IMPACTS OF LIGHTING SCHEDULES ON BUILDING ENERGY SIMULATIONS

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ABSTRACT

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Common errors in building energy simulation include incorrect lighting and plug load power densities as well as peak occupancies in spaces (Rosenbaum 2003). Inaccurate results due to these uncertain parameters support industry opinions that energy models present a pattern of behavior rather than predicting true energy performance (Clevenger 2010). This research analyzed the impact of lighting schedule definition in energy use prediction and included a limited survey addressing methods used by professionals. Three case buildings were analyzed: the Chemistry Building and the Geography Building at the Michigan State University campus, and a church project in Lansing, Michigan. Actual lighting schedules were collected and redefined through field observations and data from portable light loggers. These schedules were then used in energy models created for each building, and predicted energy use was compared to results from models previously developed during the design phase to default schedules within the program, and to available building utility data. Results showed an improvement in energy prediction accuracy when defining schedules based on averaged use patterns. As a result of the research, recommendations were developed for approaches to improve schedule definition and a data gathering tool was developed to collect required information for energy analysis during design.

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CHAPTER 1

INTRODUCTION

INTRODUCTION

1.1. Overview

Buildings account for 39% of U.S. energy use (U.S. Department of Energy 2010) which is more than any other industry. Local energy codes and sustainable certification processes seek to reduce energy consumption through design specification of materials and equipment efficiencies. As shown in Figure 1.1, HVAC equipment and lighting account for almost 50% of energy use in buildings. Focusing on improving equipment efficiency and controllability of lighting fixtures is essential in minimizing energy consumption.

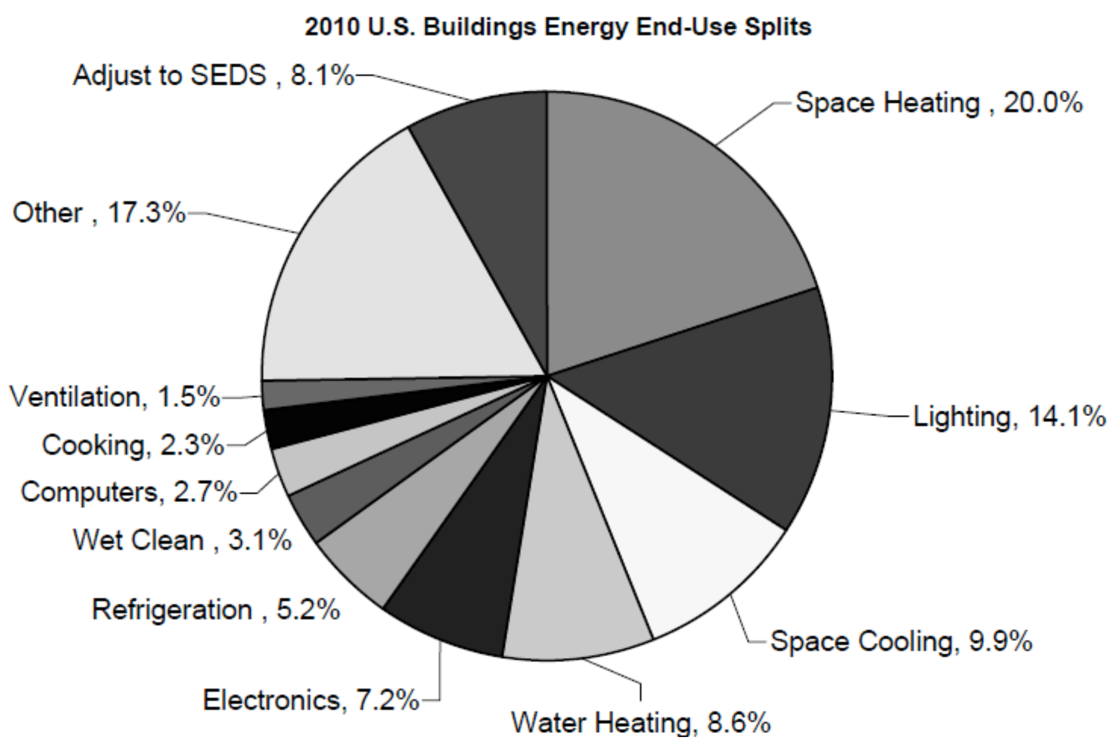


Figure 1-1: 2010 Buildings Energy End-Use Splits (U.S. Department of Energy, 2010)

In order to find optimal solutions for energy performance, many decisions are made during the design phase of a project, and simulation tools can help in evaluating energy impacts of design choices. Analysis of temperature, envelope losses, system performance, and electric loads establishes energy flow within a structure and its behavior under certain climatic conditions (Judkoff 2008). Computer simulation software is helpful in calculating the impact of all these parameters in overall energy consumption.

Predicting energy use can become challenging when lacking appropriate information. Energy modeling accuracy can range from +/- 10% to +/- 40% in residential models. However, industry experts indicate relative prediction of performance is more useful than absolute values themselves (Clevenger 2010). Results from modeling programs may not be able to accurately predict actual building energy consumption, but they can show important patterns of behavior of design options.

The need for validation and verification of software is essential. Inputs involve many assumptions and require the modeler to define human behavior in facilities. Decisions made during simulation impact results, and distance them from actual conditions. Understanding the influence of parameters that cause inaccuracies can be helpful in matching outputs closer to actual performance. This research focuses on analyzing the impact of lighting schedules. Schedule definition relies on the simulator's own judgment and information available at the time of design or, use of program default values, and is therefore an important source of inaccuracy in final results.

Codes and standards can help standardize assumptions in energy use prediction. For example ASHRAE Standard 90.1 Chapter 9 lighting requirements define the paths for compliance and specify minimum requirements, mandatory provisions and either of two prescriptive options: the building area method or space by space method. Mandatory provisions state that all interior lighting shall be controlled by an automatic system for any building larger than 5000 ft^2. This can be accomplished by installing a system that can be programmed to turn on and off lights at desired times of day or use of occupancy sensors to control lighting.

Both alternative compliance methods specify maximum densities of lighting. The building area method establishes a maximum lighting density per square foot for a specific type of building, and installed lighting power shouldn't exceed this density. The space by space method specifies a lighting density as well, but for particular spaces in a building, so the sum of all spaces establishes the maximum lighting power. Figures 1.2 and 1.3 show examples of allowable lighting power densities:

Building Area Type[a]	***LPD* (W/ft^2)**
Automotive facility	0.9
Convention center	1.2
Courthouse	1.2
Dining: bar lounge/leisure	1.3
Dining: cafeteria/fast food	1.4
Dining: family	1.6

Table 1-1: Sample Lighting Power Densities Table Using the Building Area Method (ASHRAE 2007)

Common Space Types[a]	*LPD*, W/ft^2
Office—Enclosed	1.1
Office—Open Plan	1.1
Conference/Meeting/Multipurpose	1.3
Classroom/Lecture/Training	1.4
For Penitentiary	1.3
Lobby	1.3
For Hotel	1.1
For Performing Arts Theater	3.3
For Motion Picture Theater	1.1

Table 1-2: Sample Lighting Power Densities Table Using the Space by Space Method (ASHRAE 2007)

Mandatory provisions can impact lighting scheduling definition, since central lighting control systems can be implemented during the design phase and the programmed schedule can be defined as the lighting schedule in energy simulation. Default use percentages in simulation programs consider that lights won't be used 24 hours per day. Code prescriptive paths can help define lighting wattage if an electric design is not yet complete for preliminary energy simulation.

As newer editions of codes are published, energy requirements become more stringent. Higher standards may translate into higher initial investment. Understanding lighting schedules becomes important in fine tuning energy simulations and can help to establish better approaches for predicting consumption and in life cycle cost analysis.

1.2. Need for the Study

According to Judkoff and Neymark (2006), "Extensively reducing the energy intensity of buildings through better design is possible with the use of simulation tools. However, widespread use of building energy simulation software will not occur unless the design and engineering communities have confidence in these programs." Judkoff and Neymark indicate the need for evaluation and improvement of energy simulation tools, especially when sustainable design and green certification rely on computer simulations to estimate energy savings.

There are three areas where research must be focused to improve simulation tools: 1) testing and comparing predicted results with measurements from full scale buildings and data from rooms with controlled parameters, 2) verification of program results through mathematical calculations and direct comparison of available software programming codes, and 3) the development of validation methodologies. Previous studies have not reached reasonable conclusions on errors induced by different processes or on a range of errors where energy simulations can be considered valid or real. Most of the work completed so far has focused on the impact of building envelope elements, but internal loads need to be evaluated and tested as well (Judkoff et al. 2008).

Simulation program validation can be oriented toward two goals. The first is to establish whether the software is reliable for predicting true energy when compared to field measurements and the second is to find sources of error which lead to inaccuracies in the results. Most efforts have been invested in the first goal, while the path towards program prediction improvement relies on expanding research and has less attention (Bloomfield et al. 1995). Identifying error sources in thermal analysis can contribute to the accuracy of energy predictions.

Assumptions and shortcuts in calculation methods of simulation programs are the main sources of error in energy prediction. Other contributing errors are variations in weather data, building envelope component performance and schedule definition. To improve internal load approximations in simulation, influences of external sources such as environmental and building envelope should be considered and reduced. Therefore, measurements and experiments on specific parameters must be done carefully to obtain accurate values for these inputs (Judkoff et al. 2008).

Analyzing all parameters involved in an energy simulation is a difficult task because much time, equipment, and effort are needed. Consequently this thesis research focuses on lighting, which has a significant impact on energy use. Figure 1.1 showed the impact on overall energy use in buildings. A report by the IEA (2006) recognized lighting as an opportunity to improve energy efficiency in buildings indicating up to a 70% savings could be achieved with new design strategies. Energy simulation can help to find optimal solutions. Having a better understanding of the impact of each parameter can lead to improved accuracy. This study is targeted to establishing a better understanding of lighting use and its impact on energy use prediction.

The need for further research is recommended in a University of Massachusetts study that compares energy use predicted by modeling with measured post-occupancy consumption in LEED certified schools (Lowell 2007). Although it was found that energy codes were outperformed, predicted energy use was as high as 40% more than measured consumption. The research team concluded that one of the main reasons for the difference was the energy modeler's inability to predict the building's plug loads, occupant behavior, occupancy levels, and operating hours.

1.3. Research Goal and Objectives

The primary goal of this exploratory research is to obtain a deeper understanding of lighting use schedules in energy use simulation and their impact on overall predicted results. The researcher established three activities to carry out the study. Professional energy modelers were interviewed to obtain an insight into simulation techniques, their views on software ability to predict energy use and how to handle uncertainty in schedule definition. Then, a sample building was modeled and different percentages of lighting use were assigned to establish boundary ranges of predicted energy values. The cases modeled ranged from 0% light use annually to 100% light use annually at 24 hours per day. Finally, three case buildings were selected for modeling in order to predict their energy use, and were compared with actual utility measurements. Buildings selected included the Chemistry and Geography buildings at Michigan State University and a Church Project in Lansing, Michigan.

The following objectives were established for the research:

1. Develop methods to gather lighting use data from actual buildings
2. Inquire about methods used in energy simulation addressing schedule accuracy through telephone interviews of energy modelers
3. Explore the influence of lighting schedules in energy simulations and determine methods to improve the accuracy of schedule assumptions during modeling
4. Develop recommendations for future schedule definition processes

1.4. Research Scope

The aim of this study is to better understand the impact of lighting schedule on energy simulation. Understanding errors that may occur will help the energy modeler to determine if it is worth investing time in this task or allocating efforts to others. In the future, if all efforts are combined, a code or standard can be published which defines and outlines modeling procedures for parameters that can reduce uncertainty.

Occupants impact a number of systems including lighting use, fan cycles, water heating requirements, thermostat settings, plug loads, and miscellaneous equipment use. Although a deeper understanding of energy simulation requires consideration of all these parameters, the best approach is to isolate one parameter at a time. Plug loads, fan cycles, lighting, and water heating in total represent more than 50% of energy consumed (Figure 1.1), but it is beyond the scope of this study to determine the effects of each individual parameter. Consequently, this study focuses on lighting.

This research was exploratory and conclusions were not expected to have a valid statistical significance, but it is expected to contribute to a growing effort to analyze distinct energy parameters and leads to a better understanding of the subtleties of energy simulation. It is also beyond the scope of this study to test internal calculation methods of software or discover "bugs" to be fixed within software. The intention is to explore how to approach models realistically and not limitations in software.

1.5. Expected Contributions

The fundamental purpose of this research is to determine if errors induced by occupancy schedule parameters are significant enough to recommend that energy simulators invest time in developing the information to define this parameter, or if the difference between one defined schedule and another won't substantially influence the final result. This parameter is usually defined without exact knowledge of occupant behavior and different schedules must be defined for different rooms. Knowing that predefined schedules by software companies would be accurate enough would allow the modeler to concentrate more on other parameters such as HVAC equipment definition. This research may also encourage further research on the subject and lead to a proposal for a standardization procedure for schedule definition in codes addressing energy simulation.

Results may help clarify any general misunderstandings about energy simulations among professionals. If most people in the simulation field define occupancy based on their own judgment, they might feel comfortable knowing that their colleagues also carry the same uncertainty of defining schedules without a standardized method.

1.6. Limitations

Certain limitations are embedded in this research. The first limitation is that field observations are limited to short durations. Energy simulations are based on a 365-day and 24-hour analysis. For a completely realistic schedule definition, 24-hour observations during every day of the year (perhaps over several years) should be conducted, which is not feasible unless electronic sensors and metering devices are installed to keep track of energy use and occupancy. Also, some types of building such as educational facilities will have seasonal variations in schedule operation, which makes it even harder to determine occupancy schedule.

Since human behavior is unpredictable and the number of people in a structure is dynamic, it is hard to predict what actual consumption and energy conservation habits will be. The importance of this study lies in our awareness of how these inaccuracies affect energy simulations, and in determining how to account for these inaccuracies.

1.7. Chapter Summary

This chapter establishes the main energy uses in buildings and describes the need to improve energy simulations as a design tool. It outlines the objectives, research scope and limitations of the research. Chapter 2 presents the literature review including a historical background of simulation programs along with an overview of modeling methods, simulation programs, and efforts to date in energy modeling research.

CHAPTER 2

LITERATURE REVIEW

LITERATURE REVIEW

This chapter outlines the literature review conducted to develop a background understanding on energy simulation and software. First, historical events that led to energy conservation policies are reviewed, followed by an explanation of mathematical methods used in simulation program calculation as well as the detailing of several available programs. Finally, several studies regarding energy simulation are presented in three categories: overall calibration and validation of programs, testing between various available software, and studies regarding occupancy testing.

2.1. History

The use of computer programs for energy modeling purposes is not new for designers. Although programs in the late 1960s were not flexible in terms of input information, they still allowed the calculation of heating, ventilation and air conditioning loads. Initially, envelope loads were not considered and no alternative window or wall types could be considered. Calculations were simplified enough to improve computational efficiency but were not adequate for optimizing building design (Judkoff 2008).

In October 1973, members of the Organization of Arab Petroleum Exporting Countries (OAPEC) proclaimed an oil embargo on the United States in response to the decision to resupply the Israeli military during the Yom Kippur war. Since the industrial economy relied mostly on crude oil and the OAPEC was the main supplier, the U.S. government responded with a wide variety of new initiatives to contain further dependency. The Department of Energy was also created in 1973, and the National Energy Act was established in 1978. Along with government solutions, the crisis led to greater interest in renewable energy which accelerated research, especially in solar and wind power (Fehner and Hall 1994).

As a consequence, after 1973 the approach for energy use in buildings changed as well. The general public became aware of energy saving in homes and buildings, searching for new ways to achieve lower consumption. Designers felt the need to develop tools for weighing different solutions in order to better understand building behavior and improve energy savings. The initial trend was toward active solar systems since they could be added as a supplemental HVAC system. In 1976 and 1977, architectural options and modifications gained interest as innovative design concepts were developed. However, building energy analysis systems (BEAS) were no longer appropriate under these new conditions, since subroutines to existing programs did not ensure accurate energy analysis. Changes to analysis approaches were often necessary to handle innovative design strategies, fostering an entirely new generation of building energy analysis simulations (Judkoff 2008).

A third generation program began to emerge in the mid-1980s. With the advent of more powerful personal computing, parameters could be modeled as dependent, such that energy transfer processes were not solved in isolation, with only space and time considered as independent variables. Thermal, visual, and acoustic aspects of performance had to be integrated into modeling (Clarke 2001).

By the mid-1990s, program interoperability and integration were added. A growing understanding by practitioners of energy analysis tools stimulated developers to create knowledge-based user interfaces, application quality control, calibration, validation, and user training (Clarke 2001).

Between 2000 and 2010, programs such as EnergyPlus from the Department of Energy were developed, taking capabilities to a new level by combining BLAST and DOE-2, the most common simulation engines. EnergyPlus uses computer code written in Fortran 90, a modern language with good compilers on many platforms that allows C-like data structures, mixed language modules, and backward compatibility during the development process. In these modern programs, third parties are invited to create user interfaces (Crawley et al. 1999).

2.2. Energy Estimation and Modeling Methods

A mathematical model is defined by ASHRAE (2009) as a description of behavior of a system made up of three basic components: input, system structure and parameters or properties, and output variables. Modeling can be approached from two different perspectives: forward or classical, and data driven or inverse (ASHRAE 2009). In a forward approach, output variables of a model are predicted with specified input variables in a defined structure or calculation method. The data-driven approach uses known and measured inputs and outputs, and the objective is to determine a mathematical model of the system. The main advantage of the forward approach is that systems don't need to be physically built to predict behavior, making them ideal for design and analysis stages of a project. Government sponsored simulation tools such as BLAST, DOE-2 and EnergyPlus are based on forward simulation models. A data-driven approach contains a smaller number of parameters, and thus allows identification of simpler and easier models and more accurate prediction of future system performance under determined conditions, since parameters come from actual building performance.

In choosing an analysis method, capabilities and project requirements should be matched. The method must be capable of evaluating design options with sufficient accuracy to make correct choices. ASHRAE (2009) lists several important factors that should apply for every method selected:

- Accuracy, the method should be sufficiently accurate to allow correct choices even though absolute energy prediction is not possible
- Sensitivity, where the differences in energy use between two choices can be adequately reflected
- Versatility to allow analysis of options under consideration
- Speed and cost is important as the total time (gathering data, preparing input, calculations, and analysis of output) to make an analysis should be appropriate to the potential benefits gained
- Reproducibility, meaning that the method should not allow so many vaguely defined choices that different analysts would get completely different results
- Ease of use considering the importance of speed in obtaining results and making results easy to reproduce

Clarke (2001) elaborates a series of considerations and processes that should be handled by any advanced system:

- Lag and thermal storage effect of heat transfer through a building
- Radiant and convective gains from occupant, light, and processing equipment that varies with time

- Infiltration, natural and controlled ventilation, and inter-zone air
- The effects of shortwave solar radiation impacting exposed external and internal surfaces
- Longwave radiation exchange between exposed external surfaces and the sky vault and its surroundings, as well as between internal surfaces
- Shading of external opaque and transparent surfaces caused by surrounding buildings, as well as a variety of facade shading elements
- Mapping of moving insolation patches from windows to internal receiving surfaces
- Effects of moisture

A widely used analogy is to view the building as a complex network of thermal resistances and capacitances, linking regions and representing conductive, convective, radiative, and heat storage processes. The manner in which this network can be treated mathematically is by neglecting some portions, assigning fixed values, or simplifying boundary condition assumptions. This will determine the flexibility of the techniques to emerge for the program (Clarke 2001).

Methods have changed over the years and it is important to acknowledge former models that led to current methods. J.A. Clarke (1985) defines former methods: "Steady state approximation, these methods had no mechanism for the accurate inclusion of solar gains, casual gains, longwave radiation exchanges, plant operational strategies etc., and so such models only addressed fabric heat flow (under very special boundaries conditions) and not building energy. Typical inadequacies include omission of any consideration of the dynamic response of the building, inability to deal realistically with many of the energy flows occurring within the building, and an inability to effect the correct relationship between building fabric and installed plant operation … Simple dynamic, where the simplified methods of energy assessment have been produced which address dynamic performance. These methods are mostly based on regression techniques applied to the results of multiple parametric runs of more powerful modeling systems. The results to emerge can often be reduced to simple relationships or presented in tabular or graphical form."

J.A. Clarke (2001) also describes modern contemporary programs: "Most contemporary simulation programs are based either on response function methods or on numerical methods in finite difference or, equivalently, finite volume form. The former method is appropriate for the solution of systems of linear differential equations possessing time invariant parameters. In use, it is usual to assume a high degree of equation decoupling. Numerical methods, on the other hand, can be used to solve time varying, non linear equations systems without the need to assume equation decoupling as a computational convenience. Numerical methods are favored for a number of reasons. First, to ensure accuracy it is essential to preserve the spatial and temporary integrity of real energy systems by arranging that whole system partial differential equation sets be solved simultaneously at each computational time step. Second, numerical methods, unlike their response function counterpart, can handle complex flow path interactions. Third, time varying system parameters can be accommodated. Fourth, processing frequencies can be adapted to handle so called 'stiff' systems in which time constants vary significantly between the different parts of the problem (building fabric, HVAC component, control system elements, fluid flow domains, control system elements etc.)."

One last method described by Clarke (1985) is the electrical analogue, which uses the analogy of electrical flow and heat flow: "The analogy that exists between electrical flow and heat flow has led to construction of electrical analogue devices useful in the study of complex heat flow phenomena. The technique is extremely useful as a research tool, allowing long term simulations to be completed in a short elapsed time, but has little application in a design context."

2.3. Simulation Tools

2.3.1. DOE-2

The engine on which much current simulation software relies is DOE-2. The basic mechanism of the engine is to process the information through five different subprograms, one after the other, using the previous subprogram's output as the next subprogram's input. DOE-2 runs on five different subprograms that interact with each other. The first one is the Building Description Language (BDL) subprogram that translates user inputs into computer language. The BDL subprogram also calculates thermal factors in walls and envelope components. The second module is the loads module, which calculates the heating and cooling gain loads inside the building. It considers internal heat gains such as lighting, occupancy, equipment, and plug loads. The third subprogram addresses systems, and it calculates heating and air conditioning system requirements. It considers requirements for outside air, temperature controls, and regulating accessories for equipment. The fourth module is the plant subprogram, which sizes chillers, boilers, cooling towers, and other equipment necessary to run a number of systems together. The last module is the economics subprogram, which translates calculated energy into costs according to the type of fuel specified. This subprogram is also used to carry out life cycle cost analysis as well (Hirsch et al. 1994). Figure 2.1 shows the structure of DOE-2.

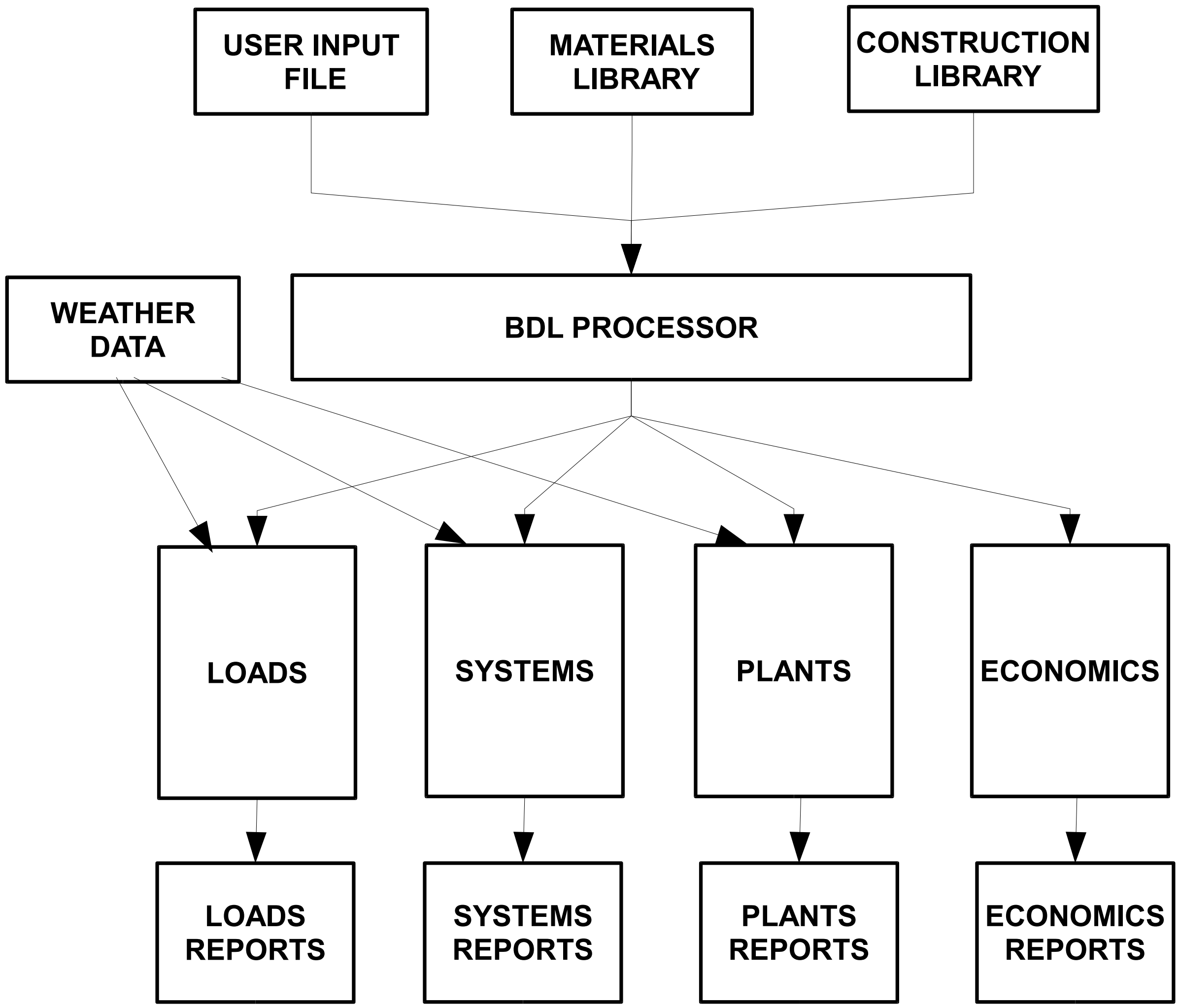


Figure 2-1: DOE-2 Simulation Engine Structure (Hirsch 1994)

2.3.2. HAP

The Hourly Analysis Program (HAP) from Carrier uses the Transfer Function Methodology (TFM) for calculating heat transfer phenomena in the software. This methodology is a derivative of the Heat Balance Method, so shortcuts and assumptions are used to reduce the volume and detail of required input to speed calculations. The methodology is best described in the Transfer Function Methodology (TFM) paper (Carrier Corporation 2005) and it is explained as follows:

"Methodology is based under the principle that conduction, convection, and radiation are the main drivers of heat transfer to or from the air in the room. The radiation heat gains from sources such as solar, lights, and even people take time to become a load; the radiant heat must first heat up the building and contents and then be conducted and released over time to the room by air convection processes causing a delay between the time a heat gain occurs and the time its full effects as cooling load appear. The convection process is governed by the temperature difference between the mass and the room air. Convection decreases as the room air temperature rises and increases as the room air temperature decreases. Due to throttling ranges in the control systems that vary the room air temperature calculations can't be made assuming constant air temperature at all times. Using night set up or not cooling during unoccupied times may cause an increase in room temperature and decrease in convection storing heat for release. Later on system start up, the room air temperature rapidly decreases and a convective rush of heat can occur. The TFM calculates the effect of the changing room air temperature on the heating and cooling requirements. This is done through the Space Air Transfer functions known as Heat Extraction.

The transfer function with heat extraction is implemented in three steps:

1. Conduction equations are used to analyze the heat flow through walls and roofs.

2. The room transfer functions are used to analyze radiative, convective, and heat storage processes of all components. Convective components are instantaneous and radiative components are stored and released over time.

3. The space air temperature transfer functions (heat extraction equations) are used to analyze the effects of the changing room air temperature on convective heat flow from mass to room air that includes behavior of room thermostat.

Results of calculations can yield important benefits such as the ability to analyze realistic transient heat transfer that occurs in all buildings. Loads can also be accurately computed for any heat gain sequence and wall or roof construction. Resulting loads are specific and customized for each application analyzed, accounting for local weather conditions, building constructions and operating schedules."

2.3.3. eQuest

A user's manual (Hirsch 2009) details the basic operation of eQuest: "The program uses a simulation engine derived from the principles of DOE-2, however it extends and expands its capabilities in several ways, including: interactive operation, dynamic and intelligent defaults, and improvements to numerous flaws that have limited its use by designers and building professionals. The program allows avoiding all the programming process while guiding the user through the creation of a detailed building model, performing automatic parametric simulations of the design alternatives."

2.3.4. EnergyPlus

EnergyPlus is best explained in its engineering reference manual (University of Illinois and LBNL 2009): "The EnergyPlus program is a collection of many program modules that work together to calculate the energy required for heating and cooling a building using a variety of systems and energy sources. It does this by simulating the building and associated energy systems when they are exposed to different environmental and operating conditions. The core of the simulation is a model of the building that is based on fundamental heat balance principles." Figure 2.2 shows the organization of EnergyPlus

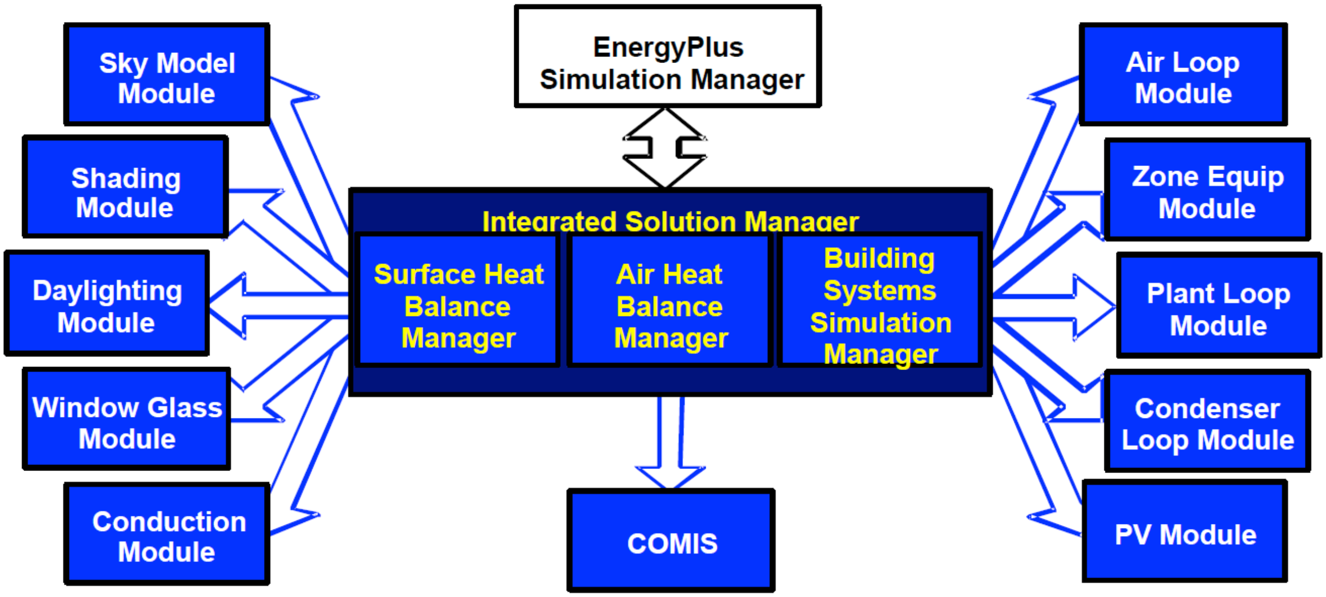


Figure 2-2: EnergyPlus Internal Elements (University of Illinois 2009) "<u>For interpretation of the references to color in this and all other figures, the reader is referred to the electronic version of this thesis</u>"

The main difference from the DOE engine is (University of Illinois and LBNL 2009): "In programs with sequential simulation, such as BLAST and DOE-2, the building zones, air handling systems, and central plant equipment are simulated sequentially with no feedback from one to the other … This simulation technique works well when the system response is a well-defined function of the air temperature of the conditioned space … lack of feedback from the system can lead to non-physical results … In EnergyPlus all elements are integrated and controlled by an Integrated Solution Manager. The loops are divided into supply and demand sides, and the solution scheme generally relies on successive substitution iteration to reconcile supply and demand using the Gauss-Seidell philosophy of continuous updating."

2.3.5. BEOpt

BEOpt is a recent tool developed by the National Renewable Energy Laboratory (NREL) to aid in the Building America project development by the US Department of Energy (DOE). The scope of the program is mostly residential, and it is a useful tool for research towards zero energy homes. In a report by Christensen et al. (2006), the basic explanation of the software is given: "Beopt software calls the DOE2 and TRNSYS simulation engines and uses a sequential search technique to automate the process of identifying optimal building designs along the path to Zero Net Energy (ZNE) … The DOE-2 simulation program is used to calculate energy use as a function of building envelope options and HVAC equipment options. Appliance and lighting option energy savings are calculated based on energy use intensity factors and schedules input into DOE-2. TRNSYS simulation program is used to calculate water heating loads and energy savings for solar water heating. TRNSYS is also used to calculate annual electrical production from a grid tied Photo Voltaic system … A prototype version of BEOpt using EnergyPlus has demonstrated technical feasibility for future use of a single simulation engine with extended capabilities." Figure 2.4 shows the internal structure of Beopt.

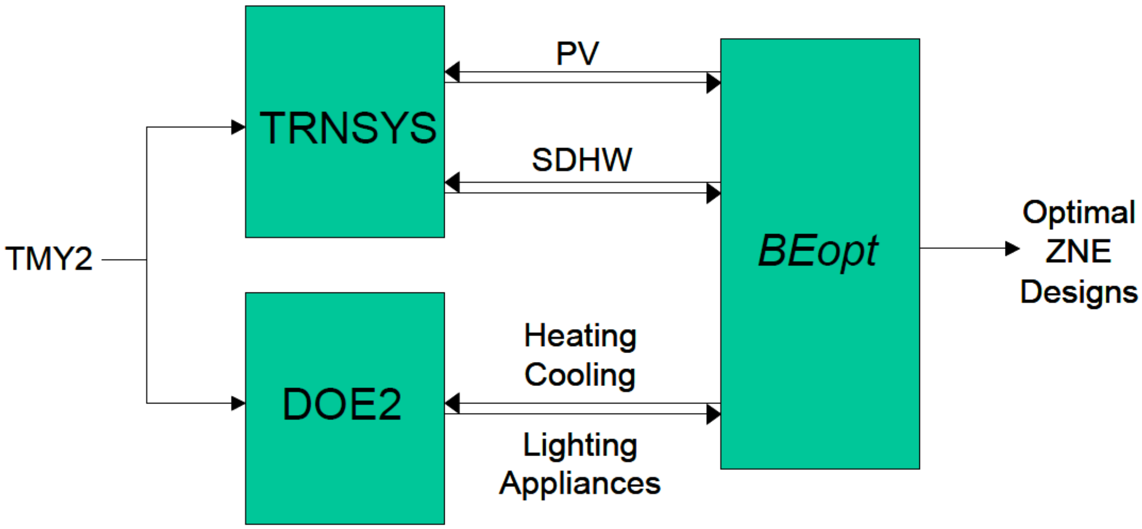


Figure 2-3: BEOpt Internal Structure (Christensen et all 2006)

It is important to emphasize that BEOpt is a tool to obtain optimal solutions for a Net Zero Structure, unlike the other tools that will report a more detailed solution of the energy behavior of the structure.

2.3.6 COMcheck

Some energy simulation programs are developed to demonstrate compliance with energy codes instead of predicting energy performance. Such is the case of COMcheck developed by Pacific Northwest National Laboratories (PNNL) for the U.S. Department of Energy (DOE). This has been a helpful tool for designers and builders to understand the requirements of building energy codes and for local authorities to enforce these codes. COMcheck is based on the ASHRAE 90.1 standard and it addresses minimum requirements for building envelope, HVAC, water heating and lighting systems (Bartlett et al. 2011). Bartlett et al. (2011) explain in their report: “Each major system must comply on its own; trade-offs between major systems are not permitted, although they are permitted under the Standard 90.1 Building Energy Cost Budget Method or under the Total Building Performance section in the IECC editions … Compliance forms similar to those used in printed guidelines are generated by the software for submission with plans and specifications …. Program enables Standard 90.1 users to only make trade-offs between above-grade wall and window components. Trade-offs allow the use of components exceeding minimum criteria to be used to offset components that fall below minimum criteria." This kind of software is limited to calculations for code compliance and it is not intended for energy analysis or approved for LEED analysis. Table 2.1 summarizes advantages and disadvantages of the modeling programs discussed above.

Description	Advantages	Disadvantages	Software
Linear differential equations with time invariant parameters	Parameters are assumed so shortcuts are used to reduce the volume of required input	Result from one system is input for the next one, but there is no feedback from system to system	DOE • eQuest • BEOpt HAP
Non linear equations with time varying parameters	Systems can be solved simultaneously, allowing feedback among them; can handle complex flow path interactions	The data input process can be more complex	EnergyPlus

Table 2-1: Summary of Some Simulation Programs

2.4. Validation and Calibration of Energy Simulations

In an effort to increase accuracy of simulation tools, two concepts are important to define: calibration and validation. Strachan (2008) indicates that these two processes are differentiated: "Calibration involves using experimental data to ensure that the model predictions align with the measured data over a realistic range of operating conditions … Validation is aimed at ensuring that this (the predictions) assumption is true." Calibration is the first step toward achieving validation of a program. In simpler words, calibration ensures that computer calculations are developed according to theoretical mathematical functions, and validation ensures that assumptions made to predict energy consumption are as close to reality as possible.

Judkoff (2008) not only defines the main goal of simulation but also identifies the need to validate results and identify where inaccuracies may be present. Building energy simulation is described as a tool to predict energy flows (including temperature, envelope losses, system performance and electric loads) either in an existing structure, modification of an existing structure or new design. The accuracy of simulation outputs depends on three factors: accuracy of input data, applicability of the tool to the building and the climate being analyzed, and the ability of the tool to predict real building performance when given perfect input data. Judkoff (2008) states: “It is rarely feasible to collect sufficient experimental data or to apply a given analysis tool to a sufficient number and range of test cases to achieve complete confidence for all situations. Therefore engineering judgment is commonly used to select test cases that represent typical applications of the tool.” Many studies have been developed in search of better approximations and understanding of variables involved in energy simulations.

In a validation process, three different approaches can be taken: first, empirical validation, where calculated results from a program are compared to monitored data from an actual building, test cell, or laboratory experiment; second, an analytical approach, where results from a program are compared to results known from analytical solutions or accepted numerical method calculations; and finally comparative testing where the program is compared to itself or to other programs (Judkoff et al. 2008).

Empirical validation implies gathering data from functional buildings or test cells where parameters may be controlled. The aim of this method is to quantify inaccuracies in calculation methods by the program, but not without considering the uncertainties from both field measurement and data analysis. Recommendations for field measurement include testing in unoccupied buildings, since it is difficult to separate building performance itself from uncertain occupant behavior such as doors opening or use of hot water (Judkoff et al. 2008). Figure 2.5 illustrates sources of simulation error identified by Judkoff.

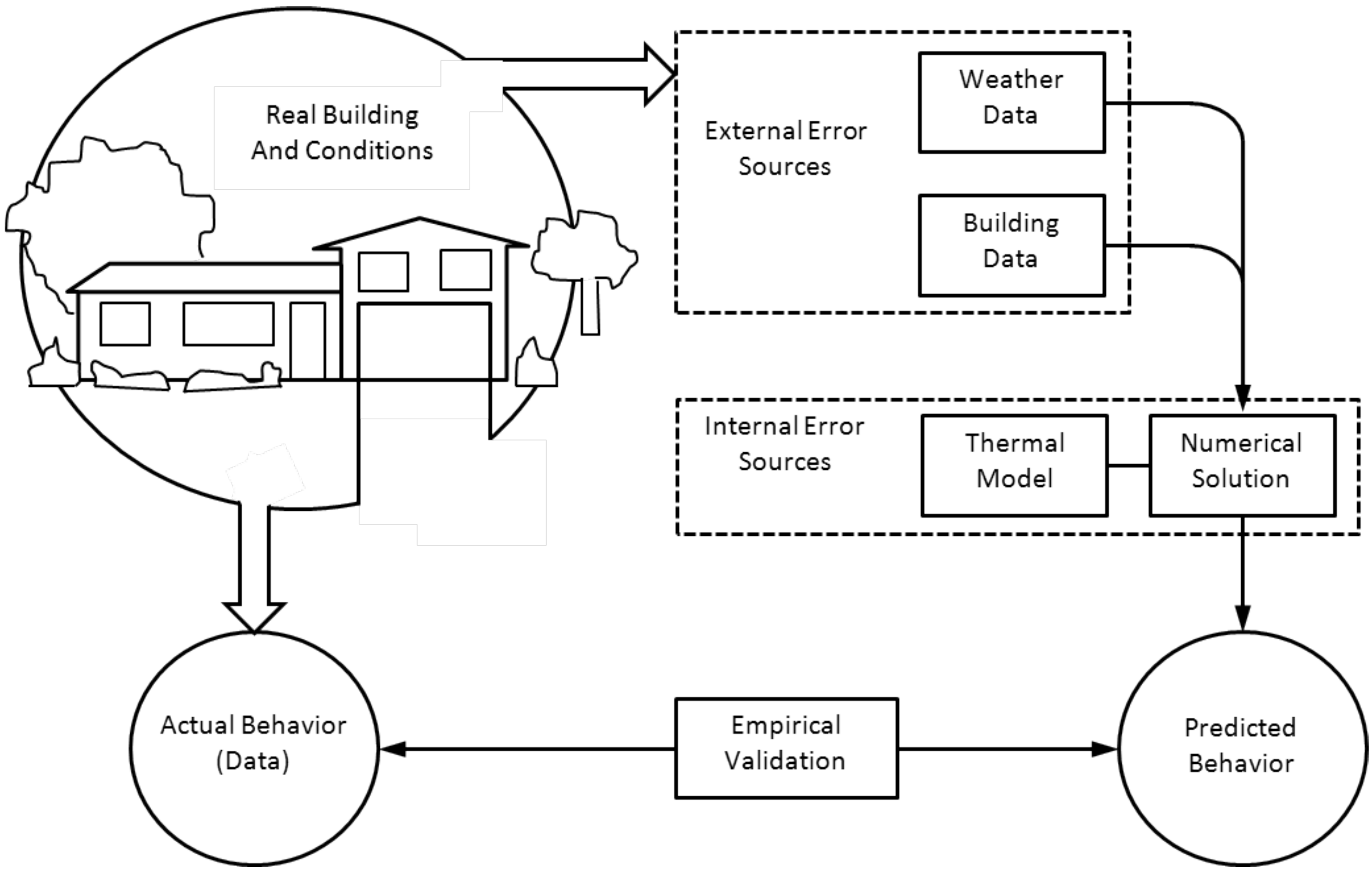


Figure 2-4: Simulation Error Sources (Judkoff et al. 2008)

The International Energy Agency (IEA) (Judkoff 2008) developed a comprehensive and integrated report of energy simulation tools which involve analytical comparative, and empirical methods. The scope included the investigation of availability and accuracy of building energy analysis tools and engineering models to evaluate the performance of innovative low energy buildings. The report was developed for use by simulation software developers, codes and standards organizations, architects, engineers, energy consultants, building owners, and researchers. There are several definitions regarding the kind of tests carried out, including comparative and empirical tests. Comparative tests determine and compare methods used to calculate parameters in different software tools in order to identify the differences between their results. Empirical validation consists of comparing predicted values with measured data in existing buildings or test facilities, and these tests result in higher costs and time-consuming activities. According to Judkoff, over eighty simulation programs have been amended through empirical validation tests, improving accuracy in the evaluation of energy efficiency measures. Recommendations of the IEA report include the support of continued development of models and more validation studies, as the few buildings that are truly useful for empirical validation studies were designed primarily as test facilities. Emphasis was placed on the growing body of literature and activity demonstrating the importance of simulation for reducing energy consumption through energy design. The continued development and validation of whole-building energy simulation programs is one of the most important activities meriting the support of national energy research programs (Judkoff 2008).

Research and experimentation on calibration was done in another study (Lee and Claridge 2002) where HVAC system performance (both mechanical and electrical) was measured in a prototype building, and results were used to optimize the simulation software through the Solver package, which is a tool for optimization. As a conclusion the authors recommend future study and development of a plug-in for an auto-calibration feature of simulation programs.

An important study was also developed using a calibration method that incorporates short term monitoring instead of long term monitoring. This study confirmed that short term methods can be as accurate as long term monitoring, although it is only possible if simulation input is derived from the procedure prescribed in the study. This finding opens the door for short term studies, potentially reducing data collection time (Soebarto 1997).

Another research effort (Zmeureanu et al. 1995) used three different analysis programs (BESA-Design, PC-BLAST, and MIRCRO-DOE2.1D) to evaluate energy consumption and cost savings in a large existing office building in Montreal. The aim of the research was to test program capabilities for predicting energy performance of buildings using information usually available to a design professional or energy consultant, as well to evaluate the impact of several energy efficiency measures or parameters with various software. The details of the research were:

- Area of building: 10,410 square meters (112,052 square feet)
- Variable air volume HVAC system
- The energy saving measures used were:
  - Insulation of floor between garage floor and ground while decreasing garage temperature

- Night setback of indoor temperature to 16 C (60 F) in the winter using programmable thermostats
- Increasing of set point to 25-26 C (77-79 F)
- Decrease of lighting power density on first floor from 25.8 to 22 W/m^2
- Decrease of lighting density from 25.8 to 11.8 W/m^2 on the first floor
- Use of task lighting of 1.4 W/m^2
- Turning off of lights in washrooms, stairwells, and garages during unoccupied hours
- Installation of timers and motion detectors as well as power management devices to turn off office equipment when not in use

There was not a significant trend in the results, although overestimates or underestimates were expected depending on the program or the user. As a recommendation the authors suggest a need for a detailed methodology for verification of the quality of inputs and calibration with utility bills, since models can be easily calibrated with these bills and better definition of unknown parameters.

A similar study (Guyon and Rahni 1996) was performed using CLIM2000 software; this program had already been tested once in small test cells where each parameter was controlled or well known. The authors carried out their research in a 100 square meter (1,076 square foot) house in an eight month time span, and close attention was paid to energy related measurements on the heating system. First, the house was modeled with no knowledge of experimental data, and this model was established as a baseline to which results were compared with final data collected. Some important results included observed decreases in error percentages during colder months, probably due to lower solar gains during these periods. Overall consumption of the building was overestimated by 5.3% over a long period. It was also emphasized that experiments carried out in laboratories gave less uncertainty than experiments in actual buildings.

Karlsson et al. (2007) conducted a study to observe the variation in predicted energy use by different programs. Values obtained through field measurements were compared to initial predictions obtained by simulating the buildings using three different software tools which remain unnamed and are addressed as programs 1, 2 and 3. The data was collected in twenty terraced low energy houses in Sweden, well insulated (U value = 0.17 W/m^2K) with a 900 W heat exchanger, with a ventilation rate of 0.35 l/m^2 and an average window U value of 0.85 W/m^2K. The monitoring program continued for approximately three years after the buildings were inhabited. Results showed that some measured values differed by 50% of the designed values due to additional heating; higher indoor temperatures were measured in the actual houses than those assumed in the initial simulation. Karlsson et al. also concluded that it is very important to study which components affect energy the most and focus on these throughout the design and construction process. The range of values measured through the twenty houses varied significantly, between 50% higher than the average and 20% below average, showing large differences depending on whether the walls were affected by sunlight, whether they were between two other houses, and on which direction the windows were facing. An important finding was that among the programs (all using as similar inputs as possible) the total energy consumption differed by 2% between programs. The study concluded that tenants are the most difficult component to model in a simulation. Recommendations were made for the need for future research on the impact of human behavior on energy use.

Research in full scale buildings usually includes many parameters and sources of error that are difficult to control. Some studies have been developed in laboratories and test cells under controlled circumstances and known conditions. Bloomfield et al. (1995) conducted a study of this kind concluding that there is still considerable doubt about the absolute accuracy of simulation program predictions, and defining three main techniques recognized for validating software: analytical, inter-model, and empirical. The research focused on comparing four programs with simple test rooms, and posed two questions: can the program be deemed valid due to the level of agreement of prediction and measurements, and what might be the reasons for discrepancies between programs and measurements. The data was collected in test rooms developed at the Energy Monitoring Company (EMC), with controlled variables such as temperatures and on-off sequence of radiators. The programs used were APACHE, CLIM2000, ESP-r, and SERI-RES. The authors defined air heating units as the biggest source of errors, followed by prediction of solar radiation entering a zone and its distribution to the enclosing surfaces.

2.5. Program Comparison

As important as it is to know how accurate results are, it is also important to know capabilities, strengths, and weaknesses of available software. No comprehensive comparative survey of tools had been conducted since 1995, until Crawley et al. (2005) conducted an important study in 2005. The results are presented in a matrix (a sample of which is included in

Figure 2.6) that places software in one column, and their features in rows such as method of calculations, capability of including renewable energy, ability to change schedules for every component, and others. Software in the matrix includes eQuest, HAP, and EnergyPlus among others. Crawley concluded that there is increased interest in validation by energy analysts. As a consequence, several program developers indicated their plans to make simulation inputs available for users to download in the near future. Crawley mentioned the issue of trust, and asked whether or not tools really perform the capabilities indicated.

Building Envelope, Daylighting and Solar (9 of the 52 rows from Table 3 in the report)	BLAST	B SIM	DeST	DOE-2.1E	ECOTECT	Ener-Win	Energy Express	Energy-10	EnergyPlus	eQuest
Outside Surface Convection Algorithm										
• BLAST / TARP	X								X	
• DOE-2				X					X	X
• MoWiTT						X		X	X	
• ASHRAE Simple	X								X	
• Ito, Kimura, and Oka correlation										
• User selectable			X						X	
Inside Radiation View Factors		X	X						X	
Radiation-to-air component separate from detailed convection (exterior)		X	X						X	X
Solar gain and daylight calculations account for inter-reflections from external building components and other buildings		P			X				X	

Table 2-2: Contrasting Capabilities of Programs (Crawley et al. 2005)

Under the standards developed by the IEA for tool validation, the Building Research Establishment (BRE) undertook work in the UK during a span of five years, from November 1989 until September 1994. A report compiling these results (Lomas et al. 1997) describes the tests carried out in test rooms with controlled conditions. This study is important because it was the largest validation work to date and compared a number of simulation programs. An important conclusion drawn is the necessity of a "blind" phase, that is, an experiment conducted without knowledge of actual measurements, providing a clear and clean snapshot of a program's capabilities when used as it would be used in the design phase of an actual construction project.

2.6. Occupancy Schedule Testing

Research has also focused on determining the impact of a single parameter in overall simulation results. This approach helps in finding sources of errors for a particular variable instead of considering the sum of errors from various parameters. This can improve modeling, since the impact of that particular parameter can be determined and evaluated. Also, uncertainty about values chosen as inputs can be reduced. If enough data can be evaluated, it may be possible to standardize variable values and develop norms or codes.

Occupancy schedule is a parameter that carries uncertainty in simulation. Improving definition of occupancy schedules, lighting schedules, schedules for plugged loads, and schedules for thermostat settings allows the modeling program to apply factors to electric consumption and HVAC systems operation, leading to more accurate approximations of energy use. However, as unpredictable as human behavior is, inaccurate assumptions will be made about these schedules. Additional research is necessary regarding this variable, because even though real models of exact occupancy schedules cannot be obtained, standardized profiles could be determined to provide a narrower range of differences among models. Standardization can be reached within buildings of the same occupancy type, and therefore, profiles for office buildings, school buildings, hospital buildings etc. could follow certain norms for schedule definition.

Efforts have been made to estimate occupancy through agent-based models such as work by Liao and Barooah (2010). This model involved simulating behavior of occupants and then graphing the results so statistical information could be used for real time estimations. Although the experimental data collected by Liao and Barooah was made in a simplified environment of only one room and one occupant, the authors concluded that simulation can produce accurate estimates for a whole building. This presents the possibility of integrating agent-based simulation into energy simulation programs so an approximation of occupancy can be defined.

A study carried out at Cambridge, Massachusetts aimed to survey a building to assess internal loads and schedules (Wasilowsky and Reinhart 2009). Researchers conducted twenty walk-through observations of a building, and also conducted online questionnaires regarding occupant schedule and appliance use. The model was run with default values in the program, which were replaced with observed values. Conclusions included the importance of carefully surveying a building during retrofit and emphasizing the importance of adequately modeling internal loads. The authors calculated the mean bias error (MBE) for both cases: 0.2% for customized loads and -17% for the default inputs. Likewise, mean square errors showed improvement from 64% for default loads to 23% for customized loads. Figure 2.7 shows measured energy against simulations with either custom (measured) or default (by the program) inputs:

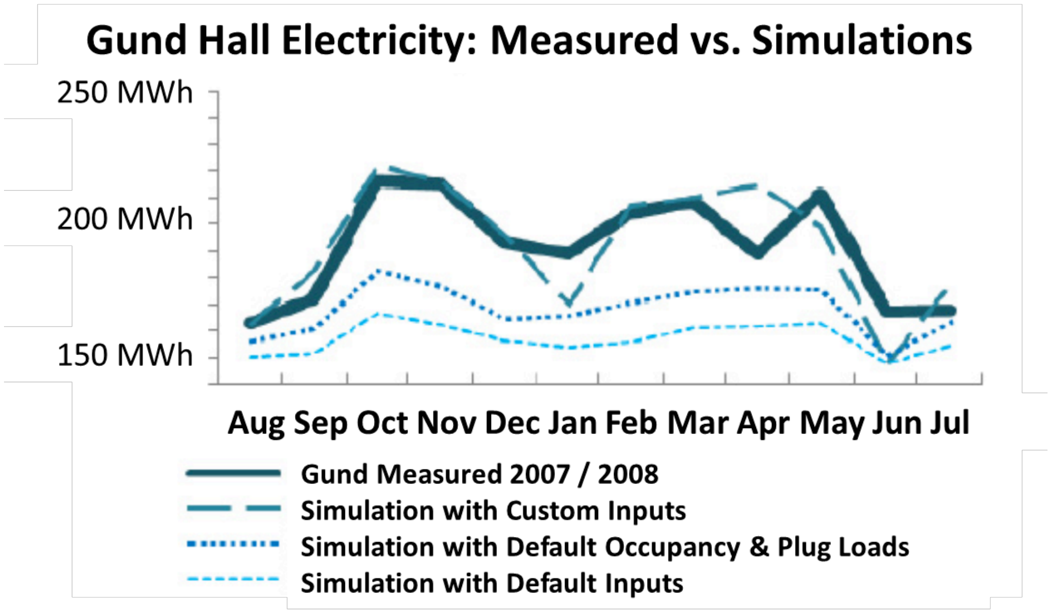


Figure 2-5: Measured Energy v. Simulated Energy (Wasilowsky and Reinhardt 2009)

Another study attempted to test the sensitivity of occupancy related parameters (Clevenger and Haymaker 2010). A range of values were defined assuming states of low and high occupancy, that is, how lighting, plug loads, hot water and people affect the structure during high and low occupancy. The authors concluded that comparing results obtained from lower occupancy values to results obtained from higher occupancy values showed differences of up to 150%, demonstrating the range of inaccuracies and the need for the study of occupancy schedules. The authors envisioned the creation of occupant files, similar to weather files which may serve as benchmarks for future models. Recommendations for future research included extended work towards a better understanding of the impact of uncertainty introduced by variable occupant behavior on accuracy of simulation results, as well as identification of the overall shortcomings of current occupant models.

A significant project developed by ASHRAE (Abushakra et al. 2001) was the 1093-RP, which focused on developing a set of library schedules and diversity factors for electricity components such as lighting and plug loads. This was developed by measuring data from thirty-two office buildings throughout one year, differentiating between weekdays and weekends. Files released were compatible with DOE-2, BLAST, and EnergyPlus, and allowed for modification as well if the profile didn't suit a proposed schedule. Figure 2.8, shows measured patterns of various projects and an average line is shown.

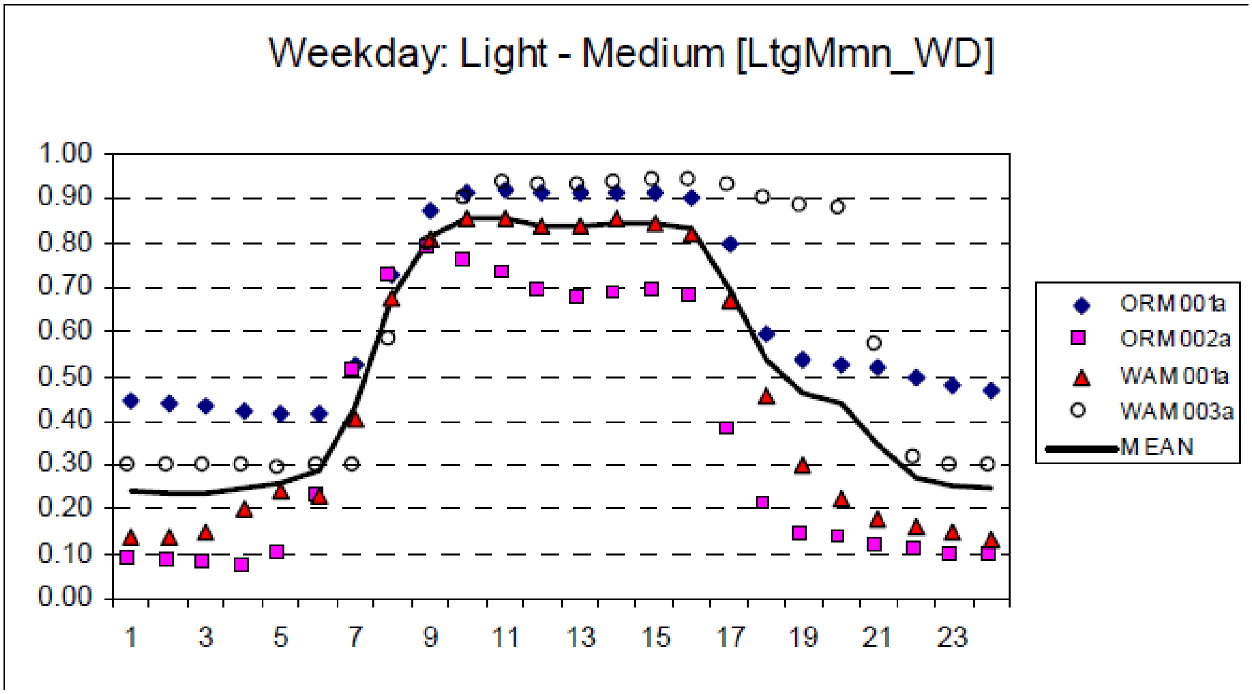


Figure 2-6: Sample Graph for Diversity Measurements in Buildings (Abushakra et al. 2001)

Even though defined profiles might be of great use, separate research (Bourgeois et al. 2005) highlights shortcomings of these results in the 1093-RP. The authors claimed the technique was valid, although it was derived independently of weather and meteorological patterns, and lighting use will show different patterns in buildings of large envelope-to-floor area ratio with daylighting design approaches. This research focused on enabling manual control, or individual instance modeling of people and equipment instead of groups. It also used energy simulations instead of predefined diversity profiles. This technique gave results as much as 62% better on energy prediction than with the defined schedules.

A recent study conducted for the New Building Institute (NBI) by Heller, Heater, and Frankel (2011) determined envelope components and operational systems that have an impact on building energy use. They defined a range of performance values for various components and systems as poor, baseline, and good. Performance values were tested using energy simulation for each characteristic and incorporated weather data from sixteen cities. The characteristics included envelope, occupancy, HVAC, lighting, operations (daylight controls, economizer and thermostats) and other direct loads. The authors found operations and occupant behavior heavily impact building energy use. Figure 2.9 shows an example chart included in their study:

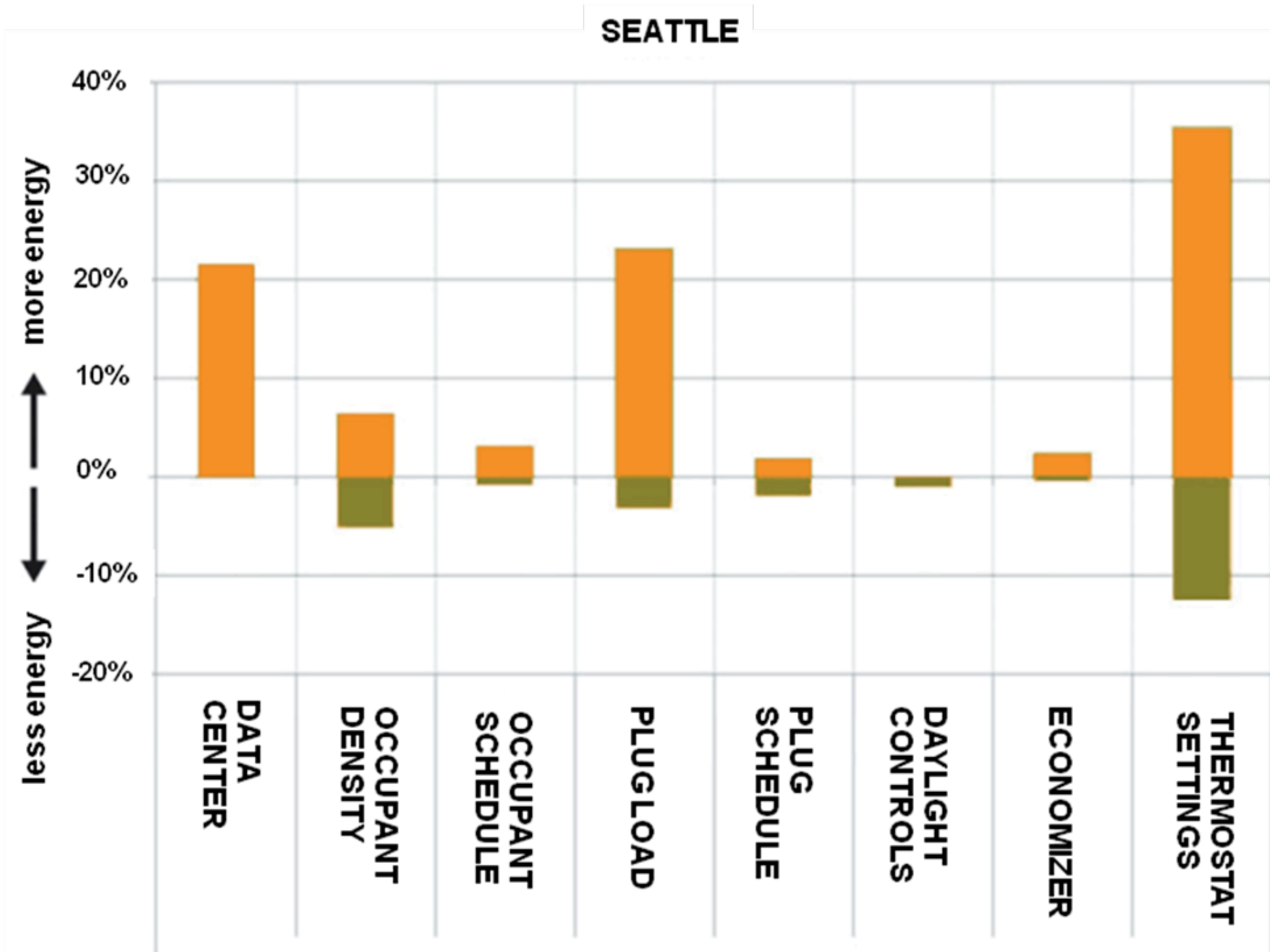


Figure 2-7: Measured Impacts of Different Performance Values of Building Characteristics (Heller, Heater, and Frankel, 2011)

The authors main conclusion was identifying responsible parties for on-going building energy performance since it was found how operational and occupant behavior heavily impacts building energy use. Study also suggests how many design options are not taken advantage of according to the climatic zone and how these should be recognized and regulated in codes.

2.7. Sources of Information

The energy modeler may use default schedules in software but there are a number of sources of information which can be available. Published sources or the owner may have information available which can assist the modeler when defining schedules.

In school classrooms, scheduling can be supported by existing and ongoing space utilization studies. In a report from Marshall University (Dober, Lidsky, Craig and Associates 2003), the purpose of these studies was stated as identifying space use percentage to make the most out of every available room and optimize scheduling. As a consequence, space utilization patterns of use were also examined. Figure 2.9 shows a sample chart from Marshall University.

Scheduled by Registrar

HEGIS CATEGORY: 200

Building	Spaces	NASF	Stations	NASF / Station	Scheduled Sections	Mean Section Size	Usage Hrs / Week per Space
Community College	1	563	20	28.2	6	18	11.0
Corbly Hall	2	2,397	89	26.9	15	22	16.0
Gullickson Hall	1	1,167			6	19	12.5
Harris Hall	2	879	49	17.3	7	9	7.5
Science Building	3	2,343	58	44.8	9	17	7.3
Smith Communication	1	625	32	19.5	7	17	18.0
Smith Hall	1	1,355	15	90.3	3	17	12.0
Sorrell Annex	2		60		7	11	14.5
HEGIS Totals:	**13**	**9,329**	**323**	**36.1**	**60**	**17**	**11.7**

Table 2-3: Space Utilization Study (Dober, Lidsky, Craig and Associates, 2003)

Similar studies have been conducted on other college campuses, where not only actual utilization was determined, but also target occupancy hours used by administration and planning departments. These types of reports may be available from an owner during design and modeling of a specific project and should be considered by the modeler. A sample chart of this information from the University of Oregon (2007) is shown in Figure 2.10:

Average Hours of Scheduled Occupancy Per Week [1]

	Fall 2006	Fall 2007	Board Objectives
Room Utilization			
Classrooms	32.5	33.8	33.0
Lower-Division Laboratories	21.0	19.2	22.0
Upper-Division Laboratories	19.2	17.5	16.0

Table 2-4: Space Utilization with Target Objectives (University of Oregon 2007)

Another available source is the ASHRAE 90.1 User's Manual (2004) which include suggested schedules by building type being modeled. According to the standard (2004): "Where the schedules are not known, you may consult values in Table G-E through G-N for guidance … Schedules can vary significantly from building to building and tenant to tenant. Over the years a number of schedules have been defined using a variety of sources … Schedules are reproduced as an example of typical input data." A sample schedule from ASHRAE 90.1 user's manual is shown in figure 2.12.

Hour of Day (Time)	Schedule for Occupancy Percent of Maximum Load			Schedule for Lighting Receptacles Percent of Maximum Load		
	Wk	Sat	Sun	Wk	Mon	Tue
1 (12-1 am)	0	0	0	5	5	5
2 (1-2 am)	0	0	0	5	5	5
3 (2-3 am)	0	0	0	5	5	5
4 (3-4 am)	0	0	0	5	5	5
5 (4-5 am)	0	0	0	5	5	5
6 (5-6 am)	0	0	0	5	5	5
7 (6-7 am)	0	0	0	40	5	5
8 (7-8 am)	0	0	0	40	30	30
9 (8-9 am)	20	20	10	40	30	30
10 (9-10 am)	20	20	10	75	50	30
11 (10-11 am)	20	20	10	75	50	30
12 (11-12 pm)	80	60	10	75	50	30
13 (12-1 pm)	80	60	10	75	50	65
14 (1-2 pm)	80	60	70	75	50	65
15 (2-3 pm)	80	60	70	75	50	65
16 (3-4 pm)	80	60	70	75	50	65
17 (4-5 pm)	80	60	70	75	50	65
18 (5-6 pm)	80	60	70	75	50	65
19 (6-7 pm)	20	60	70	75	50	65
20 (7-8 pm)	20	60	70	75	50	65
21 (8-9 pm)	20	60	70	75	50	65
22 (9-10 pm)	20	80	70	75	50	65
23 (10-11 pm)	10	10	20	25	50	5
24 (11-12 am)	0	0	0	5	5	5

Table 2-5: Sample Schedule for Assembly Occupancy (ASHRAE User's Manual 2004)

2.8. Summary

This chapter summarizes the literature that was used as background for this research. The intention of the literature review was to gain an understanding of the history and development of energy simulation software, as well as to investigate existing research related to energy simulation and prediction. The literature review helped in identifying gaps where this thesis research could be focused in order to avoid repeating existing studies and to determine the areas of interest for this study.

CHAPTER 3

METHODOLOGY

METHODOLOGY

This chapter outlines the methodology used for this thesis research; the goals were to determine the impact of schedule definition on energy simulation and to develop recommendations on procedures helpful in achieving more accurate occupancy schedules. The research used three case studies. Additionally a survey of energy modelers was conducted to obtain information on their practices for establishing occupancy schedules during simulation. Figure 3.1 shows activities carried out for the research and includes problem definition, literature review, boundary testing for the software, selection of case studies, methods for gathering information for each case study, development and administration of a survey of energy modelers, and development of recommendations, guidelines, and tools for energy modeling processes.

3.1 Literature Review

The literature review covered three primary areas. First, background research on energy modeling software development along with modeling methods and techniques was conducted. Secondly, review of existing programs was conducted with a focus on understanding the types of tests carried out in the software. Finally, articles and documents were reviewed to explore existing research on occupancy related schedules for energy simulation.

3.2 Survey

The first step in the study was to develop a survey of energy modeling professionals on how occupancy schedules are defined within their projects. General perceptions about uncertainty in simulation results and scheduled parameters were obtained as well as insight on existing procedures for defining user profiles. Upon development of the survey, proposed procedures were submitted for Human Subject review by the Institutional Review Board (IRB) at Michigan State University. Surveys were carried out by telephone. The questions used in the survey and consent forms are shown in Appendix A. The four surveyed professionals were selected based on their known involvement with LEED and energy simulation projects and also past working interactions with the research team.

3.3 Identification and Selection of Case Studies

Three buildings were selected as case studies for carrying out measurement and analysis. These buildings were selected in collaboration with Michigan State University Engineering and Architectural Services, Physical Plant Division, as well as a local architect. After meeting with these organizations and presenting the study, they consented to help and offered the selected case studies. Architectural and engineering drawings for the Chemistry Building addition and the Geography building at Michigan State University and a Lansing, Michigan church were provided. Specific data collection methods for each case are discussed below.

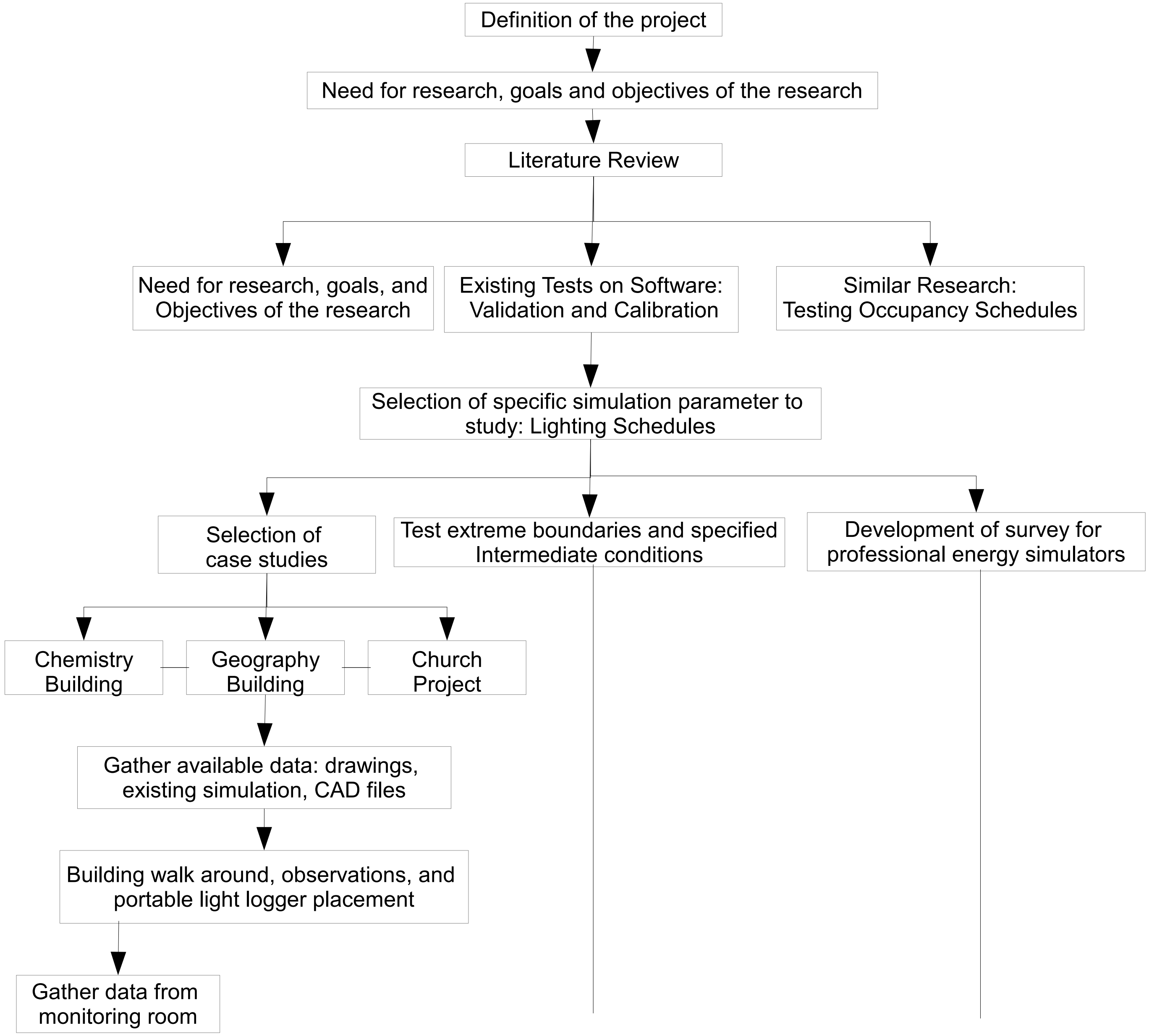
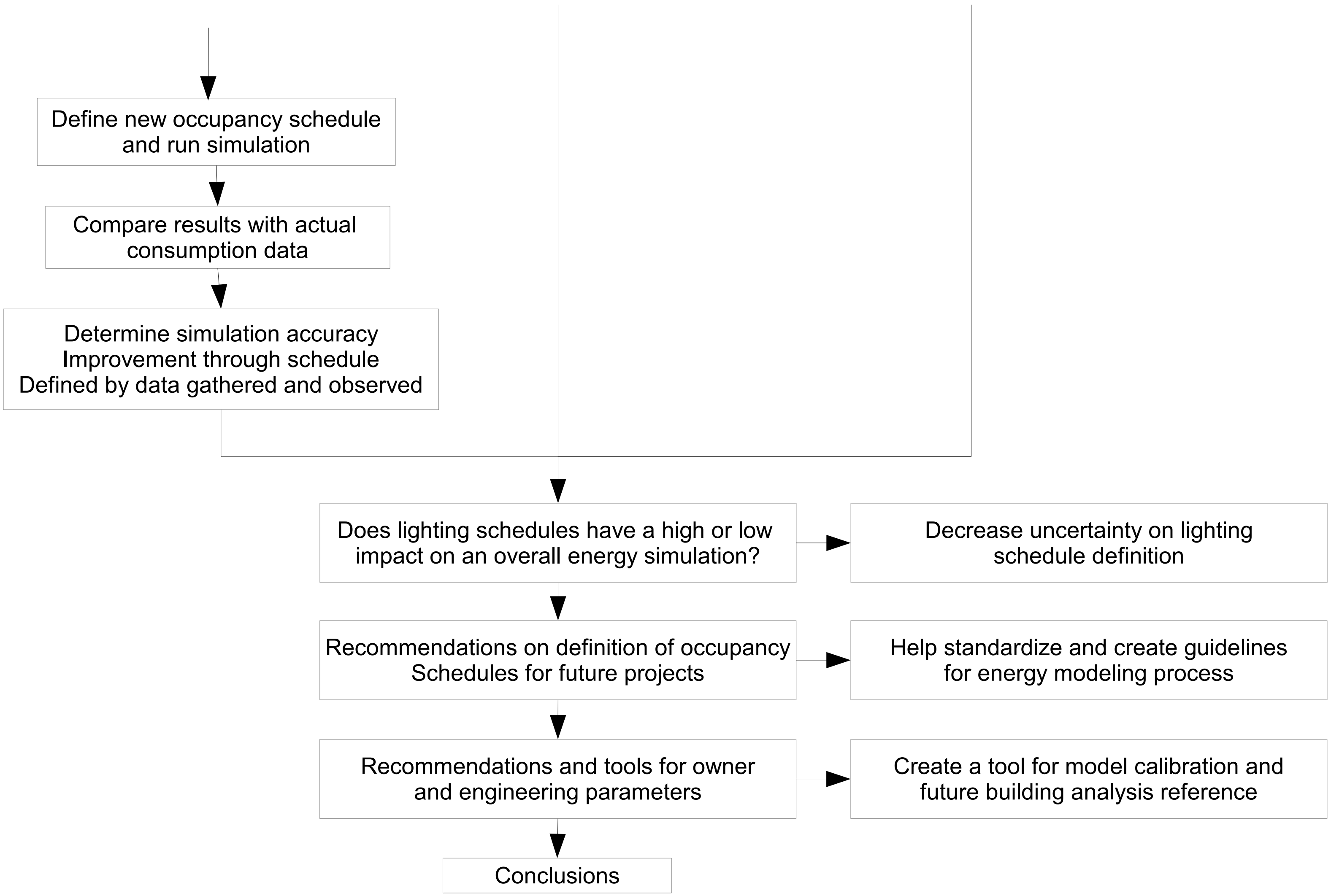


Figure 3-1: Methodology of Research

Figure 3-1 (cont'd)



3.4 Extreme and Intermediate Boundaries

Before measurements in the buildings were undertaken, boundary conditions in the software were tested. The program used throughout the research was eQuest. A simple building model (not any of case base buildings) was created in the program, guided by ASHRAE minimum envelope and HVAC system requirements and a simple rectangular shape. This simple structure helped in determining the range of predicted energy consumption when utilizing 0% lighting and 100% lighting throughout the 24 hour day in the simulations. Intermediate ranges such as 8 hour periods and 12 hour periods at 100% lighting use were also tested to understand the impact of increasing lighting use in energy predictions. These boundary tests were useful in determining the relative impact of lighting under minimum, maximum and intermediate values.

Varying occupancy percentages affect several parameters including: lighting, HVAC fans, water heating, thermostat settings, and plug loads; Siva (2010) establishes a rule of thumb where for every 3 Watts of reduced lighting, 1 Watt of HVAC is reduced. A more detailed study was carried by Sezgen and Koomey (1998), where through simulation of varying lighting loads and HVAC loads impacts were determined. Figure 3.2 shows changes in heating and cooling loads from Sezgen and Koomey's work.

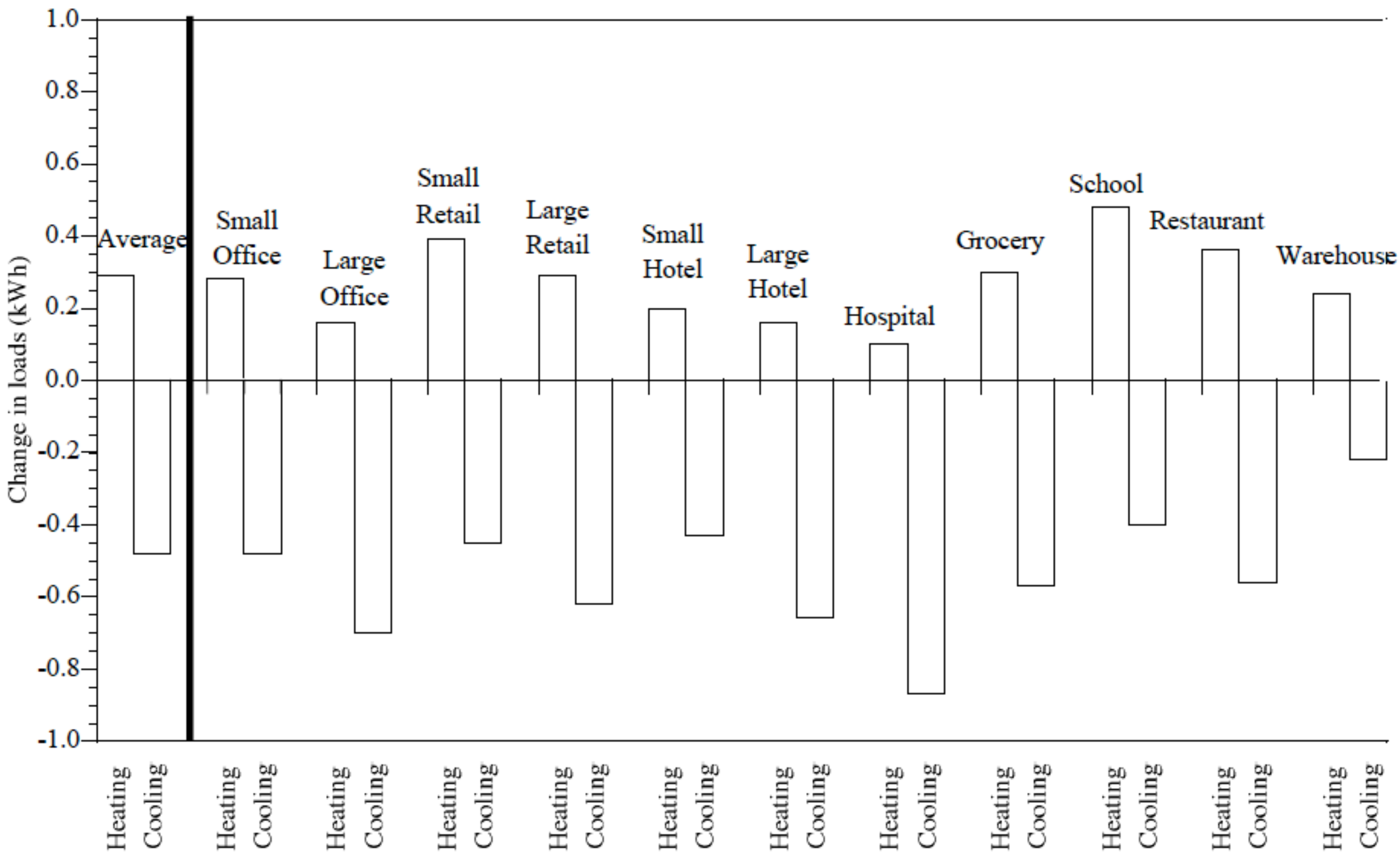


Figure 3-2: Change in Heating and Cooling Loads Caused by a 1kWh decline in lighting loads in new construction buildings (Sezgen and Koomey 1998)

3.5 Methods for Each Case Study

Due to the type of data available from each of the buildings, the data gathering process varied from case to case. The following section describes each case study and shows a breakdown of activities and data available.

3.5.1 Chemistry Addition Building

The steps for gathering data for the Chemistry Addition building included the following:

- The Engineering and Architectural Services Division from the Physical Plant at Michigan State University provided construction drawings which were used to obtain information for model development, including architectural details of the envelope, HVAC design, and lighting fixture layouts

- An existing energy simulation conducted during the design phase of this building was provided and reviewed to obtain schedules used during building design

- Visual observations of lighting use were made for spaces within the building. All 24 hours were recorded during a one week period. Observations were scheduled as shown in Table 3.1:

	1st	2nd	3rd	4th	5th
Monday	12:00 AM	5:00 AM	10:00 AM	3:00 PM	8:00 PM
Tuesday	1:00 AM	6:00 AM	11:00 AM	4:00 PM	9:00 PM
Wednesday	2:00 AM	7:00 AM	12:00 PM	5:00 PM	10:00 PM
Thursday	3:00 AM	8:00 AM	1:00 PM	6:00 PM	11:00 PM
Friday	4:00 AM	9:00 AM	2:00 PM	7:00 PM	

Table 3-1: Scheduled Visits for Chemistry Building

- Observations were recorded in a chart where hourly data defined the lighting use profile for each room, as well as an hourly average profile for the whole building as shown in Table 3.2

- Data loggers were installed for verification purposes in the basement spaces and the computer office in the third room

		HOUR OF THE DAY																							
Rooms	**Floor**	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Study Room	Basement																								
Classroom	Basement																								
Office	Basement																								
General Office	1st																								
Classroom	1st																								
Copy Room	1st																								
Undergrad Office	1st																								
Classroom	2nd																								
Computer Office	3rd																								
Bussiness Office	3rd																								
Graduate Office	3rd																								
Main Office	4th																								
Conf./ Sem. Room	4th																								
Grad. Study Room	5th																								
Instrument Lab	5th																								
Conf./ Sem. Room	5th																								
Hallways	B-5																								
Bathrooms	B-5																								
Stairway	B-5																								
	%																								

Table 3-2: Chemistry Observation Chart

- Hourly lighting schedules were defined from these field observations and then used for simulation

- The Engineering and Architectural Services from the Physical Plant at Michigan State University provided electric and steam utility metering data from the building, which was used to compare predictions from the model and to determine accuracy of the simulation

3.5.2 Geography Building

The steps for gathering data for the Geography building were the following:

- The Engineering and Architectural Services from the Physical Plant at Michigan State University provided construction drawings necessary to obtain information required to develop the model, including architectural details as well as available HVAC and miscellaneous equipment information

- Lighting fixture drawings were only available for some spaces where prior remodeling work had been conducted; consequently the researcher conducted a physical inspection to determine fixture number and type in spaces where no information was available from drawings. This approach was necessary to account for the number and type of fixtures in determining electric loads associated with lighting and to define a baseline number for 100% lighting use

- Since no previous model was developed for this building, the first simulation run used default lighting schedules within the eQuest software

- Visual observation was carried out for spaces by conducting a walk-through of the building. Access to the building after normal business hours was requested from building authorities and approved. Table 3.3 shows the schedule for the visits

	1st	2nd	3rd	4th	5th
Monday	12:00 AM	5:00 AM	10:00 AM	3:00 PM	8:00 PM
Tuesday	1:00 AM	6:00 AM	11:00 AM	4:00 PM	9:00 PM
Wednesday	2:00 AM	7:00 AM	12:00 PM	5:00 PM	10:00 PM
Thursday	3:00 AM	8:00 AM	1:00 PM	6:00 PM	11:00 PM
Friday	4:00 AM	9:00 AM	2:00 PM	7:00 PM	

Table 3-3: Scheduled Visits for Geography Building

- Observations were recorded in a chart to create a profile for each room, as shown in Table 3.4. A whole building average lighting use profile was defined from observations as well

		HOUR OF THE DAY																							
Rooms	**Floor**	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Study Room	Base.																								
Classroom	Base.																								
Office	Base.																								
Classroom	1st																								
Copy Room	1st																								
Classroom	2nd																								
Computer Office	3rd																								
Bussiness Office	3rd																								
Main Office	4th																								
Conf./ Sem. Room	4th																								
Grad. Study Room	5th																								
Instrument Lab	5th																								
Bathrooms	B-5																								
Stairway	B-5																								
	%																								

Table 3-4: Geography Observation Chart

- The Engineering and Architectural Services Department from the Physical Plant at Michigan State University provided electric and steam utility metering data of the building, which was used to compare predicted results from the model to actual consumption

3.5.3 Church Project

The steps for gathering necessary information for the Church project included the following:

- Drawings were provided by a local architect, where architectural details of envelope assemblies were obtained, as well as engineering details for HVAC and lighting systems

- An energy simulation conducted during the design phase was provided for reference; assumed schedules for occupancy used in the simulation were extracted from this existing model and predicted results obtained

- As the project is farther away than the other two buildings, LEVITON portable light loggers were used for data collection rather than physical observation. These were installed in the main rooms (Meeting and Fellowship), library, and one of the small meeting rooms. The loggers record when lights are on or off, lighting levels and if the room is occupied or not. Lighting status (being on or off) was used to define lighting use schedules for the research model in this building

- Monthly metered data was provided by the project owner to compare actual consumption to predicted results

- Additional information requested from the owner for analysis was provided including a predesign occupancy schedule and a calendar showing actual use of spaces

3.6 New Schedules and Analysis

After field observations were collected, percentages of lighting use were defined from the observation charts for all 24 hours, allowing definition of new lighting schedules for each case study according to recorded profiles. These observed schedules were used to run the simulation model developed during the research to compare and analyze differences in energy prediction with the original simulation created during the design phase. Analysis also compared metering data with the simulations of the buildings. Metered data for Chemistry and Geography buildings was provided by the Architectural and Engineering Services department from Physical Plant at Michigan State University, and monthly utility billing history was provided by the owner for the church project.

3.7 Guidelines Development

Recommendations and guidelines for lighting schedule definition during design phase were developed following the core study analysis. The recommendations and guidelines identify sources of information that can better enable the modeler to create realistic profiles of occupancy rather than using program default schedules. To facilitate collecting relevant information a collection tool was developed. The tool can help the modeler to collect information for occupancy, lighting, HVAC, for input into an energy simulation. This tool is used in conjunction with the owner, architect, and engineers so all relevant information can be collected and included in a single document.

3.8 Chapter Summary

This chapter describes the methodology used during the research. The research has six main components: literature review, a survey of energy modeling professionals, a boundary test to determine the impact of lighting variations within the software, case study observations and measurements carried out in three selected buildings, case study simulations and development of recommendations and tool for collecting information when modeling. The selected buildings were the Chemistry building and Geography building at Michigan State University, and a Church project in Lansing, Michigan. Procedures for data collection were described for each building and addressed how lighting schedules were developed from observations and measurements. Data collection and its analysis are discussed in Chapter Four. Finally, guidelines, and tools were identified as deliverables of the research and are presented in Chapter Five.

CHAPTER 4

DATA ANALYSIS

DATA ANALYSIS

The following chapter presents the data and analysis for the research. First a survey of professional energy modelers is presented and provides background on modeling processes. Then, impacts of lighting schedule variation on a sample building modeled under ASHRAE requirements are presented. Finally, lighting use patterns were recorded in three case study buildings, which were used to define lighting schedules for energy models developed for each of these buildings. Electric consumption from simulation results were compared to actual utility data which led to conclusions about the impact of schedules. As a result recommendations and a checklist for collecting information during initial simulations was developed and is presented in Chapter Five.

4.1 Interviews

Telephone interviews of five energy professionals were conducted in order to obtain their insights into energy simulation processes. A summary of the interview questions and verbatim responses are included in Appendix C.

The first question asked of the interviewees was about the software they used for simulation models, eQuest was used by three of the interviewees and TRANE Trace was used by two interviewees. Other programs also used by the interviewees included Energy 10, Ecotech, HAP from Carrier, and EnergyPlus. When asked what the purpose of the models was, all answered that they used models for energy analysis in buildings and were not limited to compliance with LEED credits. One of the participants indicated: “We are trying to move away from LEED certifications, we find more value in helping teams through schematic and design phases on a project to help evaluate design decisions".

When asked about model validation, three interviewees agreed that validation is not carried out because of associated costs and that the main objective of modeling was for comparison of design options rather than predicting energy use. One interviewee indicated however that models are used to measure and verify actual consumption.

There was unanimous agreement that one of the main sources of inaccuracy was modeling occupancy behavior and scheduling system operation hours (HVAC, lighting). Air leakage of the building was also cited by one of the professionals, as well as sloppy or careless assumptions. When asked if they spent enough time on their schedule definition process, responses varied as two interviewees indicated they do spend time on their schedules while two others indicated they use default schedules within the program. One interviewee indicated that for some projects default schedules might be used at the beginning of the project and fine-tuned after additional information can be gathered. One interviewee indicated that some consultants might overestimate occupancy to be on a safe side, since it may be better to overestimate energy use than underestimate it.

When asked about the owner's information available for creating occupancy schedules, all professionals agreed that owners generally don't have a clear idea of how a new building is going to operate; it was clarified that better information might be obtained from owners that are just moving between buildings and already have an understanding of building behavior and operation schedules. Regarding methodologies or codes followed by modelers, most of them indicated that schedule definition was developed based on each modeler's criteria, although one participant indicated they use ASHRAE developed schedules when working on LEED projects.

There was common agreement among interviewees that standard and more accurate schedules would help better predict energy use, but they indicated it would be difficult since every project is different. Interviewees commented that some universities were establishing certain requirements and guidelines for external consultants to follow, but parameters such as plug loads and equipment would be hard to normalize until submetering is carried out once the building is in operation. Again ASHRAE profile schedules were mentioned as a possible standard to follow.

From the interviews, it was concluded that there was agreement that schedules were important sources of uncertainty in energy use prediction. There is interest in reducing the uncertainty of this parameter, but energy modelers were unsure on where to get the right information, or how to use it in preparing occupancy schedules. Understanding the impact of a variable parameter such as lighting use can help in making better decisions and can shed some light on uncertainty during simulations.

4.2 Lighting Use Range Testing

In order to test the impact of lighting schedules on simulation, a model was developed of a one story rectangular sample building in compliance with ASHRAE 90.1-2007 Energy Standard minimum baseline construction and lighting requirements for climate zone 5. All lighting fixtures were specified as fluorescent. The building was modeled as having 32,000 gross square feet, approximately the size of Chemistry Building Addition, one of the case study buildings presented in Section 4.3. Window areas were taken as 40% of the wall area. Thermal transmission values of the envelope components were: U= 0.064 for exterior walls, U= 0.048 for the roof, F slab factor = 0.73 for the floor, U= 0.55 for windows, and U= 0.7 for swinging doors. Table 4.1 and 4.2 show the ASHRAE 90.1 (2007) requirements:

Opaque Elements	Nonresidential	
	Assembly Maximum	Insulation Min. R-Value
Roofs		
Insulation Entirely above Deck	U-0.048	R-20.0 c.i.
Metal Building	U-0.065	R-19.0
Attic and Other	U-0.027	R-38.0
Walls, Above-Grade		
Mass	U-0.090	R-11.4 c.i.
Metal Building	U-0.113	R-13.0
Steel-Framed	U-0.064	R-13.0 + R-7.5 c.i.
Wood-Framed and Other	U-0.064	R-13.0 + R-3.8 c.i.

Fenestration	Assembly Max. U	Assembly Max. SHGC
Vertical Glazing, -%-40$ of Wall		
Nonmetal framing (all)	U-0.35	SHGC-0.40 all
Metal framing (curtainwall/ storefront)	U-0.45	
Metal framing (entrance door)	U-0.80	
Metal framing (all other)	U-0.55	

Table 4-1: ASHRAE Requirements for Climate Zone 5 (ASHRAE, 2007)

Building Type	**Fossil Fuel, Fossil/ Electric Hybrid, and Purchased Heat**	**Electric and Other**
Residential	System 1 - PTAC	System 2 - PTHP
Nonresidential and 3 Floors or Less and < 25,000 ft^2	System 3 - PSZ-AC	System 4 - PSZ-HP
Nonresidential and 4 or 5 Floors and < 25,000 ft^2 or 5 Floors or Less and 25,000 ft^2 to 150,000 ft^2	System 5 - Packaged VAV with Reheat	System 5 - Packaged VAV with PFP Boxes
Nonresidential and More than 5 Floors or > 150,000 ft^2	System 7 - VAV with Reheat	System 8 - VAV with PFP Boxes

Table 4-2: ASHRAE Definition of HVAC Systems (ASHRAE, 2007)

The HVAC system was modeled as a packaged variable air volume (VAV) with reheat coils, in accordance with ASHRAE 90.1 as shown in Table 4.2. A schematic diagram is shown in Figure 4.1. Thermostat set points were fixed at 72 F for heating and 75 F for cooling. Functional areas of the structure were allocated as: 40% classrooms, 40% office space, 15% hallways, and 5% restroom space. The spaces were not physically modeled in the program, but functional percentages entered allowed the program to calculate lighting, people, and equipment loads according to assigned ratios of areas in the building.

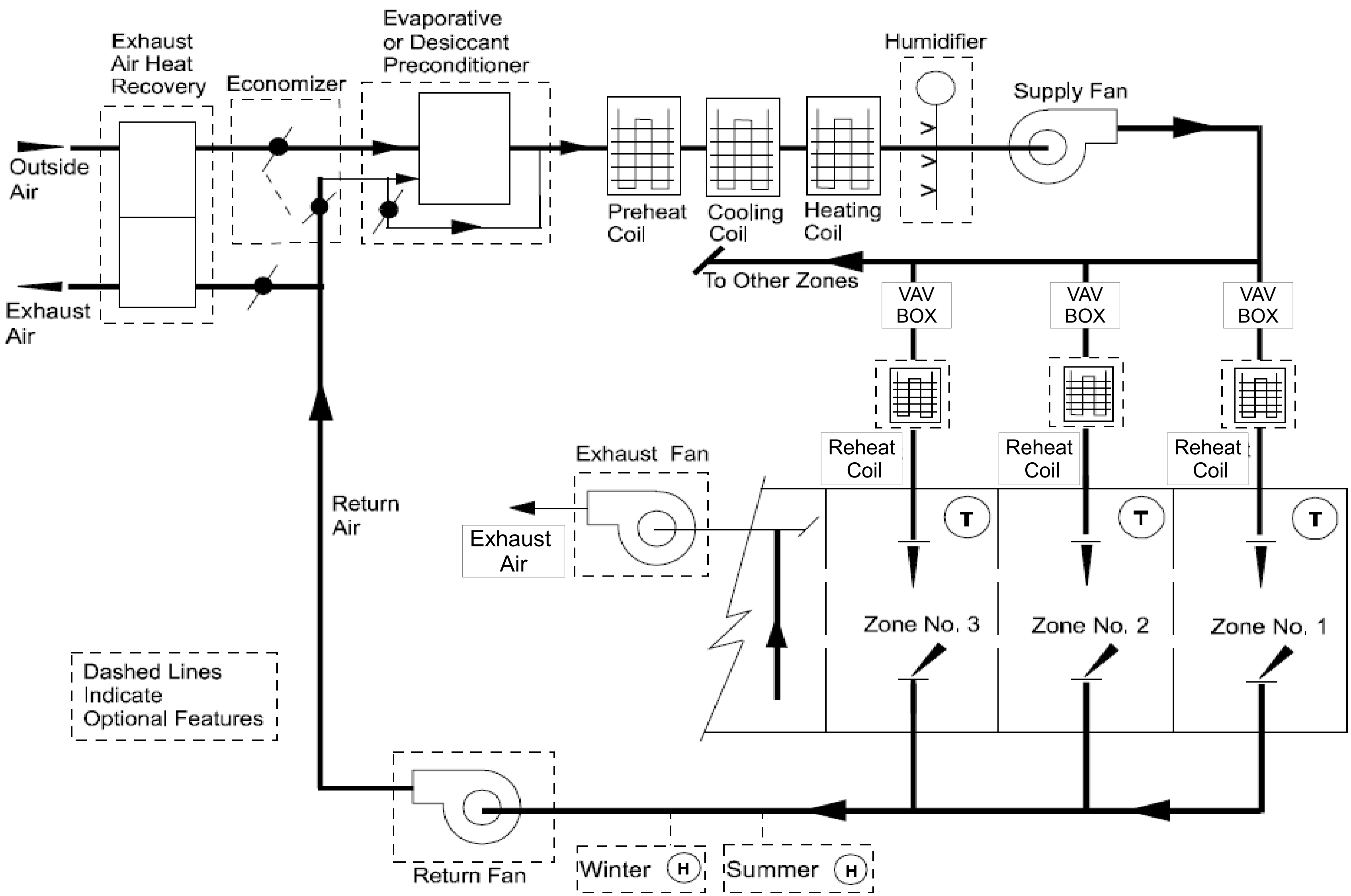


Figure 4-1: Schematic VAV with Reheat Coil System (NREL, 2006)

Several lighting schedules were used for this test including schedules using 100% lighting use during none, some, or all hours of the day, as well as default schedules defined within eQuest. Lighting schedules percentages were entered into the model reflecting the lighting which is "on" either as a total wattage load, or as the total of fixtures switched on. For example, if 100 watts are installed, 1.0 would be interpreted as 100 watts consumed and 0.0 as 0 watts consumed. If the system had a dimming system, 0.5 would simulate 50 watts being consumed. On the other hand, if three fixtures were installed, 1.0 would mean three fixtures on, 0.0 no fixtures on, and 0.33 only one fixture switched on. Tables 4.3 and 4.4 show the default schedules in eQuest and Table 4.5 show the lighting schedules for the test case.

Time	% use	Time	% use	Time	% use
0-1	0.05	**8-9**	0.054	**16-17**	0.0535
1-2	0.05	**9-10**	0.054	**17-18**	0.0521
2-3	0.05	**10-11**	0.054	**18-19**	0.0512
3-4	0.05	**11-12**	0.054	**19-20**	0.0512
4-5	0.05	**12-13**	0.054	**20-21**	0.0502
5-6	0.05	**13-14**	0.054	**21-22**	0.0502
6-7	0.0512	**14-15**	0.054	**22-23**	0.05
7-8	0.0535	**15-16**	0.054	**23-0**	0.05

Table 4-3: eQuest Default Schedule for Weekends, Holidays, and Break Periods

Time	% use	Time	% use	Time	% use
0-1	0.05	**8-9**	0.9	**16-17**	0.611
1-2	0.05	**9-10**	0.9	**17-18**	0.5005
2-3	0.05	**10-11**	0.9	**18-19**	0.679
3-4	0.05	**11-12**	0.9	**19-20**	0.679
4-5	0.05	**12-13**	0.9	**20-21**	0.6705
5-6	0.05	**13-14**	0.9	**21-22**	0.288
6-7	0.1605	**14-15**	0.9	**22-23**	0.101
7-8	0.424	**15-16**	0.713	**23-0**	0.05

Table 4-4: eQuest Default Schedule for Weekdays

Time	0%	8hr	12hr	100%	Time	0%	8hr	12hr	100%	Time	0%	8hr	12hr	100%
0-1	0	0	0	1	**8-9**	0	1	1	1	**16-17**	0	0	1	1
1-2	0	0	0	1	**9-10**	0	1	1	1	**17-18**	0	0	1	1
2-3	0	0	0	1	**10-11**	0	1	1	1	**18-19**	0	0	1	1
3-4	0	0	0	1	**11-12**	0	1	1	1	**19-20**	0	0	0	1
4-5	0	0	0	1	**12-13**	0	1	1	1	**20-21**	0	0	0	1
5-6	0	0	0	1	**13-14**	0	1	1	1	**21-22**	0	0	0	1
6-7	0	0	0	1	**14-15**	0	1	1	1	**22-23**	0	0	0	1
7-8	0	0	1	1	**15-16**	0	1	1	1	**23-0**	0	0	0	1

Table 4-5: Schedules for Test Cases

The intent of this test was to determine the boundary conditions of lighting impact on simulation examining five different scenarios, all with the same input information except with varying lighting schedules. The scenarios were: using the software default schedules, 0% lighting use, 8 hours per day at 100% lighting use, 12 hours per day at 100% lighting use, and 100% lighting use throughout 24 hours of the day. Vacation periods were registered as: summer break from May 6th to August 31st, winter break from December 16th to January 9th, and spring break from March 5th to March 13th. During the break periods, schedules were not modified; the schedules for lighting and miscellaneous loads are shown in Table 4.3. Cooling was assumed to be electric driven, while heating was provided by gas fired hot water coils. Monthly energy consumption is shown on Figure 4.2:

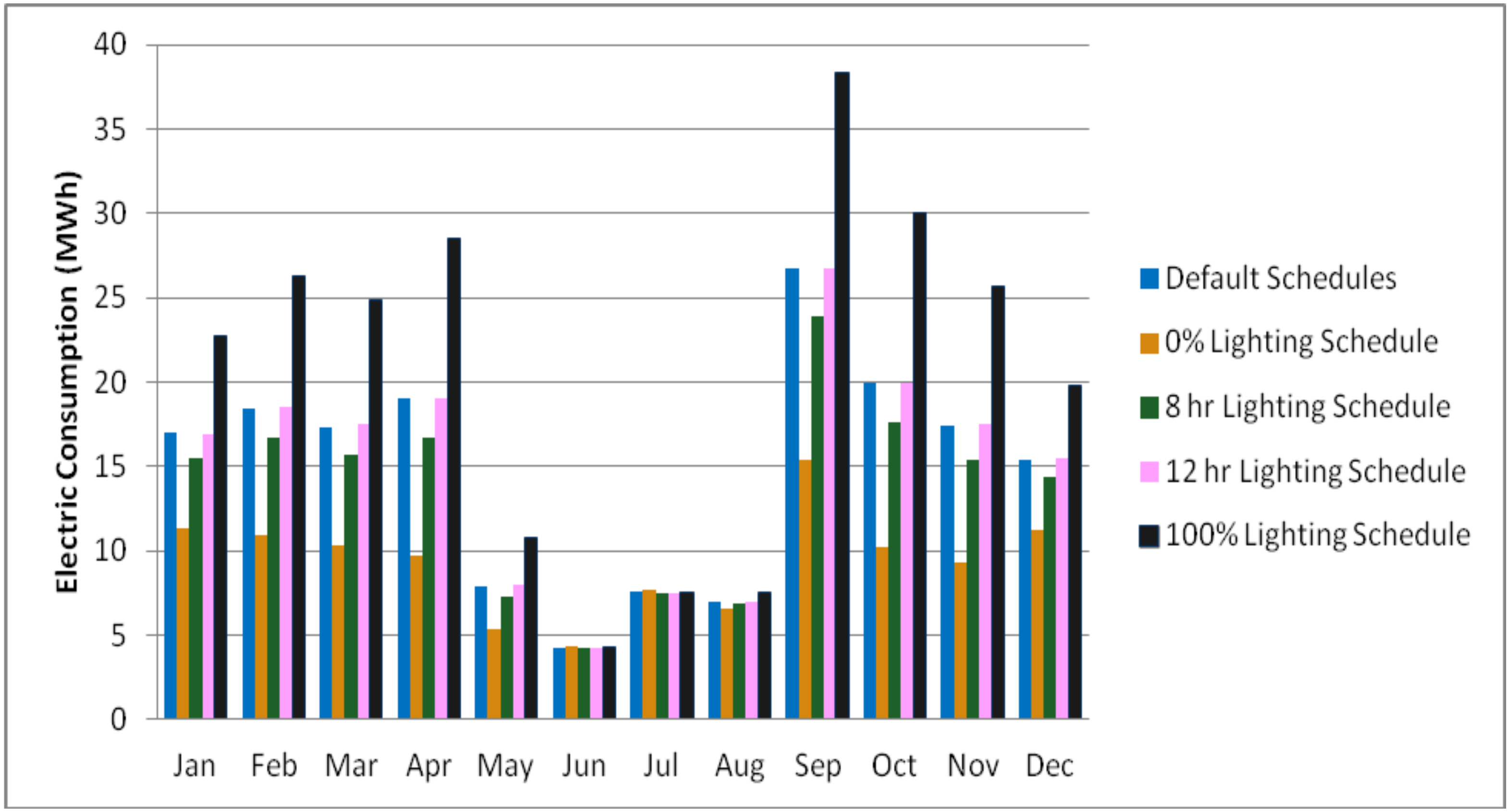


Figure 4-2: Monthly Electrical Consumption (kWh) of Test Building

Figure 4.2 shows that less energy is used during May through August when compared to other months. Although cooling load demand is higher during this period, lighting and miscellaneous equipment loads are less because of decreased use schedules defined in Table 4.3. Since lighting and equipment are defined with the same schedules during these periods, little variation in consumption occurs from case to case. Consequently variations in energy consumption are due mostly to weather dependent variables, mainly cooling loads. The monthly analysis is shown in Table 4.6:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	% Increase Against 0%	% Increase Against Default
Default Schedules	16.96	18.39	17.29	18.98	7.9	4.27	7.53	6.93	26.77	19.99	17.41	15.39	177.8	58.4%	----
0% Lighting Schedule	11.29	10.94	10.36	9.68	5.36	4.32	7.64	6.52	15.41	10.24	9.31	11.23	112.3	----	-36.9%
8 hr Lighting Schedule	15.47	16.7	15.64	16.71	7.3	4.27	7.52	6.84	23.92	17.57	15.39	14.39	161.7	44.0%	-9.1%
12 hr Lighting Schedule	16.94	18.52	17.47	19.06	7.95	4.27	7.51	6.96	26.74	19.95	17.46	15.51	178.3	58.8%	0.3%
100% Lighting Schedule	22.72	26.3	24.81	28.54	10.74	4.26	7.49	7.51	38.31	30.05	25.65	19.82	246.2	119.3%	38.4%
Range Between 0% and 100%	11.43	15.36	14.45	18.86	5.38	-0.06	-0.15	0.99	22.9	19.81	16.34	8.59	133.9		

Table 4-6: Monthly Energy Consumption (kWh) Resulting from Lighting Schedule Variations in a Hypothetical Building

The range of impact from no use of lighting and having all lighting on 24 hours is 120%. It is unclear what percentage is attributable solely to lighting since total building consumption is reported, and some of the variations are due to space heating, cooling, plug loads, fans, and equipment. Changes result from occupancy in addition to lighting loads. It is worth mentioning the highest and lowest monthly differences between the 0% case and 100% case within the year, occur in December, with 8.7 kW and September with 22.96 kWh. September had the highest energy use for every case due to cooling loads of occupied periods. June, July, and August have similar consumption patterns since they are driven by cooling loads and lighting does not have as much influence. For heating season months, electric consumption decreases since unlike cooling which is electric driven, heating is gas fired hot water based. Energy use for the eight hour and twelve hour assumptions are similar to results obtained with default schedules. Default schedules and extreme schedules vary by 38%, which is considerable if predicting actual energy use and utility cost. Figure 4.3 shows the annual peak consumption of the test building by lighting schedule and system.

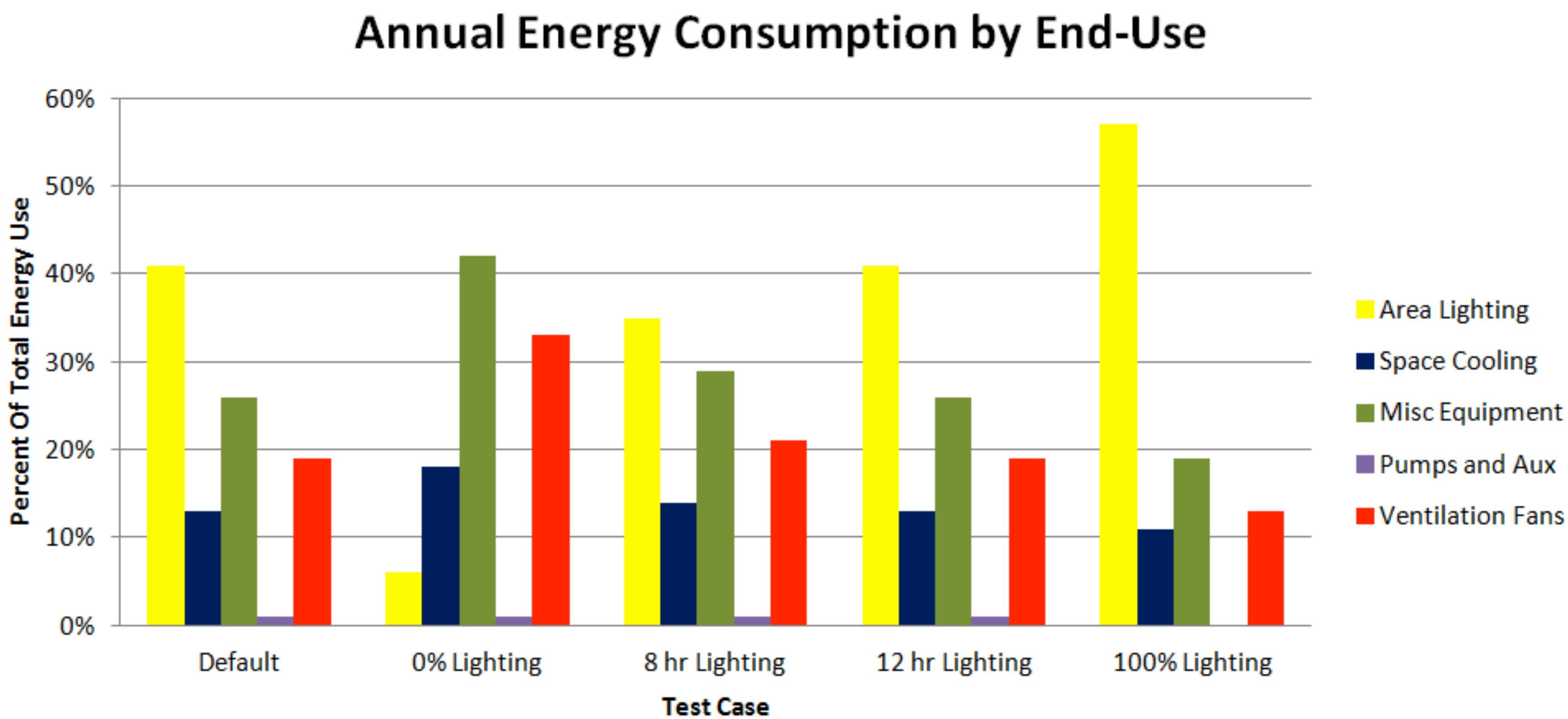
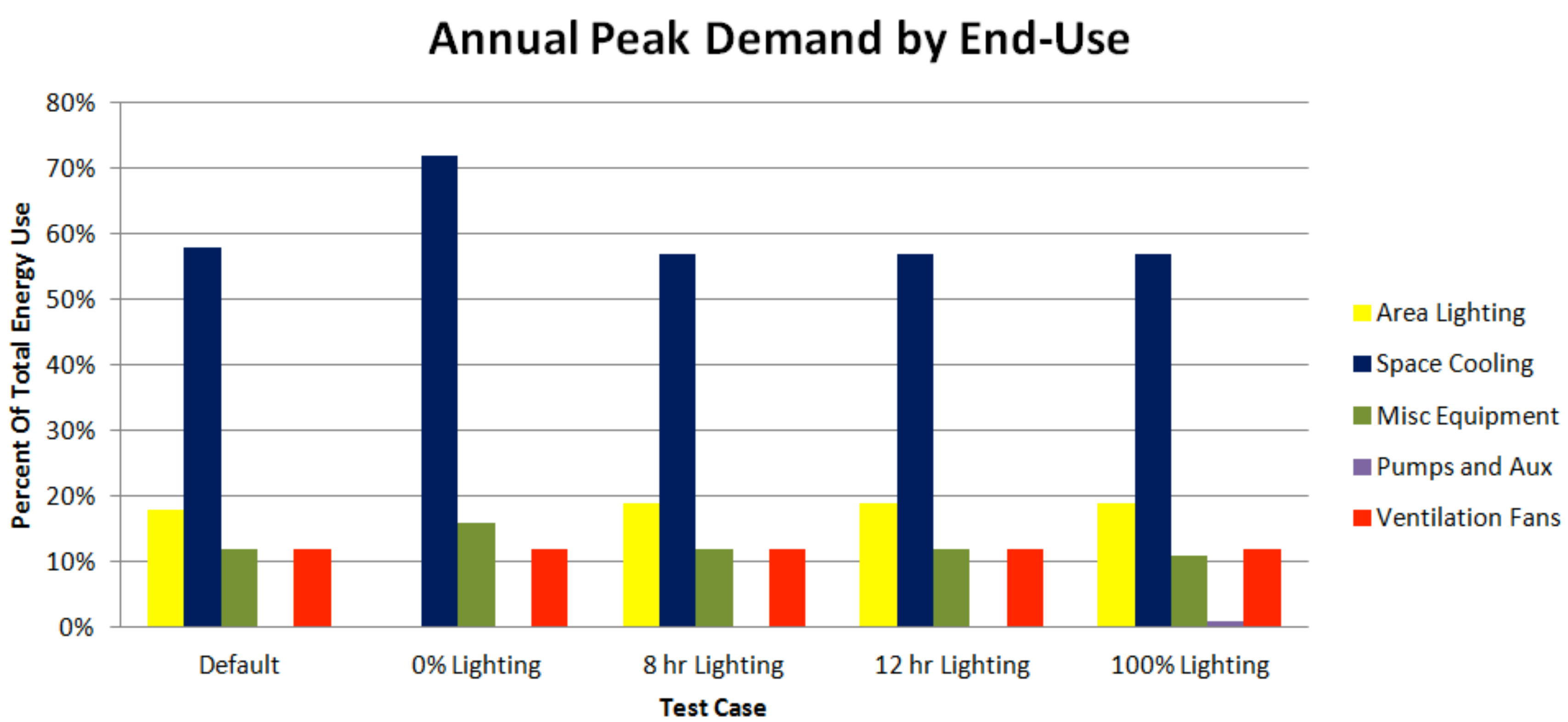


Figure 4-3: Annual Energy Consumption of Test Building



4-4: Peak Energy Consumption Consumption of Test Building

Figure 4.3 shows the impact of lighting schedule for the test building. A small amount of energy use is solely attributable to lighting in the 0% case due to use of default schedules (Table 4.3) during June, July, and August. As lighting use increases other parameters decrease, on a percent basis. The impact of lighting use ranges from 6% to 57% of total annual electrical energy use for the 0% and 100% cases, and varies 6% for intermediate situations. Default schedules show a similar behavior for intermediate testing ranges. Consequently using default schedules may be a safe approach for staying at intermediates energy prediction values.

The annual peak demand by end-use was similar for all the scenarios except for the 0% case. This makes sense if the concept of annual peak demand is considered, where even though total electric consumption from lighting is not the same for all the cases, at certain times of day, every fixture will be switched on, causing a peak demand for electricity. At this same time of day, the 0% case doesn't show a peak demand since lighting was specified as turned off.

The analysis shows the ranges of variations in prediction, but doesn't answer the question of how useful a detailed schedule will be at approximating actual energy use. As a first conclusion, lighting has a significant impact on energy and electricity use in simulation. The analysis also shows that at assumed intermediate lighting intensities, the energy use is similar to that from default schedules defined by the software.

4.3 Building Case Studies

After boundary testing of the impact of lighting on simulations three case studies were selected. Through measurements and observations in the buildings, lighting use patterns were recorded and then defined in simulation models. Along with observed and measured schedules, the simulations were run with default schedules within the program and research schedules constructed from observations and measured data for each building. Energy predicted from simulations was compared to measured utility data, and also compared among the schedules. Architectural drawings were used to determine information necessary for describing wall types and mechanical and electrical systems for each case study building. Additionally, the researcher met with the design engineer or the building maintenance manager. Each building is described separately below.

4.3.1 Chemistry Building

The Chemistry addition building is a 32,034 ft^2 structure built to expand the original Chemistry building built in 1963 at Michigan State University, East Lansing, Michigan. This eighteen million dollar project was developed in 2008 and it achieved LEED Silver certification under LEED NC 2.2. It consists of five above grade floors and two below grade floors. Functions of rooms by floor in the building are described in Table 4.7.

Fifth Floor	1 Graduate Study Room
	1 Instrument Lab
	1 Conference / Seminar Room
	1 Administrative Office
	Hallway
	Restrooms
	Stairways
Fourth Floor	1 Main Office
	1 Conference / Seminar Room
	1 Mail / Copy Room
	Hallway
	Restrooms
	Stairways
Fourth Floor	3 Computer Offices
	1 Business Office
	1 Graduate Office
	1 Teaching Lab
	Hallway
	Restrooms
	Stairways
Second Floor	3 Classrooms
	Hallway
	Restrooms
	Stairways
First Floor	General Chemistry Office
	1 Classroom
	1 Copy Room
	Hallway
	Restrooms
	Stairways
Basement	3 Teaching Labs
	1 Classroom
	Hallway
	Restrooms
	Stairways
Sub Basement	Mechanical Room
	Stairways

Table 4-7: Room Distribution in Chemistry Addition Building

Figure 4-5: Chemistry Building

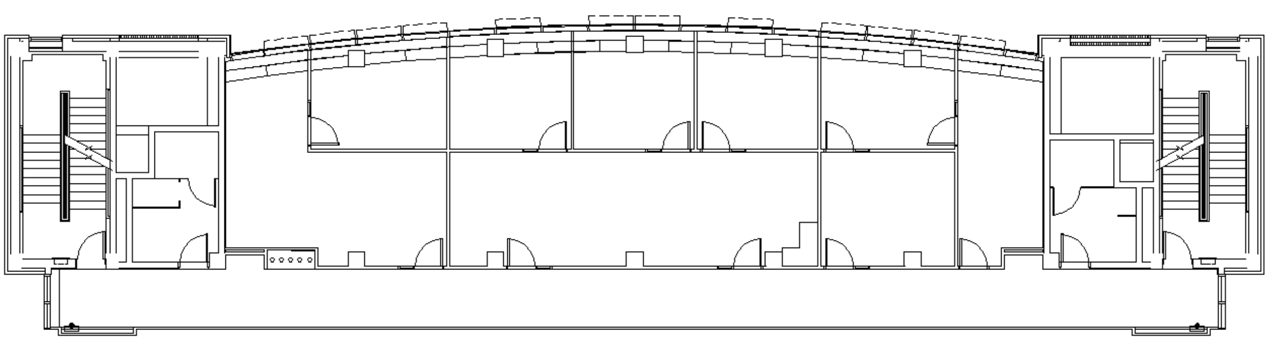


Figure 4-6: Typical Floor Plan of Chemistry Addition Building

The Chemistry building has three different types of wall construction: a main curtain wall façade, masonry walls at the East and West stair cases, and a steel louver system at a utility duct wall. The roof uses pavers over polystyrene insulation and roof membrane. Detailed descriptions of construction assemblies are provided in Appendix B.

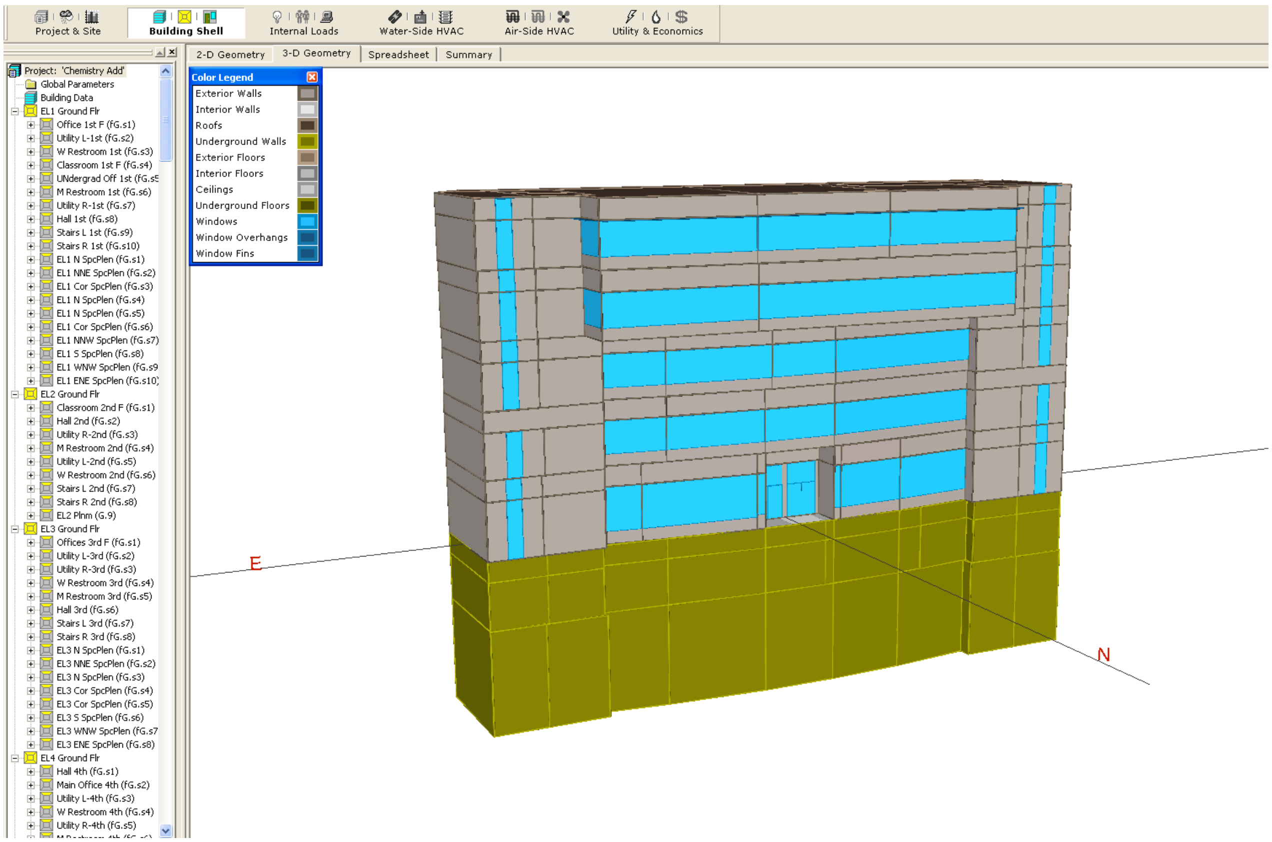


Figure 4-7: Chemistry Building Model Screenshot

The chemistry building HVAC system uses a chilled water air handler unit with variable air volume (VAV) boxes and hot water reheat coils. A schematic generic design of a VAV system is shown in Figure 4.7. The cooling coil is fed by an absorption chiller that distributes water to other buildings in addition to the Chemistry Building. Stair cases are not air conditioned but have unit ventilator fans with hot water coils to provide heat.

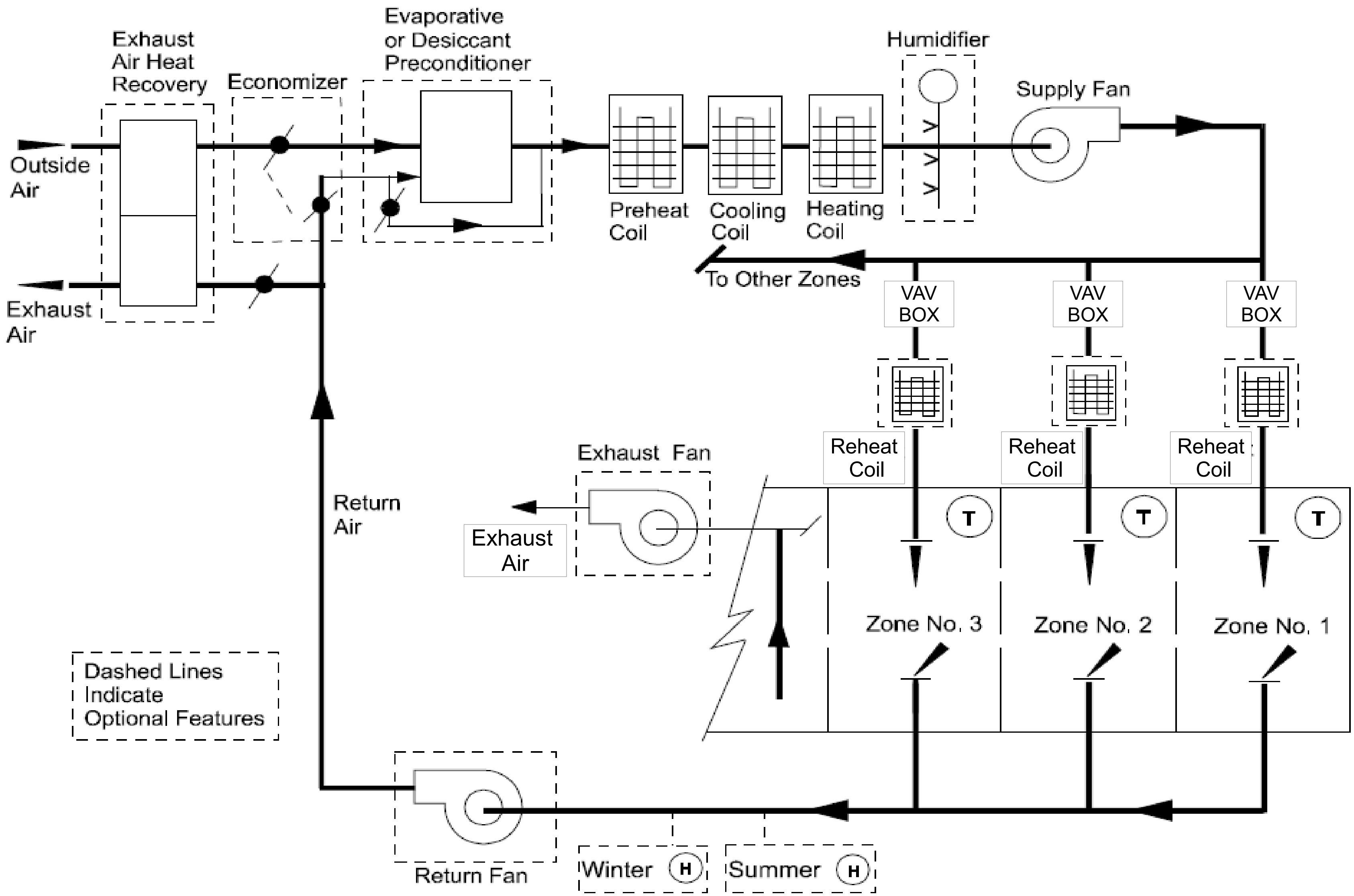


Figure 4-8: Schematic VAV with Reheat Coil System (NREL, 2006)

Chemistry Building Data and Results

As stated before, the Chemistry Addition underwent the LEED certification process and an energy model was developed for LEED documentation. This model was reviewed and results were compared to predictions obtained from models developed for the research.

The first schedule considered was the lighting profile used for the original model developed during the design phase and for LEED certification of the project. Schedules showed throughout the research represent either wattage percentages or percentage of fixtures turned on. This schedule was used for all spaces regardless of their use: classrooms, offices, bathrooms, hallways and conference rooms. The same schedule was used throughout the year without break occupancy variations considered during break periods. Lighting use is indicated as a percentage of light use, where 0 represents all lights switched off and 1 represents 100% of lights turned on. The schedule used for the original design model is shown in Table 4.8:

Hour	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Holiday
0-1	0.05	0.05	0.05	0.05	0.05	0.015	0.015	0.015
1-2	0.05	0.05	0.05	0.05	0.05	0.015	0.015	0.015
2-3	0.05	0.05	0.05	0.05	0.05	0.015	0.015	0.015
3-4	0.05	0.05	0.05	0.05	0.05	0.015	0.015	0.015
4-5	0.05	0.05	0.05	0.05	0.05	0.015	0.015	0.015
5-6	0.05	0.05	0.05	0.05	0.05	0.015	0.015	0.015
6-7	0.2965	0.2965	0.2965	0.2965	0.2965	0.015	0.015	0.015
7-8	0.7980	0.7980	0.7980	0.7980	0.7980	0.015	0.015	0.015
8-9	0.9	0.9	0.9	0.9	0.9	0.015	0.015	0.015
9-10	0.9	0.9	0.9	0.9	0.9	0.015	0.015	0.015
10-11	0.9	0.9	0.9	0.9	0.9	0.015	0.015	0.015
11-12	0.9	0.9	0.9	0.9	0.9	0.015	0.015	0.015
12-13	0.9	0.9	0.9	0.9	0.9	0.015	0.015	0.015
13-14	0.9	0.9	0.9	0.9	0.9	0.015	0.015	0.015
14-15	0.9	0.9	0.9	0.9	0.9	0.015	0.015	0.015
15-16	0.9	0.9	0.9	0.9	0.9	0.015	0.015	0.015
16-17	0.798	0.798	0.798	0.798	0.798	0.015	0.015	0.015
17-18	0.5005	0.5005	0.5005	0.5005	0.5005	0.015	0.015	0.015
18-19	0.2965	0.2965	0.2965	0.2965	0.2965	0.015	0.015	0.015
19-20	0.2965	0.2965	0.2965	0.2965	0.2965	0.015	0.015	0.015
20-21	0.1010	0.1010	0.1010	0.1010	0.1010	0.015	0.015	0.015
21-22	0.1010	0.1010	0.1010	0.1010	0.1010	0.015	0.015	0.015
22-23	0.05	0.05	0.05	0.05	0.05	0.015	0.015	0.015
23-24	0.05	0.05	0.05	0.05	0.05	0.015	0.015	0.015

Table 4-8: Schedule Used in Chemistry Addition Model during Design Phase

The software can define a set of default schedules based on what the user defines as the main function of the building. Tables 4.9 and 4.10 show the default lighting schedules within the software for academic buildings. For the energy model developed during this research, break periods were defined for the academic year to simulate occupancy variation. Two default schedules were created, one which considered break periods and one which didn't. These default schedules were used for the first run of the model to obtain initial results and subsequent simulations were run with the research schedules.

Hour	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Holiday
0-1	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
1-2	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
2-3	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
3-4	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
4-5	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
5-6	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
6-7	0.0512	0.0512	0.0512	0.0512	0.0512	0.0512	0.0512	0.0512
7-8	0.0535	0.0535	0.0535	0.0535	0.0535	0.0535	0.0535	0.0535
8-9	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054
9-10	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054
10-11	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054
11-12	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054
12-13	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054
13-14	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054
14-15	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054
15-16	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054
16-17	0.0535	0.0535	0.0535	0.0535	0.0535	0.0535	0.0535	0.0535
17-18	0.0521	0.0521	0.0521	0.0521	0.0521	0.0521	0.0521	0.0521
18-19	0.0512	0.0512	0.0512	0.0512	0.0512	0.0512	0.0512	0.0512
19-20	0.0502	0.0502	0.0502	0.0502	0.0502	0.0502	0.0502	0.0502
20-21	0.0502	0.0502	0.0502	0.0502	0.0502	0.0502	0.0502	0.0502
21-22	0.0502	0.0502	0.0502	0.0502	0.0502	0.0502	0.0502	0.0502
22-23	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
23-24	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05

Table 4-9: Default Software Schedule for Unoccupied Periods in Academic Buildings

Table 4.9 shows a maximum 5.4% of total installed lighting wattage used during peak periods. The chemistry building has many office spaces that continue to be occupied during academic break periods. Consequently, defining office spaces with the default schedule shown in Table 4.9 results in an underestimation of lighting use.

Hour	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Holiday
0-1	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
1-2	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
2-3	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
3-4	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
4-5	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
5-6	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
6-7	0.1605	0.1605	0.1605	0.1605	0.1605	0.1605	0.1605	0.1605
7-8	0.424	0.424	0.424	0.424	0.424	0.424	0.424	0.424
8-9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
9-10	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
10-11	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
11-12	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
12-13	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
13-14	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
14-15	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
15-16	0.713	0.713	0.713	0.713	0.713	0.713	0.713	0.713
16-17	0.611	0.611	0.611	0.611	0.611	0.611	0.611	0.611
17-18	0.5005	0.5005	0.5005	0.5005	0.5005	0.5005	0.5005	0.5005
18-19	0.679	0.679	0.679	0.679	0.679	0.679	0.679	0.679
19-20	0.679	0.679	0.679	0.679	0.679	0.679	0.679	0.679
20-21	0.6705	0.6705	0.6705	0.6705	0.6705	0.6705	0.6705	0.6705
21-22	0.288	0.288	0.288	0.288	0.288	0.288	0.288	0.288
22-23	0.1010	0.1010	0.1010	0.1010	0.1010	0.1010	0.1010	0.1010
23-24	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05

Table 4-10: Default Software Schedule for Occupied Periods in Academic Buildings

A research schedule, shown in Table 4.11, was defined from observations conducted in the building. The purpose was to see if schedules developed from observations of occupancy could improve the accuracy of simulations from those developed during the design stage. The process for gathering field information included the following:

- Access to the building was requested from the building manager for after-hours operation observation
- A preliminary walkthrough of the building was conducted to determine if all rooms were observable from the interior of the structure
- From engineering drawings, lighting fixtures were counted. No specific fixture model was specified on the drawings so the following assumptions were made according to lamp type:
    - 2'x4' troffer – 65 Watts with electronic ballast (2 tubes assumed)
    - 4'x4' troffer - 130 Watts with electronic ballast (4 tubes assumed)
    - Downlight – 50 Watts
    - Wall Mounted – 50 Watts
- Observations inside the building were carried out during a span of one week, for several hours per day until all 24 hours were observed
- During walkthroughs, fixtures which were switched on were counted, and percent lighting use determined. If three out of four lamps were on, the lighting use for that space was taken to be 75%

- Spaces that had closed or locked doors typically still had a window which allowed the space to be observed
- The instrument lab on the fifth floor was the only inaccessible room due to safety concerns. However, this room has an exterior window which allowed observations of lighting use from the outside of the building
- Hallways, bathrooms, and stairs were considered together throughout all floors and were assumed to use the same schedule
- Lighting loggers were installed in three rooms: a classroom in the basement, a study room in the basement, and a computer office. These were intended to provide additional information for these rooms and were considered when defining schedules for simulation but because there were not enough sensors for installation in every room they could only provide supplementary information to the observations

		HOUR OF THE DAY																							
Rooms	**Floor**	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Study Room	Basement	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100	100	100	0	0	0	0	0
Classroom	Basement	0	0	0	0	0	0	0	0	0	0	100	100	0	0	0	0	0	0	0	0	0	0	0	0
Office	Basement	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100	100	0	0	0	0	0	0
General Office	1st	0	0	0	0	0	0	0	0	90	100	100	100	100	75	100	100	100	0	0	0	0	0	0	0
Classroom	1st	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100	0	0	0	100	100	100	0	0	0
Copy Room	1st	0	0	0	0	0	0	0	50	50	50	50	50	50	50	50	50	50	50	50	50	50	0	0	0
Undergrad Office	1st	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100	0	0	0	0	0	0
Classroom	2nd	0	0	0	0	0	0	0	0	0	100	100	100	100	33	0	100	100	100	33	33	66	33	33	0
Computer Office	3rd	0	0	0	0	0	0	0	90	90	90	90	90	90	90	90	80	80	0	0	0	0	0	0	0
Bussiness Office	3rd	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	0	0	0
Graduate Office	3rd	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100	50	50	0	0	0	0	0	0	0
Main Office	4th	10	10	10	10	10	10	10	60	80	90	100	100	90	100	100	95	95	90	65	80	50	25	50	25
Conf./ Sem. Room	4th	50	0	0	0	0	0	0	0	0	100	100	50	100	75	75	100	50	50	100	50	50	50	50	50
Grad. Study Room	5th	0	0	0	0	0	0	0	100	100	0	0	0	50	100	100	0	0	0	0	0	0	0	0	0
Instrument Lab	5th	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Conf./ Sem. Room	5th	50	50	50	50	50	50	50	50	50	25	25	25	25	100	100	0	50	100	100	100	50	100	75	50
Hallways	B-5	50	50	50	50	50	50	50	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Bathrooms	B-5	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Stairway	B-5	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
	Average %	24	22	22	22	22	22	22	45	56	71	82	85	84	85	85	72	72	63	55	48	46	32	32	28

Table 4-11: Percentage of Lighting Fixture Use Schedule from Observations by Zone in the Chemistry Building

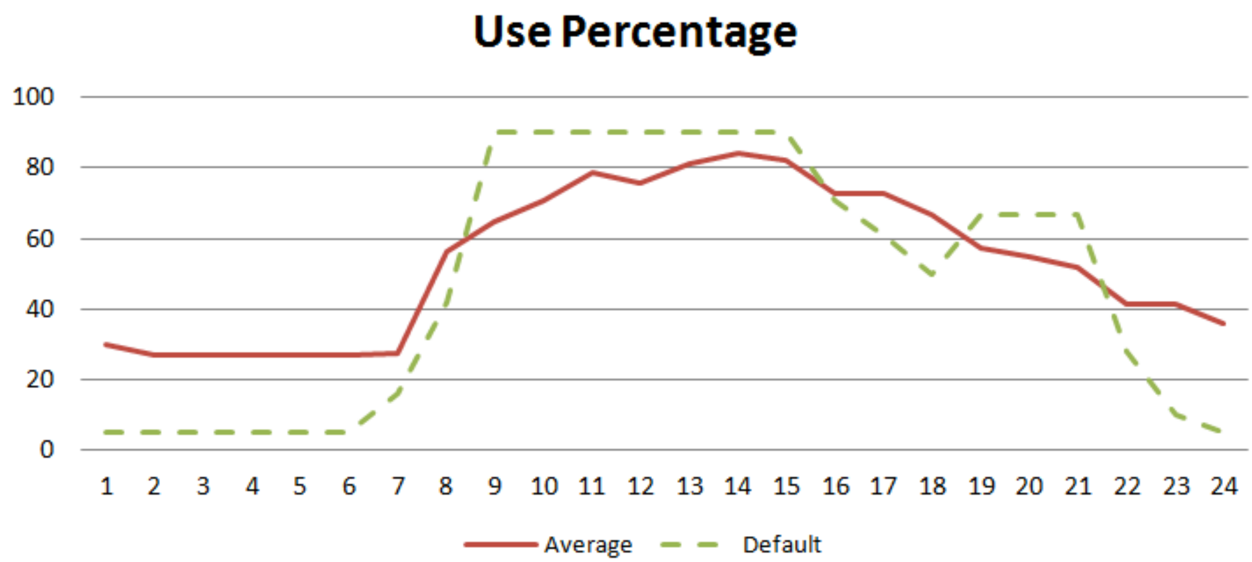


Figure 4-9: Building Average Lighting Profile v Default Lighting Schedule Profiles in Chemistry Building

Table 4.11 shows the number of fixtures turned on at the moment of observation. All rooms were observable enabling fixture counts for each room. For example, in the hallways, there were fourteen fixtures installed which were all on from 7:00 a.m. to 11:00 p.m., and seven of them were off from 12:00 p.m. to 6:00 a.m., yielding 100% use and 50% use respectively. Average lighting use was calculated for each hour and a profile was developed as shown in Table 4.11 and Figure 4.8 labeled as average. The model developed during the research, called the "Research Model", used three types of schedules: one using individual schedules for each room as recorded in Table 4.11 during observations, a second one using a single schedule for the whole building defined by the average use percentages calculated from hourly observations in Table 4.11 and a third one using default schedules within the program (Tables 4.9 and 4.10). Total predicted annual electric consumption from these three cases and from the original model developed during the design phase were compared to actual measured electric consumption from the control room at Physical Plant during the 2010 year. MSU Physical Plant monitors approximately fourteen million square feet of space at this central control room.

The models developed during the design phase and the research models were developed for different reasons and used different approaches, so direct comparison of these models involved many variables besides lighting variations that makes comparisons difficult. The original model substitutes metered chilled water for the chiller and cooling tower loads, consequently cooling loads do not show in the electric consumption predictions. Miscellaneous loads were lower compared to those considered in the research model. The original model did not consider seasonal variations, and used the same schedules throughout the year, while the research model used different schedules for the academic year and break periods. Table 4.12 shows annual electric consumption predicted by the original design phase model. Table 4.13 show annual electric consumption using program default schedules and again without consideration of break periods.

	Original Model
	Electricity kWh (x000)
Space Cool	0
Heat Reject.	0
Space Heat	0
Hot Water	0
Vent. Fans	18.61
Pumps & Aux.	9.9
Misc. Equip.	29.07
Area Lights	102.46
Total	160.04
Measured Utilities	214
% Difference	25.2%

Table 4-12: Annual Electric Consumption Predicted Measured Utility by Original Model in Chemistry Building

	Research Model / Default Schedules Without Break Periods
	Electricity kWh (x000)
Space Cool	2.07
Heat Reject.	7.88
Space Heat	0
Hot Water	0
Vent. Fans	23.57
Pumps & Aux.	21.71
Misc. Equip.	184.32
Area Lights	64.03
Total	303.58
Measured Utilities	214
% Difference	41.9%

Table 4-13: Annual Electric Consumption Predicted by Research Model without Break Periods and Software's Default Schedules

To compare the original and research models, modifications were made to normalize them and remove variables that cause differences between the models. Miscellaneous loads included in the research model were added to the original model to balance this load. Tables 4.12 and 4.13 shows the difference is large. The chiller was substituted by a chilled water meter in the research model to remove this load and to match the system to the original model. Also, occupancy schedules were kept constant throughout the year to test results without lower occupancy due to break periods. Results from these normalized schedules are shown in Table 4.14.

	Normalized Original Model without Break Periods	Normalized Research Model with Break Periods and Default Schedules	Normalized Research Model without Break Periods and Default Schedules
	Electricity kWh (x000)	**Electricity kWh (x000)**	**Electricity kWh (x000)**
Space Cool	0	0	0
Heat Reject.	0	0	0
Space Heat	0	0	0
Hot Water	0	0	0
Vent. Fans	25.71	14.39	23.57
Pumps & Aux.	12.47	5.91	6.55
Misc. Equip.	129.35	141.24	184.32
Area Lights	102.46	47.86	64.03
Total	269.99	209.4	278.47
Measured Utilities	214	214	214
% Difference	26.2%	2.1%	30.1%

Table 4-14: Modified Original and Research Models to Normalized Conditions

The three models were developed in eQuest, although the original model was developed under version 3-63 and the research model under version 3-64. The research model that considers unoccupied periods shows decreased electric use due to lower consumption during break periods. The original model and research model using default schedules without consideration of break periods predict electric consumption less accurately, but similarly with 269 MWh for the original model and 278 MWh for the research model.

To compare impacts of lighting variations in simulations, schedules were varied in the research model. Simulation results were obtained considering break periods and also for constant occupancy throughout the year. For each of these scenarios, three simulations were run: using default schedules within the program (Tables 4.9 and 4.10), one with observed schedules (Table 4.11) and another with an average schedule obtained from observations (Table 4.11). Results are displayed in Tables 4.15 and 4.16.

	Research Model / Default Schedules Without Break Periods	Research Model / Observed Schedules Without Break Periods	Research Model / Average Schedule Without Break Periods
	Electricity kWh (x000)	**Electricity kWh (x000)**	**Electricity kWh (x000)**
Space Cool	2.07	2.07	2.07
Heat Reject.	7.88	7.9	7.9
Space Heat	0	0	0
Hot Water	0	0	0
Vent. Fans	23.57	24.27	23.7
Pumps & Aux.	21.71	21.72	21.71
Misc. Equip.	184.32	184.32	184.32
Area Lights	64.03	75.86	66.66
Total	303.58	316.14	306.36
Measured Utilities	214	214	214
% Difference	41.9%	47.7%	43.2%

Table 4-15: Annual Electric Consumption in Chemistry Building by Different Lighting Schedules and no Break Periods

	Research Model / Default Schedules With Break Periods	Research Model / Observed Schedules With Break Periods	Research Model / Average Schedule With Break Periods
	Electricity kWh (x000)	**Electricity kWh (x000)**	**Electricity kWh (x000)**
Space Cool	1.72	1.72	1.72
Heat Reject.	6.02	6.09	6.03
Space Heat	0	0	0
Hot Water	0	0	0
Vent. Fans	14.39	14.69	14.43
Pumps & Aux.	18.47	18.47	18.47
Misc. Equip.	141.24	141.24	141.24
Area Lights	47.68	55.08	49.46
Total	229.52	237.29	231.35
Measured Utilities	214	214	214
% Difference	7.3%	10.9%	8.1%

Table 4-16: Annual Electric Consumption in Chemistry Building by Different Lighting Schedules and Break Periods

Tables 4.15 and 4.16 show that not including break periods in the model has an impact on electric use prediction. Energy predictions differ over 40% in all cases where constant yearly occupancy is considered, while cases with break periods considered were within 11% of measured utilities. Comparing the different schedules used in Table 4.16, use of the default schedule predicted electric use slightly more accurately with a 7.3% difference compared to 10.9% with observed schedules. A comparison of annual electric consumption prediction and monthly electric consumption prediction is shown in Figures 4.9 and 4.10.

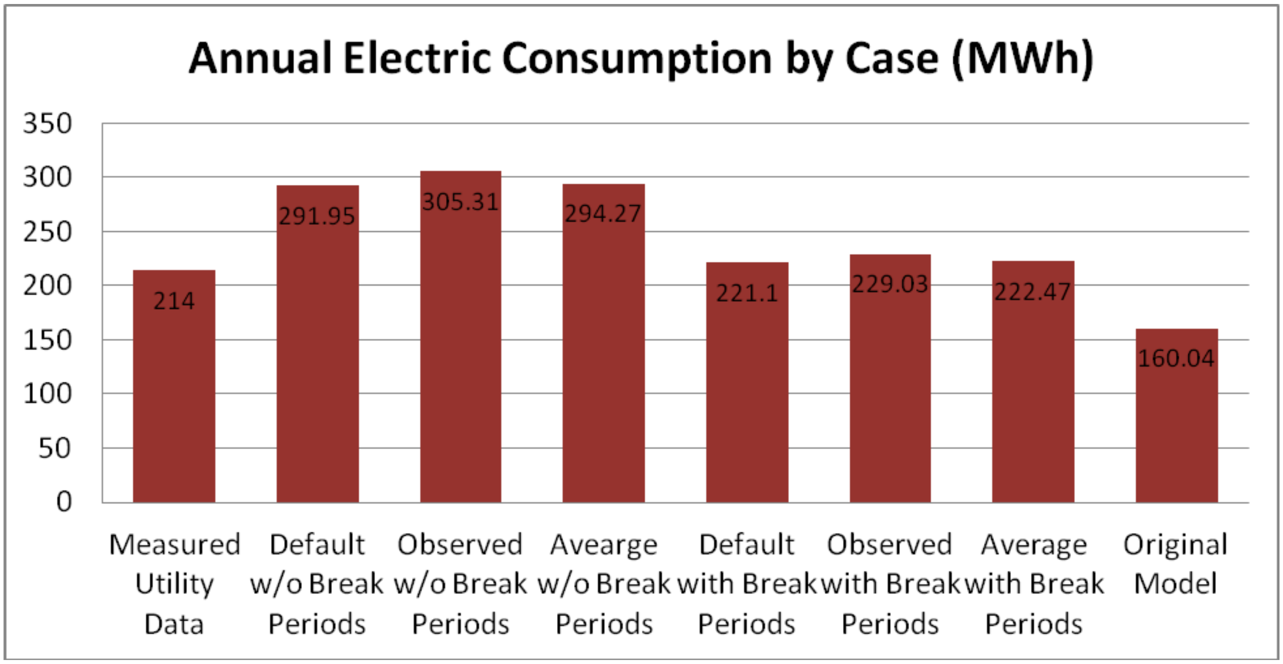


Figure 4-10: Comparison of Annual Electric Consumption in Chemistry Building

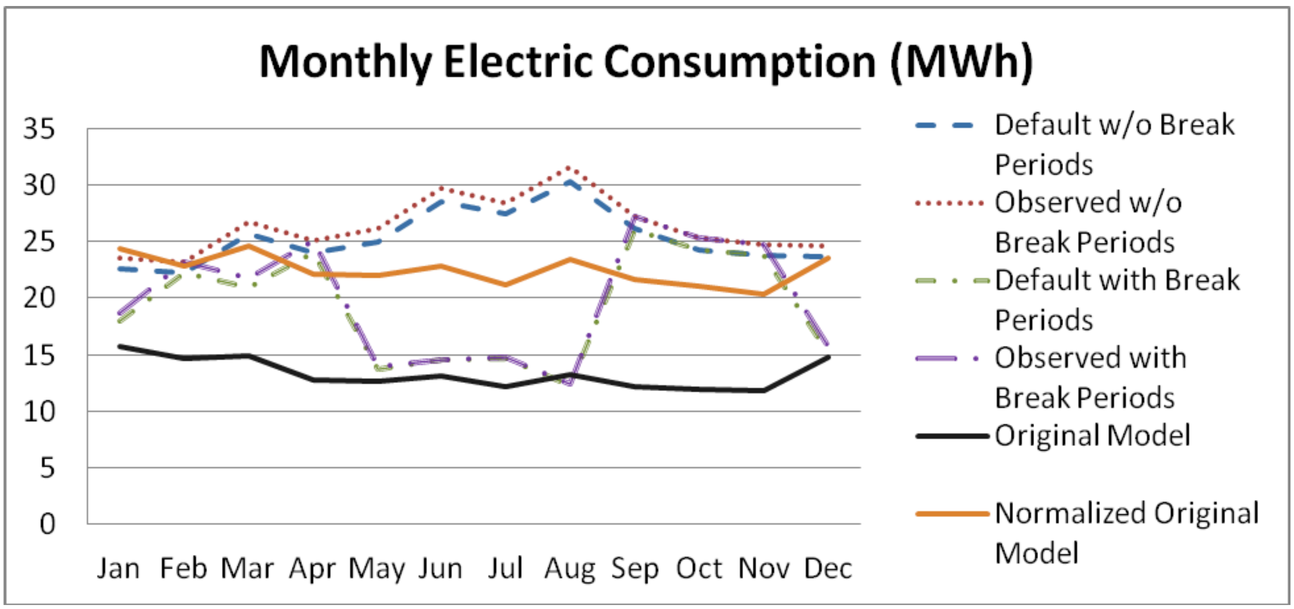


Figure 4-11: Monthly Electric Consumption by Different Models and Lighting Schedules in Chemistry Building

Additional Information for Chemistry Building

Additional information for classroom spaces was also available for the Chemistry building from Michigan State University (MSU). MSU similar to most universities tracks classroom space utilization. This information was considered along with the observations in forming the research model. Table 4.17 shows an example of reports from MSU that may be available from other owners.

Capacity Group	Room	Total Capacity	Enroll Limit	Actual Enroll	Actual Enroll % of Capacity	Actual Enroll % of Limit	Weekly Hours	Use Hours	Use Hours % of Weekly
30-39	BCC N124	468	374	316	68%	84%	50	40	80%
	BCH 111	320	272	222	69%	82%	50	14	28%
	BH 106A	240	204	135	56%	66%	50	24	48%
	BH 106B	330	276	233	71%	84%	50	22	44%
	BH 120	455	360	283	62%	79%	50	40	80%
	BH 12C	240	208	188	78%	90%	50	28	56%
	CEM 085	720	681	657	91%	96%	50	28	56%
	CEM 109	870	792	852	98%	108%	50	30	60%
	CEM 110	780	726	732	94%	101%	50	28	56%
	CEM 183	570	534	496	87%	93%	50	26	52%
	CEM 281	930	851	909	98%	107%	50	31	62%
	CEM 283	870	838	786	90%	94%	50	31	62%
	CEM 287	690	568	539	78%	95%	50	31	62%
	COM 165	342	235	217	63%	92%	50	26	52%
	COM 171	340	260	214	63%	82%	50	29	58%
	COM 173	340	206	165	49%	80%	50	30	60%
	COM 175	238	167	155	65%	93%	50	24	48%

Table 4-17: Information from Campus Monitoring by Capacity

Figure 4.17 shows weekly hours of use for classrooms as well as expected occupancy. Twenty eight hours are recorded for classroom use in CEM 085, which corresponds to the basement classroom observed in table 4.11. Assuming a classroom with a 500 W lighting load installed would yield: 28 hours x 500 W @ 100% use = 14 kWh per week. The same approach was used with the observed classroom information from table 4.9 and results are summarized below. A 500 W load per class was also estimated:

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	
Class 2nd Floor	0	0	0	0	0	0	0	0	0	100	100	100	100	33	0	100	100	100	33	33	66	33	33	0	
Class 1st Floor	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100	0	0	0	100	100	100	0	0	0	
Class Basement	0	0	0	0	0	0	0	0	0	0	100	100	0	0	0	0	0	0	0	0	0	0	0	0	
Average Use (%)	0	0	0	0	0	0	0	0	0	33.3	66.7	100	66.7	44.3	33.3	33.3	33.3	33.3	44.3	44.3	55.3	11	11	0	**Total (Watts)**
Consumption (kWh)	0	0	0	0	0	0	0	0	0	0.17	0.33	0.50	0.33	0.22	0.17	0.17	0.17	0.17	0.22	0.22	0.28	0.06	0.06	0	3.052

Table 4-18: Load Analysis from Observed Schedules in Chemistry Building

Table 4.18 shows an average lighting use for classrooms observed in the Chemistry Building, and this overall average is then multiplied by an assumed 500 Watt installed load. This results in 3.052 kWh per day and 15.2 kWh per week. This is an 8% increase from the use estimated from the 14 kWh obtained from campus information. As stated before, additional factors should be considered in lighting use estimation, for example rooms are often used before or after scheduled class periods or for meetings. Figure 4.11 shows information collected from the Registrar's Office for regularly scheduled events and unplanned events including study sessions and meetings.

4	5	6	7	8
9:10a-10:00a CEM 143 001 10:20a-11:10a CEM 251 001 11:30a-12:20p CEM 251 002 12:40p-2:00p SPN 330 003 3:00p-3:50p CEM 993 001 4:00p-6:00p CEM 993 Midterm Exam-Dr. Piecuch	8:00a-8:50a CEM 251 003 9:10a-10:00a CEM 251 004 10:20a-11:10a CEM 152 005 11:30a-12:20p CEM 384 002 12:40p-1:30p CEM 384 003 1:50p-2:40p CEM 152 003 3:00p-3:50p CEM 152 004 4:10p-5:00p CEM 252 032 7:00p-8:30p SL - Chaldean American Student Organization	9:10a-10:00a CEM 143 007 10:20a-11:10a CEM 251 006 11:30a-12:20p CEM 251 007 12:40p-2:00p SPN 330 003 3:00p-3:50p CEM 993 001	8:00a-8:50a CEM 251 014 9:10a-10:00a CEM 251 008 11:30a-12:20p CEM 143 014 12:40p-1:30p ZOL 483 001 1:50p-2:40p CEM 251 009 3:00p-3:50p CEM 251 013 5:30p-6:20p CEM 143 012	10:20a-11:10a CEM 251 010 11:30a-12:20p CEM 251 011 12:40p-1:30p CEM 251 012 3:00p-3:50p CEM 993 001 4:00p-6:00p Study session for CEM 993-Professor Piecuch

Figure 4-12: Classroom Schedule in April from Registrar's Office

From Figure 4.11 a schedule can be defined assigning to each hour the percentage of time a classroom will be used. If the class is scheduled to be used from 9:10 a.m. to 10 a.m., then the room will be scheduled to be used fifty minutes out of sixty, therefore 83% will be assigned. Following this procedure for each day, and obtaining a weekly average use for each hour, the following schedule was defined:

Hour	Monday	Tuesday	Wednesday	Thursday	Friday	Average
0-1	0	0	0	0	0	0
1-2	0	0	0	0	0	0
2-3	0	0	0	0	0	0
3-4	0	0	0	0	0	0
4-5	0	0	0	0	0	0
5-6	0	0	0	0	0	0
6-7	0	0	0	0	0	0
7-8	0	0	0	0	0	0
8-9	0	0.83	0	0.83	0	0.33
9-10	0.83	0.83	0.83	0.83	0	0.66
10-11	0.67	0.67	0.67	0	0.67	0.54
11-12	0.67	0.67	0.67	0.5	0.67	0.64
12-13	0.67	0.67	0.67	0.67	0.67	0.67
13-14	1.00	0.67	1	0.67	0.5	0.77
14-15	0	0.67	0	0.67	0	0.27
15-16	0.83	0.83	0.83	0.83	0.83	0.83
16-17	0	0.83	0	0	0.5	0.27
17-18	0	0	0	0.5	0.5	0.20
18-19	0	0	0	0.33	0	0.07
19-20	0	0.5	0	0	0	0.10
20-21	0	0.5	0	0	0	0.10
21-22	0	0	0	0	0	0
22-23	0	0	0	0	0	0
23-24	0	0	0	0	0	0

Table 4-19: Weekly Lighting Use Estimation from Registrar's Classroom Schedule

Different profiles obtained using different approaches for classroom CEM 085 (basement classroom) are shown in Figure 4.12. Comparing the profiles with the default schedule and average building profiles, which predicted electric consumption more accurately, it was expected that using Registrar's profiles and the sensor log profiles would give more accurate predictions. However the data seem to show that for overall building energy prediction it may be more accurate to define an average occupancy schedule for all spaces with similar use than defining an individual schedule for each individual room.

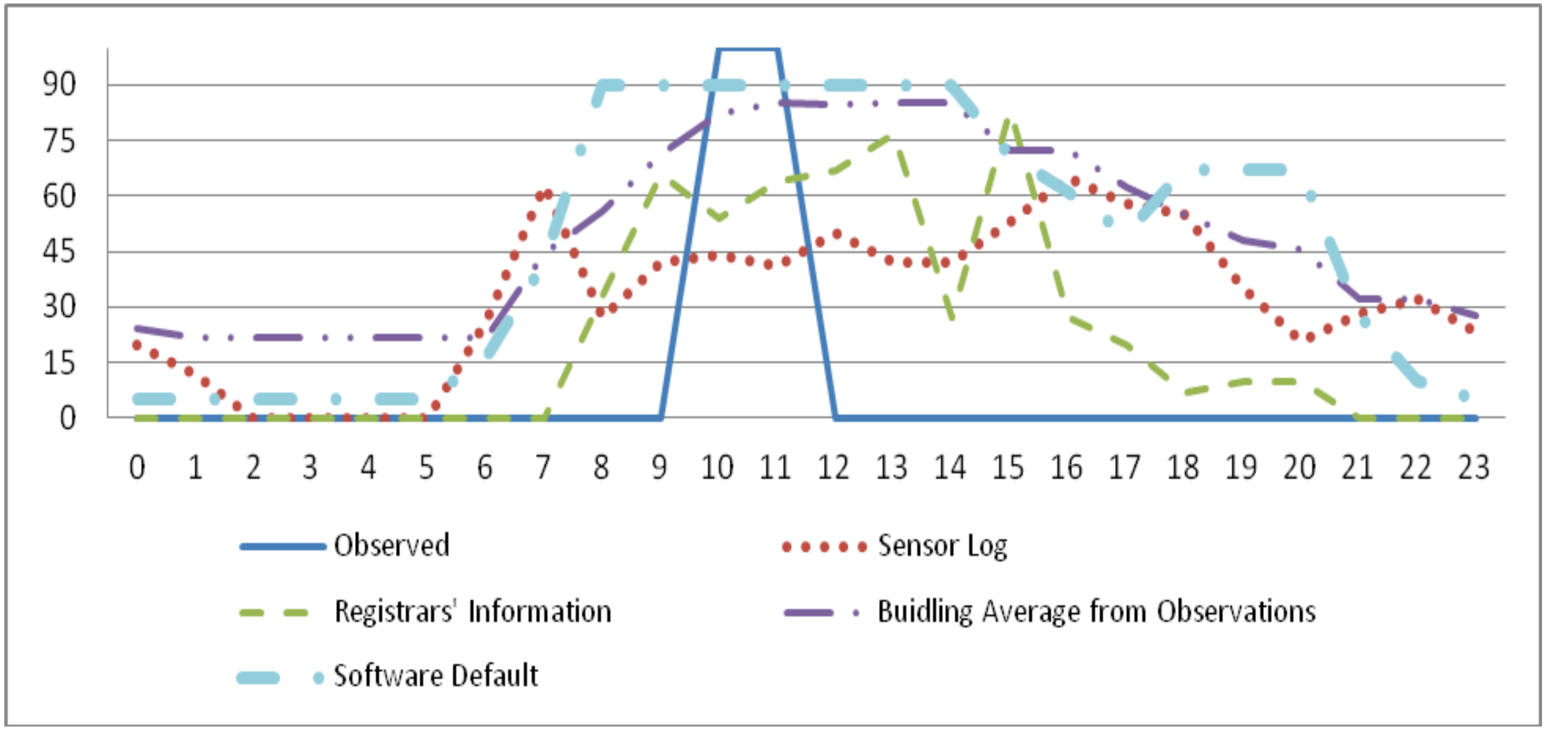


Figure 4-13: Hourly Lighting Use Percentages Obtained Through Several Data Collection Methods in Basement Classroom at Chemistry Building

4.3.2 Geography Building

The Geography building was built in 1965 and its total area is 31,221 ft^2. It is located on the Michigan State University Campus in East Lansing, Michigan. It consists of three floors, two above grade, and one below grade. Function of rooms by floor in the building is shown in Table 4.20.

Second Floor	27 Offices
	3 Computer Labs
	2 Work Rooms
	2 Server Rooms
First Floor	20 Offices
	3 Conference Rooms
	2 Storage
	1 Kitchen
	1 Lounge
Basement	27 Offices
	6 Labs
	3 Media Rooms
	1 Computer Lab
	1 Storage Room

Table 4-20: Room Distribution in Geography Building

Figure 4-14: Geography Building

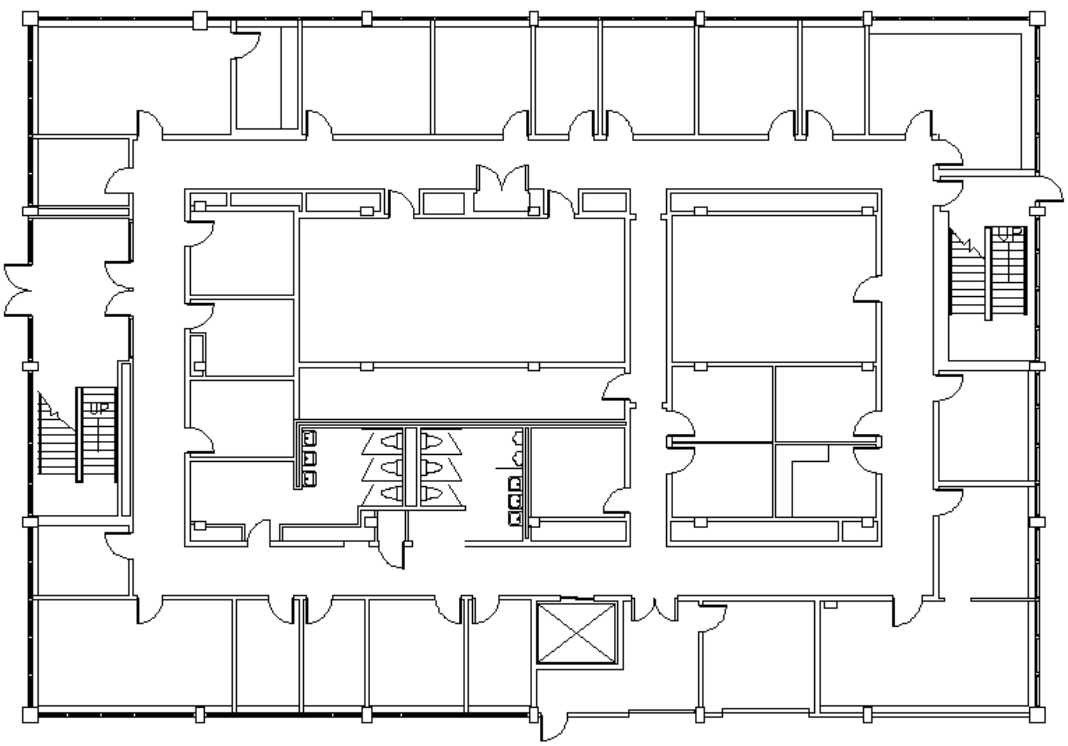


Figure 4-15: Typical Floor Plan of Geography Building

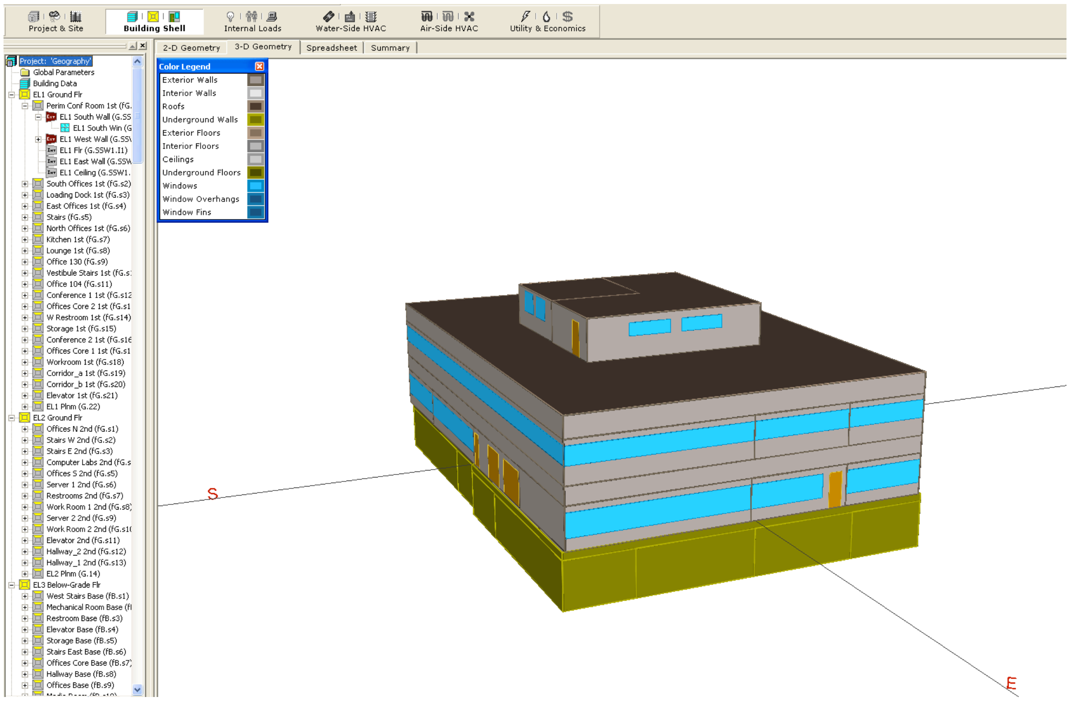


Figure 4-16: Geography Building Model Screenshot

This building has a concrete masonry unit (CMU) construction for all walls and an insulated concrete slab roof. Descriptions of construction assemblies are shown in Appendix B.

The HVAC system in the Geography building consists of two air handling units (AHU) fed by one chiller. One AHU supplies cooling for the first and second floor and the other one provides for the basement only. The AHU system provides only cooling and ventilation. Hot water reheat coils provide heating during the winter.

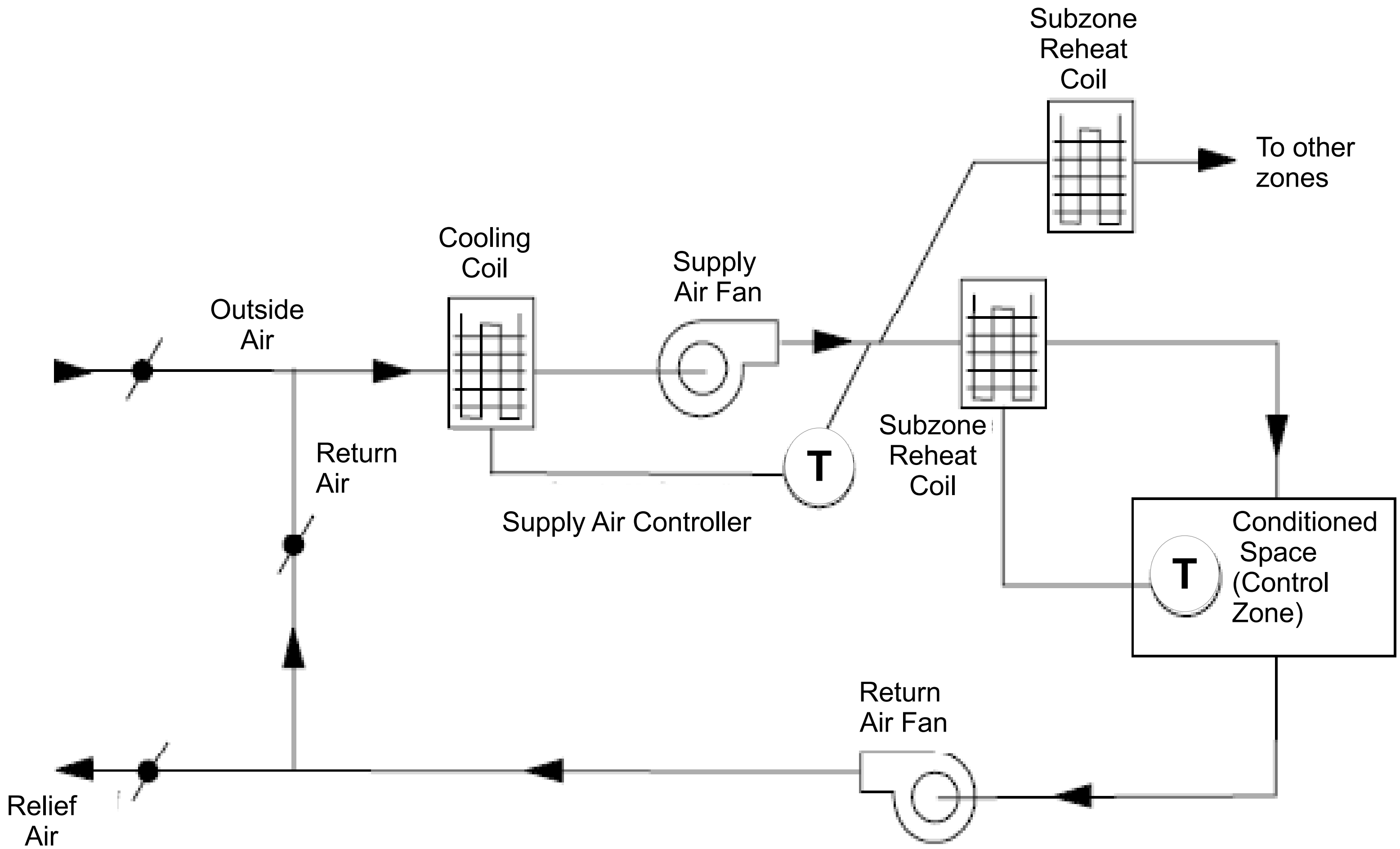


Figure 4-17: Schematic Design of Constant Volume AHU with Reheat (NREL, 2006)

Geography Data

There was no previous energy model of the Geography building, making this case slightly different from Chemistry. Only a research model was developed and no original model was available for comparison. Since it is a campus building, it was defined as an academic building with the same default schedules represented in Tables 4.9 and 4.10. Procedures for obtaining required information for the Geography building included:

- An initial walkthrough was carried out to become familiar with the building and to understand space distribution, and how measurements would be collected
- Drawings provided included lighting fixture layouts for renovated areas, but not for non-renovated areas. Consequently fixtures were counted and lamp types were recorded during the first walkthrough
    - Lighting fixtures were recessed fluorescent troffers, at 32 Watts per tube. Some lamps had four tubes, other had two tubes, and some just one tube
- Walkthroughs were conducted during a span of one week, and covered all 24 hours of the day. Access to the building was requested from and granted so that the researcher had access to the building at all times
- Most of the spaces were closed and locked during the visits. Access to some office spaces, conference rooms, or computer labs access was not granted. These spaces were counted as “on or off” and the researcher could not determine exactly how many lamps were switched on, but a small window allowed observations of the interior. Office spaces were counted and the percentages of use were defined as the number of spaces using

light. It is worth mentioning that sometimes offices were occupied but with the lights off, due to good daylighting within the space

- In spaces where access was allowed, lamps were counted to determine the percentage of lights on and to define use profiles
- Basement spaces were not as easily observable, as some of the rooms were not only locked but behind another door. Also, some doors did not have a window through which observations could be made. These spaces were considered as "on" if they were open, and "off" if unoccupied and closed
- Lighting loggers were not used in this building
- Results in Table 4.21 are shown as percentages. Use percentages were calculated as follows:
    - Hallways (1^{st} Floor, 2^{nd} Floor, and Basement) and bathrooms: fixtures were counted, and the percentage represents number of fixtures on to the total of fixtures installed. For example, out of twenty six lamps in the basement hallway, twenty two were on so 85% use is defined
    - Perimeter offices, Internal Offices (1st Floor, 2^{nd} Floor, and Basement): use percentage was defined as the total of spaces observed on to the total of existing spaces; for the first floor, there are fourteen offices in the perimeter, if four were observed to be on, then 28% was defined as the lighting use. Spaces that were unobservable were considered as lights off. Some spaces were closed but it was possible to determine if the lights were on or off

    - Perimeter conference room, lounge, kitchen, server room, and internal work rooms: these spaces were observable all times so the same procedure as for hallways was applied
    - Computer labs and internal conference rooms: these were spaces with restricted access, so only when a door was open could lights be observed. One of three computer labs was opened at all times, so only when the other labs were opened could a full count could be made, otherwise, these closed labs were considered as off

- Bathrooms were considered as a single space throughout the building; hallways were grouped for the first and second floor and considered individually for the basement due to asymmetry in design and differences in fixture quantities

			HOUR OF THE DAY																							
Rooms	**Floor**	**Qty**	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Perim. Offices	1st	14	0	0	0	0	0	0	0	7	29	43	36	43	50	50	57	29	21	21	0	7	0	0	7	7
Intern Offices	1st	5	0	0	0	0	0	0	0	0	0	0	20	20	20	20	20	20	20	20	0	0	0	0	0	0
Perim. Conf. Room	1st	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Intern. Conf. Room	1st	2	0	0	0	0	0	0	0	0	0	100	100	75	75	45	0	0	0	0	40	25	25	75	0	0
Intern Work Rooms	1st	1	0	0	0	0	0	0	0	50	0	50	50	50	100	100	100	100	100	0	0	0	0	0	0	0
Lounge/ Kitchen	1st	1	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0	0	0
Perim. Offices	2nd	28	0	0	0	0	0	0	0	18	32	32	39	32	32	36	29	32	25	18	18	7	4	7	9	9
Computer Labs	2nd	3	50	50	50	50	50	50	50	50	0	50	75	50	40	50	50	50	50	50	50	100	50	45	45	20
Intern. Work Rooms	2nd	2	0	0	0	0	0	0	0	0	100	100	50	100	50	50	0	0	0	0	0	0	0	0	0	0
Server Rooms	2nd	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bathrooms	Gen	4	100	50	50	50	50	50	50	50	0	100	100	100	100	50	0	100	100	100	100	0	50	50	25	25
Offices	B	35	0	0	0	0	0	0	0	3	9	17	14	23	26	40	29	14	17	11	11	9	6	6	3	3
Hallways	1 + 2		100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Hallways	B		10	10	10	10	10	10	10	100	100	10	10	10	10	85	85	85	85	85	85	85	85	85	85	85
		AVG	19	15	15	15	15	15	15	27	26	43	42	43	50	45	34	38	37	29	29	24	23	26	20	18

Table 4-21: Lighting Fixture Use Schedule by Zone in Geography Building

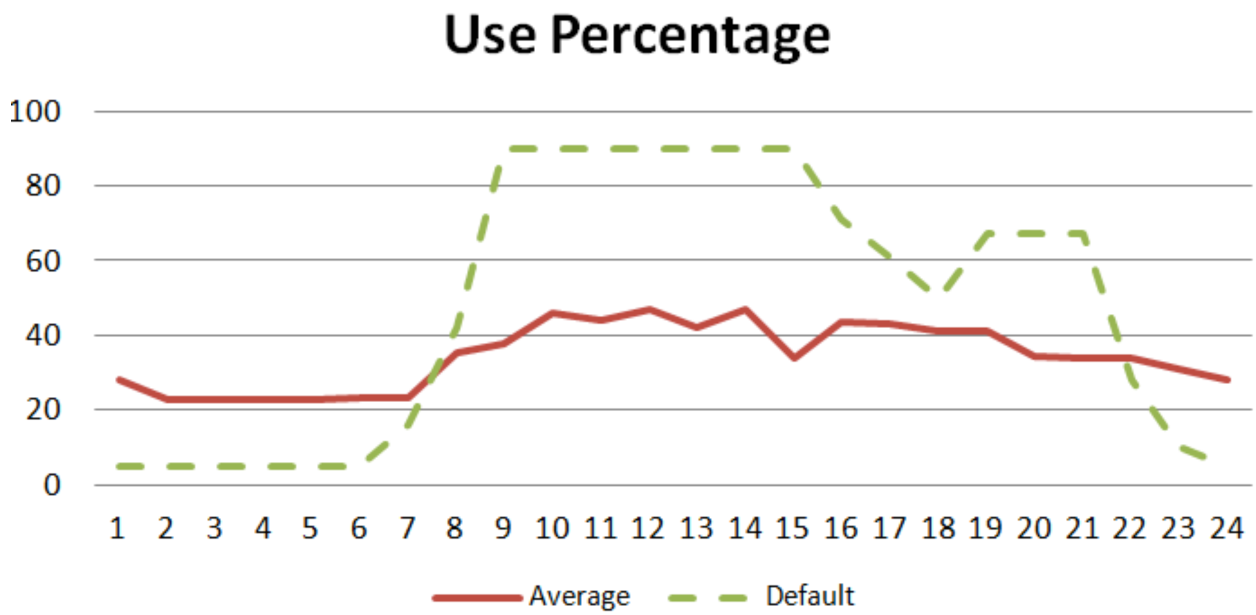


Figure 4-18: Geography Average Lighting Profile from Observations v Software Default Schedule

The average lighting profile shows much lower lighting use compared to the Chemistry building, due to the nature of the building. The Geography building has a high percentage of offices, as the majority of the spaces are intended for faculty and administrative use, while the Chemistry has a broader space distribution including laboratories, offices, classrooms, conference rooms, and study rooms.

In addition to the default schedules (Tables 4.9 and 4.10), two schedules were defined for the research model from Table 4.18. Individual schedules for each room as well as a schedule of average hour by hour use profile for the entire building were created. Figure 4.17 compares hourly profiles from default schedules with averaged observed schedule. Results from simulations are presented in Table 4.22 and it shows a comparison against actual metered electrical use from the Physical Plant throughout the 2010 year. No original or previously developed model exists so this analysis was not carried out in the Geography building.

	Research Model / Default Schedules	Research Model / Observed Schedules	Research Model / Average Schedule
	Electricity kWh (x000)	**Electricity kWh (x000)**	**Electricity kWh (x000)**
Space Cool	46.6	89.46	45.33
Heat Reject.	2.54	4.47	2.51
Space Heat	0	0	0
Hot Water	0	0	0
Vent. Fans	69.48	124.7	68.53
Pumps & Aux.	6.97	11.7	6.76
Misc. Equip.	12.87	12.87	12.87
Area Lights	64.4	103.08	40.12
Total	202.86	346.28	176.12
Measured Utilities	741	741	741
% Difference	72.6%	53.3%	76.2%

Table 4-22: Annual Electric Consumption Predicted v Measured Utility Data for Geography Building

Table 4.22 shows a large difference of simulation energy use against measured utilities. This difference resides in the air handling unit in the basement working on 100% outside air, consequently large heating and cooling loads result from conditioning intake air flow during winter and summer. This was not considered in the research model at first. A second research model was developed to include these loads and the results obtained are presented in Table 4.23. The software program does not model these types of systems directly, so an alternative method had to be developed to be able to reflect these loads. The system was sized to move 12,000 CFM of outside air according to guidance from the department of Engineering and Architectural Services at Michigan State University.

	Research Model / Default Schedules w/ 100% OA	Research Model / Observed Schedules w/ 100% OA	Research Model / Average Schedule w/ 100% OA
	Electricity kWh (x000)	**Electricity kWh (x000)**	**Electricity kWh (x000)**
Space Cool	186.37	246.89	182.29
Heat Reject.	9.47	10.75	9.38
Space Heat	0	0	0
Hot Water	0	0	0
Vent. Fans	227.64	313.25	228.89
Pumps & Aux.	35.18	48.47	34.74
Misc. Equip.	12.87	12.87	12.87
Area Lights	64.4	103.08	40.12
Total	535.93	735.31	508.29
Measured Utilities	741	741	741
% Difference	27.7%	0.8%	31.4%

Table 4-23: Annual Electric Consumption Predicted with 100% OA Requirements v Measured Utility Data for Geography Building

Table 4.23 shows increased cooling loads due to the 100% outside air which must be cooled during summer or heated during the winter. Miscellaneous loads and lighting loads remained the same and the only variation was the quantity of air conditioned. Since the only parameter varied was lighting schedule, impacts of lighting were able to be determined. Lighting consumption based on observed schedules was calculated as 103 MWh annually, while for the average and the default schedules were 64 MWh and 40 MWh annually, yielding a 200 MWh difference in electric annual loads for the building among cases. A graphic comparison of these predictions is shown in Figure 4.18. Observed schedules gave the most accurate prediction in this case with a 0.8% difference from metered consumption. Default schedules yielded a 27% difference and averaged schedules yielded a 31% difference from metered consumption.

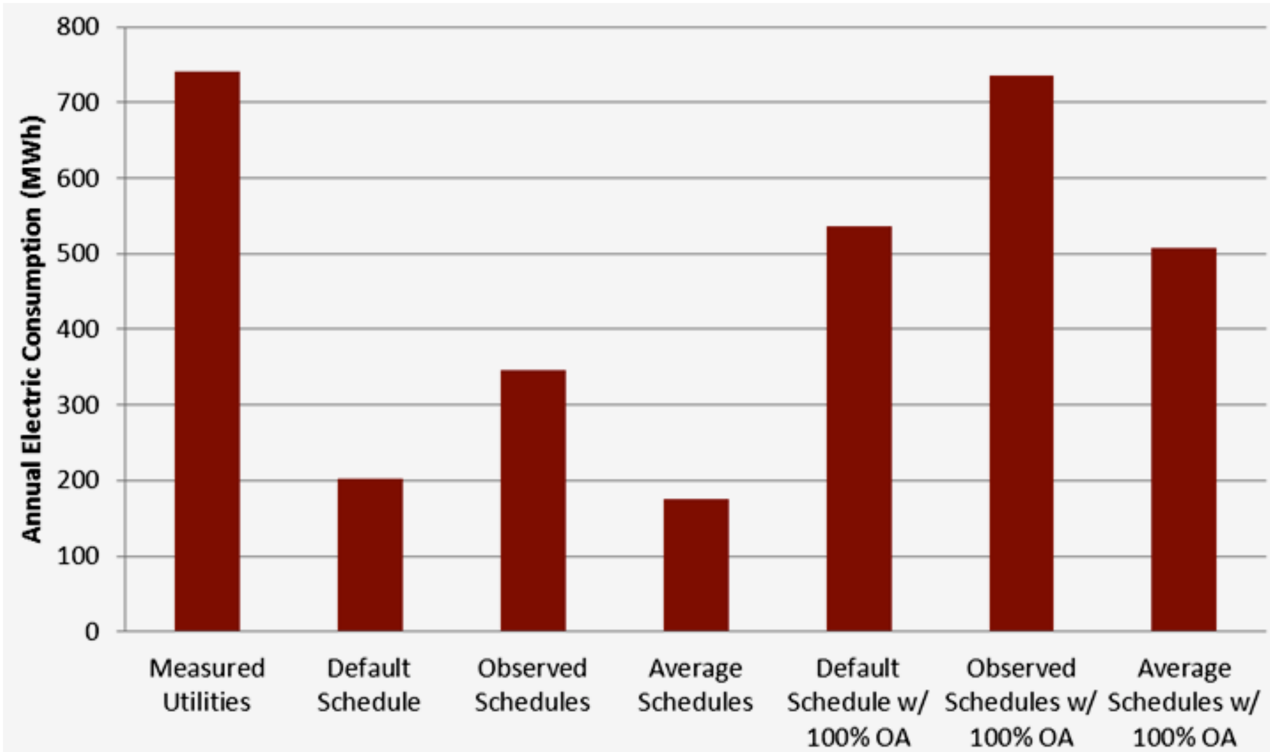


Figure 4-19: Comparison of Annual Electric Consumption in Geography Building

Figure 4.19 compares profiles obtained from the schedules used in the building model. Peak consumption is shown during summer months, June to September which is influenced by cooling loads. Heating is steam based so the load during winter months will mostly be reflected in steam measurements, not in the electric components considered in this research. The average schedules show a steady behavior throughout the year and follows a similar pattern to the default schedules within the program.

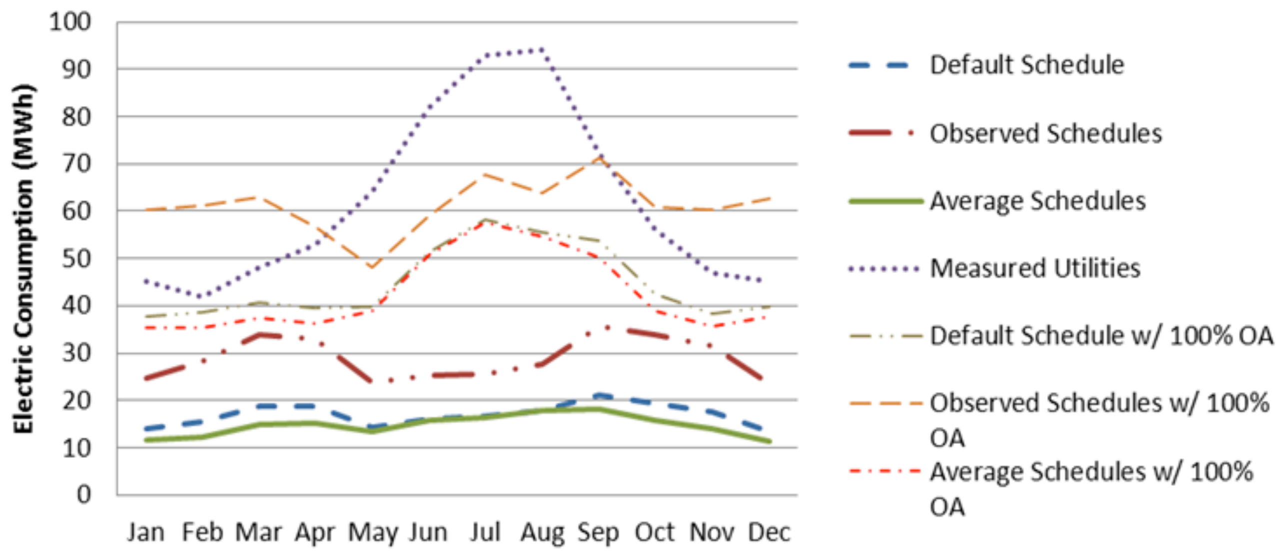


Figure 4-20: Monthly Electric Consumption by Lighting Schedules in Geography Building

4.3.3 Church Project

This building is a 4,050 ft^2 new building and is intended for weekly worship meetings. The building is located in Lansing, Michigan. The building was completed in 2010 and is pursuing LEED certification. It is a one story building, and has the following rooms:

- One main meeting room
- One main Fellowship room
- A kitchen
- A library
- 2 smaller meeting rooms
- A small attic

Figure 4-21: Church Project Building

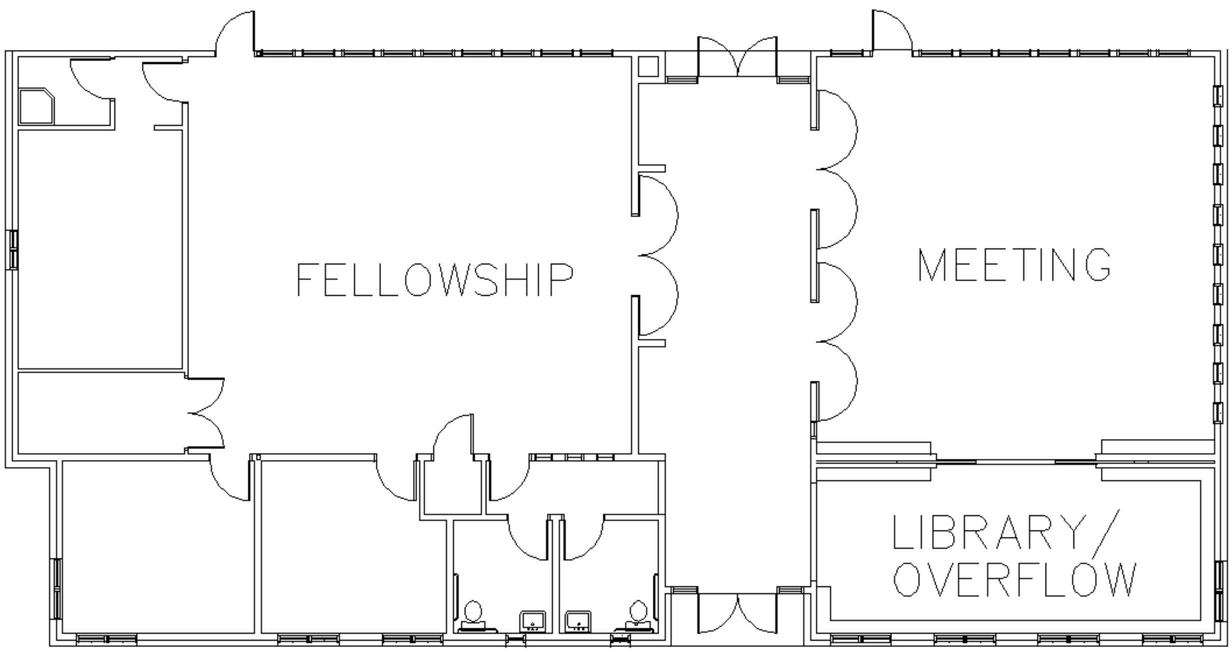


Figure 4-22: Floor Plan for Church Project

The church project has 2x6 wood frame construction with R-19 insulation, and a facebrick exterior layer. The roof uses a wood truss structure with R38 insulation. Roof and wall construction is shown in Appendix B.

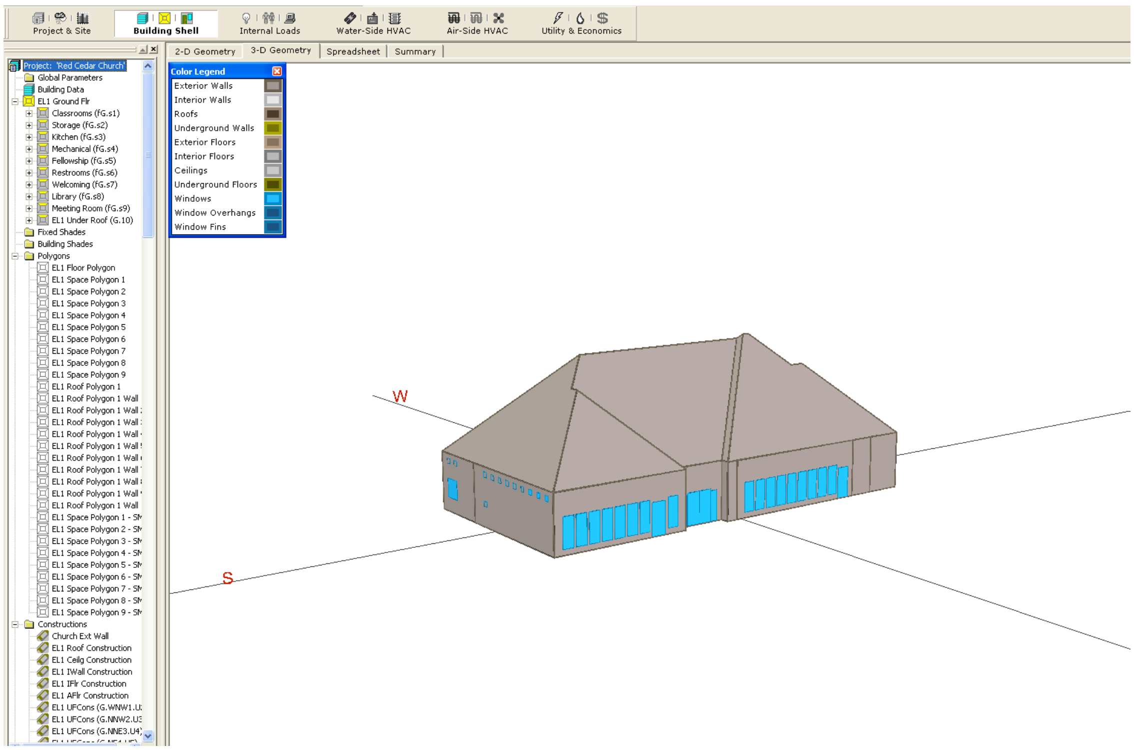


Figure 4-23: Church Project Building Model Screenshot

This project was not air conditioned but incorporates operable windows and natural wind turbines for natural cooling. Its design includes two separate gas furnaces supplying different zones. One furnace supplies the meeting zone and the other the fellowship zone. A schematic design of the system is shown in Figure 4.23. The building also utilizes an energy recovery unit which captures heat from exhaust air during cold months. Furnace fans provide fresh air for occupancy by drawing in outside air.

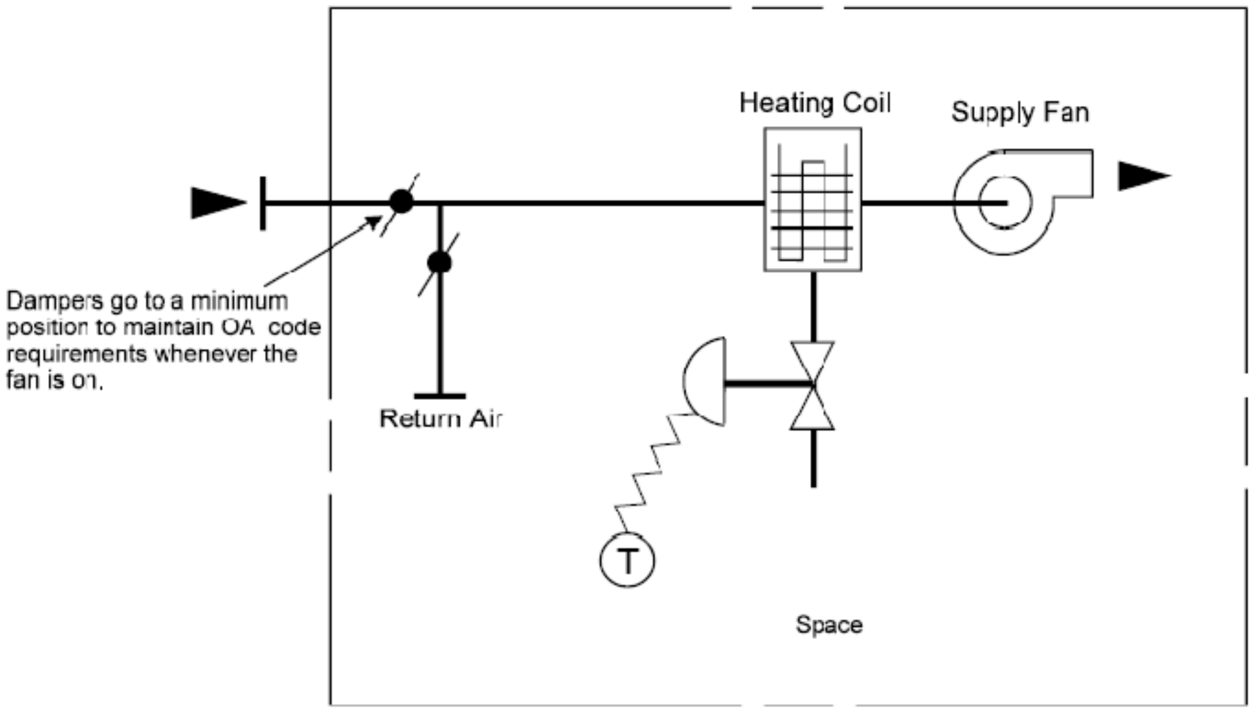


Figure 4-24: Schematic Design for Furnace System (NREL, 2006)

Church Project Data and Results

Data gathering for this project varied from the other case studies. Continuous observation of spaces was not possible since there was limited access to the building so the researchers used occupancy sensors to collect field data. The data collection for this project is described below:

- Drawings were provided by the architecture and engineering team from the project. A previously developed energy model was provided with this information package
- Calendar records of scheduled meetings in the building were provided and were used as a documentation of room use
- The owner's original predesign program statement indicating hours of operation and occupancy level by room was reviewed

- Lighting sensors were installed in four rooms where occupancy was most significant, and sensors measured the presence of people in the room, if the lights were on or off, and lighting levels in the rooms
- Sensors were used to record two weeks of data and then results were averaged for the period
- Electric utility records were provided by the owner for comparison to energy simulations from the design phase and from measured schedules. These records included measurements from July to December in 2010 and January to July 2011; predicted electric consumption from research models was compared against available data for 2011 while the remaining months were assumed the same as 2010 data

The analysis for this building includes a previously developed model referred to as the original model, and a model created for the research referred to as the research model. The original model was created for the LEED certification process which requires use of ASHRAE 90.1 Appendix G, which requires buildings be modeled as fully air conditioned, even though no air conditioning system was going to be installed. During the research two simulations were run to determine electric consumption with the air conditioning system modeled and electric consumption without the air conditioning. The intention of removing the air conditioning system was to compare the original model to the research model, developed without an air conditioning system.

Tables 4.24 to 4.29 present the schedules used for the research model. Table 4.24 shows the default schedule within the software, used for all spaces in the building. Measurements recorded with the light loggers for the Main Meeting room, a smaller meeting room, the library, and the Fellowship room are shown in Tables 4.25, 4.26, 4.27, and 4.28 respectively. Each of these schedules was used for its corresponding room for the simulation while the other rooms where simulated with the default schedule. The light loggers recorded data every twenty minutes, with additional recordings every time movement was detected, so more than three recordings per hour could be obtained from each logger. The loggers collected information on occupancy, light level, and if lights were on or off. A sample logged session is shown in Appendix D. Once the recordings were collected, schedules were defined as followed:

- External light (sunlight, street lights) influenced readings on the sensor so lighting levels were difficult to set as baseline to determine use percentage. Instead, schedules were defined according to the "on" or "off" readings. If an event was recorded as "on", 100% lighting use was assumed

- The number of "on" readings for every hour were counted, and a percentage of "on" to the total number of readings during that hour defined the light use percentage. For example, if the Fellowship room logged six recordings from 12:00 p.m. to 1:00 p.m., and two were recorded as "on", then 33% was taken as the light use for that hour (two out of six measurements within an hour the lights were on)

- Loggers recorded periods where lights were "off" but showed the space as occupied. The defined schedule would show 0% light use for those periods but this doesn't imply the rooms were not in use

The third schedule defined was an average of lighting use from all four sensors to define a single profile for building lighting use. Each hour of every day was averaged, and finally values for every day were averaged into a single value. A composite schedule is shown in Table 4.29. This schedule was used for every room of the building during the third run of the simulation.

Hour	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
0-1	0.035	0.035	0.035	0.035	0.035	0.040	0.050
1-2	0.035	0.035	0.035	0.035	0.035	0.040	0.050
2-3	0.035	0.035	0.035	0.035	0.035	0.040	0.050
3-4	0.035	0.035	0.035	0.035	0.035	0.040	0.050
4-5	0.035	0.035	0.035	0.035	0.035	0.040	0.050
5-6	0.035	0.035	0.035	0.035	0.035	0.040	0.050
6-7	0.035	0.035	0.035	0.035	0.035	0.040	0.050
7-8	0.128	0.128	0.128	0.128	0.128	0.128	0.407
8-9	0.204	0.204	0.204	0.204	0.204	0.210	0.730
9-10	0.204	0.204	0.204	0.204	0.204	0.482	0.824
10-11	0.204	0.204	0.204	0.204	0.204	0.482	0.900
11-12	0.204	0.204	0.204	0.204	0.204	0.482	0.900
12-13	0.204	0.204	0.204	0.204	0.204	0.659	0.577
13-14	0.204	0.204	0.204	0.204	0.204	0.720	0.220
14-15	0.427	0.427	0.427	0.427	0.427	0.720	0.220
15-16	0.427	0.427	0.427	0.427	0.427	0.720	0.220
16-17	0.427	0.427	0.427	0.427	0.427	0.659	0.220
17-18	0.580	0.580	0.580	0.580	0.580	0.543	0.161
18-19	0.569	0.569	0.569	0.569	0.569	0.598	0.050
19-20	0.547	0.547	0.547	0.547	0.547	0.638	0.050
20-21	0.460	0.460	0.460	0.460	0.460	0.550	0.050
21-22	0.460	0.460	0.460	0.460	0.460	0.550	0.050
22-23	0.460	0.460	0.460	0.460	0.460	0.550	0.050
23-24	0.259	0.259	0.259	0.259	0.259	0.312	0.050

Table 4-24: Software Default Schedule for Church Projects

Hour	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
0-1	0	0	0	0	0	0	0
1-2	0	0	0	0	0	0	0
2-3	0	0	0	0	0	0	0
3-4	0	0	0	0	0	0	0
4-5	0	0	0	0	0	0	0
5-6	0	0	0	0	0	0	0
6-7	0	0	0	0	0	0	0
7-8	0	0	0.7	0.6	0.8	0	0
8-9	0.83	0.6	0	0	0.167	0	0
9-10	1	1	0	0	0	0	0
10-11	1	1	0	0	0	0	0
11-12	1	1	0	0	0	0	0
12-13	1	1	0	0	0	0	0
13-14	1	1	0	0	0	0	0
14-15	0.6	1	0	0	0	0	0
15-16	0	1	0	0	0	0	0
16-17	0	1	0	0	0	0	0
17-18	0	1	0	0	0	0.143	0.25
18-19	0.25	0.25	0	0	0.25	0	0.4
19-20	0.2	0	0	0	0	0	0
20-21	0	0	0	0	0	0	0
21-22	0	0	0	0	0	0	0
22-23	0	0	0	0	0	0	0
23-0	0	0	0	0	0	0	0

Table 4-25: Average Values Recorded by Logger in Main Meeting Room at Church Project

Hour	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
0-1	0	0	0	0	0	0	0
1-2	0	0	0	0	0	0	0
2-3	0	0	0	0	0	0	0
3-4	0	0	0	0	0	0	0
4-5	0	0	0	0	0	0	0
5-6	0	0	0	0	0	0	0
6-7	0	0	0	0	0	0	0
7-8	0	0	0	0	0	0	0
8-9	0	0	0	0	0.43	0	0
9-10	0	0	0	0	0	0	0.57
10-11	0	0	0	0	0	0	0.5
11-12	0	0	0	0	0	0	0
12-13	0	0	0	0	0	0	0
13-14	0	0	0	0	0	0	0
14-15	0	0	0	0	0	0	0
15-16	0	0	0	0	0	0.6	0
16-17	0	0	0	0	0	0	0
17-18	0	0	0	0	0	0.43	0
18-19	0	0	0	0.25	0	0.43	0
19-20	0	0	0	0	0	0	0
20-21	0	0	0	0	0	0	0
21-22	0	0	0	0	0	0	0
22-23	0	0	0	0	0	0	0
23-0	0	0	0	0	0	0	0

Table 4-26: Average Values Recorded by Logger in Meeting Room at Church Project

Hour	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
0-1	0	0	0	0	0	0	0
1-2	0	0	0	0	0	0	0
2-3	0	0	0	0	0	0	0
3-4	0	0	0	0	0	0	0
4-5	0	0	0	0	0	0	0
5-6	0	0	0	0	0	0	0
6-7	0	0	0	0	0	0	0
7-8	0	0	0	0	0	0	0
8-9	0	0	0	0	0	0	0.33
9-10	0	0	0	0	0	0	0.63
10-11	0	0	0	0	0	0	0.5
11-12	0	0	0	0	0	0	0
12-13	0	0	0	0	0	0	0
13-14	0	0	0	0	0	0	0
14-15	0	0	0	0	0	0	0
15-16	0	0	0	0	0	0	0
16-17	0	0	0	0	0	0	0
17-18	0.25	0	0	0.25	0	0.18	0
18-19	0.5	0	0.25	0.66	0	0.5	0
19-20	0.25	0	0.66	0.5	0	0.28	0
20-21	0	0	0.66	0.5	0	0	0
21-22	0	0	0	0.25	0	0	0
22-23	0	0	0	0	0	0	0
23-0	0	0	0	0	0	0	0

Table 4-27: Average Values Recorded by Logger in Library at Church Project

Hour	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
0-1	0	0	0	0	0	0	0
1-2	0	0	0	0	0	0	0
2-3	0	0	0	0	0	0	0
3-4	0	0	0	0	0	0	0
4-5	0	0	0	0	0	0	0
5-6	0	0	0	0	0	0	0
6-7	0	0	0	0	0	0	0
7-8	0.43	0	0	0.25	0.54	0	0
8-9	0.13	0	0	0.5	0.5	0	0
9-10	0	0	0	0.66	0.66	0	0
10-11	0	0	0	0.5	0.66	0	0
11-12	0	0	0	0.5	0.5	0	0.43
12-13	0	0	0	0.5	0.5	0.22	0.5
13-14	0	0	0	0.66	0.57	0.5	0.5
14-15	0	0	0	0	0.66	0.5	0.66
15-16	0	0	0	0	0.63	0.66	0.63
16-17	0	0	0	0	0.22	0.66	0.13
17-18	0	0	0	0	0	0.66	0
18-19	0	0	0	0	0	0.22	0
19-20	0	0	0	0	0	0.22	0
20-21	0	0	0	0	0	0	0
21-22	0	0	0	0	0	0	0
22-23	0	0	0	0	0	0	0
23-0	0	0	0	0	0	0	0

Table 4-28: Average Values Recorded by Logger in Fellowship at Church Project

Hour	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Weekly Average
0-1	0	0	0	0	0	0	0	0
1-2	0	0	0	0	0	0	0	0
2-3	0	0	0	0	0	0	0	0
3-4	0	0	0	0	0	0	0	0
4-5	0	0	0	0	0	0	0	0
5-6	0	0	0	0	0	0	0	0
6-7	0	0	0	0	0	0	0	0
7-8	0.108	0	0.175	0.213	0.335	0.000	0.000	0.119
8-9	0.240	0.150	0	0.125	0.274	0.000	0.083	0.125
9-10	0.250	0.250	0	0.165	0.165	0.000	0.300	0.161
10-11	0.250	0.250	0	0.125	0.165	0.000	0.250	0.149
11-12	0.250	0.250	0	0.125	0.125	0.000	0.108	0.123
12-13	0.250	0.250	0	0.125	0.125	0.055	0.125	0.133
13-14	0.250	0.250	0	0.165	0.143	0.125	0.125	0.151
14-15	0.150	0.250	0	0.000	0.165	0.125	0.165	0.122
15-16	0	0.250	0	0.000	0.158	0.315	0.158	0.126
16-17	0	0.250	0	0.000	0.055	0.165	0.033	0.072
17-18	0.063	0.250	0	0.063	0.000	0.353	0.063	0.113
18-19	0.188	0.063	0.063	0.228	0.063	0.288	0.100	0.141
19-20	0.113	0	0.165	0.125	0	0.125	0.000	0.075
20-21	0	0	0.165	0.125	0	0	0	0.041
21-22	0	0	0	0.063	0	0	0	0.009
22-23	0	0	0	0	0	0	0	0
23-0	0	0	0	0	0	0	0	0

Table 4-29: Building Average Schedule from Measurements for Church Building

Because the original model and the research model were developed under different assumptions and different software, both models had to be modified so that parameters other than lighting that could influence results were normalized, minimizing their impact. The software used for the original model was HAP from Carrier Corporation and the research model was developed with eQuest. The original model was developed under ASHRAE Appendix G requirements due to LEED certification process. ASHRAE Appendix G requires the model to include air conditioning throughout the building even though it was not part of the project. The research model did not include air conditioning, so the first step toward normalization was removing the air conditioning system from the original model. Miscellaneous loads assigned in the research model were also set as the same in the original model. Table 4.30 shows the original model and both the modified original model and research model. The original model predicted 68 kWh consumed annually against 38.3 kWh and 38.98 kWh from the modified models, showing the impact of including the uninstalled air conditioning systems in the original model.

	Original Model	Original Model without A/C	Normalized Research Model
	Electricity kWh (x000)	**Electricity kWh (x000)**	**Electricity kWh (x000)**
Space Cool	2.817	0	0
Heat Reject.	0	0	0
Space Heat	0	0	0
Hot Water	0	0	0
Vent. Fans	29.953	2.193	2.79
Ext. Usage	0	0	1.09
Misc. Equip.	26.637	26.637	22.52
Area Lights	9.454	9.454	12.58
Total	68.861	38.284	38.98
Measured Utilities	16.71	16.71	16.71
% Difference	312.1%	129.1%	133.3%

Table 4-30: Normalized Comparison of Models

	Research Model / Default Schedules	Research Model / Measured Schedules	Research Model / Average Schedule	Research Model / With Original Model's Schedules
	Electricity kWh (x000)	**Electricity kWh (x000)**	**Electricity kWh (x000)**	**Electricity kWh (x000)**
Space Cool	0	0	0	0
Heat Reject.	0	0	0	0
Space Heat	0	0	0	0
Hot Water	0	0	0	0
Vent. Fans	2.8	2.81	2.81	2.81
Ext. Usage	1.09	1.09	1.09	1.09
Misc. Equip.	9.08	9.08	9.08	9.08
Area Lights	12.58	6.64	3.21	11.57
Total	25.55	19.62	16.19	24.55
Measured Utilities	16.71	16.71	16.71	17.71
% Difference	52.9%	17.4%	3.1%	38.6%

Table 4-31: Predicted Electric Load by Research Model with Different Lighting Schedules

The research model was modeled without an air conditioning system, and with heating and hot water as gas fired, no electric loads were estimated for cooling loads. Yet, ventilation fan electric loads were obtained because fans for the heating system, ventilation system, and energy recovery system still run on electricity. Miscellaneous loads were reduced from those in the original model, according to conversations with the building administration about actual use patterns within the kitchen, which is the room with the highest installed electric load. Lighting schedule was the only parameter which varied in the research model. Predicted electrical energy use using the average building schedule (Table 4.29) predicted electric consumption most accurately. The default schedule (Table 4.24) estimates a much higher use than the measured utilities because it assumes more hours of use in the building. Although observed schedules (Tables 4.25 to 4.28) define low occupancy hours for the building, rooms that were not logged were defined with the default schedules (Table 4.24) resulting in higher predicted electric consumption, yet lower than using solely default schedules in every room. Monthly consumption for the models is shown in Figure 4.24.

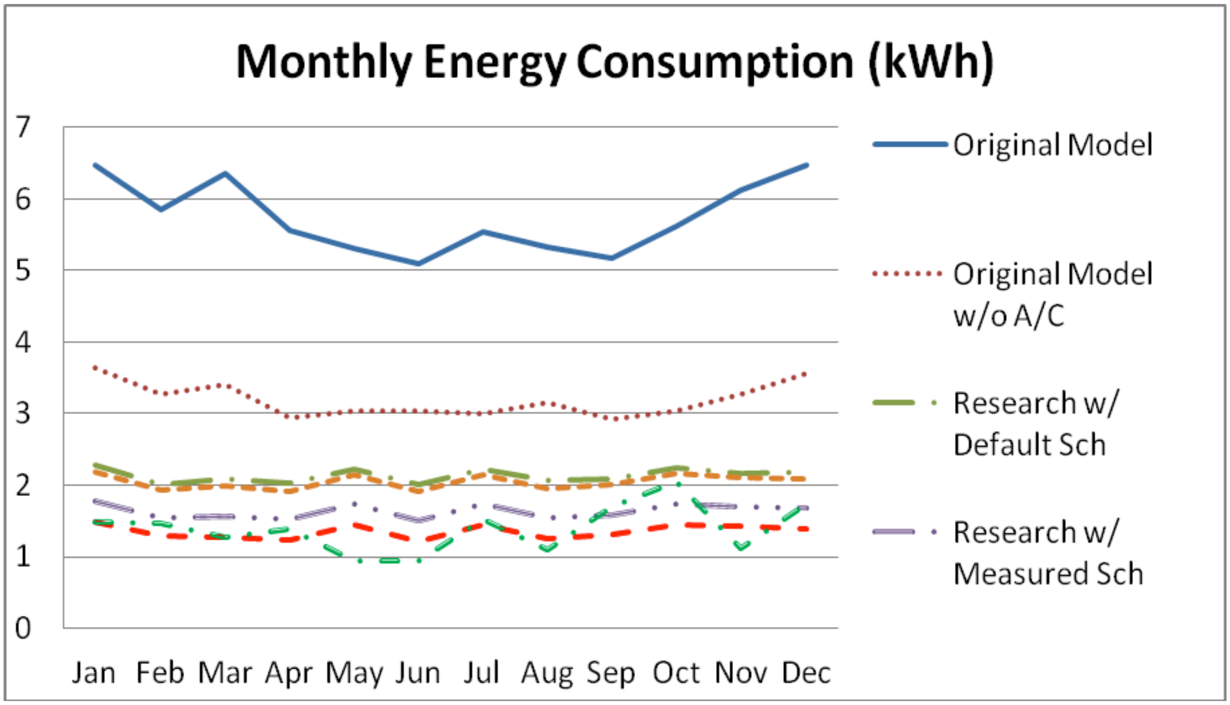


Figure 4-25: Monthly Consumption by Different Simulation Runs

Table 4.31 and Figure 4.25 allow comparison of different schedules used for the simulations. The average schedule used in the research model yielded consumption predictions which most closely matched measured data. It is also noticeable that the data used by the modeler based on ASHRAE Appendix G requirements overestimates energy use in the building.

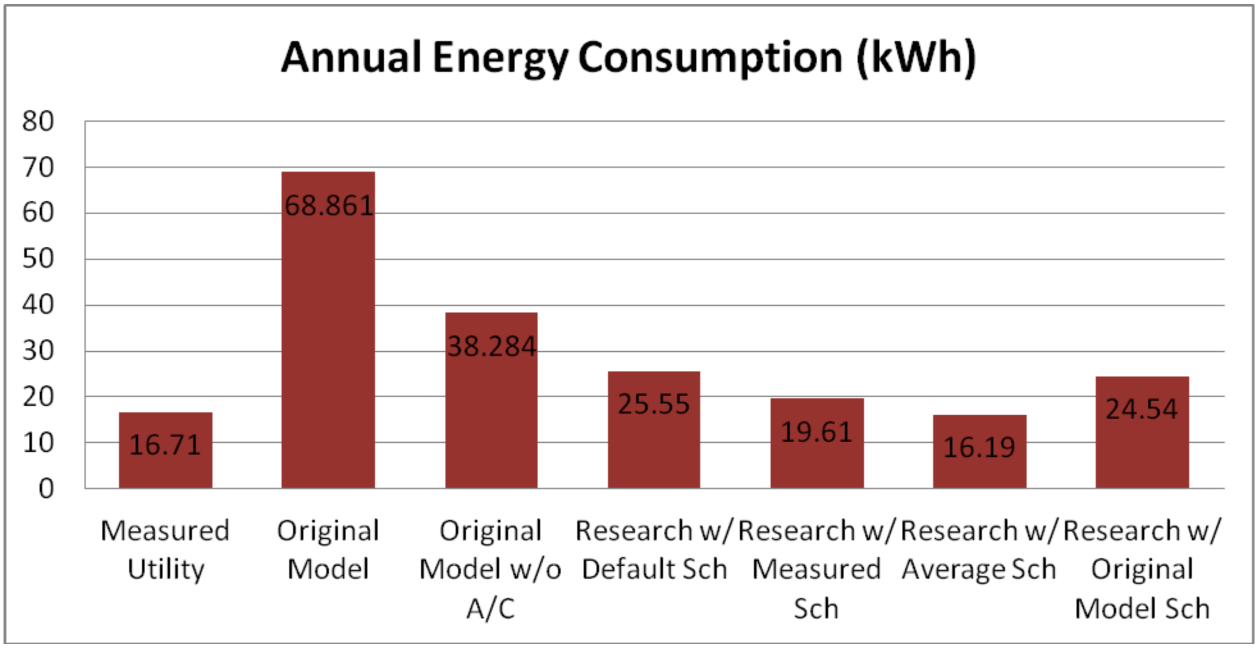


Figure 4-26: Annual Electric Consumption Predicted by Each Model

Default schedules in the church project (Table 4.24) show a greater use of lighting than the estimated use by the building administration. Default schedules assume lighting use throughout all 24 hours of the day, while the building is used only a limited number of hours per week. This is why default schedule electric use prediction is 52.9% off against 3% when using the average building schedule. It appears that average use of several rooms is a better approach than individual schedules for each room.

<u>*Additional Information for Church Building*</u>

During the research, a predesign occupancy schedule was provided by the owner and shown in Table 4.32. Although no simulation was run with this schedule, a comparison of schedule profiles was conducted in order to draw conclusions about the accuracy of predesign occupancy estimations to measured schedule occupancy. This is shown in Figure 4.26.

The schedule from the owner's predesign occupancy statement was defined under the following assumptions: scheduled meetings are assumed to use 100% lighting; what is scheduled as occasional use was assumed as three hour meetings, two times per week (out of five weekday evenings) meetings, resulting in 40% lighting use; finally, very occasional use was defined as a three hour meetings, one time per week, every two weeks resulting in one time out of ten days, or 10%. The schedule is presented in Table 4.33.

LOCATION	SUNDAYS	SATURDAYS	WEEKDAY EVENINGS	WEEKDAY BUSINESS HOURS
Meeting Room	12:30 - 1:45 pm - Meeting for Worship - 25-30 adukts jooined by 20-25 children at 1:15 pm	Occasional use - Weddings, Memorials, Retreats - 75 people	Very occasional use - 50 people	Very occasional use
Fellowship Room	12:30 - 1:15 pm - 20 children for First Day School	Occasional use - 75 people	Very occasional use - 50 people	Very occasional use
Kitchen	12:30 - 2:30 pm - 5 people	Occasional use	Occasional use	Very occasional use
2 Small Rooms	12:30 - 1:30 pm - 5 - 10 children, adults	?	5-10 People 2hr. Meetings, 2-3 days a week	Very occasional use
Library	9:30 - 11:00 pm - Small Worship Group	?	5-10 People 2hr. Meetings, 2-3 days a week	Very occasional use

Table 4-32: Predesign Occupancy Schedule Provided by Owner

Hour	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Weekly Average
0-1	0	0	0	0	0	0	0	0
1-2	0	0	0	0	0	0	0	0
2-3	0	0	0	0	0	0	0	0
3-4	0	0	0	0	0	0	0	0
4-5	0	0	0	0	0	0	0	0
5-6	0	0	0	0	0	0	0	0
6-7	0	0	0	0	0	0	0	0
7-8	0	0	0	0	0	0	0	0
8-9	0	0	0	0	0	0	0	0
9-10	0.5	0.5	0	0	0	0	0	0.143
10-11	0.5	0.5	0	0	0	0	0	0.143
11-12	0.5	0.5	0	0	0	0	0	0.143
12-13	0	0	0	0	0	0.25	0.5	0.107
13-14	0	0	0	0	0	0.25	0.75	0.143
14-15	0	0	0	0	0	0.25	0	0.036
15-16	0	0	0	0	0	0	0	0
16-17	0	0	0	0	0	0	0	0
17-18	0	0	0	0	0	0	0	0
18-19	0	0	0	0	0	0	0	0
19-20	0.5	0.5	0	0	0	0	0	0.143
20-21	0.5	0.5	0	0	0	0	0	0.143
21-22	0.5	0.5	0	0	0	0	0	0.143
22-23	0	0	0	0	0	0	0	0
23-24	0	0	0	0	0	0	0	0

Table 4-33: Schedule Defined from Owner's Predesign Occupancy Statement

From Table 4.33, Mondays and Tuesdays were planned as very occasional use, resulting in 50% weekly use (it was assumed to be used once every two weeks) for three hours. Very occasional use on Saturdays was assumed as one event per month resulting in 25% average per week. For Sundays, the percentage was based on the minutes within an hour the room was scheduled to be used. The meeting room was scheduled from 12:30 p.m. to 1:45 p.m., so 50% (30 minutes) from 12:00 p.m. to 1:00 p.m. is defined and 75% (45 minutes) from 1:00 p.m. to

2:00 p.m. A weekly average was then calculated from these assumptions and compared to weekly averages from the sensor collected data. Differences from Table 4.25 (Main Meeting Room Schedule from Loggers) can be seen, since during the time frames services are scheduled, the loggers recorded the room as occupied but lights as “off”. During the services, lighting may not have been necessary due to sufficient daylighting in the room.

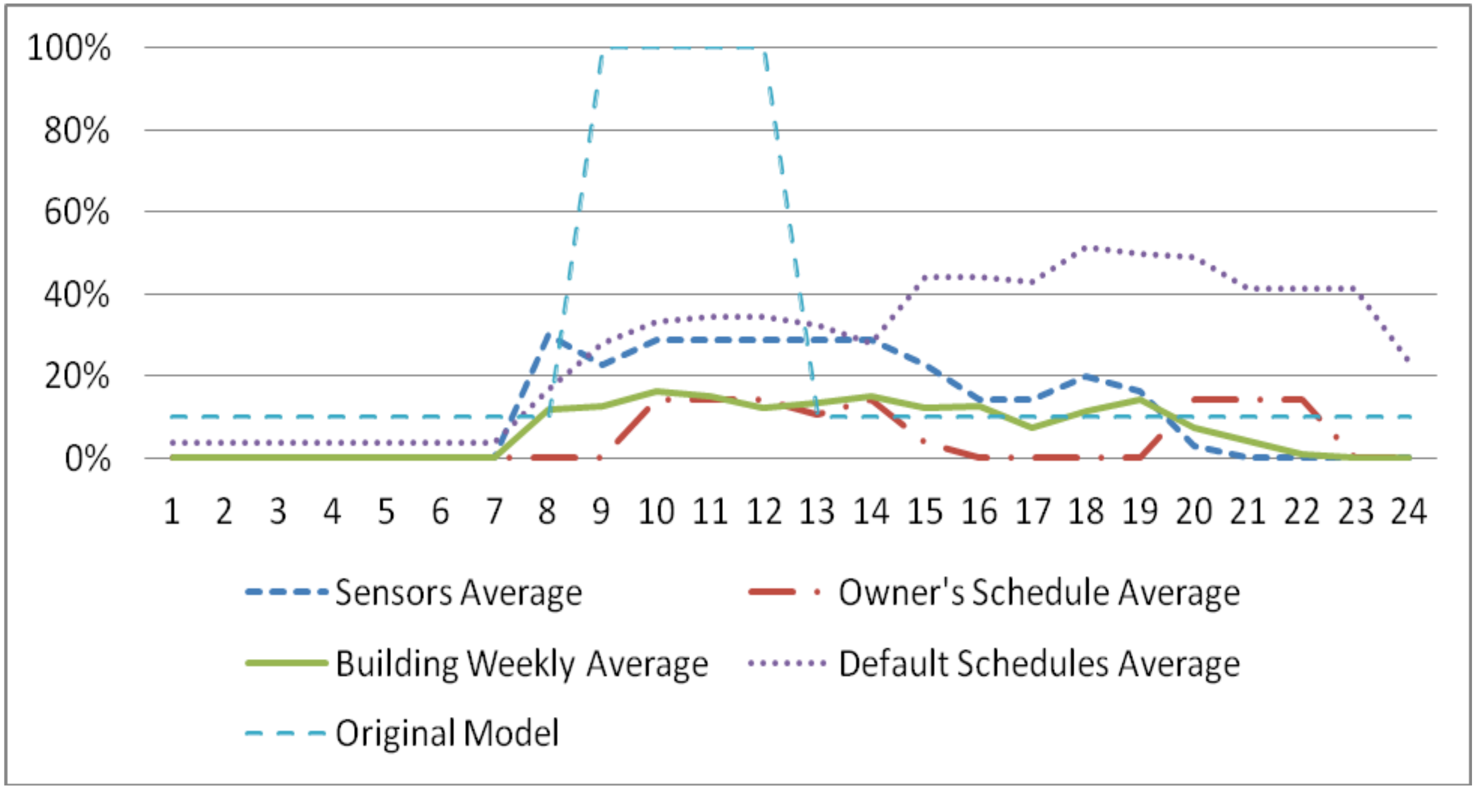


Figure 4-27: Average Daily Lighting Use Profiles for Various Methods in Main Meeting Room

From Figure 4.26, the profile defined by the owner's information is closer to the average building schedule defined from logger measurements; data recorded with the logger present a higher use than what the owner estimated, but the logger recorded lighting use which doesn't necessarily reflect actual occupancy of the room due to lights that are left switched on after the room is used.

4.4 Chapter Summary

This chapter shows the information collected during the research and its analysis. Insights from four energy modeling professionals were gathered through interviews and opinions from their experience were collected. Then, a boundary test range was carried out to test impact of lighting in a building modeled in compliance with ASHRAE 90.1 Energy Standard requirements. Finally, it describes the process of observation through the Chemistry and Geography buildings at Michigan State University and the Church project in Lansing, and how schedules were defined from data gathered. Also, the process of recording occupancy and lighting use with data loggers and how the schedules were defined according to this gathered information was described. The main conclusions from interviews, boundary analysis and case studies include:

- Energy modeling professionals agree that main sources of inaccuracy in energy simulation are occupancy assumptions and system scheduling
- The lighting use range test showed that boundary values for electric consumption from lighting can vary by as much as 120%. The difference between default schedules and intermediate schedules (8 and 12 hour) is within 10%, showing that use of default schedules may be appropriate for average structures

- The Chemistry building case study showed fairly accurate predictions with 7.3% over metered readings when using default schedules and 10.9% and 8.1% with observed and averaged schedule definitions. For academic buildings defining occupancy break periods is important and has an impact on energy prediction. Without this differentiation, the research model predicted 40% more electric use than metered data

- The Geography building case study showed electric consumption predictions differed from metered data by 27.7% for default schedules, 0.8% for observed schedules and 31.4% for average schedules (after including the outside air requirements of the system). Large differences in lighting loads seem to result in large differences in HVAC loads which indicates the importance of educated assumptions when defining lighting schedules

- The Church case study project showed 52.9% increase over metered data when using default schedules, 17.4% for measured schedules and 3.1% for averaged schedules. From this project, it was concluded that use of ASHRAE Appendix G for energy analysis on LEED buildings may introduce inaccuracies

- Daylighting may influence actual lighting use in rooms, and should be considered when analyzing the owner's predesign occupancy schedule

- From the case base buildings, even though the averaged schedules were not always the option that predicted electrical consumption most accurately, they were generally more accurate than default schedules and the levels obtained from observed use. Average schedules differed 10% in Chemistry and the Church project, and 31% in Geography. Considering all parameters that vary in a project, averaging hourly use by space type in a building may be the best approach for estimating lighting use

- Even existing buildings are difficult to model and predict energy consumption, and there are many interactions among parameters to isolate only one. Equipment such as pumps, snow melting devices and elevators can yield large differences in miscellaneous loads. Depending on assumptions made for various parameters, energy predicted can be accurate for the wrong reasons and the model can mislead further energy analysis

- LEED requirements for certification require following ASHRAE 90.1 Appendix G, may require the modeler to make assumptions that don't necessarily reflect the actual building. ASHRAE Appendix G based models are intended to compare to a proposed building to a minimum standard, but not necessarily to model actual performance

CHAPTER 5

GUIDELINES, TOOLS, AND RECOMMENDATIONS

GUIDELINES, TOOLS AND RECOMMENDATIONS

This chapter presents recommendations for steps relating to occupancy that can improve accuracy when creating energy models. These recommendations and tools flow from the data and analyses presented in Chapter 4 and are based on the interviews, observations, measurements and simulations. The recommendations address using available information from owners, breaking down spaces into groups with similar use, defining an averaged schedule for each of these groups, and considering daylighting, occupancy sensors and automatic lighting controls when defining lighting use schedules.

5.1 Guidelines and Recommendations

5.1.1 Breakdown of Spaces According to Use

Loads and energy modeling programs require the user to specify the main building use when starting a new project. This specification for the building generates a list of default values for several parameters such as outside ventilation requirements, occupancy schedules, and lighting schedules. These default values are applied to the building as a whole regardless of space distribution within the building. This means for example that office spaces in a school building are assigned the same schedule as classrooms. Spaces could be broken down into specific use classifications to improve accuracy. The following are detailed space use descriptions used in the case studies of academic buildings, but could be expanded to reflect the types of spaces that can be found within any structure:

- Classroom
- Hallway
- Bathroom
- Faculty Office
- Administration Office
- Copy / Office Equipment Room
- Study Room
- Computer Room
- Meeting / Conference Room
- Laboratory
- Kitchen / Break Room
- Mechanical/ Electrical/ Storage

5.1.2 Grouping of Spaces with Similar Use Characteristics

From the Chemistry Building and the Church Project, schedules defined from averaging the observed patterns predicted energy consumption which most closely matched metered data. Recordings from sensors in individual rooms showed that scheduling based on an individual space can result in underestimating weekly use, because there are unforeseen situations such as lights being left on, people using the rooms after hours or people that occupy the room and don't use the full lighting load or no load at all. The following characteristics may make averaging spaces better use approximations:

a) Offices: depending on a space user, offices will be constantly occupied or occupancy will be very variable. From observations, there was a noticeable difference between faculty offices (single occupancy) and administrative offices (single or multi occupancy). Faculty tends to occupy their spaces for shorter periods than administration offices, so decreasing lighting use in these spaces is adequate. Secretarial offices and lobby spaces can be considered to use 100% lighting during office hours, while single occupancy administrative offices were observed to be occupied most of the time with short periods of absence.

b) Classrooms and Study Rooms: these are very unpredictable spaces within a building. Even though some information can be obtained for these rooms by requesting an owners predesign occupancy schedule or from administrative offices as shown in chapter four, events such as people staying after class, extra class sessions, study groups, and people that don't turn off the lights should be accounted for, but are difficult.

c) Laboratories: laboratories can include computer laboratories where access is granted to any occupant, or laboratories where access is limited to specific occupants. Regardless of the final use, these spaces are occupied whenever people need to use the labs, and an average use should be a better approach than fixing weekly hours for lighting in these spaces.

d) Common Spaces: we can include in this category restrooms, hallways, and stairways, or spaces that are not controlled by the occupants of the building, and are controlled by custodians or building administration. These spaces will have fairly constant lighting use since safety of building users should be ensured. It was observed during night hours and times of low occupancy, light levels maybe reduced at times, so a 50% load reduction can be assumed for some hours. Bathrooms tend to be spaces that are kept with lights on even afterhours, consequently load reduction shouldn't be considered unless the owner's requirements and design documents support this decision, for example when occupancy sensing controls are used.

e) Conference and Meeting Rooms: these spaces usually need to be reserved in order to avoid conflicting activities from groups within a building. People leaving the lights on after using the room or having lights off for screen projections during meetings should also be considered. Averaging the hours of use of these spaces will be a better approach than assigning 100% use for expected use hours.

f) Religious or Mass Meeting Rooms: these rooms will show a low use percentage because people occupy these rooms for specific weekly or monthly activities. This is not a place of work that holds occupants for several hours per day, but people instead gather for specific activities and times, although there might be general illumination. These spaces will usually have well defined use hours and expected occasional events, so an analysis similar to that shown in Table 4.28 can be helpful.

Table 5.1 shows a summary of spaces observed throughout the three base cases, and considers an average of observed lighting use and hours of use from the Chemistry building, Geography Building, and the Church project. For example, general office data averages observations from Chemistry and Geography.

	Avg Hours Use Daily	Avg Lighting % Used Daily
General Office	12	40%
Personal Office	14	15%
Classroom	7	25%
Study Room	7	30%
Conference Room	12	30%
Common Spaces (Restrooms, Hallways)	24	65%
Specialty Laboratory	24	100%
Computer Laboratory	24	50%
Mass Gathering Rooms	4	10%

Table 5-1: Estimated Hours of Use and Percentages for Spaces Observed

5.1.3 Owner and/or Users Specify Schedules and Room Use

The owner should be the first source of guidance for definition of building use patterns. It is expected that the owner will have an idea of how many hours rooms will be used. The energy modeler should seek this information along with building policies regarding working schedules with questions such as:

- What are the working hours for occupants?
- Are people expected to work after hours?
- Are classes given on particular time schedules, or does this vary between semesters?
- Are there regularly scheduled meetings every week in certain rooms?
- Are there fixed meetings in the meeting rooms or are events planned weekly?
- Can laboratories be accessed at any time or is entrance restricted?
- Are there occasional and non-typical events?

5.1.4 Request Space Use Tendency Information Available

University campuses are usually under continuous monitoring to control how spaces are being used within buildings. These studies show occupancy numbers and hours of use for a variety of spaces that could be used to help define a schedule. Information such as that presented in section 4.3.1 and in Tables 4.17 and Figure 4.11 for the Chemistry Building can be useful.

5.1.5 Automatic Lighting Control

Automatic lighting control systems can help program desired use patterns. If automatic controls are being planned as part of the design process, the model simulation should be coordinated with the system to match its schedule. Not only timely control of lights can be achieved, but intensities as well dimming features can be considered. This will define both hourly control and wattage. Programmed schedules can be used in the simulation program, or the modeler can recommend to the lighting control programmer the schedule to use in order to achieve the owner's desired requirements.

5.1.6 Daylight and Occupancy Sensors

When sensors are included as part of the design, uncertainty in schedules can be reduced. Daylight sensors are set to attenuate lighting fixtures to a desired level of luminance within a space according to incidence of natural light. Although the percentage of light used will be dependent on how much external light enters through windows, percentages of light level used throughout day lit hours can be determined with a daylight analysis. Better control can be obtained from occupancy sensors assuring spaces will be turned off once people have left the room. This will decrease uncertainty for unforeseen activities in rooms such as offices and classrooms, where once working hours are over, percentages can be defined as 0%. Some rooms will still carry uncertainty due to unscheduled use, such as in study rooms and conference rooms. However, including sensors in these rooms will support assumptions of lower percentage of use per hour, since there is some certainty that if people leave the room, lights will be turned off.

5.1.7 Use of Default Schedules

Using standard default schedules in energy simulation programs may not be the best approach occupancy behavior for a specific project. Using default schedules becomes convenient when all spaces in a building share the same function and have similar occupancy patterns. Example of these cases can be office buildings where all spaces are designed as working spaces and have similar working hours. Using a single default schedule for mixed buildings where spaces vary may not be accurate. Analysis of default schedules and their validity for a building design should be carried out to avoid representing varying spaces with the same schedule, such as office spaces in academic buildings.

5.1.8 Submetering and Calibration

If energy monitoring and analysis is part of the ongoing activities once the building is completed, it's important to monitor main end-use electric loads and consumption patterns. This information will help in comparing results to the energy model and to calibrate the model. As the model is more finely calibrated, more accurate results can be obtained and future predictions can be more realistic. Lighting load circuits should be designed to be installed from the same electric center so submetering can be easily installed.

5.1.9 Integrated Design

Developing an energy model involves summing assumptions from many different fields: from understanding optimal architecture and materials used to optimization of engineering systems. Gaining team input on use patterns will be the best approach to an accurate model, and will provide a good baseline that can be improved as utility measurements are obtained. The following team members can help to provide the following inputs:

- Owner: occupancy schedules, lighting schedules, building policies, and design requirements. These should set the energy efficiency goals, and the baseline energy model created is a first step towards reaching this goal.
- Architect/ Interior Design: materials, windows, finishes, and structural characteristics that can help influence thermal performance and aesthetics.
- Electrical Engineer: lighting design densities, plug load estimations, and information regarding installed equipment and important loads in the building.
- Mechanical Engineer: HVAC system optimization, design features that help to reduce thermal loads and utility costs. Design values used for some parameters become an important input for the model, and it's important to keep track of the design assumptions made through the design phase.

5.2 Data Gathering Tool

The research showed some obstacles to gathering information for developing an accurate model. One of the reasons is that building maintenance crews are not fully involved during the design process. They typically have knowledge of how equipment actually works, but they lack knowledge of design decisions and parameters during this phase. Also, equipment models specified in construction documents were different from the models installed, generally with similar capabilities but probably with better pricing when the purchase was done. On the Geography building, the HVAC system was shown in the drawings without specification of models, design or sizing parameters.

It is important during the design phase, modeling to implement a data gathering tool where decisions can be documented, so people that build the model or people conducting future energy analysis and verification can have access to this information. Also, schedules that were defined during the design process can be recorded and verified if necessary during the occupancy period.

The proposed tool lists three main types of data to be collected. First, a summary of available construction data and specific architectural details should be compiled. If desired, individual details of construction assemblies, wall, roof, and floor construction can be attached. Contact information for professionals responsible for design should also be included.

Project
Owner
Architect
Civil Engineering
Electrical Engineering
Mechanical Engineering
Energy Modeler

ARCHITECTURE FEATURES

EXTERIOR WALLS

#	Wall Type	Insulation type / R Value	Cont. Ins. R Value	Manufacturer	Brand	Detail on Sheet #	Comments
1	Wood Studs						
2	Concrete						
3	Wood Studs						
4	Metal Studs						
5	Wood Studs						

ROOF

#	Type of Construction	Insulation R Value	Manufacturer	Brand	Detail on Sheet #	Comments

Figure 5-1: Architectural Information Summary Chart

Figure 5-1 (cont'd)

WINDOWS

#	Type of Window	Manufacturer	Model	U Value	SHGC	Frame Material	Location	Detail on Sheet #	Comments
1	Fixed								
2	Fixed								
3	Operable								
4	Door								
5	Fixed								
6	Fixed								

DOORS

#	Type of Door	Manufacturer	Model	U Value	Material Type	Glass U Value (if any)	Location	Detail on Sheet #	Comments
1	Swinging								
2	Non Swing								
3	Swinging								
4	Overhead								

GROUND FLOOR

#	Exposure	Construction Material	Ext/ Cav Insulation	Interior Insulation	Finish	Slab Edge Insulation	Detail on Sheet #	Comments
1	Earth Contact	2 in Concrete						

Figure 5-1 (cont'd)

BASEMENT

#	Construction	Insulation/ R Value / Depth	Manufacturer	Brand	Detail on Sheet #	Comments
1	6 in Concrete					

CEILING

#	Construction	Insulation/ R Value	Manufacturer	Brand	Detail on Sheet #	Comments
1	Lay in Acoustic Tile					

PARTITIONS

#	Construction	Insulation/ R Value	Manufacturer	Brand	Detail on Sheet #	Comments
1	Frame					

The second information block includes descriptions and assumptions for spaces made during the design phase. This information will be useful for energy simulation, and eventually can be verified through measurements during the occupied periods yielding better model calibration. Information collected should include lighting fixture specification sheets and information on special equipment included in any space. If an energy model is not developed during the design phase of the project, this information will be helpful to record for cooling and heating load calculations, as well as future reference for development of energy models at later stages of the project. Figure 5.2 shows the Space Design Value Summary. Figure 5.3 shows an hourly breakdown for spaces.

Spaces and Zones

Space Name	Description	Area (ft^2)	Occupants	Lighting Load (W)	Lighting Density (W/ft^2)	Task Lighting (W)	Task Lighting Density (W/ft^2)	Plug Load (W)	Plug Load Density (W/ft^2)	Outside Airflow (CFM)	Design Flow (CFM)
		1		0	0	0	0	0	0		
		1		0	0	0	0	0	0		
		1		0	0	0	0	0	0		
		1		0	0	0	0	0	0		
		1		0	0	0	0	0	0		
		1		0	0	0	0	0	0		
		1		0	0	0	0	0	0		
		1		0	0	0	0	0	0		

Figure 5-2: Space Summary and Design Values Summary Chart

Space:	Hour	Mon	Tue	Wed	Thur	Fri	Sat	Sun	Holiday
Schedule for:	0-1								
	1-2								
	2-3								
	3-4								
	4-5								
	5-6								
	6-7								
	7-8								
	8-9								
	9-10								
	10-11								
	11-12								
	12-13								
	13-14								
	14-15								
	15-16								
	16-17								
	17-18								
	18-19								
	19-20								
	20-21								
	21-22								
	22-23								
	23-24								

Figure 5-3: Schedule Summary Chart

Engineering systems and miscellaneous equipment installed in the building is the last set of required information. This information should be supported with attached specifications and technical manuals of the brand and model installed. This will provide for future references and accurate descriptions of the HVAC system and equipment loads in the model. Figure 5.4 shows a sample System Description Summary chart.

HVAC and Equipment

General Description

Cooling	DX Coils
Heating	Furnace
System Type	Split System
Other / Observations	
Model:	
Manufacturer:	
Efficiency / COP	
Add Spec sheet / Info	

Design Parameters

Thermostat Setpoint

Cooling:	Heating:

Design Temperatures Inside

Cooling:	Heating:

Design Temperatures Supply

Cooling:	Heating:

Return Air Path	Direct
Minimum Outside Air %:	

Fans

Pressure Drop (in H_2O):	
Pressure Drop (in H_2O):	

Chiller

Chiller Type	
Condenser Type	
Model	
Manufacturer	

Economizer

Type	Drybulb Temperature
Limit:	

Boiler

Capacity	
Efficiency	
Fuel	
Model	
Manufacturer	

Figure 5-4: Systems Description Summary

Miscellaneous Equipment

Equipment	Description / Observation / Notes	Model	Manufacturer	Location	Amps / Volts / Phases	Power (kW)	Comments / Observations

Figure 5-5: Miscellaneous Equipment Description Summary Chart

Information in these charts is intended to be maintained in the building administration or building maintenance office. All information should be supported with architectural drawings or technical drawings, so the reviewer or energy modeler can have all important information available from a single source. The more detail provided, the easier it will be for an external entity to analyze the building either for energy improvements, envelope retrofitting, ongoing model verification or load analysis.

5.3 Chapter Summary

This chapter presents recommendations based on the experiences and observations from the researcher during the investigation. Guidelines presented recommend the breakdown of spaces according to use and grouping these similar spaces so they are defined under a single schedule representing average use for these spaces. Also, support of schedule definition can include additional information gathered from owners and administrative entities. A data collection tool was presented for recording design assumptions and decisions during the design phase of a project. Chapter Six provides a summary of the research, presents conclusions, identifies limitations and suggests future areas of research.

CHAPTER 6

CONCLUSIONS, LIMITATIONS, AND FUTURE RESEARCH

CONCLUSIONS

Chapters 4 and 5 presented impacts of lighting schedules from case studies and provided recommendations for improving schedule definition in simulation. This chapter presents lessons learned from the analysis, limitations of the research and suggestions for future research.

6.1 Summary

The research focused on determining the impact of lighting use variations on building energy simulations and how assumptions carried out during the early stages of a project can influence energy consumption predictions. Three case study buildings were selected where actual lighting use patterns could be observed and measured to define "use" schedules. Observations consisted of walkthroughs of the buildings and recording of percentage of fixtures turned on and spaces with lights on. Measurements included installation of light sensors, which recorded the status of lighting fixtures as on or off, and were used to determine percentage of time lights were used.

The selected case studies were the Chemistry Addition and Geography buildings at Michigan State University and a Church project in Lansing, Michigan. The schedules for the first two were collected by walkthroughs while for the church the sensor method was used. Information collected was used to prepare research energy models which were compared to metered data.

Results showed that using research schedules averaged among spaces was the best approach throughout the case studies. The research also showed that assumptions made during the design phase model heavily impact accuracy.

6.2 Conclusions

Based on the interviews, the boundary test, and the case studies analyzed, the following conclusions can be drawn regarding lighting use predictions:

- Well defined lighting schedules can help close the gap between inaccuracies in energy modeling. Although it was found that improving one parameter improves energy prediction, it is difficult to ignore relationships among other parameters that will influence overall energy use
- Miscellaneous equipment use is an important factor in energy prediction. It is hard to define how often a pump or a snow melting system is going to function. Schedules for these loads can impact energy prediction and can mislead project teams when considering energy efficiency improvements. Total energy consumption can coincidentally be accurate but for the wrong reasons. The Chemistry building showed similar energy prediction between the design phase model and the research model even though the design model had high lighting loads and lower equipment loads while the research model estimated lower lighting loads and higher miscellaneous loads
- Differences in lighting load estimations can result in differences of up to 120% in energy prediction. Default schedules are defined for specific building types with a constant behavior pattern. Using default schedules may be a good approach for average buildings

but deeper analysis is necessary before using default schedules in a model for more complex buildings

- Analysis of individual spaces and their distribution should be conducted for each energy model. The academic buildings included in the study showed variations of spaces and included classrooms, offices and laboratories. Use patterns varied among these spaces and using one standard schedule for all of them leads to inaccuracies
- Professionals agreed during interviews that occupancy and systems schedules (HVAC, lighting, equipment) are important sources of inaccuracy. There is no defined methodology or standard for establishing schedule definitions, a code or standard would help to make the modeling process faster and more accurate but it would be difficult since every building and owner is different

6.3 Limitations

Conclusions were drawn from the observations and models created, but there are several limitations of the study as indicated below:

- In research of this nature, three case studies are not sufficient to draw conclusions of statistical value. This research serves more an educational purpose and hopefully sets a path for similar studies where energy simulation can be further investigated
- Observations were demonstrative of procedures that can be used and implemented to record schedules. Expanding the number of observations could lead to detailed and accurate schedule definition. This research also considers only observations when classes are in session and not break periods for the case studies of the buildings at Michigan State

University. Observing Holidays and unoccupied periods as well as academic periods would help to profile an entire year

- Influence of other electric loads was not explored
- Not all building types were analyzed, results may vary in other buildings types

6.4 Future Research

The research focused only on lighting, other research can be conducted addressing other parameters. Some possible additional studies which can add to the understanding of energy simulations can include:

- Miscellaneous equipment schedules research. Patterns of specific equipment could be determined so they can be more accurately modeled in future projects. Patterns of equipment such as elevators, snow melting devices and water pumps can be monitored with an amperage meter and average use can be determined
- This research applied methodologies to gather data that fit with the time and budget of the research. Better technology and constant monitoring can be implemented to develop other measuring techniques not only for lighting use control, but for other parameters so use patterns can be better defined. Cameras could be installed throughout a building to monitor occupancy behavior and patterns. Electric measuring of specific end use loads can be monitored to test accuracy of specific parameters and to isolate individual parameters from overall energy consumption

6.5 Expected Contributions

Lack of knowledge of actual lighting patterns for a building during design makes simulation difficult. Accurate occupancy and lighting schedule definition can be time consuming and confusing if the proper information is not at hand. The fundamental purpose of this research was to evaluate the impact of lighting schedules on energy simulation and to find ways to improve lighting schedule input. A better understanding of the impact of lighting schedules on simulation can lead to refined outputs and more accurate simulations. The research may lead to addressing other parameters or standardize codes for schedule definition and energy simulation parameters.

Improvement of energy prediction tools is also beneficial for life cycle cost analysis of projects. Increasing accuracy in energy simulation tools increases reliability when comparing design options, particularly when the simulations can be supported with economic analysis.

APPENDICES

APPENDIX A

Survey Questionnaire

Date __________

Name ________________________

Title __________________________

Energy Simulation Experience (Years) ___________

Phase 1 interview: Perceptions and Experiences

1. What simulation(s) tool(s) or software do you use?

2. What is the main use of the simulation tools? LEED EA credits? Design tool during planning and design phase of project?

3. Do you carry out validation of your energy prediction results?

4. How accurate compared to real energy performance of a building does energy simulations are?

5. What do you think is the biggest source of inaccuracy in energy simulations?

6. In your experience with projects, what has been the most challenging process of the simulation?

7. Do you use energy simulations as design tools, or only as a mean to comply with LEED EA Credits?

8. How accurate do you think occupancy schedules can be defined in energy simulation compared to real occupancy?

9. Do you consider that inaccuracies in scheduled definition increase or decrease considerably building energy simulation? Is this of your concern when in design?

10. What information is usually given by (or requested to) the owner/ architect for you to have the adequate information for the simulation?

11. How accurate do you think occupancy schedules can be defined with the appropriate information through the design phase?

12. Is there a technique, model, or code you follow to define occupancy schedules? Do you use the program's default schedules?

13. Is there an established methodology throughout your company to define occupancy schedules?

14. How would you improve occupancy and lighting use schedule definition?

15. Do you verify occupancy and lighting schedule in the post construction phase?

16. How much do you think standardization (or a set of guidelines) schedule definition according to building type will improve energy simulations?

Phase 2: Validation

1. What do you think of the presented information? Any particular interesting points?

2. What do you think of the guidelines and recommendations presented?

3. What do you think of the data gathering tool?

4. Any of this information is applicable to future projects?

5. Any additional recommendation/ suggestions?

Michigan State University
School of Planning, Design and Construction
Construction Management Program

PARTICIPANT CONSENT FORM
Construction Professionals

SENSITIVITY OF LIGHTING SCHEDULE PARAMETER IN BUILDING ENERGY SIMULATION SOFTWARE

Principal Investigator: Tim Mrozowski
Secondary Investigator: Federico Steinvorth

Interview

The School of Planning, Design and Construction at Michigan State University is conducting research to evaluate impact of assumed lighting use schedules on computer-based building energy predictions. Energy modeling programs have become important design and decision making tools. This research aims to improve understanding of energy prediction results and create recommendations and tools to improve the modeling process.

As a participant in this research, you are being asked to answer interview questions, relating to your experience in energy modeling processes and high performance building design. You must be at least 18 years old to participate in this research. Your participation in this research project is completely voluntary. You have the right to say no. If you are uncomfortable, you may change your mind at any time and withdraw from the interview. You may choose not to answer specific questions or to stop participating at any time. Whether you choose to participate or not will have no effect on your grade or evaluation. Your privacy will be protected to the maximum extent allowable by law. Your name and title will not be used in any publication. The estimated time to complete this interview is approximately 45 minutes. As a participant, you may request a copy of this consent letter for your records.

This research project is not funded. The researchers are employed by Michigan State University and the data collected will be used for a graduate Master's thesis.

If you have concerns or questions about this study, such as scientific issues, how to do any part of it, or to report an injury, please contact:

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*If you have any questions or concerns about your role and rights as a research participant, would like to obtain information or offer input, or would like to register a complaint about this research study, you may contact, anonymously if you wish, the **Michigan State University Human Research Protection Program** at 517-355-2180, FAX 517-432-4503, or e-mail irb@msu.edu, or regular mail at: 207 Olds Hall, MSU, East Lansing, MI 48824.*

You indicate your voluntary agreement to participate by beginning this phone interview.

APPENDIX B

Chemistry Building Construction Data

Material Name	Thickness (ft)	Conductivity (Btu/h-ft-°F)	Density (lb/ft3)	Spec. Heat (Btu/lb-°F)	R-Value (h-ft2-°F/Btu)
1/4in Spandrel Glass	0.021	0.59	172	0.2	0.04
MinWool Batt R11	0.296	0.025	0.6	0.2	11.84
MinBd 2in R-6.9	0.167	0.024	15	0.17	6.96
Wood 1in	0.083	0.07	37	0.6	1.19
Air Lay <4in Vert	n/a	n/a	n/a	n/a	0.89
GypBd 5/8in	0.052	0.0926	50	0.2	0.56
Surf Air Film Vert	n/a	n/a	n/a	n/a	0.68
				Total R	22.15
				U Value	0.05

Table B-1: Main Façade Wall Layer Chemistry Building

Material Name	Thickness (ft)	Conductivity (Btu/h-ft-°F)	Density (lb/ft3)	Spec. Heat (Btu/lb-°F)	R-Value (h-ft2-°F/Btu)
Facebrick	0.333	0.7576	130	0.22	0.44
Air Lay <3/4in Vert	n/a	n/a	n/a	n/a	0.9
Cellulose 3.5in R-13	0.292	0.0225	3	0.33	12.98
Plastic Film Seal	n/a	n/a	n/a	n/a	0.01
CMU MW 12in Hollow	1	0.4959	58	0.2	2.02
Surf Air Film Vert	n/a	n/a	n/a	n/a	0.68
				Total R	17.02
				U Value	0.06

Table B-2: Facebrick Wall Chemistry Building

Material Name	Thickness (ft)	Conductivity (Btu/h-ft-°F)	Density (lb/ft3)	Spec. Heat (Btu/lb-°F)	R-Value (h-ft2-°F/Btu)
Facebrick	0.333	0.7576	130	0.22	0.44
Air Lay <3/4in Vert	n/a	n/a	n/a	n/a	0.9
Cellulose 3.5in R-13	0.292	0.0225	3	0.33	12.98
Plastic Film Seal	n/a	n/a	n/a	n/a	0.01
Steel Siding	0.005	26	480	0.1	0.00
Surf Air Film Vert	n/a	n/a	n/a	n/a	0.68
				Total R	15.01
				U Value	0.07

Table B-3: Utility Duct Wall Chemistry Building

Material Name	Thickness (ft)	Conductivity (Btu/h-ft-°F)	Density (lb/ft3)	Spec. Heat (Btu/lb-°F)	R-Value (h-ft2-°F/Btu)
Asph Roll Roof	n/a	n/a	n/a	n/a	0.15
Polystyrene 4in	0.333	0.02	1.8	0.29	16.65
Polystyrene 4in	0.333	0.02	1.8	0.29	16.65
Chem Roof M4	0	n/a	n/a	n/a	1.7
Felt 3/8in	0.031	0.11	70	0.4	0.28
Conc LW 80lb 8in	0.503	0.2083	80	0.2	2.41
				Total R	37.85
				U Value	0.03

Table B-4: Roof Layers Chemistry Building

Geography Building Construction Data

Material Name	Thickness (ft)	Conductivity (Btu/h-ft-°F)	Density (lb/ft3)	Spec. Heat (Btu/lb-°F)	R-Value (h-ft2-°F/Btu)
Steel Siding	0.005	26	480	0.1	0.00
Polystyrene 2in	0.167	0.02	1.8	0.29	8.35
MinWool Batt R7	0.188	0.025	0.6	0.2	7.52
Steel Siding	0.005	26	480	0.1	0.00
CMU MW 6in Hollow	0.5	0.3571	65	0.2	1.40
GypBd 5/8in	0.052	0.0926	50	0.2	0.56
Surf Air Film Vert	n/a	n/a	n/a	n/a	0.68
				Total R	18.51
				U Value	0.05

Table B-5: Main Wall Assembly Geography Building

Material Name	Thickness (ft)	Conductivity (Btu/h-ft-°F)	Density (lb/ft3)	Spec. Heat (Btu/lb-°F)	R-Value (h-ft2-°F/Btu)
Felt 3/8in	0.6	0.11	70	0.4	5.45
Insul Bd 1in	0.083	0.025	2	0.2	3.32
CMU MW 4in Hollow	0.333	0.3003	76	0.2	1.11
Surf Air Film Horiz	n/a	n/a	n/a	n/a	0.76
				Total R	10.64
				U Value	0.09

Table B-6: Roof Assembly Geography Building

Church Project Construction Data

Material Name	Thickness (ft)	Conductivity (Btu/h-ft-°F)	Density (lb/ft3)	Spec. Heat (Btu/lb-°F)	R-Value (h-ft2-°F/Btu)
Face Brick 4in	0.333	0.7576	130	0.22	0.44
GypBd 5/8in	0.052	0.0926	50	0.2	0.56
FiberGlass Batt R19	0.511	0.025	0.6	0.2	20.44
Church Ext Wall M4	n/a	n/a	n/a	n/a	0.12
PartBd Underlay 5/8"	0.052	0.1796	75	0.29	0.29
Surf Air Film Vert	n/a	n/a	n/a	n/a	0.68
				Total R	22.53
				U Value	0.04

Table B-7: Wall Assembly Church Project

APPENDIX C

Interview #1

What simulations tools do you use?

"For smaller projects I use Energy-10 or eQuest Wizard. For bigger projects Ecotech, Trane TRACE or eQuest"

What is the main use of simulation tools?

"Use of simulation tools is not only for LEED certification, we also use simulation tools for energy analysis. Also we use the tools for Life Cycle cost analysis, and to implement energy conservation measures"

Do you validate results?

"We rarely do validations mainly because there is a cost associated that is usually not paid, and the owner doesn't ask for this validation"

What do you think are the main sources of inaccuracies in simulations?

"Schedules of operation such as HVAC, light, and people"

Do you spend some time defining the schedules?

"I don't spend much time defining the schedules; I usually use the default schedules within the software; not even owners know how buildings are going to work"

What information is usually requested from owners for better simulations?

"It is difficult to get information from owners since they are not sure how the building is going to operate either"

How much do you think standardization or guidelines to schedule definition can help improve energy simulations?

"Better schedules would probably make simulations more accurate, but I don't think standardization is possible since all buildings are different."

Interview #2

What simulations tools do you use?

"HAP from Carrier, and recently started using eQuest"

What is the main use of simulation tools?

"We use simulations both for LEED credits and energy analysis in buildings"

Do you validate results?

"We collect data from owners for as long as they are willing to provide us with it. Usually energy simulations turn out predicting less energy than actual use. We don't verify lighting use itself because it involves a cost that won't be paid. This would definitively be a method of improving the model."

What do you think are the main sources of inaccuracies in simulations?

"Occupancy schedules, and lately I realized how leaky buildings impact energy predictions"

What do you think is the most challenging process of the simulation?

"The simulation itself is not challenging, but the USGBC and LEED reviewers make the process harder."

Do you spend some time defining the schedules?

"Yes, I like spending time on defining schedules; I try talking to users and owners for information, and analyze room by room to make better schedules"

What information is usually requested from owners for better simulations?

"It is difficult to get information when it's a new building; the owner knows more about his/her project when it is a replacement building than when it is a new one."

Is there a methodology or code followed in your company to define schedules?

"There is not really a method we all follow; when it's a LEED project we are working on, we use the ASHRAE proposed schedules, when it's an energy analysis project we all define schedules independently and with our own criteria"

How much do you think standardization or guidelines to schedule definition can help improve energy simulations?

"There are already some schedules in ASHRAE 90.1 that can be used, and programs such as HAP have a database of schedules that can be used. Improving schedules makes better simulation models".

Additional Comments

"LEED don't require modeling some models such as snow melting systems and dehumidification systems, so in one project we projected $18000 on energy cost annually, and the actual cost from the building turned out to be $34000. After model calibration and analysis, we predicted annual energy cost to be $25000"

Interview #3

What simulations tools do you use?

"Mainly eQuest and EnergyPlus. For smaller projects we've been using BEOpt and Open Studio"

What is the main use of simulation tools?

"We don't do many LEED projects, we are trying to move away from LEED certifications. We work mostly on projects during schematic and design phase to help evaluate design decisions."

Do you validate results?

"No, we don't intend to validate results, our objective is to compare design solutions throughout schematic and design phase, but it is not our intention to predict energy use."

What do you think are the main sources of inaccuracies in simulations?

“Starting with weather files we have inevitable inaccuracies, but within the project occupancy behavior I think is the biggest source on inaccuracy; it is important to take educated guesses on this issue.”

Do you spend some time defining the schedules?

“I would say we do like spending time on our schedules, although we might use the default schedules within the program if we don’t obtain real data from the owners. It is better to spend time on schedules when data is gathered from existing buildings. We might not spend more time on the schedules on the first stages of the simulation, but as the design is moving along we try to calibrate the model with data.”

What information is usually requested from owners for better simulations?

“Usually owners are in the same “dark room” as we are when assuming conditions for the model. Sometimes they might have the information, but most of the times they have the same knowledge on the building as we do.”

Is there a methodology or code followed in your company to define schedules?

“I would say it’s done on an individual basis, we all know where to get the required information but it is up to each modeler to come up with their own assumptions.”

How much do you think standardization or guidelines to schedule definition can help improve energy simulations?

“I could divide this answer in two: I think it would make the modeling process itself faster and more efficient, but in terms of accuracy it would be hard to tell if a standard would improve energy predictions since every project is different and has its own particularities”.

Interview #4

What simulations tools do you use?

“TRACE 700 for whole building analysis and we have our own excel sheets for system loads and utility calculations and projections”

What is the main use of simulation tools?

“We do both energy analysis, and LEED credits along with external designers, we review the designs of external designers so they comply with our requirements. We use the models to carry out measurement and verification process.”

Do you validate results?

“We do verification process with utility data from measurements.”

What do you think are the main sources of inaccuracies in simulations?

“It’s hard to tell, some predictions go under and some go over. I would say sloppy assumptions have a big impact on accuracy, and trying to determine the user’s behavior within the building.”

What is the most challenging process of the simulation?

"People are complex and buildings are complex, so it's very easy to make mistakes and difficult to reflect building behavior."

Do you spend some time defining the schedules?

"I don't think consultants involve the right people in the schedule discussion, so they overstate occupancy to be on a safe side."

What information is usually requested from owners for better simulations?

"They apply general details, usually not much information about details on how buildings will be occupied are requested"

How accurate can predictions are with the right schedule definition?

"They could be very accurate, it's a matter of finding the right people. There are so many parameters during design that designers are concerned about, that they give little importance and don't focus on occupancy"

How much do you think standardization or guidelines to schedule definition can help improve energy simulations?

"There's a big potential to create standards or guidelines and that's where I think we are going to. Even though we can normalize these issues, plug loads and equipment with electric load impact as big as HVAC systems are still unpredictable during the design phase".

How can simulations be improved?

“If a space by space analysis is done, it could be more accurate, and by surveying the occupants that know how the building behaves. Once again, if the right answers are asked to the right person can bring good solution, but it’s a challenge when not knowing who the occupants are”

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