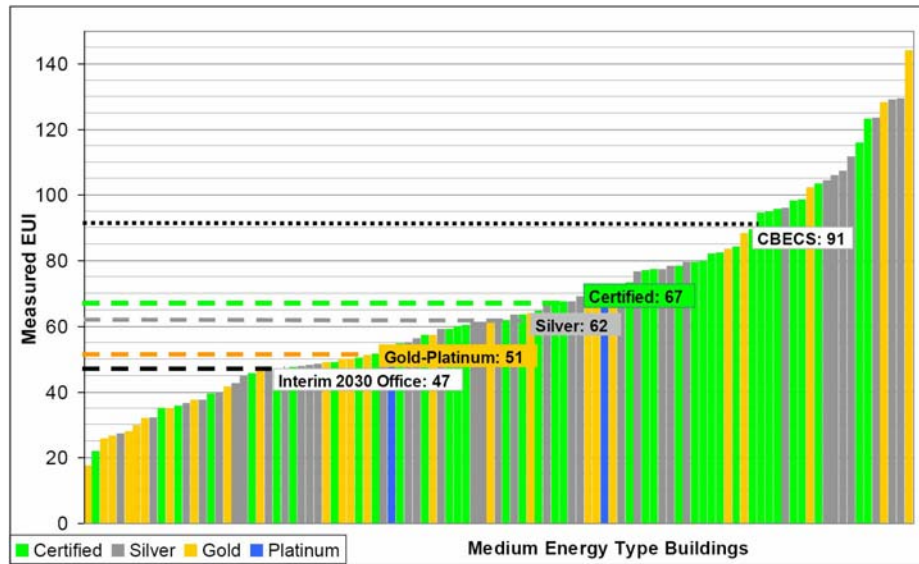
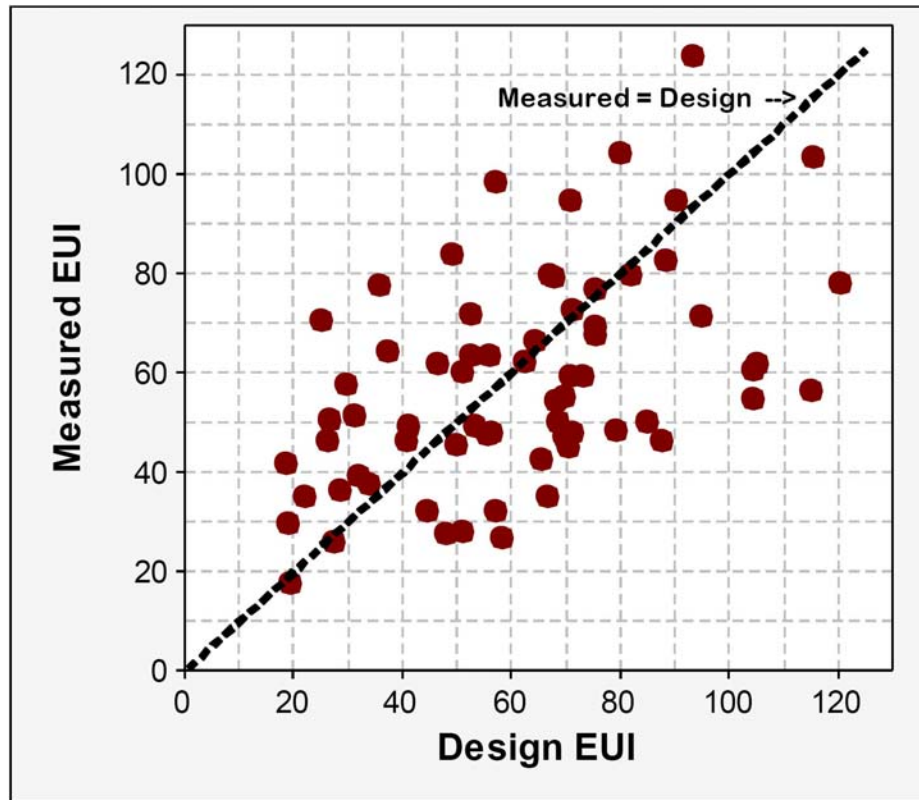Figure 6.34: LEED Buildings EUI Distribution (*NBI*, 2008)

Figure 6.35: LEED Buildings Measured and Modeling EUI Comparison

211

Table 6.12: Compare Measured and Simulation Building Performance Aspects

Aspect	Measurement	Simulation
Building & systems	As-built	Designed
Operation &controls	With problems	Perfect ideal
Human behavior	Actual & dynamic	ideal and simplified
Equipment performance	Actual with faults and degradation	Assumed default w/o fault
Weather data	Real-time	Weather files(TMY2/TMY3)
Internal load	Actual &Dynamic	Assumed & designed
Engineering quality control		no guidance

Even though so many aspects exist and may cause discrepancy between measured and simulated building performances, the immediate comparisons between measurement and simulation for certain systems are available by utilizing Virtual Building monitoring system. Our case building has been occupied since May 2010, and it experiences continuous commissioning on building HVAC, lighting, window shading ect. systems after initial occupation. So, a whole year stable measured building performance is still not available at this point. However, certain system's performance can be verified by comparing the measurement data Virtual Building collected with simulation results.

Before we do performance verifications, the building design model needs to be finalized. The finalization includes small changes and modifications of existing designs discussed in previous sections. It is necessary to clarify that those small changes on building design do not have big impacts on building's performance and thus is not the major purpose of this research. Those changes includes, to refine building's shape under the designed aspect ratio 3:1, placement of window on building facades with the designed WWR values, control strategies etc. The final case building simulation model can be seen in Figure 6.36.

One control strategy, when analyzing data from Virtual Building monitoring system, is that the corridors' setpoint is 1.5 ^oC lower than office rooms in winter and 1.5 ^oC higher in summer. This control method can further save building's HVAC energy

consumption since corridors are not constantly occupied and thus the they do not need to control at the same thermal comfort level as office rooms. The temperature control of one office room and one corridor is shown in Figure 6.37. In our simulation, we adopt this method and finalize our models control strategy.

To verify building's energy performance, the case building's finalized model is simulated in EnergyPlus. To compare with Virtual Building's monitoring performance, we choose the energy rate delivered by GSHP to building and compare the simulation results with real-time measurement results. The comparison is shown in Figure 6.38. The result shows that the model basically predicts GSHP delivered cooling energy for July and August two summer months even though there is one week we don't have Virtual Building measurement results because of commissioning. However, the Virtual Building measurement result show average cooling energy rate 92KW but the simulation result has average value of 86KW. To explore the cases of difference between simulation and measurement results, we refer to Table 6.12 and analyze the key factors which may affect case building's energy performance.

One factor is climate condition difference. In Figure 6.39, the outdoor air temperature is plotted in terms of Virtual Building real-time monitoring and simulation weather data (TMY3). In 2010 summer, the average outdoor air temperature is 24.8 ^oC compared with simulation weather data's average value of 21.0 ^oC. Although other climate conditions are not immediately available for building performance comparison, the outdoor air temperature give a good indication on potential building performance variance caused by weather conditions.

To evaluate the impact of outdoor air temperature on building's energy performance, the real-time weather data is downloaded from Virtual Building database. Outdoor air temperature and RH is incorporated into simulation weather file and building's energy performance is re-simulated in the same model. The average building cooling
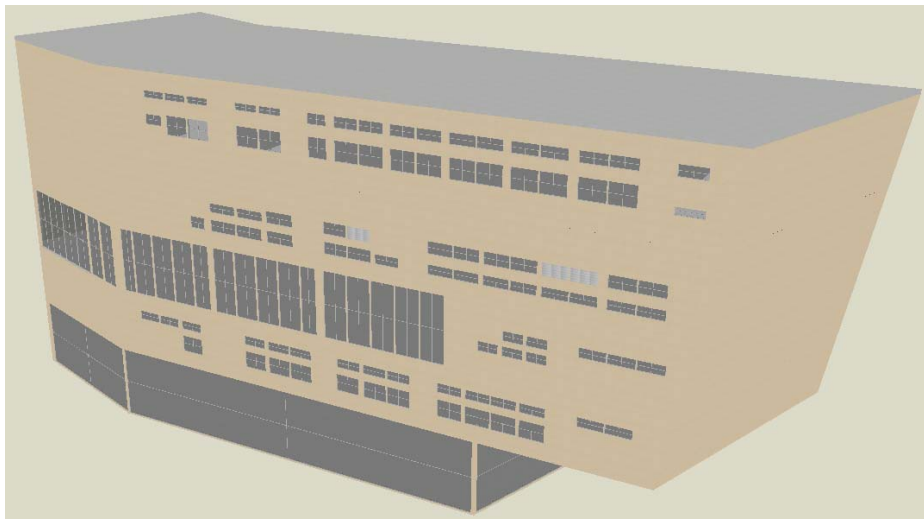
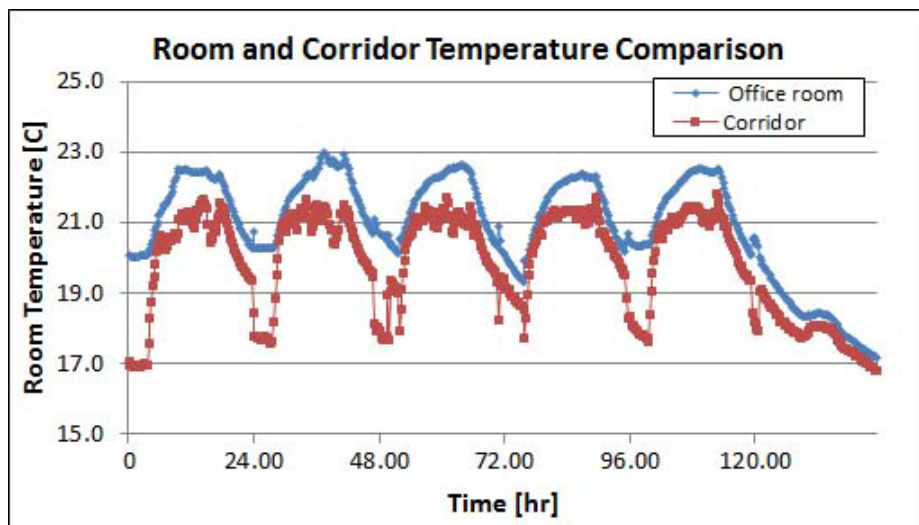Figure 6.36: Case Building Finalized Model

Figure 6.37: Corridor and Office Room Temperature Control Comparison
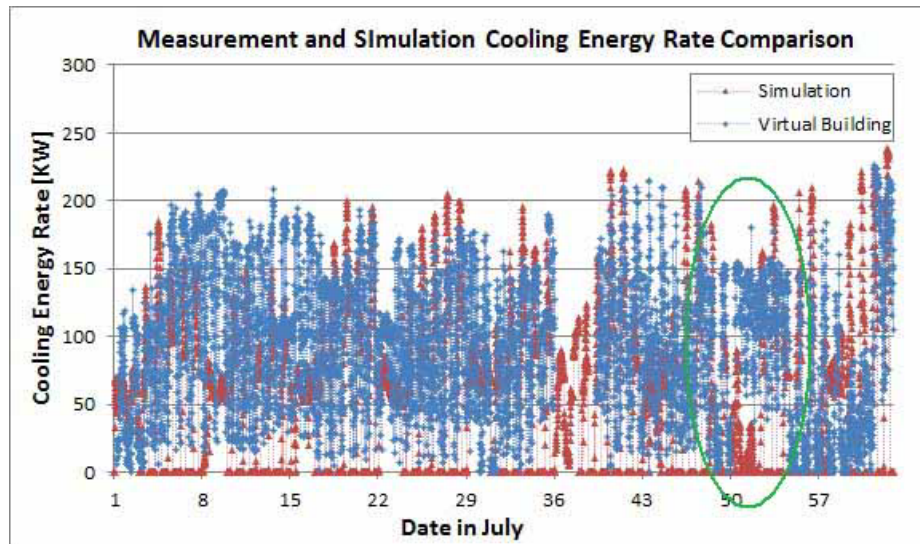
Figure 6.38: Measurement and Simulation Cooling Energy Rate Comparison
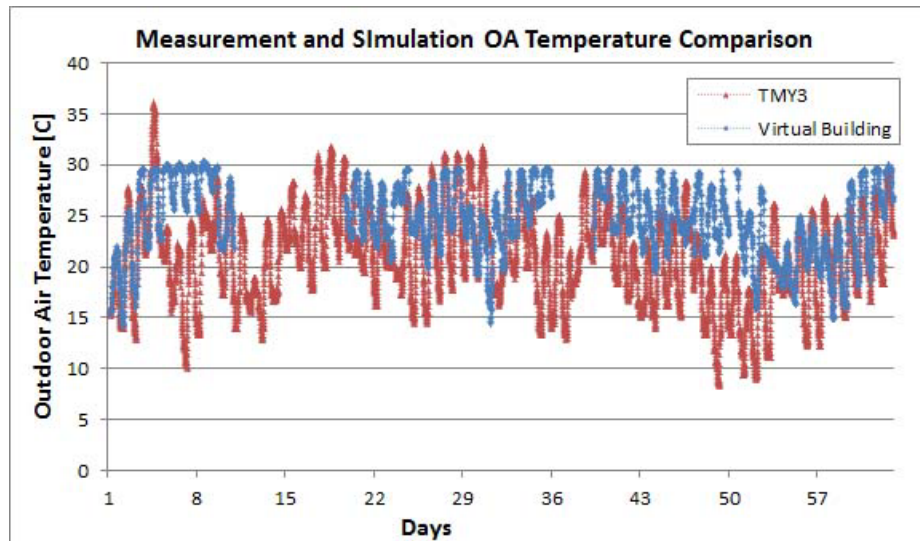
Figure 6.39: Measurement and Simulation Outdoor Air Temperature Comparison
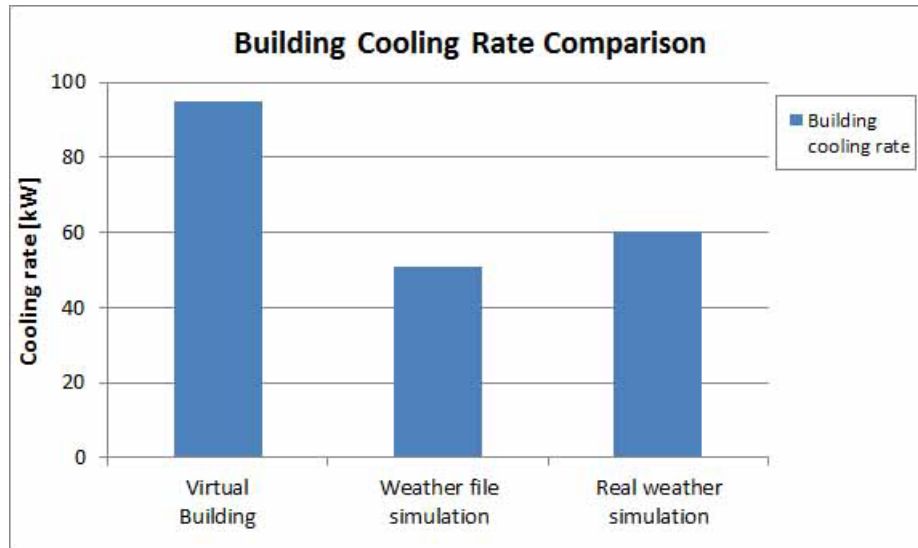
Figure 6.40: Building Average Cooling Rate Comparison

rate is compared in Figure 6.40 for Virtual Building measurement result, simulation result using weather file, and simulation result using real-time weather data.

It is found that the relative high outdoor air temperature can contribute to higher building cool rate in the summer time. However, the simulated result is still lower than Virtual Building measurement results. There a couple of other factors which are not considered but could significantly affect building's cooling energy usage. The solar radiation weather data for direct and diffuse solar radiation is needed to better assess the solar heat gain through building facade. Because our case building has large glass facade area, the radiation data can significantly influence building's cooling energy. In addition, the radiation data and and outdoor luminance data are also important for evaluating building's lighting energy consumption. Our case building has an automatic control window blinds system, the available of daylight can affect the operations window blinds and the dimming control of general lighting.

Occupant behavior is a very complex factor that may affect the internal occupancy, internal heat load, equipment and building systems operations. Building energy simulation assumes a design occupancy level and work schedule. However, the real oc-

cupancy level is very dynamic. The behaviors of occupant also need detail survey analysis to understand: how occupant use office equipments, how occupants control general lighting and task lighting, how occupants open window and adjust control equipments such as thermostat setpoint. All these occupant activities need comprehensive survey and documentation in order to better tune the simulation model to better calculate building energy performance.

Another important factor to consider is building's control and operations strategies. It is found in Figure 6.38 that the Virtual Building measured GSHP operation is slightly different from design operation condition. The actual building's GSHP system is turned on even at some night time. The longer operation time for GSHP can be another important attribute which makes the actual energy consumption higher than simulation results. In real building control system the control logic and algorithm is more complicated than most simulation control schedules. Moreover, the actual cycling operation of GSHP system in the building makes the supply cooling energy rate fluctuate over time. However, simulation result always gives continuous and smooth output.

All these factors together require additional investigation on building user behavior by survey or site investigation to detailed look at internal load and system operations, collect long-term reliable and comprehensive weather data to refine our model. Also the model needs to be updated with continuous commissioning and modifications and renovations on building systems.

In all, the integrated design platform provides both monitoring and simulation tools to evaluate building performance. Virtual Building collects long-term monitoring data to compare with CHAMPS-Multizone simulation results. Initial study shows similar energy performance trend between simulation and measurement. To conduct detailed building performance comparison, long-term comprehensive measurement

and survey data are needed to cover all related building systemsm, operation and occupant behaviors.

6.8 Summary

This chapter introduces the integrated building performance design platform, how to analyze design parameters, and apply the parametric building performance studies on a case building design. The design parameters are categorized as climate conditions and urban context, building form and massing, building envelope systems, interior program design, HVAC system designs and verification by the integrated design platform.

Climate conditions and urban context is the first design parameter considered in building design. The global and US climate conditions are analyzed and a prototype office building energy performance is studied in major cities of different US climate zones. The building's urban context refers to its surrounding environment which can have significant influence on building performance. This study analyzes compact and loose urban context scenarios and finds that open or loose urban context, because of better utilization of solar radiation and daylight, gives better building energy performance for our case building located in US climate zone 6A.

The building's form and massing design is studied under different aspect ratio and orientation. It is found that small aspect ratio number tends to have better energy performance. However, the optimal energy performance is not achieved at aspect ratio 1:1, but between aspect 2:1 and 3:1. Finally, rectangular building shape is recommended for our case building with South/North orientation (South/North side is longer than West/East side).

Building envelope design consists of opaque external walls and fenestration system. Based on ASHRAE 90.1 standard, to achieve minimum opaque wall U value, a multilayer light weight wall assembly is designed, and its performance is proved the best building energy design among other building wall assembly options. The fenestration system design is achieved by comparing window type, building orientation, and

WWR. Double pane low-E window exhibits the best building energy performance. And the study also finds that large WWR can increase building cooling energy demands, but for total energy performance especially when applying at building's South facade, the overall energy performance is acceptable.

External circulation and interior circulation are analyzed for case Building's interior program in accompany with opaque and glass partition settings. It is found that glass partition wall shows slightly better building energy performance because it allows more daylight penetration. However, the exterior and interior circulation design exhibit similar energy performance.

The case building's HVAC system design is studied in terms of its air systems and terminal equipments, and plant systems. The terminal system design considers VAV, CAV and radiant panel with dedicated outdoor air system. Radiant panel and DOAS is proved to be the optimal design in terms of energy and IEQ performance. The dedicated outdoor air system can reduce fan energy consumption and provide better IEQ. On the plant system side, ground source heat pump system provides both heating and cooling energy and show higher thermal energy efficiency compared with traditional chiller-boiler system.

The iterative design process and optimization can select building design parameters by considering their interaction and coupling effects. The optimal building performance is achieved based on defined optimization objectives. The GSHP system is energy efficient in reducing thermal energy content consumption, but its effectiveness on cost is related to electricity and natural price. The selection of optimal design parameters is determined by the type of parameters and the optimization objectives. Simple design parameters or those have loose interaction with others exhibit the same optimal design value under differernt optimization objects. Parameters have highly coupled with others (i.e. window to wall ratio) shows different optimal solutions under

different optimization goals.

Finally, the building's energy performance is verified by the integrated design platform which compares simulated result with Virtual Building measurement data. Building orientation design is taken as an example to demonstrate the capability of integrated design platform. The simulated result exhibits similar energy performance with measurement data. However, the average energy use of simulated model is slightly higher than measured data, and the difference is caused by climate conditions, building occupancy profile, operation strategies and occupant behaviors.

The integrated design study applies design parameters to our case building for optimal building performance study. In this platform, simulation programs such as CHAMPS-Multizone and EnergyPlus are used as modeling tools to study design parameters and their impact on building performance. Virtual Building is demonstrated to be a useful tool to compare real-time building performance data with building simulation result and verify building design. For futture research, more comprehensive measurement are needed to dynamically map building management system to Virtual Building monitoring system. To verify building performance, it is also important to understand builidng operation, occupant behaviors.

CHAPTER VII

Conclusions

This dissertation demonstrates a first attempt in developing an integrated building performance design platform which requires both modeling and monitoring software. Building design process and design parameters that have major impact on building's performance are investigated. The characteristic of each design stage is described and the design parameters involved in each design stage are analyzed. A combined heat air moisture and pollutant transport model called CHAMPS-Multizone is developed to support building performance simulation for design. To measure and monitor building performance, a Virtual Building database system is developed to collect both building static data and dynamic data in a hierarchical structure. Finally, the design parameters are analyzed and selected to optimize building's performance.

CHAMPS-Multizone describes the heat, air, moisture and pollutant transport for whole building analysis. In the CHAMPS-Multizone program, several models are introduced, including climate and solar radiation model, building envelope and fenestration model, zone quantities balance model, HVAC model, and air flow model. Two models are implemented in CHAMPS-Multizone for climate and solar calculation – ASHRAE Clear Sky Model for design day calculation and Perez Diffuse Sky model for climate filed based solar radiation condition. There are two building envelope models considered in CHAMPS-Multizone implementation. One is integrated

CHAMPS-BES model, which calculates detailed 1D and 2D heat, air, moisture, and pollutant transport through building envelope; and the other is the CTF method, which can perform simple and fast heat transfer calculation for building envelope. Window system is also implemented in CHAMPS-Multizone by using U value and SHGC to calculate heat flux and solar radiation transfering to buildings. The HVAC model calculates heat, moisture and pollutant fluxes from HVAC system supply and return duct. The power law model is implemented for air flow network model. All the quantities calculated by the models described above are integrated in zone model and eventually the program copmputes building's indoor heat, moisture and pollutant densities.

The numeric solution methods for coupled heat, moisture and pollutant transport were implemented into computer codes. A variable order multi-step integration method is used to solve models in CHAMPS-Multizone. The interaction of different solvers and exchange of multiple models' calculation variables are integrated in a ping-pong numerical framework. CHAMPS-Multizone model is tested by comparing simulation results with some other well-established models. The CHAMPS-Multizone model exhibits good computation accuracy even though small variance exists because of model implementation and solving methods difference.

The Virtual Building approach, as a new Building Information Modeling (BIM) method, uses hierarchical structure to store static building information and dynamic performance data. The modeling structure is implemented in an object oriented database called "Cache" with web-based graphical user interface. Also, a wireless sensor network is deployed to a testbed case building transferring wireless signals to Virtual Building system. The case building's HVAC system real-time performance is studied by using Virtual Building measurement data. And the building systems performance is calculated and explained under certain environmental conditions.

The integrated building performance design platform analyzes the entire buildings design process. Major design parameters: climate conditions and urban context, building shape and orientation, building envelope and fenestration systems, building zoning and internal configurations, building environmental and HVAC systems, energy usage and occupied performance, are analyzed by applying integrated design approach to combine CHAMPS-Multizone simulation with Virtual Building performance monitoring. The case building demonstrates good energy performance in relative open urban context especially at building's South side. The building's aspect ratio of 3:1 with South orientation shows plausible energy performance when comparing with various of other design options. Opaque building envelope with U value of 0.23 and LowE window system gives the best energy performance. And both internal and exterior circulation program show similar energy performance. For building environmental system, the dedicated outdoor air system with radiant panels exhibits the good IEQ and energy performance with ground source heat pump system. Multiple parameters based building performance optimization is conducted, and optimal building performance as well as design parameters are determined by iterative optimization study. Finally, the case building performance is verified in the integrated design platform by comparing simulation results with Virtual Building's measurement data.

This research develops and demonstrates a new concept of integrated building design platform to combine building simulation with performance monitoring. A new combined heat, air, moisture and pollutant transport model for whole building analysis is developed. It also develops and demonstrates the usage of a new BIM method (Virtual Building Database) to store real-time building performance data for comparison with the simulated performance. The design parameters can be assessed through performance-based simulation and select the optimal building parameters. CHAMPS-Multizone serves as a fundamental tool to assess building energy, and IEQ performance. And, Virtual Building provides real-time building performance mon-

itoring data to compare design performance with actual built environment. The integrated design platform consisting of both CHAMPS-Multizone and Virtual building is the original contribution of this study and serves to assist optimal building performance design analysis.

However, certain limitations exist in this study and need to be addressed in future work. The CHAMPS-Multizone program can simulate well-mixed zone quantities balance. The actual dynamics in zone caused by air flow and some other physical phenomena can not be simulated in CHAMPS-Multizone. From building system point of view, a complete building environmental system modeling tool is needed to capture both air and water system performance. The limited capacity of HVAC system simulation makes it is necessary to use CHAMPS-Multizone in combination with EnergyPlus for building performance prediction. Hence a coupling approach should be developed to enable the use of EnergyPlus within CHAMPS-Multizone for combined primary and secondary energy system simulations.

The Virtual Building monitoring system can well store measurement data logged by building management system (BMS). A more flexible data transfer strategy is needed to transfer data between Virtual Building and BMS, most importantly to communicate via BACNET and some other BMS protocol to achieve dynamic data transfer. The design of data transfer module should also take into account the nature of various BMS from industry.

In addition, this study demonstrates how simulation and Virtual Building monitoring technology can assist building performance design. However, the actual building design process is a very complex process involves different design teams. A detailed design-stage oriented building performance simulation model is needed for building performance prediction under more complex design activities.

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