

A LONG-TERM BUILDING STUDY OF ENERGY USAGE AND THERMAL
COMFORT IN RELIGIOUS FACILITIES

A Thesis

by

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ABSTRACT

Buildings represent a large portion of total US energy usage. Religious facilities, which consume a significant percentage of the total floorspace and energy usage in the commercial sector, have generally not been the focus of efficiency studies or building energy audits. Religious facilities are characterized by unique patterns of occupancy and energy use. This thesis presents the results of a long-term, in-depth energy study of architecturally similar church buildings in different climates in an effort to identify energy efficiency opportunities in religious buildings.

A clear relationship between energy use and climate is evident, with HVAC and lighting systems consuming the majority of energy in the buildings. HVAC usage in the buildings show the expected pattern of increased electricity for cooling in the summer and natural gas for heating in the winter, with overall building performance comparing favorably to similar religious facilities. The energy savings from implementing temperature setbacks were experimentally verified and quantified. An analysis of faulty operational settings and equipment in HVAC systems reveal the large energy saving potential from correcting faulty conditions. The increased energy consumption of condenser units with higher outdoor temperatures is quantified experimentally.

Analysis on building occupancy and lighting reveal the infrequent, yet consistent use of the building. The majority of lighting is condensed in the meeting areas and hallways. Due to the infrequent usage of the building, the energy and cost saving potential of occupancy based lighting control is limited. Two separate experimental

instances demonstrate the limited energy savings associated with occupancy based lighting control.

An analysis of thermal comfort reveals the overall comfort conditions of the building and main meeting areas. During winter and summer months, the buildings are often uncomfortable to many occupants, possibly from insufficient preconditioning or from occupancy during unexpected time periods. An analysis of comfort, through monitoring of CO₂ levels throughout the building, highlights the need for additional outdoor air during space conditioning.

DEDICATION

I would like to dedicate my thesis to my marvelous wife and our three darling kids.

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CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

Religious buildings are places of significant importance to cultures throughout the world. As places of worship, thermal comfort in these buildings is of paramount importance to allow participants to focus on their devotions. Although there are many different methods of worship across many different religions, many of these buildings follow similar occupancy patterns and structure. Most religious buildings have one or more large gathering areas to accommodate large groups of people, which during specific periods of time are occupied at full capacity. Generally there will also be multiple classrooms or offices in these buildings to accommodate smaller meetings or other use. Religious facilities are thus unique compared to other commercial buildings in that they are typically characterized with no or minimal occupancy for the majority of the time, with relatively infrequent periods near maximum occupancy.

Despite consuming a significant portion of the total floor space and energy use in the commercial sector, religious facilities have received remarkably limited attention in the literature [1]. As buildings consume a large portion of total energy consumption [2], there exists a significant number of energy studies on various types of commercial buildings. However, among all of these building studies, very few focus specifically on religious facilities and their unique occupancy and energy usage.

Literature Review

Energy Studies on Religious Facilities

The few publications on religious facilities consist of experimental and simulation-based energy studies on mosques in the Middle East. A long-term energy study of several mosques in Saudi Arabia was conducted in [3, 4]. In this study, five representative mosques were evaluated based on utility bills and power meters to measure total energy usage and energy end use. They found that for these mosques, which were located in a hot, humid climate, the majority of electricity (71%-79%) was devoted to the HVAC system in space conditioning [4].

Several other papers were later published regarding the energy and comfort performance for three of the five mosques. Using representative days from the data sample, they found that people were often outside the comfort zone defined by Fanger's Predicted Mean Vote (PMV) model, despite active space conditioning [5, 6]. Only one of the three mosques had wall insulation, and they observed that this mosque was generally more comfortable and had a lower energy use index, reinforcing the energy and comfort benefits of insulation. Another paper evaluated potential energy efficiency measures through simulations of a typical mosque [7]. They found significant energy savings from adding insulation to an uninsulated mosque and including temperature setbacks in the HVAC control strategy. Additionally, they found some minor benefits from including thermal zoning in the HVAC operational strategies.

Other studies include evaluations of thermal comfort and energy usage in mosques. Budaiwi explored in simulation how different envelope parameters affect the

energy performance of mosques [8]. Ah-Homoud, also in simulation, optimized envelope parameters for mosques in achieving minimal energy consumption [9]. A study on thermal comfort in mosques in Kuwait found that the perceived comfort for the occupants was 2.6 °C above that predicted by Fanger's PMV model [10].

Strikingly, there are no notable publications regarding religious facilities beyond these specific studies of Middle Eastern mosques. Although mosques are similar to other religious facilities in that occupancy patterns are typically characterized by infrequent, intense occupancy, the specific occupancy and usage patterns are distinctly different from other types of religious buildings. Generally, mosques are occupied during 5 prayers each day, ranging from 45 to 60 minutes. The time of each prayer depends on solar time, so they vary throughout the year, but in a predictable fashion for any given mosque [8]. Other types of religious buildings are characterized by intense occupancy on Saturday or Sunday, and sporadic usage during the rest of the week. Currently the literature lacks a definitive study of these other types of religious facilities with different usage patterns, less predictable patterns of occupancy, and locations in a wide range of climates.

Other Commercial Energy Studies

Beyond the specific focus on religious buildings, this thesis is distinct with regard to the depth and comprehensive nature of the study. Within the broader field of commercial building energy analysis, published studies will generally fall into two major categories: experimental studies and building simulation studies. Most experimental

studies focus on a specific building technology or subset of a building, and comprehensive experimental studies are limited. An example of a comprehensive experimental building study includes one by Yang, who performed an extensive study of a building using multiple types of sensors throughout the building, including sound, lighting, occupancy, temperature, relative humidity, and CO₂ for a commercial office building [11]. Typically experimental studies look at energy savings from a particular building technology retrofit or an isolated element of building performance. Some examples of building technology retrofit papers include papers that evaluate savings from implementing thermostat temperature setbacks during unoccupied times [12] and savings from different types of reflective coatings or paint to the walls or roof [13]. Different types of isolated building performance evaluations include papers that discuss the CO₂ levels found in different environments and the effects on participants [14], thermal comfort of participants in different building types [12, 15], and determination of actual building occupancy schedules [11, 16, 17]. These papers play an important role in providing guidelines for commercial buildings with respect to energy use, occupant health, and thermal comfort. With unique patterns of occupancy and building usage, religious facilities stand to benefit from a similar evaluation.

The second major group of studies analyzes building performance through simulation. One of the primary benefits of these simulations is the ability to rapidly determine potential energy and cost savings from many potential technology retrofits and operational changes. There are many examples that look at simulations for schools, office buildings, and other commercial facilities [16, 18-22]. These papers are invaluable

in providing insight on the energy saving potential for buildings. However, one of the main drawbacks of building simulations includes the possibility of error in the building simulation compared to actual building use and potential energy savings. Therefore, experimental validation is an essential accompanying element in accurately determining energy efficiency best practices.

CO₂ Levels in Buildings

CO₂ levels in buildings are a concern primarily for comfort reasons. A summary of different CO₂ levels are given in Table 1. At high levels (>10,000 ppm), there are immediate and potential long-term health risks, but typically buildings lie comfortably below those limits [23]. Instead, ASHRAE Standard 62 is designed to control CO₂ levels as a means of regulating building ventilation. Their requirement is sufficient to remove odorous bioeffluents from the space. Although the focus in the standard is one of occupant comfort, other studies suggest that other health benefits may come from lower CO₂ levels. A recent study suggests there may be some significant performance degradation on mental tasks with even moderate levels of CO₂ [24]. Another survey of 100 different large commercial building found a correlation between sick building syndrome and elevated CO₂ levels [6]. This study does state that CO₂ can be considered a surrogate for other occupant-generated pollutants, and it doesn't suggest CO₂ is the root cause of sick building syndrome.

Table 1. Summary of CO₂ levels

Background	400 ppm (300-500 ppm)
ASHRAE Recommended Limits	1,100 ppm (700 ppm above background)
Minor Degradation of Performance	1,000 ppm
Major Degradation of Performance	2,500 ppm
Health Danger	>10000 ppm

Building Occupancy and Lighting

Multiple papers have emphasized the importance of knowing building occupancy on total energy consumption and use, and many of these are summarized in [16].

Building occupancy significantly affects the consumption and the potential for reduction in energy use [25, 26]. These parameters are important to obtain accurate estimation of savings for potential energy retrofits, especially when predicting energy reduction in building energy simulation software programs [27, 28]. The studies further show the strong importance of knowing accurate occupancy schedules to accurately predict energy consumption [29, 30].

Other papers demonstrate the significant errors generally observed between default and actual occupancy schedules in buildings. A study by Duarte found that actual building occupancy in a studied office building varied 46% from the default office occupancy schedule recommended by ASHRAE [31]. Zhao et. al. also found that the occupancy schedule of an actual building varies significantly with the default schedule of an office building. Their estimated energy usage changed due to this difference in

occupancy, and this difference in usage varies significantly by climate [16]. These significant errors, which occur in office buildings with a default office building schedules, will be exacerbated when predicting energy use in religious buildings with default office occupancy schedules, since churches have very atypical usage patterns. Knowledge of actual occupancy patterns in religious facilities is necessary to accurately predict energy usage in these facilities.

Erickson demonstrated that predicting actual building occupancy schedules, even with training data, is difficult [17]. He demonstrates in simulation the potential for accurately estimating energy savings when HVAC systems are controlled with accurate occupancy schedules. Yang et. al. demonstrated through simulation and occupancy ground truth data that the fixed occupancy schedule by ASHRAE deviates significantly from actual occupancy schedules, and that this significantly affects energy usage [11]. The paper uses long-term data to develop expected patterns of occupancy and shows close agreement between predicted energy consumption and actual consumption. The paper further illustrates the importance of knowing actual building occupancy in order to accurately determine building energy use. When prediction of energy usage is tightly coupled with accurate schedules, a representative occupancy schedule of religious buildings will facilitate accurate prediction of energy usage. No established church occupancy characteristics have been published to date, and one of the goals of this thesis is to experimentally determine a representative building occupancy schedule for religious facilities in the United States.

CHAPTER II

BUILDING ENERGY STUDY SETUP AND DATA COLLECTION

In performing the building energy study, utility bills for ten different churches were analyzed. These specific buildings were chosen for several reasons. First, each of the buildings was constructed according to the same floorplan, eliminating discrepancies in building energy based on building construction. Second, the buildings were built in a similar time period (approximately 30 years ago). With an expected lifetime of 50+ years, these buildings have operated for a significant time period but still have many years of remaining operation. An in-depth study was then performed on two of the buildings. The two buildings are located in Orem, Utah and College Station, Texas. The two buildings chosen for in-depth study were selected based on location. The church in College Station is located near Texas A&M University, and the church in Orem, Utah is located close to Brigham Young University, where Dr. Bryan Rasmussen completed his faculty development leave. These two locations have distinct climates that allow comparisons based on weather. College Station is located in a hot, humid climate, while Orem is located in a cool, dry climate.

Building Details

Building Construction

Each of the ten buildings was built in a similar time period and with the same floorplan. The layout of the building is shown in Figure 1, with the building divided into meeting areas, classrooms, hallways, and offices. The construction materials, total

square feet, and building layout are identical, and the HVAC systems are comparable with minor differences due to climate. The details of the church buildings are summarized in Table 2.



Figure 1. Layout of building and division according to room use.

In each building, there is a hallway that wraps around the two main meeting areas. A collapsible wall between these two areas can be removed for large meetings. Classrooms and offices along the perimeter of the meet buildings are used for religious classes and community activities.

The churches are approximately 20,000 ft². The primary wall construction on the interior is painted cinder block, and the exterior of each church is brick. There are double-paned windows in each classroom and office, and the flooring throughout the

majority of the church is commercial grade carpet. There is also a crawl space located below the church and an accessible attic for maintenance access.

Expected building occupancy includes three separate congregations that meet on a staggered schedule for three hours each Sunday for worship services. There are meetings and activities in the building that take place consistently throughout the week. These meetings and activities typically occur either in the evenings or mornings, outside of typical business hours.

Table 2. Building details for all ten studied church buildings

Construction Date	1980s
Dimensions of Building	(210 ft. x 100 ft.) 21,000 ft. ²
Window Type	Double pane
Roof Height in Main Gathering Area	20-30 ft.
Roof Height All Other Areas	8.5 ft.
Interior Wall Construction	Cinder Block
Exterior Wall Construction	Brick
Roof Type	Shingles
Attic/Roof Insulation	Batt Insulation
Number of Classrooms and Offices	31
Total Number of Meeting Areas	4

The ten buildings selected for utility analysis were chosen based on varied geographical location and climate zones. Buildings were selected so that every climate zone, as defined by the 2003 Commercial Building Energy Consumption Survey (CBECS), was represented by two buildings. As each building has the same floorplan and similar occupancy patterns, the principal difference in building energy usage results from differences in climate. The general geographical location of each of the ten buildings and their associated CBECS climate zone is summarized in Table 3.

Table 3. Location and climate zone for each of the studied churches

Building Index	Location (US State)	CBECS Climate Zone
1	New York	1
2	Idaho	1
3	Utah	2
4	Illinois	2
5	Oregon	3
6	Ohio	3
7	California	4
8	Georgia	4
9	Texas	5
10	Florida	5

Typical Weather

For the two buildings selected for in-depth study, the first is located along the Wasatch mountain front in Orem, Utah and the second is located in College Station, Texas. The typical weather patterns are very different in these locations, and a summary of typical outdoor air temperatures is provided in Figure 2. Orem, Utah is characterized by cold and dry weather. While the summer temperatures may exceed 100 °F during the summer months, the change in temperature between peak temperatures is significant. Additionally, the winter months are typically characterized by consistent temperatures below freezing with consistent snowfall. The weather in College Station is significantly warmer than Orem, as seen in Figure 2. Although the peak summer temperatures are comparable between the two cities, College Station has a much warmer average low temperature in the summer. Additionally, the average humidity in College Station is significantly higher than Orem. The weather in the winter for College Station is much milder, with temperatures rarely dropping below freezing.

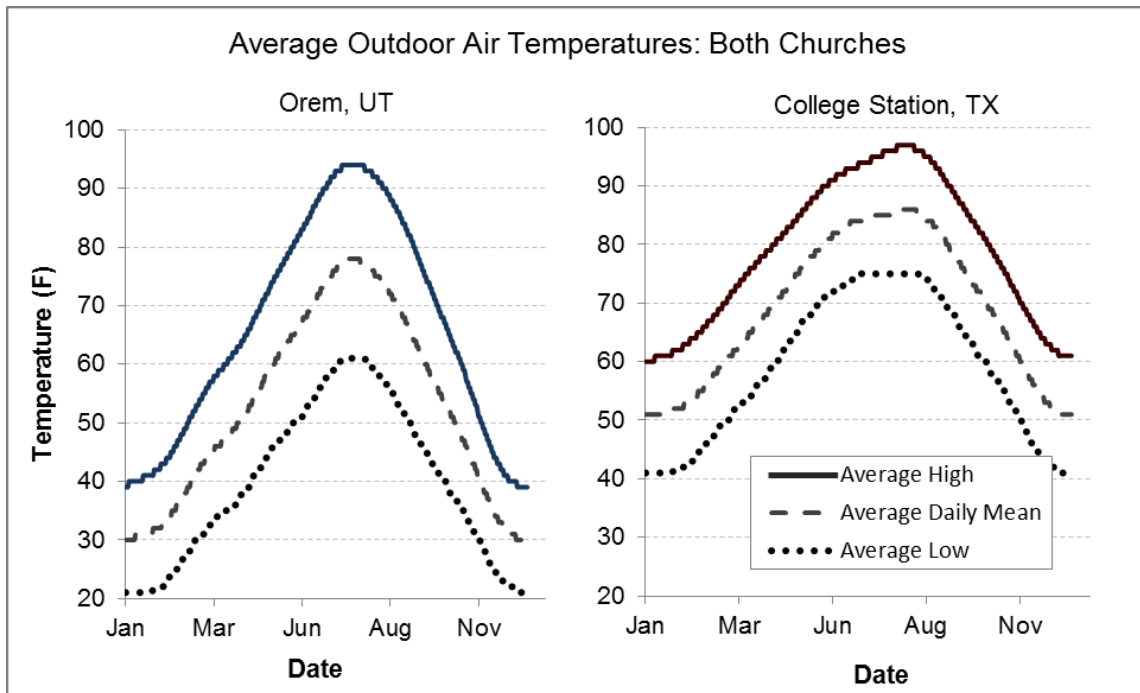


Figure 2. Average outdoor air temperature for the two different churches.

Building Lighting and HVAC Systems

Fluorescent lighting is found throughout the building. The majority of lights are T8 or T12 fluorescent lamps, but there are some smaller residential-style light bulbs in closets and other small areas. The HVAC system consists of multiple residential split systems that use vapor compression for cooling and natural gas furnaces for heating. There are four different mechanical rooms throughout the building, and a total of ten different residential systems. Figure 3 shows the mapping of each of the ten different residential split systems to the appropriate areas in the church. The majority of the systems are smaller sized units of approximately 1-2 tons. The systems servicing the

main meeting areas are larger units with two, 4-5 ton units each. In addition to these systems, there are several mini-split systems that condition individual offices.



Figure 3. Zoning of the church buildings for the different HVAC systems.

Each HVAC unit is equipped with a programmable thermostat. These thermostats are generally set to 69-72°F for heating and 72-75°F for cooling. The master thermostat for each system is located in the mechanical rooms, but there are smaller thermostats located in the conditioned space. These smaller thermostats allow the user to temporarily adjust the temperature control within a few degrees. During unoccupied periods, the buildings are given temperature setbacks of 60°F and 80°F for heating and cooling, respectively. Details for the churches and their locations are summarized in Table 4.

Table 4. Building characteristics of the two church buildings

Component	Church Details	
	Orem Church	College Station Church
Location	Orem, Utah USA	College Station, Texas USA
GPS Location	40°17'56"N 111°41'47"W	30°36'5"N 96°18'52"W
GPS Location	(40.298753, - 111.696486)	(30.601433, -96.314464)
Elevation	4,780 ft.	370 ft.
Orientation	West	Southeast
CBECS Climate Zone	2	5
CBECS Region/Subregion	West/Mountain	Central/West South Central
HVAC System Type and Count	8 Residential Split Systems 2 Furnace Only Systems 5 Mini-split Systems	10 Residential Split Systems 4 Mini-split Systems

Energy Study Setup

The sensors used for the in-depth study included temperature/relative humidity, light/occupancy, electrical current, and CO₂ data loggers.

Current Data Loggers

The current clamps were installed around the compressor wires to measure compressor and condenser fan power. They come in 0-20 A and 0-50 A sizes. The compressor power ratings were used size the clamps to the compressors. One current clamp was installed around each individual HVAC condenser unit and mini-split system in order to estimate total energy usage for space conditioning.

CO₂ Sensor

A CO₂ sensor was used in the College Station church to evaluate CO₂ levels in various areas of the building. A single CO₂ sensor was rotated throughout the building to determine representative CO₂ levels.

Temperature/Relative Humidity (TRH) Data Loggers

The TRH data loggers are capable of measuring both temperature and relative humidity at specified intervals. The sample rate was chosen to obtain as much data as reasonable while maintaining reasonable periods of time between downloads. The data were sampled every 30 seconds, resulting in the time between downloads of approximately two weeks. In addition to measuring room conditions, these loggers were

installed in supply air ducts to measure supply air conditions. The change in supply air temperature was used to derive the state of the furnaces.

Light/Occupancy (LO)

The LO sensors are state dependent, so a time stamp was recorded when a change in lighting or occupancy was sensed. The period of occupancy for the loggers was set for five minutes. If no occupancy instances were detected over a period of five minutes, the LO logger would record the state as unoccupied. The distance that the sensor reaches is either 5m or 12m, depending on the type of logger. In the study, the loggers were set to the highest possible light sensitivity due to the relatively low light levels found throughout the buildings.

Sensor Placement

Since the sensors were placed in unmonitored, public locations, the location for installation for each logger was chosen to be as discrete as possible while still recording the desired measurements. Each sensor was secured using wire rope. The TRH loggers were placed as far as reasonable from the vents to prevent recording the supply air temperature instead of the average room temperature. Additionally, the TRH loggers were placed away from lights to prevent conduction from the light sources causing an artificial heating of the logger. When possible, the LO loggers were placed next to a light to prevent false triggering of the light sensor from incoming sunlight. An example of an installed TRH and LO data logger is shown in Figure 4.



Figure 4. An example of Light/Occupancy (left) and Temperature/Relative Humidity (TRH) data loggers.

TRH and LO data loggers were installed in each room, and the overview of the placement and coverage of these sensors is shown in Figure 5. Additional TRH loggers were installed in the air handling units for each of the ten systems to gather supply air conditions. The data logger locations and specifications are summarized in Table 5.



Figure 5. Placement of Light/Occupancy and Temperature/Relative Humidity data loggers in the church.

Table 5. Sensor specifications

Type of Logger	Locations	Number	Accuracy and Specifications
Light/Occupancy (LO)	All rooms	53	5-12 meter range Light Threshold: >65 lux
Temperature/ Relative Humidity (TRH)	All rooms.	49	Temp: $\pm 0.21^{\circ}\text{C}$ RH: $\pm 3.5\%$
	Inside supply air ducts.	10	
AC Current	Outside condenser units	16	$\pm 4.5\%$ of full scale (20 A and 50 A loggers)
CO ₂	Representative rooms	1	± 50 ppm or 5% of reading, whichever is greater

Data Collection and Compilation

Data Collection

The study was done for two different buildings, one located in Orem Utah, and the other in College Station, Texas. Data for the Orem Church was collected between mid-July and the end of December 2013. Data for the College Station church was collected from late January to the end of December 2014.

Data were downloaded every two weeks for the TRH and current data loggers. Since the LO loggers are state dependent and the loggers come with extended memory, data could be collected for months between downloads without running out of memory. However, to safeguard against the possibility of losing the data from lost loggers, bad batteries, and other disturbances, these loggers were downloaded approximately every 4-6 weeks.

Missing Data from Data Collection

The majority of downloads occurred with few problems throughout the duration of the study. There are however instances of missing data. An error in the TRH data logger software significantly and unexpectedly decreased the battery life of these loggers at the first part of the study. Multiple TRH loggers had instances of missing data in the Orem church until the batteries were replaced and the data logger software was updated.

There are also limited instances of sensors either being altered or going missing. In almost all instances these sensors were eventually found, but there inevitably remain instances of missing data.

Data Compilation

Each data set was exported to a Comma Separated Variable (CSV) file and read into Matlab. The developed Matlab script inputs the data and processes all the individual files into a single dataset. Post processing checks on the dataset, such as automatic checks for sections of missing data, were implemented to improve the reliability of the dataset. Additionally, furnace state estimation and a sunlight filter were implemented as discussed below.

Furnace State Estimation

Since natural gas meters were not installed on each individual air handler and the current clamps only measured the power coming from the condensing unit (compressor and condenser fan), temperature data loggers were installed inside the air handler to estimate the state of the furnace by analyzing the supply air temperature.

The large initial temperature change when the system is turned on and off is leveraged to ascertain the state of the furnace. The temperature change resulting from weather occurs over a much slower time scale. When observing temperature changes, a window of 20 minutes was examined to look at the maximum change in temperature during that window. A threshold for the temperature gradient as well as the absolute supply temperature was used to estimate when the furnace was on. These calculated furnace states were manually checked and then included in the dataset as furnace data.

Sunlight Filter

One of the problems experienced when collecting data came from the high level of light entering from the windows, resulting in false triggering of the light sensor. When the light sensor was located next to a light, masking tape was added to the sensor, which blocked enough light to prevent triggering of the sensor from sunlight but allowed triggering from artificial lighting. At other times, however, the LO data logger was located too far from the light. In these instances, the light level from sunlight was greater than the artificial light. In these cases, preference was given to allowing more light into the sensor to ensure that the light from the fixtures was sufficient to turn on the light sensor at the cost of allowing the sunlight to turn on the sensor.

In creating the sunlight filter, each room was manually scanned to determine the time of day when the false triggering occurred. This window of time varied significantly depending on the window orientation. As the sensors were positioned such to capture the light switch, the occupancy was correlated with the lighting to eliminate instances when the light was triggered without any associated occupancy inside the time window. Each file was manually inspected to ensure reasonable results without eliminating periods of artificial lighting. This method does leave some instances of falsely triggered lighting around periods of occupancy. However, the falsely triggered lighting primarily occurred in some classrooms and a couple offices, which, as is shown later in the thesis, constitutes a small portion of the total occupancy and lighting in the building. An example of the lighting filter is shown in Figure 6.

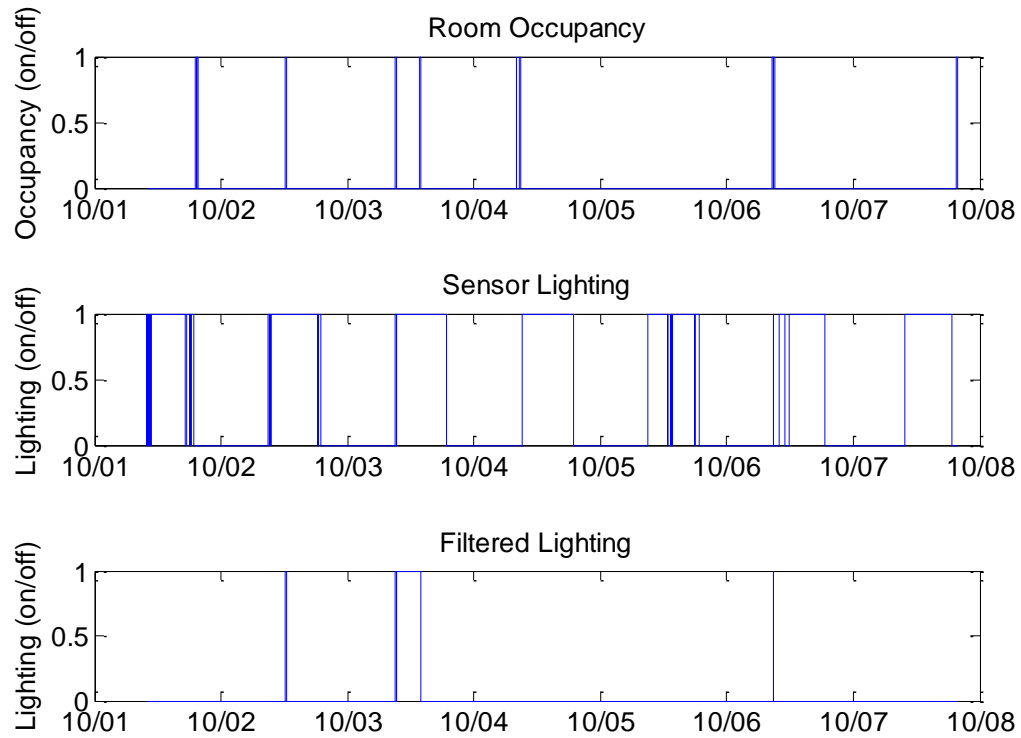


Figure 6. An example of the sunlight filter removing false instances of lighting from sunlight.

Special Building Notes

As the goal of the study was to passively measure building conditions, all the loggers were left unattended during the entire study. During data collection, loggers that had been modified or interrupted were corrected. Since the buildings were passively monitored, the researchers had no control over the building operational changes or retrofits. The following events took place during data collection at the two churches:

- Midway through data collection in the Orem church, in early October 2013, occupancy based lighting controls were installed in all the classrooms and offices in this church.
- In the College Station church, the HVAC system that services the main worship area failed and was replaced. Upon replacing, the thermostat was initially set to a constant temperature for several weeks before being programmed with temperature setbacks.

CHAPTER III

UTILITY ANALYSIS AND GENERAL BUILDING ENERGY CHARACTERISTICS

This chapter presents the overall building energy characteristics based on utility and data logger data. The chapter begins by analyzing the utility for the ten different churches and comparing the average energy usage with climate. The utility data for the two churches in College Station and Orem are then analyzed in additional depth. This usage is compared with the 2003 Commercial Building Energy Consumption Survey (CBECS). The total energy consumption is then estimated from the measured data and compared to reported usage from the utility bills. An estimation of the electricity breakdown is then presented. To conclude this chapter, the ability to achieve similar estimation results from using only a subset of sensors is analyzed.

Utility Analysis across Multiple Climate Zones

Utility data were obtained and analyzed for all of the churches. Locations were selected so that two churches in each CBECS climate zone were analyzed. Lower climate zones are defined as areas with more heating days, while higher climate zones have more cooling days. Each church is heated with natural gas and cooled using vapor compression systems. The base energy usage was estimated by finding the electricity usage in months that don't require cooling. The cooling energy was determined by subtracting the base usage from the total energy usage in the cooling months. Natural gas in each building is used for space conditioning and domestic hot water. The domestic hot

water usage was removed to determine the natural gas usage for space heating. The resulting annual heating and cooling energy use for each building is displayed in Figure 7.

As seen in the figure, there is a strong dependence of cooling and heating energy with climate. A clear trend shows the increasing cooling energy and decreasing heating energy with climate zone. Space conditioning for cooling constitutes a relatively minor portion of total electricity usage in cooler climates. In the churches located in warm climates, a significant portion of electrical usage is devoted to cooling the building. This trend is consistent with the 2003 CBECS, with a strong overall correlation of total energy usage in religious facilities to climate zone.

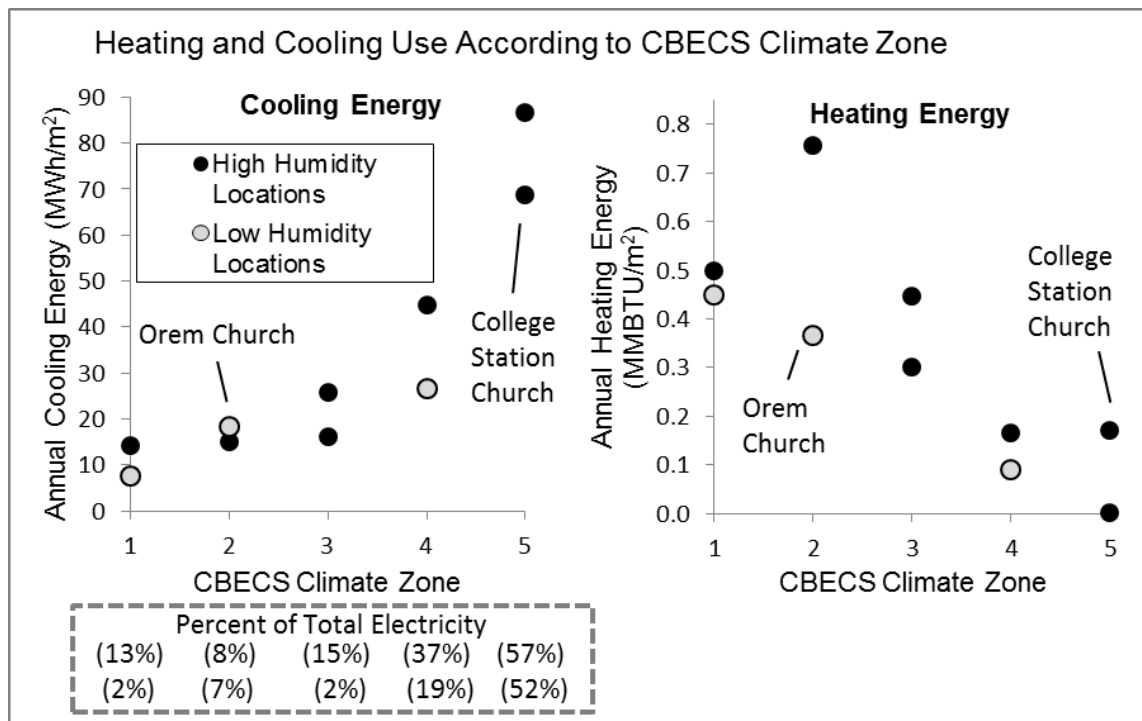


Figure 7. Comparison of annual cooling and heating energy use for architecturally identical buildings located in multiple climates.

These same utility bills were then compared based on cooling and heating indices. As no universal method for estimating cooling and heating indices exist, online tools were used to estimate the heating and cooling index. Once again, the churches were separated based on high and low humidity locations. The results are summarized in Figure 8.

As seen in the figure, the actual energy use is approximately linearly correlated with the estimated use based on heating and cooling indices. Of particular note is the separation of cooling and heating energy based on the relative humidity of the locations.

Overall, the dependence of building energy on climate is verified with Figure 7 and Figure 8.

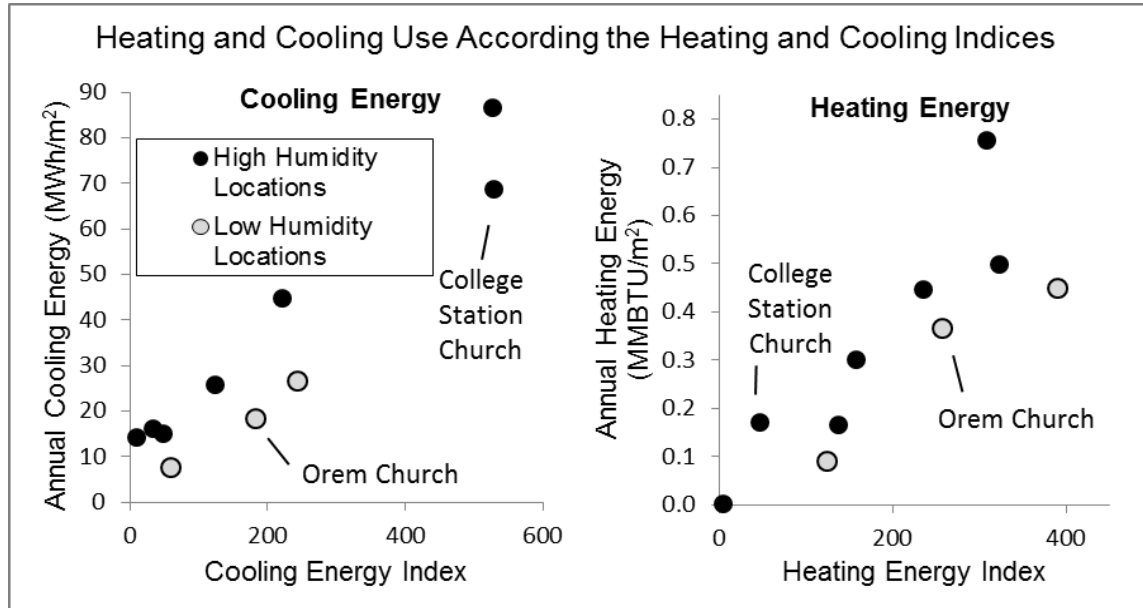


Figure 8. Correlation of building cooling and heating energy based on cooling and heating indices for multiple church buildings.

Comparison of Energy Usage for Studied Buildings

Utility Analysis

In analyzing basic building characteristics and energy usage trends, utility data from 2013 for both churches are displayed in Figure 9. In the College Station church, a significant portion of electricity goes towards cooling in the summer, while the Orem church has more modest cooling usage. The two churches have similar base (non-HVAC) electricity usage in temperate months, consistent with buildings that have similar occupancy and usage patterns. The small rise in electricity usage in both

churches during colder months is attributed to heating by individual mini-split systems and power draw from air handling units for the furnaces.

The natural gas usage shows the expected trend of increase usage through the winter months. During the summer, the only consumer of natural gas is the domestic hot water heater. The small usage during the summer months reflects that usage, with increased usage in the winter months to heat the buildings.

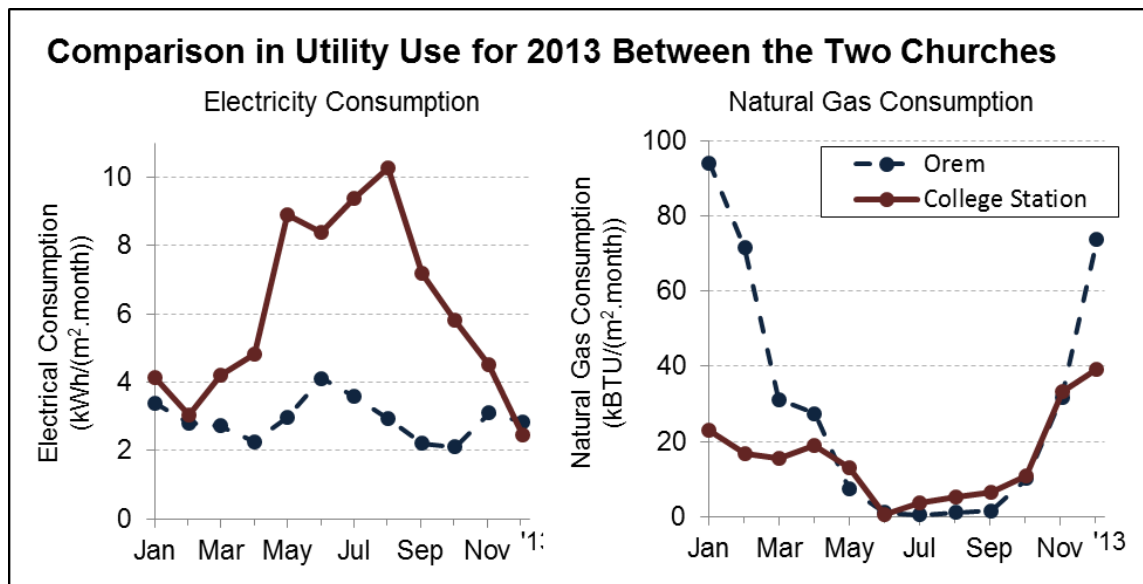


Figure 9. Comparison of utility usage between the two church buildings in Orem and College Station.

As was shown in Chapter 2 in Figure 2, the average peak temperature in the summer for the Orem church was similar to that of the College Station church. However, the significant reduction in cooling energy in the summer can be attributed to humidity and the average low temperature. The lower humidity decreases the energy requirement

to cool the air. Also, the larger drop in temperatures during the night decreases the overall heat gain that needs to be rejected.

Also of note is the large thermal inertia of each building. The walls of the building are primarily constructed of concrete blocks and therefore have high thermal inertia. During the peak temperatures of the day, the large thermal inertia of the building delays the temperature peak of the building. This is supported by Figure 10. As the indoor room temperature reaches a maximum in the late afternoon, the outside temperature has already dropped, potentially reducing the heat load (and consequent cooling requirements) on the building. Throughout the night, the cooler temperatures reduce the building temperature as a form of precooling for the following day. The thermal inertia of the building may reduce the cooling requirements of the building in Orem and therefore may cause a lower peak in electricity during the summer months.

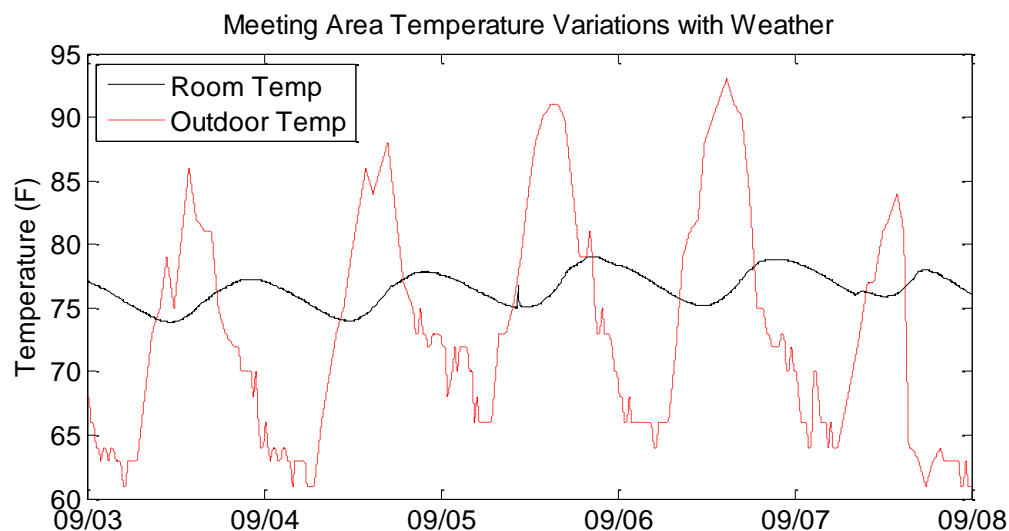


Figure 10. The large thermal inertia of the building results in a delay in peak temperature of several hours.

Energy Balance

The goal of the energy balance is to ensure all the major energy consumers in the church are accounted for when analyzing energy-saving opportunities. To perform the energy balance, the total electrical consumption is estimated by analyzing collected data and comparing this to the actual usage from the utility bills. If major energy uses are missed, then opportunities to reduce that usage will likewise be overlooked. While the goal is to match measured usage to the utility bills, differences will inevitably occur because of differences in billing cycles from calendar months, the inability to account for all loads in the buildings, and lost sensor data from missing or corrupted data loggers.

The major loads used in predicting the total electricity usage in the both churches include indoor lighting, parking lot lighting, condensing unit and air handler usage, and plug loads. Major lighting and HVAC loads were experimentally determined with the data loggers. Smaller plug and other loads were estimated with a small power meter to determine estimated average loads. Although this representative average of plug loads will be subject to estimation errors, the total contribution of the peripheral loads constitutes a small percentage of the total energy usage. The complete details of all loads used in the energy balance are described in Appendix A.

The results from the energy balance for both churches are summarized in Figure 11. Utility information was available for 2012-2014, and therefore the predicted usage in the Orem church can be compared to the actual usage in 2013 during the period of the energy study. Data gathered at the College Station is compared to actual usage from the 2014 utility bills. In the Orem church, the total estimated usage compares favorably with

the utility bills. Although there are some discrepancies, the largest difference in months occurs in July with about a 17% difference from the actual usage. In this month, the first month of data collection, only the 2nd half of the month is available for analysis, leading to extrapolation errors. From the energy balance in the Orem church, all major energy consumers are accounted for in the predicted energy usage through sensor data.

In the College Station church, the measured usage tends to under-predict the utility data for some months. All the same loads were accounted for in this church as in the Orem church, but there is a discrepancy between measured usage and the utility bills for March, May and July. The full cause of this discrepancy is unknown, and additional investigation as to the cause of the underestimation is warranted.

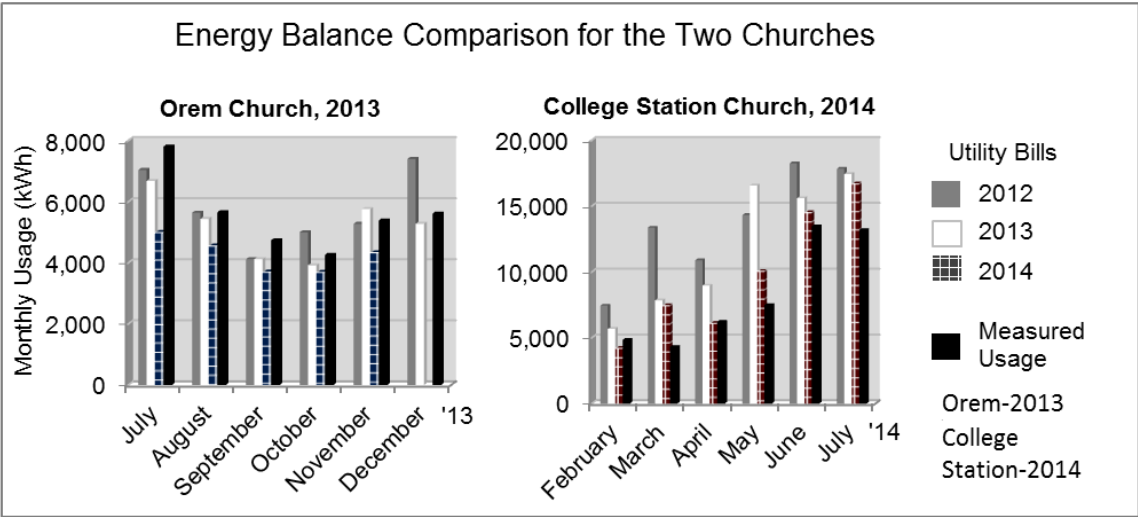


Figure 11. Comparison of utility bill electricity to estimated usage for the buildings in Orem and College Station.

CBECS Comparison

While few papers in the literature exist to benchmark the energy use for the two different churches, there are statistics that provide an estimation of expected use. The primary source of information regarding religious facilities and their expected energy use come from the 2003 CBECS [32]. The 2003 CBECS details the expected energy of different types of commercial buildings, including religious facilities, across different census regions, climates, building age, and building size. In comparing differences in energy use according to these metrics, the base energy intensity is used (kWh/m^2). Although there are additional, more optimal ways to benchmark building energy use [33], this method provides an overall estimate of the church building performance compared to other religious facilities.

Figure 12 shows the comparison of utility usage in the Orem and College Station churches to the expected usage according to region, subregion, climate zone, building size, and building age. This figure demonstrates that, according to energy intensity, both churches perform well in energy use compared to other counterparts. Based on the large percentage of energy devoted to HVAC, the best predictors of actual performance are likely the climate zone and to some extent the subregion. For both electricity and natural gas, both churches have lower energy intensities than their corresponding climate zone and subregion average intensity. Several likely factors that contribute to this lower energy use include temperature setbacks during unoccupied times, thermal zoning, and insulation. Previous studies have demonstrated the effectiveness of these measures to reduce building energy use [7].

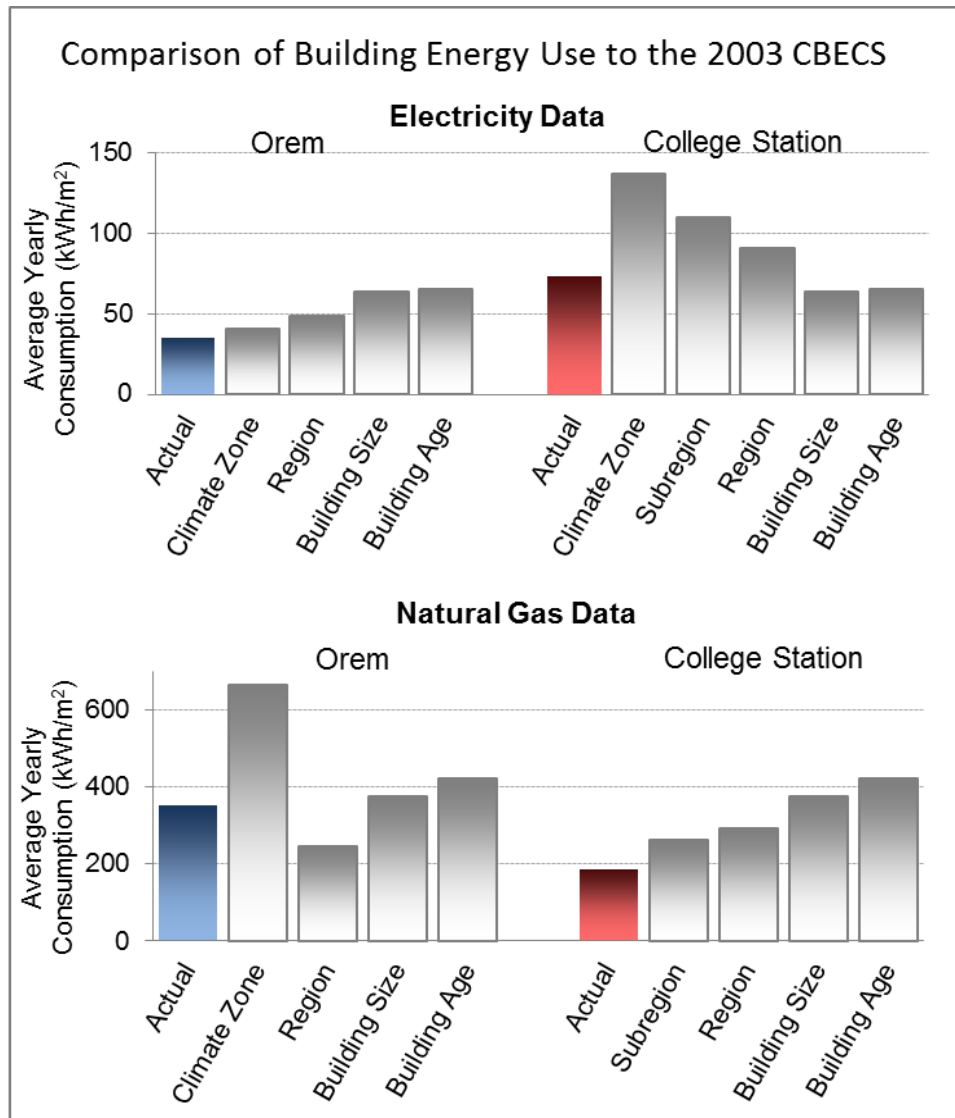


Figure 12. Energy intensity of the two church buildings in Orem and College Station compared to the 2003 CBECS averages.

Experimental Energy Usage Breakdown

Figure 13 shows the estimated electricity consumption for the Orem and College Station churches based on measured current draw from the HVAC system, measured indoor lighting consumption, estimated outdoor lighting load, and estimated peripheral

loads. As can be seen from the usage for the Orem church, the HVAC system makes up a significant portion of the electricity use in July, but most other months the contribution is minimal. Even in July, the total contribution from the HVAC system is less than 50% of the total. Lighting makes up the majority of estimated electricity use, with both indoor and outdoor lighting contributing a significant portion. Plug loads and other small electrical equipment constitute a minor portion of the total.

The College Station church, in contrast to the Orem church, has a significant portion of the total electricity use devoted to the HVAC system as noted earlier in the utility analysis. The average usage from lighting and peripheral loads is overall lower than the Orem church, but the total use for heating and cooling causes the total average electricity usage to be significantly higher in College Station.

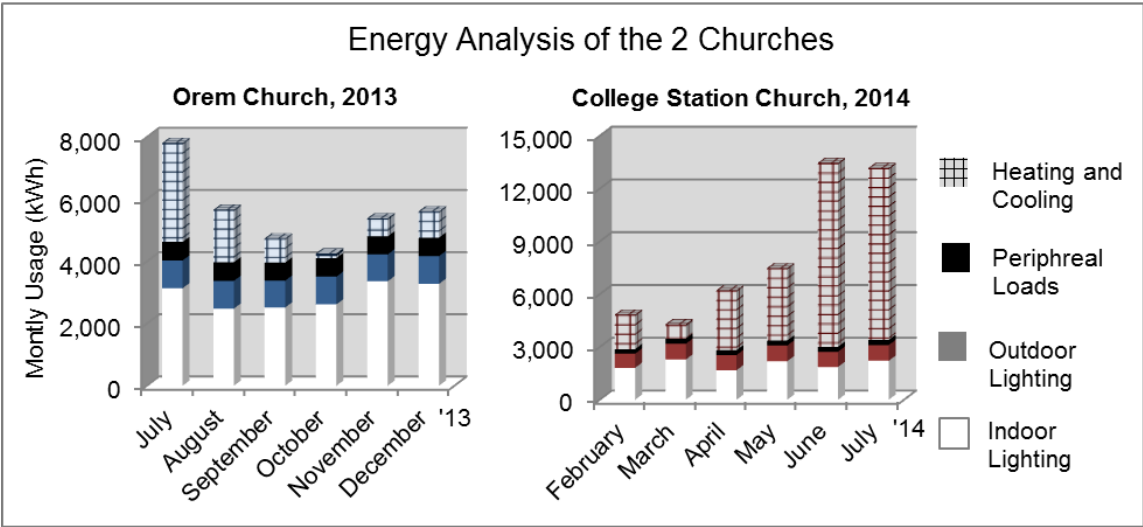


Figure 13. Experimentally determined energy end use in the two buildings in Orem and College Station.

Energy End Use Breakdown, CBECS comparison

Using the data from the energy balance, the electricity breakdown in each church is compared to the 2003 CBECS average for religious facilities. The 2003 CBECS provides data on the end use breakdown of electricity for religious facilities at a national level. The measured usage over the course of data collection was averaged together to provide a single energy breakdown that represents the average breakdown over the course of the year. Although only covering approximately 6 months, these months include all major seasons typically seen throughout the year (half the summer, one transition season between summer and winter, and half the winter). The data are presented in Figure 14. The end use breakdown shows that overall electricity usage in religious facilities is heavily influenced by the climate zone for space conditioning. The other major electricity use is for lighting, with other end uses constituting a relatively small fraction of the total for both studied churches and the CBECS national average.

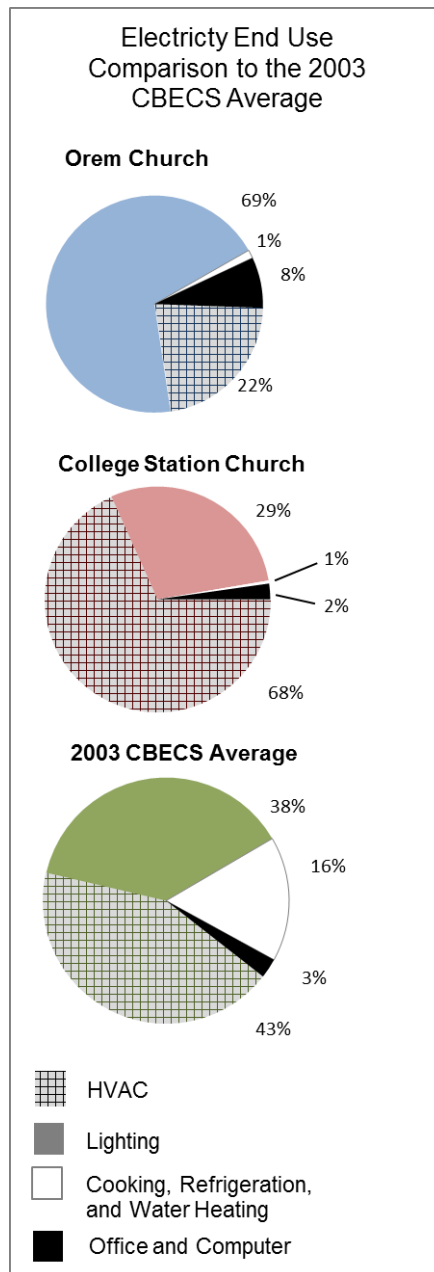


Figure 14. Comparison of electricity end use breakdown for the two churches to the 2003 CBECS breakdown for religious facilities.

The breakdown based on all divisions available in the 2003 CBECS is shown in Table 6. Since each of the churches is equipped with natural gas for space and water

heating, these estimated percentages of total usage are significantly lower than the CBECS average. The CBECS average is a national average over all climate zones and all sizes of religious facilities. As seen in the table, the actual breakdown of electricity for an individual church is highly dependent on climate zone.

Table 6. Energy usage breakdown for the two churches and the 2003 CBECS

	CBECS Total (kWh/(m ² ·yr))	Orem Total (kWh/(m ² ·yr))	College Station Total (kWh/(m ² ·yr))	CBECS Percent	Orem Percent	College Station Percent
Space Heating	3.2	0.3	0.4	7%	1%	1%
Cooling	11.1	2.8	18.0	24%	15%	56%
Ventilation	5.5	0.9	3.5	12%	5%	11%
Water Heating	0.4	0.0	0.0	1%	0%	0%
Lighting	17.4	12.5	9.3	38%	69%	29%
Cooking	0.4	0.0	0.0	1%	0%	0%
Refrigeration	6.7	0.2	0.1	15%	1%	0%
Office Equipment	0.4	0.7	0.4	1%	4%	1%
Computer	0.8	0.7	0.3	2%	4%	1%
Total	45.9	18.1	32.1			

Estimation of Loads Using a Subset of Sensors

In analyzing energy and usage patterns, detailed data are necessary to accurately understand how the building is operated. Some methods in determining building energy usage include metering power coming into junctions boxes or analyzing utility bills. However, these methods only provide a rough estimate on aggregate consumption and provide little detail on the breakdown or time of usage. In order to obtain an increased level of detailed data, individual areas and systems need to be monitored. Analyzing

building energy usage by installing only a subset of sensors presents the opportunity to reduce monitoring costs and time over installation in every area and system. Installation of sensors in strategic areas can potentially capture all the significant energy uses and trends by extrapolating the data to include unmonitored areas. The comprehensiveness of the study presented in this paper provides the opportunity to simulate predicted energy consumption if only a subset of sensors were employed to monitor building energy and usage.

In analyzing the prediction capabilities of a subset of sensors, areas of lighting were divided into classrooms, offices, meeting areas, and hallways. In each of the four room types of rooms, the occupancy and lighting patterns and usage are expected to be similar. An analysis on estimating the electricity usage for cooling by sampling a subset of air conditioning compressors was also performed. If only a sample of systems is continuously monitored, typically the power from the other systems is estimated using a one-time measurement or predicting the power through manufacturer data. In the analysis presented in this section, average values for power for each system were determined by analyzing when the systems were operating over the course of the year.

To analyze the estimation of lighting and cooling loads, initially each sensor was taken individually and scaled to predict the total usage. This produced a range of values for estimated usage. The loads were then estimated looking at the characteristics for two of the sensors in each area. All possible combinations of two sensors within each area were evaluated to produce another set of predicted values. This prediction was done for increasing number of sensors, each time looking at all possible combinations of using

the number of sensors. When the subset number of sensors equals the actual number of sensors in each set, there exists only one possible combination of sensors, which represents the actual use.

The predicted range of energy usage for each set of sensors is plotted in Figure 15. The estimation for the lighting in the classrooms and the offices, as well as the estimated cooling usage, is displayed in the figure. The median value is displayed, and the edges of the boxes represent the 25 and 75 percentiles. The edges of the whiskers extend beyond the box by 1.5 times the height of the box. The furthest data point within this range defines the edge of the whisker. Any data located outside the range of the whiskers are plotted as outliers.

For a low number of sensors, the estimated values tend to under predict the actual usage. The majority of rooms or systems have limited usage, resulting in the under prediction. Typical aberrances in usage result in large usage, as often the cause of the anomaly is equipment or lighting being left on for significant time periods. As one of the main purposes of analyzing building consumption is to identify areas of high energy usage, anomalous uses will likely be missed if only a subset of sensors are used. Problem areas in buildings will consequently be overlooked and energy efficiency opportunities will be missed.

In general, even for small numbers of sensors, the estimated usage closely correlates with the actual usage. However, even for a large number of rooms, there is significant spread in the estimation data. Building managers attempting to estimate total building usage using a small set of sensors take a significant risk in the assumption that

the subset of sensors represents total usage. Although accurate estimation is possible, there is a large uncertainty of the result obtained from the subset of sensors.

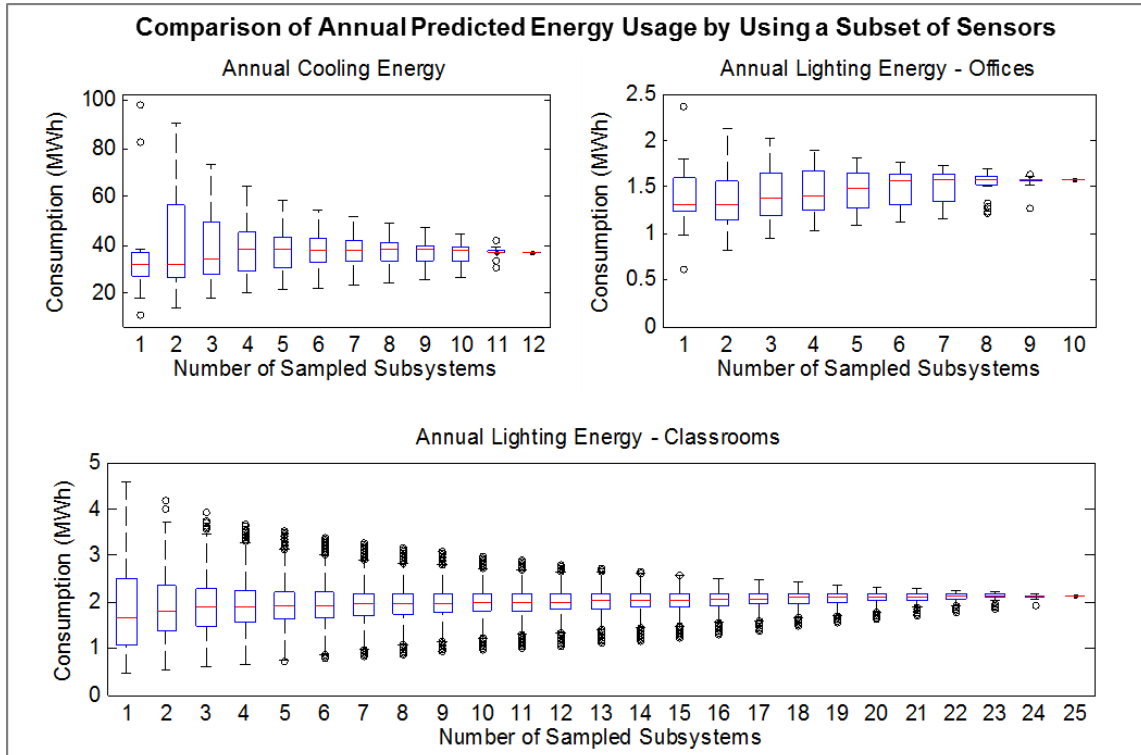


Figure 15. Estimation of lighting and cooling usage using only a subset of the available sensors. The box plot for each number of subsystems plots the data using all possible combinations of that number of subsystems.

Summary

This chapter presented, through analysis of multiple church buildings, the strong dependence on energy intensity to climate zone, verifying the 2003 CBECS for religious facilities. Since the usage patterns and construction are similar for all buildings, the major difference in building energy use results from difference in climate patterns. General trends of the study also reveal the dominant usage of electricity for space conditioning and lighting. Since energy for space conditioning consumes such a significant percentage of total energy, the reliance of building energy consumption on climate zones is magnified. Finally, the chapter presented the estimation errors in energy usage if only a subset of sensors were used in the energy study. An analysis on the potential errors in estimating energy consumption reveals the substantial risk in using only a small set of sensors to predict total building energy consumption and end use.

CHAPTER IV

BUILDING OCCUPANCY AND LIGHTING

This chapter discusses an in-depth analysis of experimental results for building occupancy and lighting. The chapter starts with an analysis of occupancy trends and distribution. Building lighting is then discussed with an extended analysis on the distribution of lighting according to the type of room. The energy saving potential of occupancy based lighting control is then presented. The chapter concludes with an experimental analysis on the efficacy of occupancy based lighting control.

Occupancy Patterns

Occupancy patterns can be used to identify accurate building schedules for building energy simulation and for building managers to identify accurate temperature control settings. As schedules are typically programmed over the time scale of a week, consistent patterns of weekly occupancy are most useful for identifying appropriate schedules in HVAC control. In analyzing building occupancy in this study, the complete dataset is compiled into a composite week, which will identify consistent building use and mitigate the effect of anomalous uses.

Figure 16 shows the basic occupancy patterns of the two churches on both consistency and intensity of usage. The first figure for each church shows the probability that someone occupied the building at that particular time of the week during data collection. The data, analyzed over the entire course of the study, does not have any information regarding the magnitude of usage. Points of probability of 1 signify that

every week over the course of data collection at least one person occupied the building during that time period. As can be seen in the figure, the building is consistently used throughout each week with regularly scheduled activities. Sunday is the day with the largest time of use, but many other days have consistent use as well.

The second figure shows the average magnitude of building usage throughout the study of approximately 40 rooms. This figure reveals that the dominant usage of the building occurs on Sunday. Although there is consistent usage on many days other than Sunday, the extent of this usage is limited to small areas of the building.

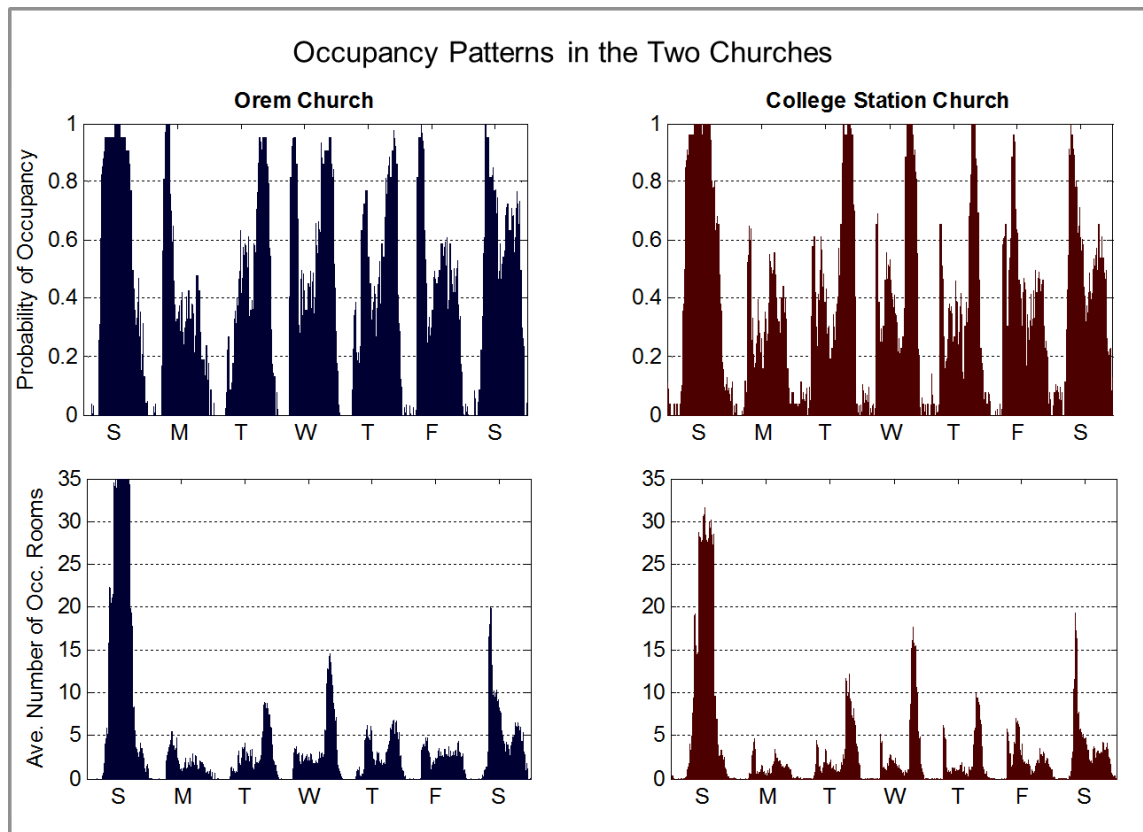


Figure 16. Occupancy patterns for the two studied church buildings. The plots on the top show the probability of any occupancy within the building during the week. The bottom plots show the average magnitude of building usage during the week.

In creating accurate building occupancy patterns, schedules based on a representative week is most useful. Gathering long term data to reliably determine building schedules is expensive. Figure 17 shows the breakdown of building use for the Orem church over the course of data collection. With the exception of a couple of weeks with unique building occupancy, observing one week of occupancy data is sufficient to reliably estimate average long-term building usage. Special events, as shown in weeks 9 and 11 of the study, are typically known *a priori* and can be avoided when estimating building schedules.

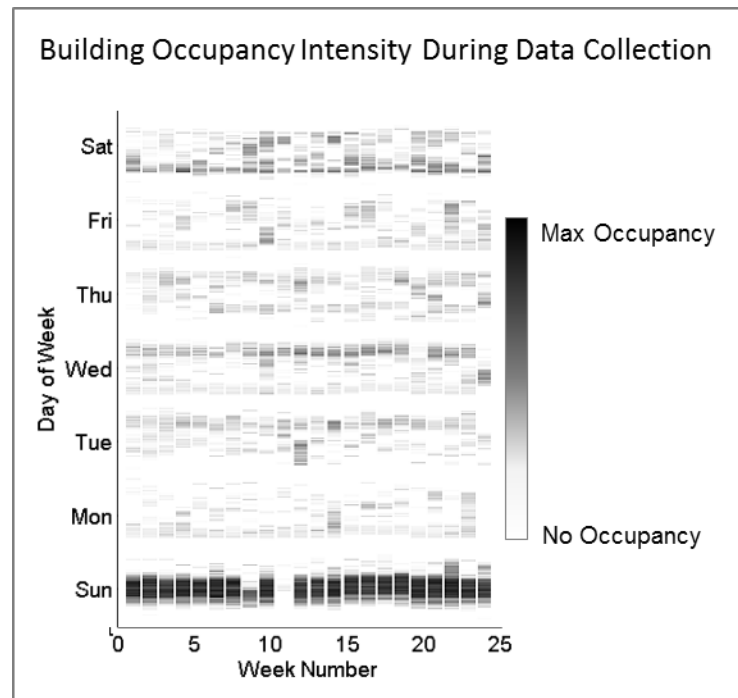


Figure 17. Breakdown of building occupancy during the course of data collection in the Orem church. Excluding a couple anomalous weeks, a consistent building occupancy schedule can be obtained by analyzing a single week of occupancy.

Occupancy Distribution

Analyzing the occupancy distribution not only provides insight on usage patterns of the church, but can provide information useful for building operators in keeping occupants thermally comfortable. Knowing the average length of room occupancy can guide building operators in setting appropriate temperature setpoints to keep occupants comfortable.

The length of time rooms are occupied in meeting areas is displayed for the Orem church in Figure 18. These data show the length of time meeting areas are occupied per meeting area over an average week. In analyzing the occupancy usage of the data, a space is considered unoccupied if there are no occupancy events over 5 minutes. This distribution is shown for number of counts of occupancy in each time window as well as total time in each time window.

The data is divided separately into Sundays and all other days. The third column is the combined total over all days. As seen in the figure, most instances of occupancy generally occur for shorter duration of occupancy. On the contrary, as a percentage of total time occupying the church, longer periods of occupancy (over one hour) constitutes the most significant bin of the histogram. Occupancy patterns are similar between Sundays and other days, but in general, rooms are occupied for longer instances on Sundays.

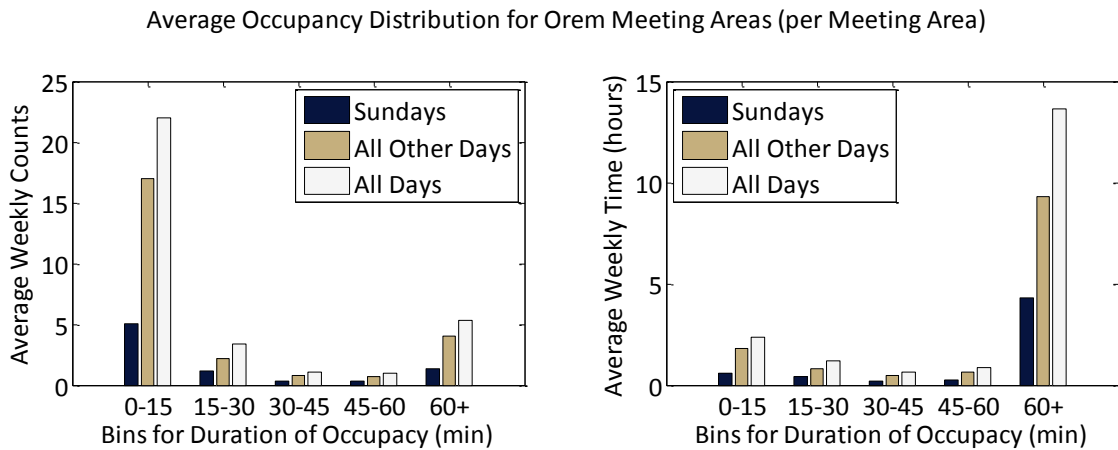


Figure 18. Histogram of building occupancy according to the length of occupancy in the meeting areas in the Orem church.

This same histogram is shown for the offices and classrooms in the Orem church in Figure 19. This figure shows that similar occupancy patterns are seen in the classrooms and office as in the meeting areas. The average number of instances, especially for shorter durations, is very comparable for the different room types. The main difference is in the reduced total time of occupancy as seen on the right of Figure 18 and Figure 19.

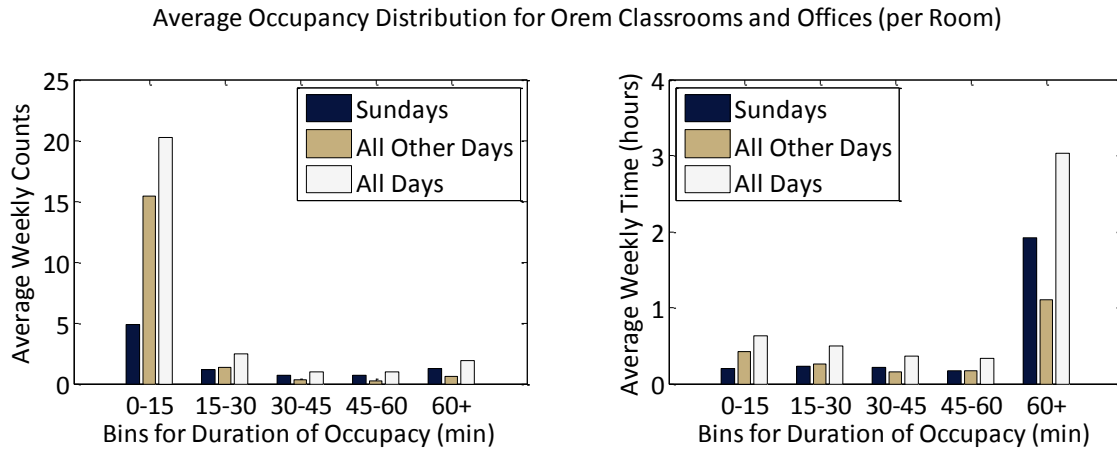


Figure 19. Histogram of building occupancy according to the length of occupancy in the classrooms and offices in the Orem church.

As seen in Figure 20 and Figure 21, the occupancy patterns for the College Station church are very similar to the Orem church. The majority of instances of occupancy are only for short durations, but as a function of total time of occupancy, longer durations are dominant. The total time of occupancy for the classrooms and offices in College Station (Figure 21) is markedly lower than the Orem church. The total time at shorter periods of occupancy are slightly higher, but the total time at longer periods is noticeably shorter.

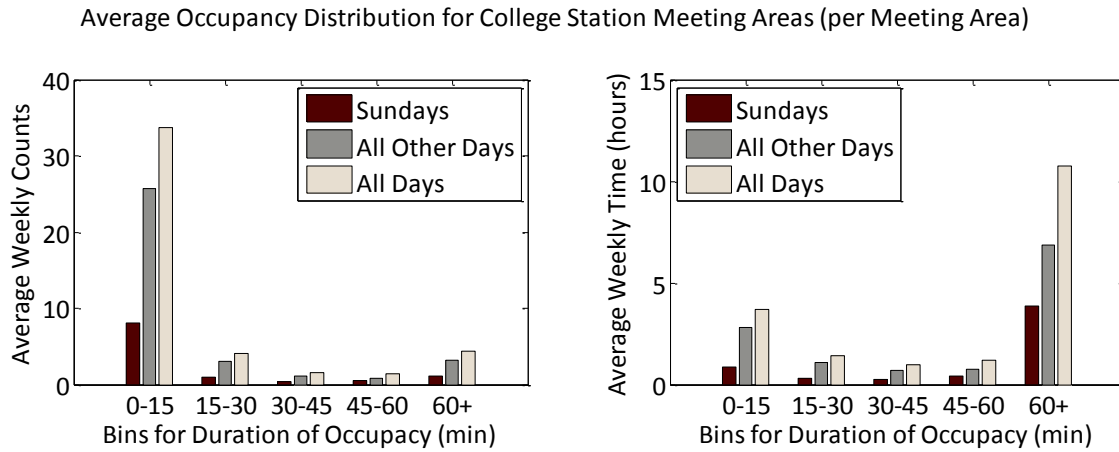


Figure 20. Histogram of building occupancy according to the length of occupancy in the meeting areas in the College Station church.

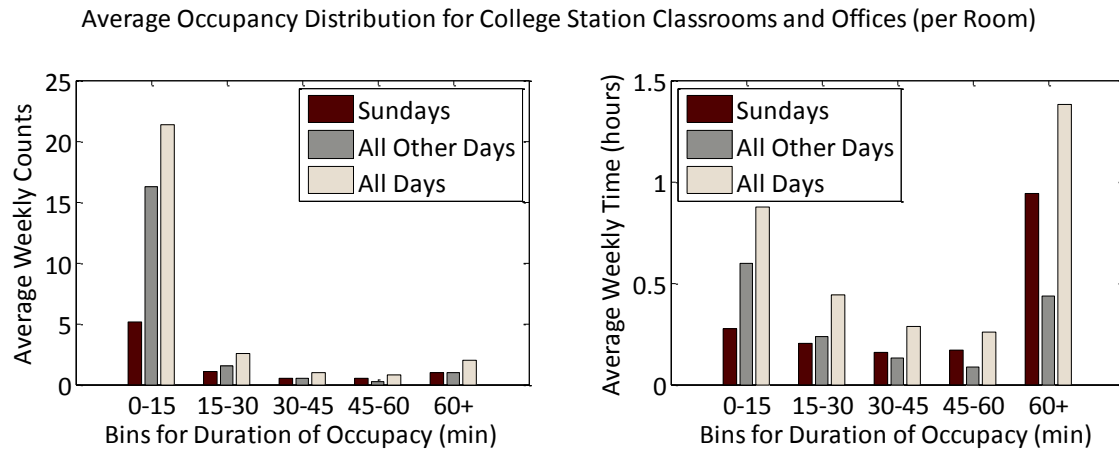


Figure 21. Histogram of building occupancy according to the length of occupancy in the classrooms and offices in the College Station church.

Lighting Usage

Aggregate Building Lighting

Similar to occupancy, the energy for lighting for each individual week is summed over the course of the entire study to determine a representative week. The lighting power correlated to each lighting sensor is used to estimate total lighting power in the building. The lighting power is broken up into three different categories: lights that remain on for security or safety, lights on during occupied times, and lights on during unoccupied times. By separating the lighting according to usage, the potential energy savings by eliminating lighting during unoccupied times may be estimated.

Figure 22 shows this aggregate lighting plot for the Orem church divided into the three categories. As seen in the figure, the base usage from lighting that remains on is minor compared to the total lighting power. The majority of remaining usage is for lighting when rooms are occupied. There are instances in which lighting is wasted throughout each day. The overall use for unoccupied periods is relatively small, which indicates that lights are generally turned off when the space is not in use. There are some instances in which lighting is wasted, presenting opportunities to reduce that waste, e.g. overnight between Monday and Tuesday.

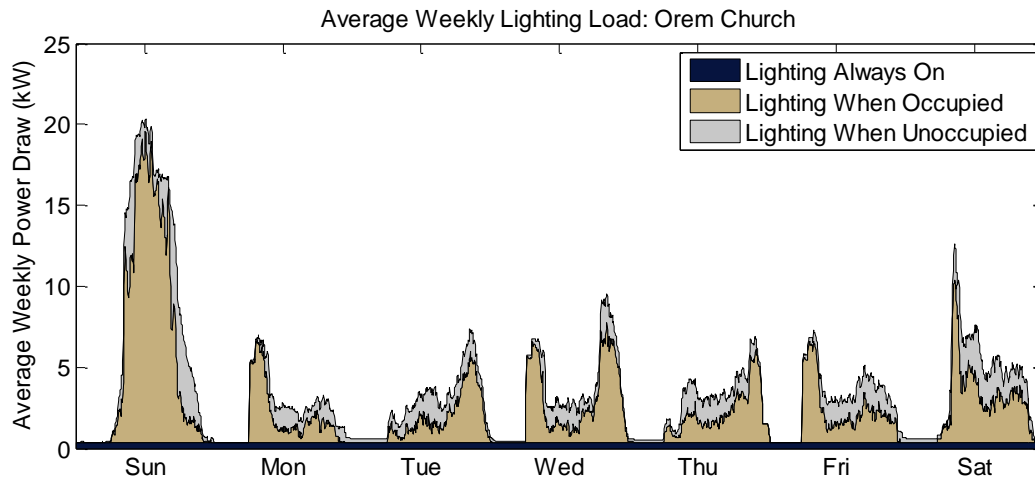


Figure 22. Average power draw from lighting in the Orem church over the course of the study. Heavy occupancy on Sunday results in significantly larger lighting energy use.

This same analysis is presented in Figure 23 below. The trends found in the church are very similar in that the majority of lighting is used during occupied times. There are a few more instances of waste overnight where lights are left on, but these instances comprise a relatively small portion of the total.

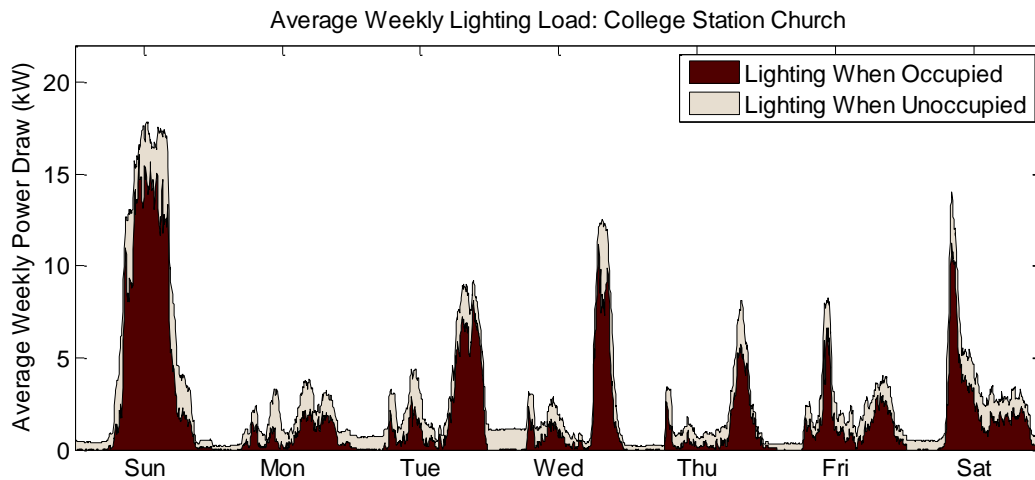


Figure 23. Average power draw from lighting in the College Station church over the course of the study. Similar patterns are seen in the College Station church when compared to the Orem church (Figure 22).

Breakdown of Lighting Usage

To analyze the energy saving potential by different types of rooms, the total lighting for each type of room is broken up based on occupancy. Figure 24 shows the total lighting energy consumed for each of the four areas for both churches. For meeting areas, which consume the largest portion of total lighting energy, the majority of lighting use occurs when the space is occupied. Because of the magnitude of total use, in absolute terms, the meeting areas also have the largest amount of wasted energy due to lighting. The hallways consume a significant portion of the total energy, and the majority of that energy goes to unoccupied times or to lights that are always left on. Thus, as a percentage, the hallways have the most significant energy saving potential of all the areas, although the magnitude of the wasted energy is relatively small. Classrooms and offices have very limited lighting usage. The potential energy saving opportunities in

these areas is overstated due to some instances of false triggering of the light sensors. Overall, the lighting data suggest that there are greater amounts of wasted lighting in the meeting areas and hallways. This conclusion is reinforced as people are generally less likely to turn off lighting in public areas due to uncertainty about occupancy or intentions of other occupants. However, turning off lighting in smaller rooms such as classrooms and offices is a common practice in many facilities.

The average energy used per room can provide a better indicator of the potential of an area to save energy by installation of occupancy sensors. In analyzing the total lighting per space in the church, a room was defined as an area having a distinct set of lights that were controlled by its own switch. The data in Figure 24 further emphasize the larger energy saving potential of the meeting areas and the minimal energy saving potential in classrooms and offices. This illustrates the importance of analysis based on data, since common practice is to place occupancy-based lighting controls in classrooms, before installing them in the large meeting areas.

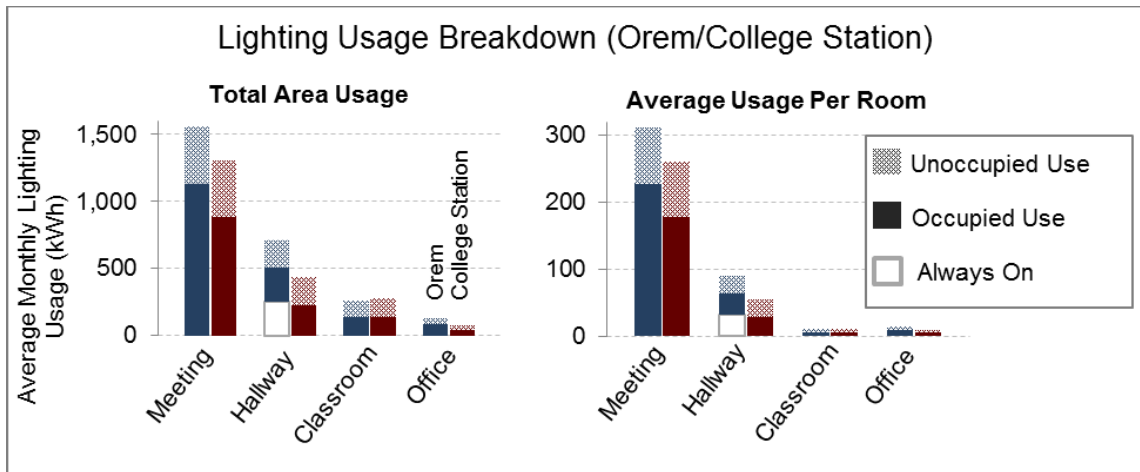


Figure 24. Breakdown of lighting according to different types of rooms for both churches.

Breakdown of Lighting and Potential for Occupancy Sensors

Figure 25 shows the occupancy and lighting patterns for the different areas of the building. Originally, each area was treated separately. But the meeting areas and hallways had similar patterns of occupancy, as did the classrooms and offices. This additional analysis also reveals the extent to which each room type is used. The approximate potential for occupancy sensors can quickly be gaged by the percentage of time the lighting is on but the space is unoccupied.

Previous figures already indicate the larger use of energy for lighting in meeting areas and hallways, but this larger use could be accounted for by a larger number of light fixtures, as opposed to increased usage as a percentage of time. However, as seen in Figure 25, the meeting areas and hallways are used significantly more often than the classrooms and hallways. Although the total occupancy (as a percentage) for the meeting areas and hallways is approximately triple that for the classrooms and offices, the total

occupancy for all areas of the church is relatively small. In general, the buildings are characterized by sparse and intermittent occupancy.

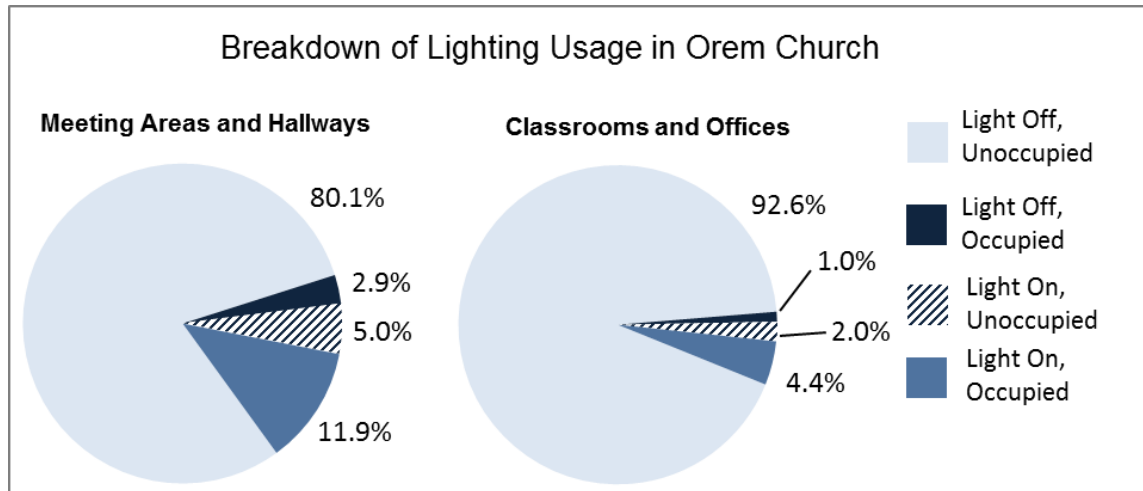


Figure 25. Breakdown of lighting characteristics for different building areas in the Orem church.

The breakdown for the College Station church is shown in Figure 26. The overall patterns are very similar, with similar trends for both occupancy and lighting. The total occupancy in the meeting areas and hallways is slightly lower, but overall this figure strengthens the assumption that the buildings have similar occupancy and lighting usage.

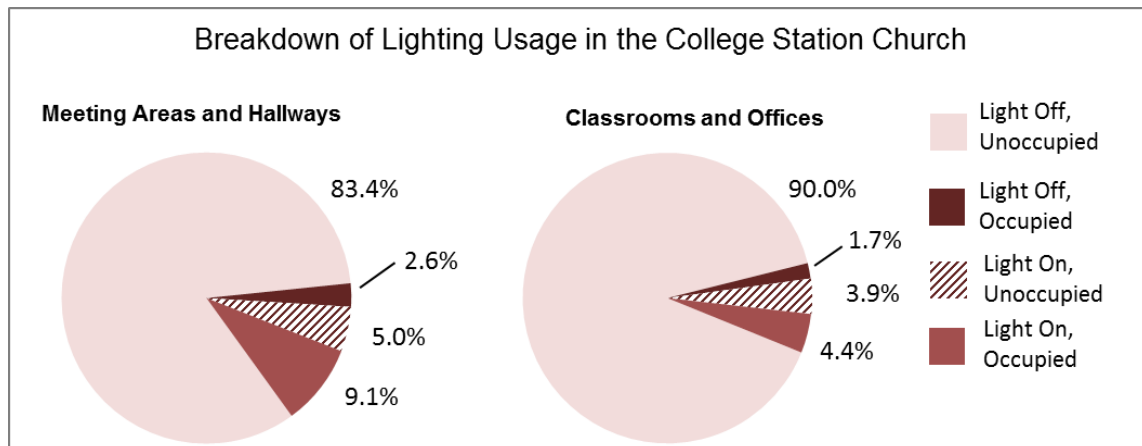


Figure 26. Breakdown of lighting characteristics for different building areas in the College Station church.

Lighting Retrofit

As lighting technologies evolve, more efficient lighting offers ways to reduce energy usage without altering building operation. Often the cost of these new lighting options decreases over time, increasing the economic feasibility of the retrofit until the new lighting type becomes standard. As the majority of lighting in the two studied churches is T8 fluorescent lamps, a common retrofit option is to replace the lamps with LED equivalents. Figure 27 shows the payback period of the LED lamp retrofit as a function of lamp cost. This figure shows the percentages of current lighting for different areas of the church (Figure 25). This figure does not assume a labor cost associated with installation or additional savings from reduced maintenance cost. As the capital cost of the retrofit decreases over time, the payback period also decreases and the economic feasibility improves. However, as seen in this particular instance, the total lighting from the church is low enough that retrofitting lighting in any of the church has a long

payback period. In general, buildings with sporadic use, such as religious facilities, suffer from low potential economic savings from lighting retrofits.

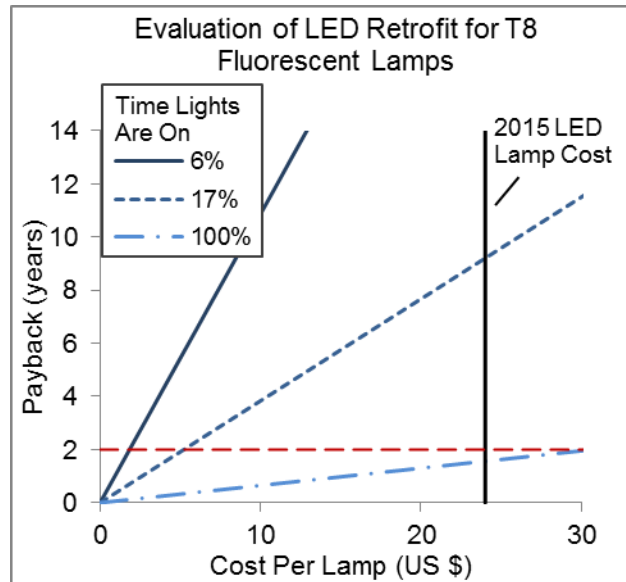


Figure 27. Anticipated payback period for replacing T8 fluorescent lamps with LED equivalents. Percent time of reduced lighting was taken from Figure 25 for the classrooms/offices (6%), and hallways/meeting areas (17%).

Occupancy Based Lighting Control

Knowing that occupancy and lighting contribute significantly to the total building energy consumption, occupancy based lighting control often is an important step to reducing lighting usage. The feasibility and cost effectiveness of this retrofit in sporadically used buildings, such as church buildings, are evaluated in this section.

Occupancy based lighting control is a popular first step in improving energy efficiency because of the relative simplicity and high visibility. However, in sporadically used buildings, such as many churches, the cost savings often are not high enough to

justify the implementation costs. Figure 28 shows the theoretical savings payback period as a function of the percentage of lighting saved for different numbers of fluorescent lamps. The implementation costs were used based on common estimated costs from energy assessments [7]. Most of the classrooms and offices in the two churches have 4-8 lamps per switch. The number of lamps per switch in the hallways, foyers, and meeting areas range from approximately 16 to 48 lamps. Lines indicating a 2-year payback period is shown, a typical payback period for industrial and commercial facilities.

This plot emphasizes the payback as measured by percentage of time lighting is reduced. This represents reduction of time when the lighting is on but the space is unoccupied. However, sensors that detect occupancy will trigger the lighting whenever the space is occupied, even if the occupant would typically leave the light off due to sufficient daylight. The percentage of time when the space is currently occupied but lighting is off will be added to the lighting usage with occupancy based lighting control. Therefore, the amount of savings from this retrofit will be reduced in practice by the current percentage of time the space is occupied without lighting. This reduction will increase the payback period for occupancy based lighting control. As seen in the Figure 25, Figure 26, and Figure 27, the intermittent usage of the building results in limited economic feasibility of occupancy based lighting control.

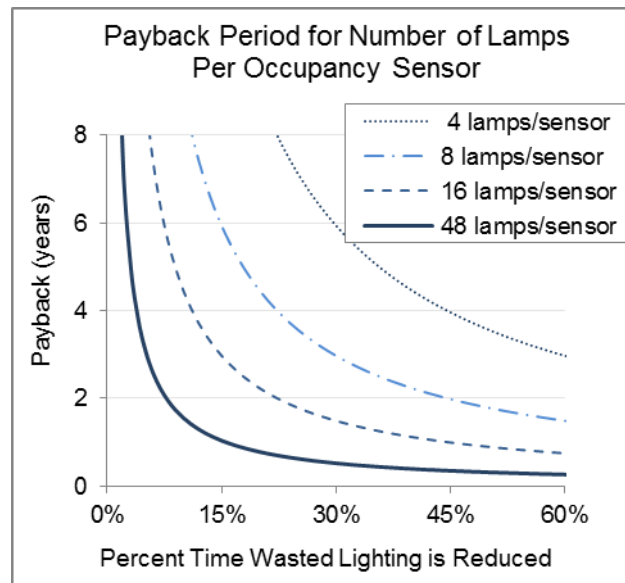


Figure 28. Anticipated payback period for installation of occupancy sensors as a function of percent wasted lighting saved and number of T8 fluorescent lamps attached to each sensor. Data from typical implementation costs were taken from [34].

Occupancy Based Lighting Control: Experimental Comparison

There are two experimental comparisons that can be made from the course of the study in the two churches. The first instances occurred in the Orem church. Prior to the study, there was no occupancy based lighting control in the church. About halfway through the study, in late September 2013, the facilities manager had the classrooms, offices, and one of the smaller meeting areas retrofitted with occupancy based lighting control. Sensors were not installed in the other meeting areas, restrooms, hallways, or foyers.

The second instance involves a comparison of the two churches. The church in College Station has no occupancy based lighting control in the building except in the

restrooms, while the Orem church had no lighting control in the restrooms. Having similar occupancy and lighting usage, the churches are compared to evaluate the effectiveness of the occupancy based lighting control in the College Station church.

Occupancy Based Lighting Control in the Orem Church

Occupancy based lighting control was installed over the course of several days in late September 2013 during data collection at the Orem church. In comparing actual energy savings from the sensors, lighting data is compared for rooms with before and after the retrofit. Since there are likely to be some small variations in usage due to variations of seasons, school years, or other factors, a comparison of lighting usage is also made in the meeting areas and hallways. These areas, which have no retrofit, serve as a control by evaluating natural variations in usage.

Figure 29 shows the result of occupancy based lighting control for the Orem church. As seen in the figure, no energy savings are seen by the installation of occupancy sensors in the classrooms and offices. The original potential energy savings were small (Figure 28). There are still instances when lighting is left on during periods without occupancy, which occur in the time after someone leaves before the timer turns off the light in a space, demonstrating that not all instances of wasted lighting can be saved with occupancy based lighting control.

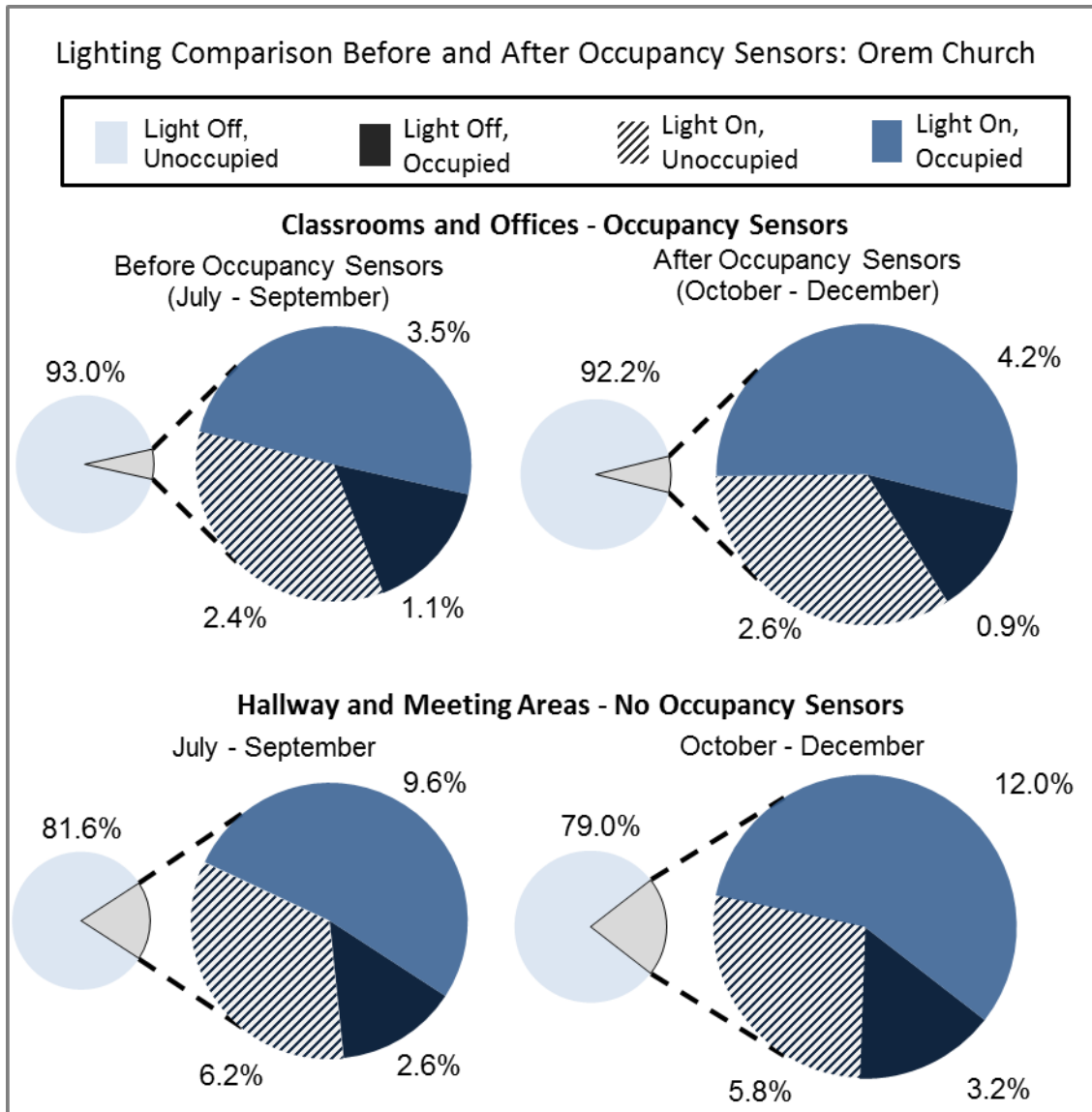


Figure 29. Analysis of energy savings from the installation of occupancy sensors in the classrooms and offices in the Orem church. Little change in overall lighting characteristics was seen. The bottom two figures show the lighting characteristics in an area without occupancy sensors.

Occupancy Based Lighting Control in Restrooms: Orem and College Station Churches

Restrooms are often a good potential candidate for occupancy based lighting control. The Orem church had no control on lighting in the restrooms during the entire study. In the College Station church, the only space with occupancy based lighting control is the restrooms. The leftmost graph in Figure 30 shows the lighting characteristics of the two restrooms in the Orem church. There are no windows in the restroom and there are approximately eight lamps in each restroom for both churches. The amount of wasted lighting in the restrooms exceeds 10%, which represents a reasonable potential for energy savings.

The two figures on the right of Figure 30 show the actual performance of the two restrooms with occupancy based lighting control in the College Station church. Despite the presence of occupancy based control, the lighting usage compared to the Orem church is similar for the women's restroom and significantly worse for the men's restroom in the CS church.

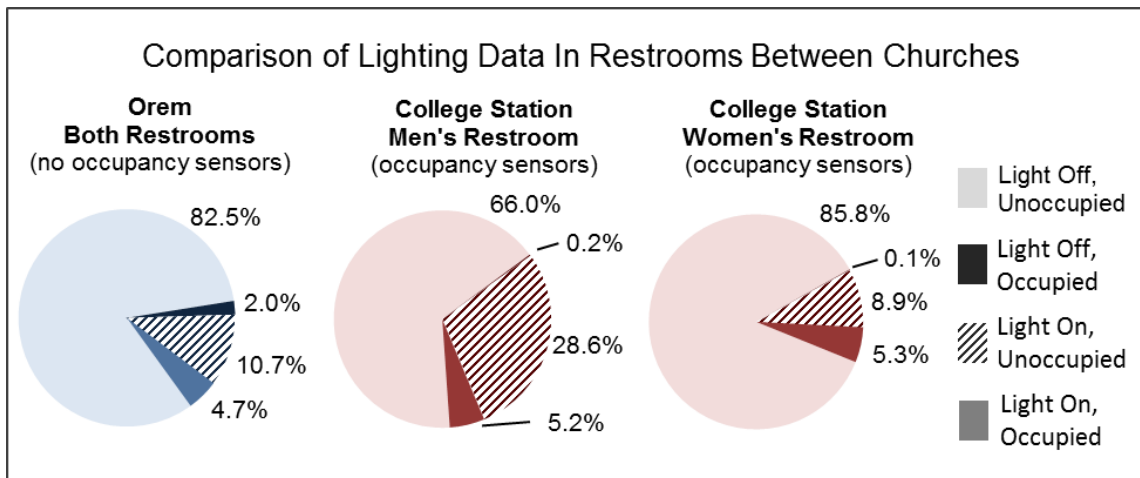


Figure 30. Comparison of lighting characteristics for the restrooms in both churches. The Orem church had no occupancy sensors, while both restrooms in the College station church had occupancy sensors.

The increased consumption of lighting during unoccupied times comes from an oversensitive occupancy sensor that responds to air movement from the HVAC system. An example of the lighting and occupancy data from the men's restroom is given in Figure 31. Since there are no windows, the only variation of movement in the rooms when the space is unoccupied comes from the HVAC system. The power draw from the compressor that services the restroom is shown in the 3rd plot of Figure 31. As can be seen in the figure, the lighting during unoccupied times correlates with the instances of HVAC usage. This highlights the need for proper sensitivity settings on occupancy based lighting control to achieve the desired savings.

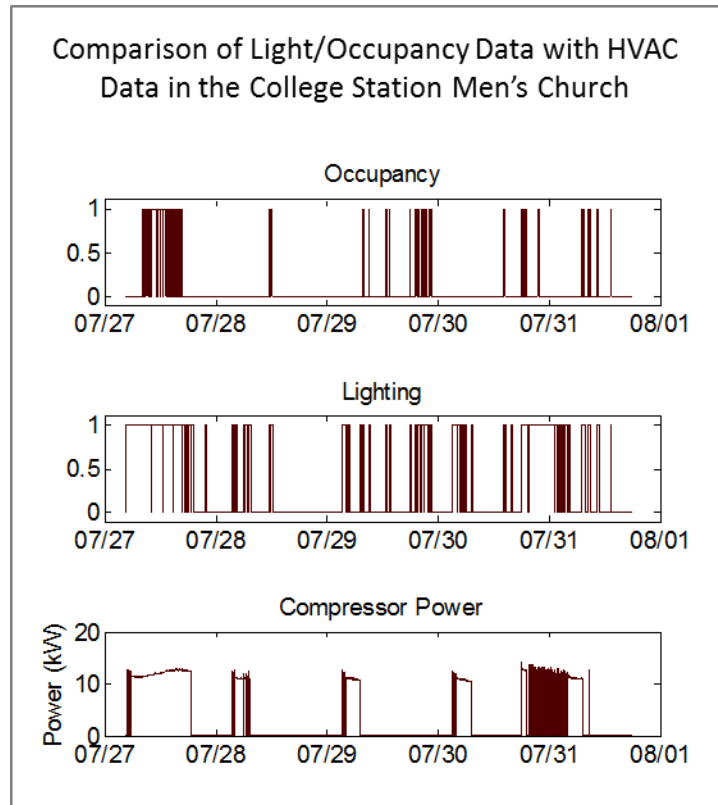


Figure 31. Over sensitive occupancy sensors allow the airflow from the ventilation system to trigger the occupancy sensors, resulting in poor lighting performance.

However, even with all instances of HVAC triggered lighting removed, the performance of the lighting in the restrooms in the College Station church is no better than the Orem church, as indicated in Figure 32. The remaining instances of time with the light on during unoccupied times come from the long duration of time on the timers.

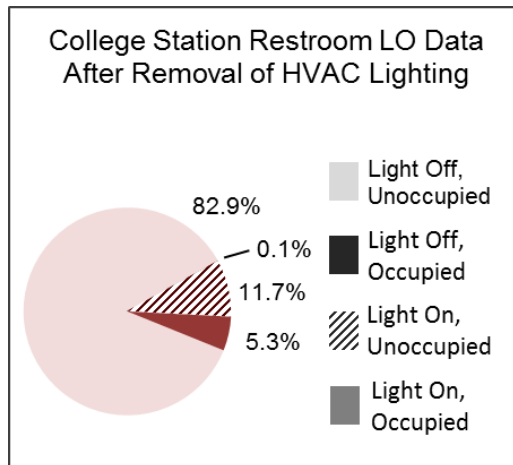


Figure 32. Estimated lighting usage with the removal of lighting instances triggered by the ventilation system in the College Station church.

A histogram of lighting time after the end of occupancy was used to determine the effect of timer length on occupancy. The timers on the Women's and Men's restrooms were determined experimentally to be 15.5 and 16.5 minutes, respectively. This is displayed in Figure 33.

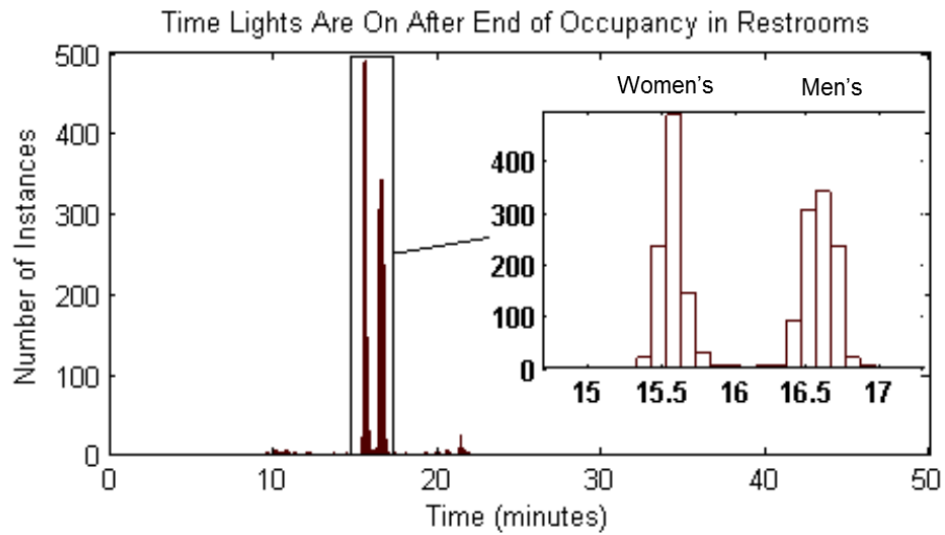


Figure 33. Evaluation of timer lengths for occupancy based lighting control in the College Station restrooms.

Using the occupancy data from the restrooms, the timer can be changed and lighting performance evaluated. Figure 34 shows the effect of the occupancy timers on the extent of wasted lighting in the restrooms. The tradeoff in reducing the timer length is the increased possibility of turning off the lights while the space is occupied. Without significant periods of lighting during unoccupied times, the decreased savings from necessary timer lengths reduces the energy saving potential of occupancy based lighting control.

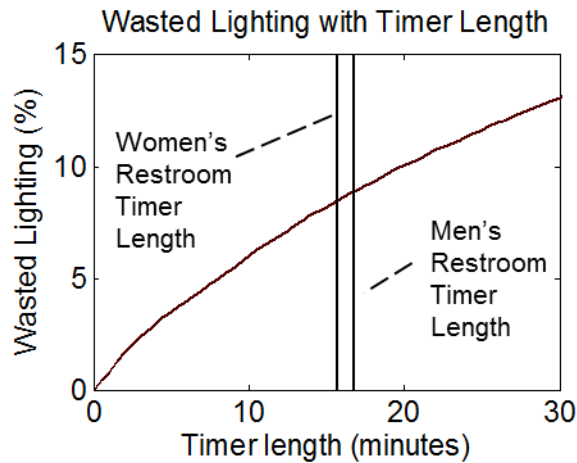


Figure 34. Percentage of time lighting is wasted as the timer length is varied on the occupancy based lighting control.

Recommendations for Lighting Use

An analysis of lighting in both churches reveals several general recommendations.

- A significant portion of lighting is consumed during periods of no occupancy, and this wasted lighting is found most prevalently in meetings areas and hallways.
- The economic feasibility of lighting retrofits is limited because of the reduced lighting usage compared to other commercial facilities.
- Due to the intermittent occupancy and usage of religious facilities, the energy saving potential of occupancy based lighting control is limited in all areas, but especially classrooms and offices.
- Incorrect sensitivity of sensors and long timer lengths decrease the energy savings of occupancy based lighting and should be considered when evaluating this potential retrofit. Installation of occupancy sensors with the

option to manually turn off lighting by occupants would help improve the performance of occupancy based lighting control.

Summary

This chapter has shown that the occupancy and lighting characteristics are very similar between the buildings and show patterns of infrequent, yet consistent usage. These schedules vary significantly from standard schedules for commercial buildings. The majority of lighting is condensed in the meeting areas and hallways. Due to the infrequent usage of the building, the energy and cost saving potential of occupancy based lighting control is limited. Experimental evaluation of this control demonstrated the limited energy savings associated with occupancy based lighting control.

CHAPTER V

BUILDING HVAC USAGE AND TEMPERATURE CONTROL

This chapter analyzes the energy use associated with heating and cooling in the church buildings. The chapter begins by analyzing the general HVAC usage for both churches in regards to gross usage. A quantification of potential energy savings from temperature setbacks is then presented. The chapter then specifically analyzes the waste that occurs from faulty operational settings. The chapter concludes by looking at the dependence of power requirements for condenser units based on outdoor air temperatures.

Overall Usage Patterns

The energy use specifically related to the HVAC systems are shown below in Figure 35. This shows the experimental estimations of heating and cooling requirements for each of the buildings based on data logger data. The average percentage of use for all the systems is shown for each of the churches. As expected, and consistent with earlier analysis, there is a larger heating use in the colder Orem climate and a significantly larger A/C use for the warmer College Station. Note that data were only collected for July-December in the Orem church, so no estimation is made from the first half of the year.

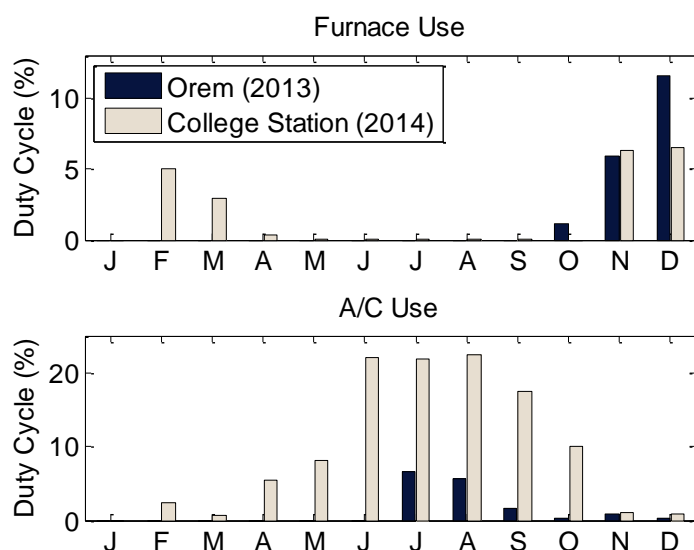


Figure 35. Furnace and A/C use for both buildings over the course of data collection. This figure reports the average time the systems were run in heating or cooling mode.

As was seen previously, energy intensity for both electricity and natural gas is lower by most metrics than other comparable religious facilities (Figure 12). As a significant portion of this chapter is devoted to large amounts of waste and loss in the HVAC system, the removal of this waste will further improve the energy intensity compared to other religious facilities.

One of the most likely reasons these buildings perform well to other religious facilities is the inclusion of temperature setbacks in the building during unoccupied times. Each HVAC system is set to push back the temperature setpoints during periods without occupancy to 60°F and 80°F for heating and cooling, respectively. As was analyzed and discussed in Chapter 4, the overall occupancy of the building is minimal. Although there are regularly-occurring meetings and activities throughout the week, the

total occupancy is relatively small with the exception of Sundays (Figure 16). For a majority of time, each building benefits from the energy savings generated by implementing temperature setbacks.

Figure 36 shows an example of the temperature setbacks for both heating and cooling. Each of these instances occurred over several days in which no occupancy occurred and the systems were run in unoccupied mode. Note that although the setpoints are set for 60°F and 80°F, the thermostats are located in select rooms and so the temperature in neighboring rooms may deviate by a small amount from the setback temperature. For this reason, as seen on the right of Figure 36, the temperature setback for this particular room is approximately 78.5°F for heating.

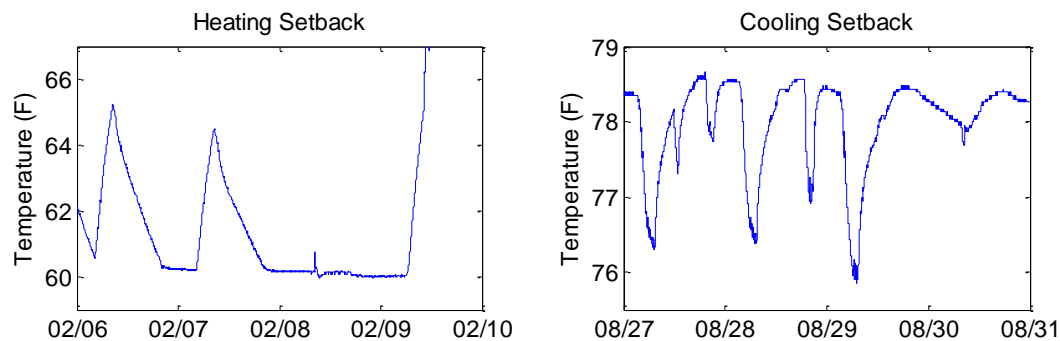


Figure 36. Example of heating and temperature setbacks for the College Station church. Each church had 60 °F and 80 °F heating and cooling setbacks for all areas.

Quantification of Energy Savings from Temperature Setbacks

As mentioned above, a likely contributing factor to the favorable energy intensity of each building is the lower energy usage for heating and cooling due to temperature setbacks. Temperature setbacks in buildings during unoccupied times is an established energy efficiency measure that is commonly implemented in many buildings. There are manual temperature overrides in the building for each system that allows an occupant to temporarily switch the system to “occupied” and allows some control over the temperature setpoint.

The HVAC system servicing the main worship area in the College Station building was replaced in early May 2014. After installation of the new system, the thermostat controlling the temperature in the main meeting area was not given the temperature setbacks as typically found throughout the building. This operational change continued for several weeks before it was discovered and corrected to include temperature setbacks.

The problem took so long to discover because temperature setbacks inherently operate when the building is not occupied, thereby increasing the difficulty in diagnosing the lack of temperature setbacks. Figure 37 shows the temperature of the main meeting area for one week without temperature setbacks and for two other time periods that had temperature setbacks. The different temperature profile with no temperature setbacks is clear as the space is controlled to a near-constant temperature.

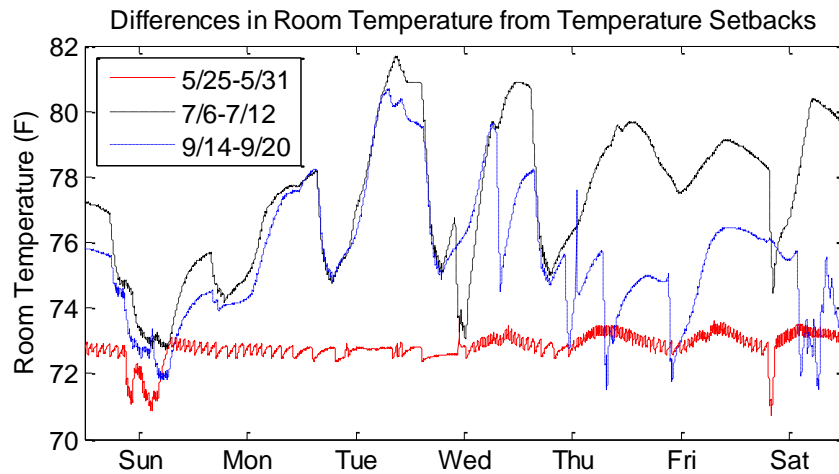


Figure 37. Verification of a period of time without temperature setbacks for the main meeting area. The space temperature for two comparable time periods is also shown to verify the temperature setbacks.

Due to the comprehensive nature of the study, the energy savings from including temperature setbacks can be quantified. To analyze the savings in energy consumption, a 4-week window was taken for time periods with and without temperature setbacks. These time periods are summarized in Table 7. Two different time windows with temperature setbacks were analyzed and compared to the time period without setbacks. The first time period is a 4-week period closely following the 4-week period without temperature setbacks. As this time period occurs later in the summer, the average temperature is several degrees warmer during this time period. However, this provides a comparison with minimal probability for equipment degradation or changes. The second time period for comparison occurs in September and October of that same year. Although several months later, this time period has an overall similar average

temperature. The expected use of the HVAC system in this time period is similar to the time period without setbacks.

Table 7. Comparison of energy usage for three time periods, two with temperature setbacks and one without setbacks

Time Period	Operational Condition	Average Outdoor Temperature over Time Period	Total Energy Usage
5/18/2014 - 6/14/2014	No temperature setbacks	78.2 °F	631 kWh
6/29/2014 – 7/26/2014	Temperature setbacks	82.6 °F	432 kWh
9/7/2014 – 10/4/2014	Temperature setbacks	77.6 °F	407 kWh

The average energy usage for the different time periods is presented in Figure 38. This figure shows the average use for each day of the week over the 4 week time period. As seen in the figure, the total Sunday usage, when the building is heavily occupied, is similar for all three buildings as there is minimal time with temperature setbacks. However, during other days in the week, especially near the end of the week, the average daily energy use for time periods with temperature setbacks is significantly lower than the time period without the setbacks. Note that although the average outdoor temperatures may be comparable over the entire time period, there are significant fluctuations in daily HVAC use due to normal weather patterns. The average weekly total usage, which represents the sum of each individual daily usage, is also displayed on the figure to summarize the energy savings from temperature setbacks. Over normal operation with temperature setbacks, the increased energy usage without temperature

setbacks ranges from **46-55%**. Since this operational change only affects periods without occupancy, these savings represent a significant portion of total energy that can be reduced with minimal impact on thermal comfort for occupants. As the standard practice is to implement temperature setbacks, the total energy use for each building is significantly reduced over maintaining the buildings at a constant temperature.

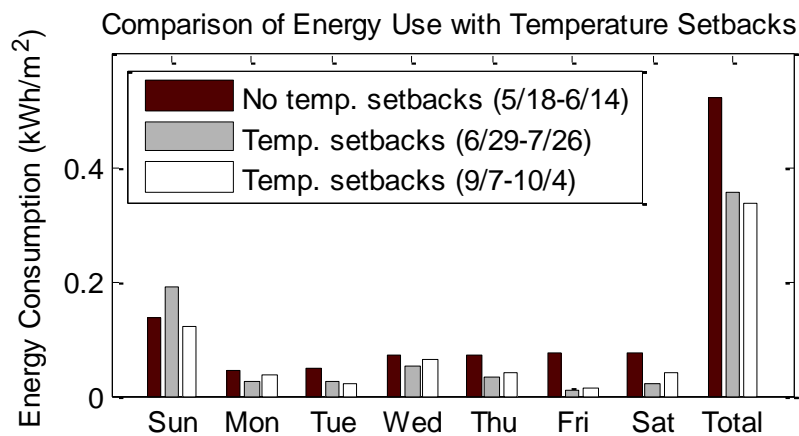


Figure 38. Comparison of average daily use for conditioning the main meeting area with and without temperature setbacks.

Anomalous HVAC Conditions

Although the overall building energy use compares favorably with comparable buildings, several points of obvious waste were discovered and analyzed. Each of these instances of significant energy waste indicates the potential to further decrease energy use. All instances occurred in the College Station church, with no obvious instances of waste in the Orem church. Each instance was analyzed using a combination of data from

space occupancy, HVAC system power, and room temperature. The three different systems that are analyzed and presented are shown in Figure 39. This figure shows the same previous HVAC mapping as in Chapter, but overlays the areas that were affected by the anomalous systems.

There are a total of ten areas that are conditioned in each building. There are an associated ten air handlers to provide conditioned space to each area. The eight systems that condition areas along the perimeter of the building are equipped with a single condenser unit outside. The two main meeting areas in the center are each equipped with to larger condenser units outside. This results in a total of ten air handler units in the building with twelve condenser units.

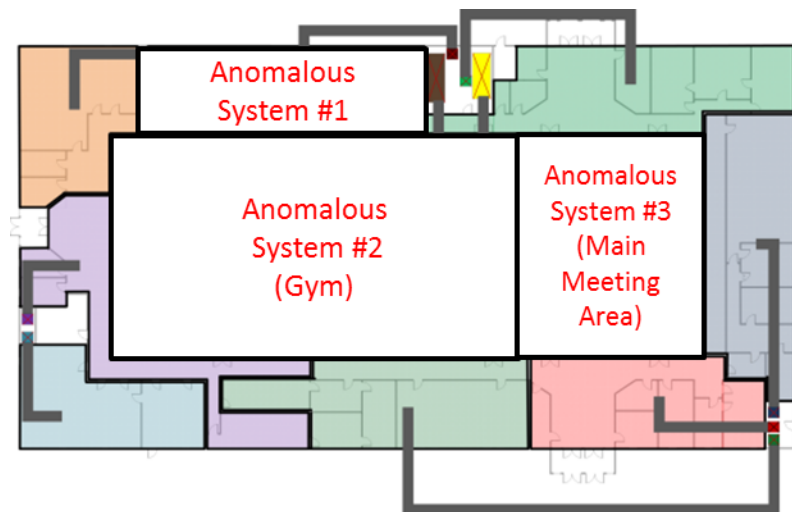


Figure 39. Diagram depicting service areas for the three different identified anomalous systems.

Each of these anomalous systems is discussed individually in the following sections. As will be shown, the symptoms regarding each condition are unique and all result in excess electricity usage for cooling. The energy use attributed to each system is summarized in Figure 40. As seen, especially in the summer months, the total energy use attributed to the anomalous systems is comparable to the remaining combined usage of the other systems. The energy usage for both Anomalous Systems #1 and #2 are shown for the entire year as their state remained constant over the course of the entire year. The energy usage for Anomalous System #3 is only shown for the month of June. The energy usage for every other month throughout the year was consistent with expected use. Therefore, this normal usage is not shown for the other months.

Note that these other seven systems each only have a single condenser unit, which is smaller than either of the condenser units for the larger systems. Consequently, each of these seven systems is expected to consume significantly less energy than Anomalous Systems #2 and #3. Also note that Anomalous System #3 is the same main meeting area that was discussed for temperature setbacks. However, as will be shown, the anomalous energy usage is attributed to a different cause than the lack of temperature setbacks.

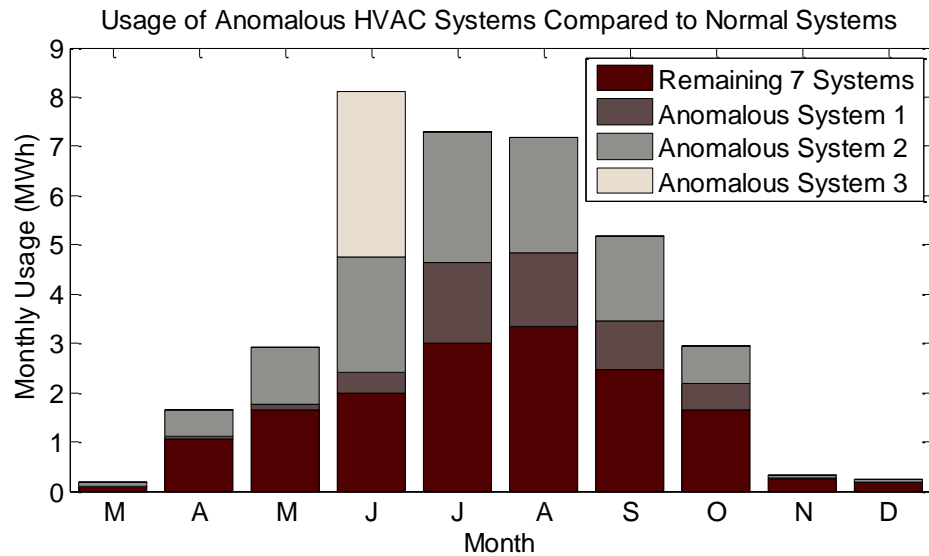


Figure 40. Demonstration of large total usage of the three anomalous systems compared to the seven normal operating systems.

Anomalous System #1- Faulty Sensor

Throughout the course of data collection, this particular system consumed significantly more energy than similar systems due to a faulty sensor. Evidence of this faulty sensor is shown in Figure 41. This figure compares the temperature and energy use of the faulty system with a normal system for a two week period in July 2014. As can be seen in the figure, the anomalous system remained on for days at a time, with the only fluctuation in power consumption coming from weather loads. The normal system shows the expected sporadic use to condition the space when occupied or to maintain the temperature setbacks. The second subplot verifies that the increased energy consumption doesn't come from a larger heat load in the space. Both rooms have a cooling setpoint during occupancy of 75 °F and a cooling temperature setback of 80°F. During a time period when normally unoccupied, the researchers observed that the temperature

displayed at the thermostat was above the cooling setpoint, even though the actual temperature of the space was below the setpoint by a significant margin. The system ran continuously in an attempt to lower the room temperature further.

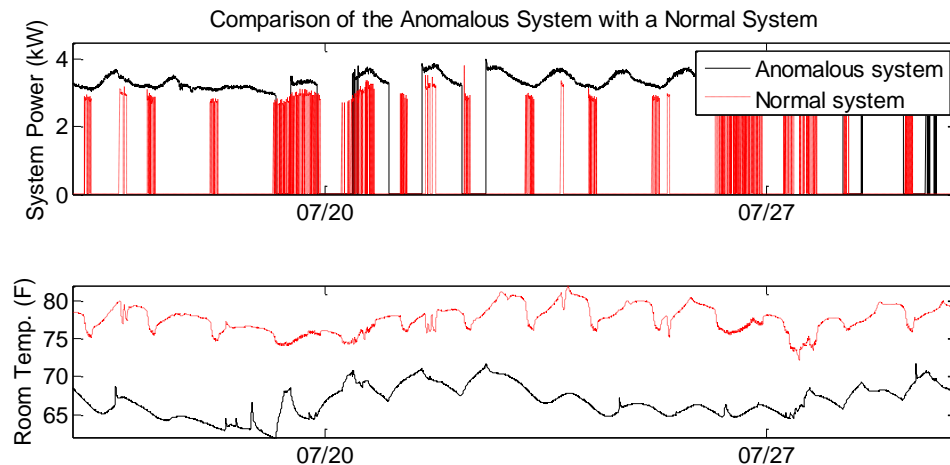


Figure 41. Power consumption and space temperature for the faulty system and a normal system. The faulty system remained on for days, resulting in overcooling of the conditioned space.

Discussions with occupants revealed awareness of a problem in the system. Some comments included complaints of incorrect temperature setpoints and incorrect air flow in the building. The researchers also discovered the windows in those rooms were opened to heat the space during periods of occupancy in the summer.

The increase in energy use compared to two normal systems is shown in Figure 42. Although the operational settings were the same, the system consumed considerably more energy compared to other systems. These other two systems were also along the perimeter of the building, had similar capacities, and conditioned similar rooms. As seen

in the figure, the overcooling of the space led to the large energy usage of the anomalous system. During the summer months, the anomalous systems consumed several times more energy than comparable systems in the mid-summer. The analysis of this faulty system shows an example of how operational faults can both decrease occupant comfort and increase consumed energy.

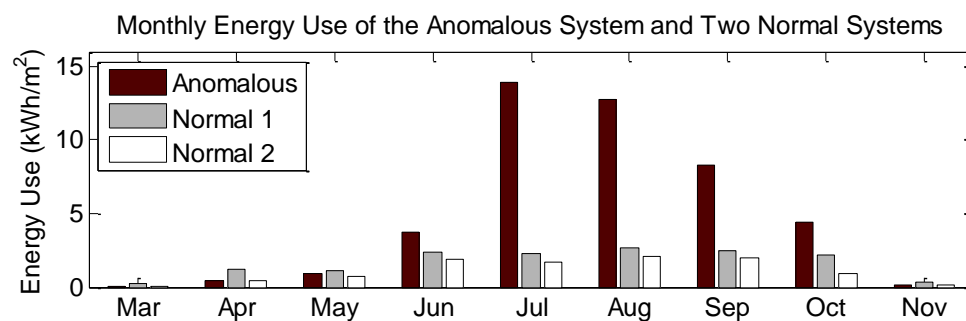


Figure 42. Comparison of energy usage for the first anomalous systems with two normal systems of similar capacity and use.

Anomalous System #2 - Incorrect Thermostat Schedule

The second instance of large HVAC usage occurs in the system servicing one of the large meeting areas. This affected area is a gymnasium that can be used for overflow seating, cultural, or other activities. During data collection, the thermostat was set to occupied mode for large instances of time during the summer months. There were still some instances in which the temperature setbacks were realized, but these periods of time were shorter and much less frequent than the other HVAC systems in the church. Since there were no instances of time in which the system operated with normal temperature setbacks, comparisons can't be made against the same system. Instead, the

energy use of the gym is compared to the other large meeting area to compare losses in this area.

The average space temperature for this system, along with the condenser unit power, for a couple of days is displayed in Figure 43. This figure also shows the temperature profile and condenser unit power for the other main meeting area, for comparison. As seen in the temperature profile, the gymnasium is conditioned to a constant setpoint for several days. Additional data reveal that instances with a temperature setback are limited and the system is set to a constant setpoint for a significant portion of the total time. The figure also shows that one condenser unit serves as the primary unit with the additional condenser as the backup to meet large capacity. As such, one system almost continuously runs while the other system is also used during the middle of the day with higher heat loads.

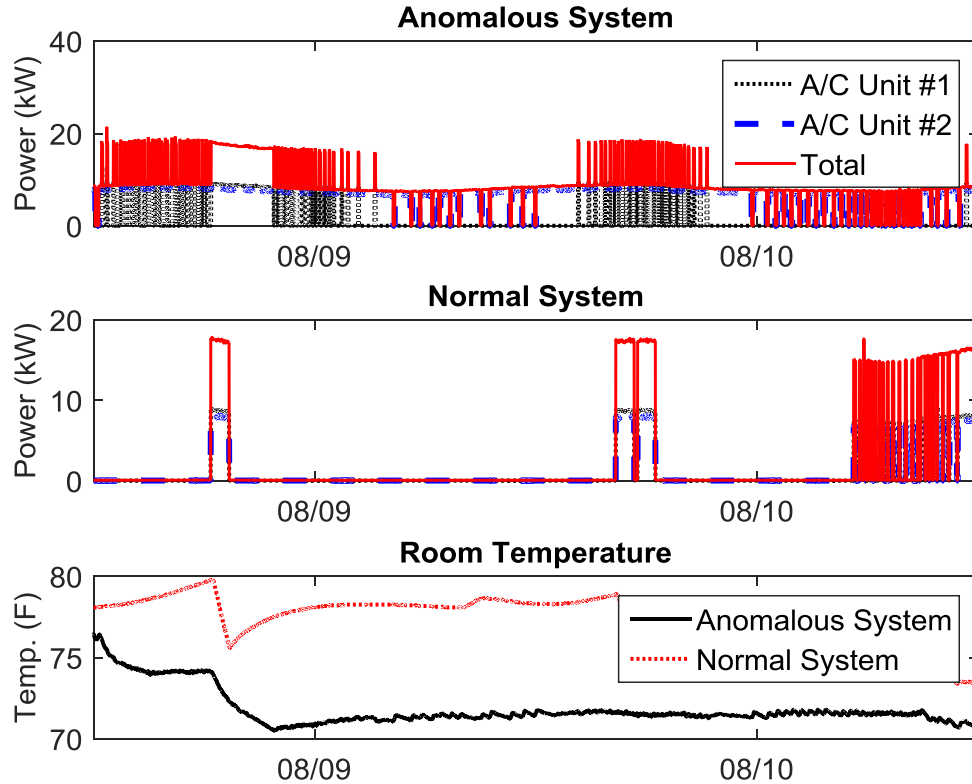


Figure 43. Verification of the constant temperature setpoint for the anomalous system, resulting in significantly larger usage over the normal system with temperature setbacks.

The increased energy usage from the anomalous system is shown in Figure 44. With the exception of May (temperature setbacks in the main meeting area) and June (discussed with Anomalous System #3), the gymnasium shows an increase in energy intensity compared to the other meeting area for the summer months. Both meeting areas are comparable in roof height and are equipped with identical HVAC systems. As with the quantification of energy savings from temperature setbacks, this scenario demonstrates the benefits of relaxing temperature setpoints during periods without occupancy.

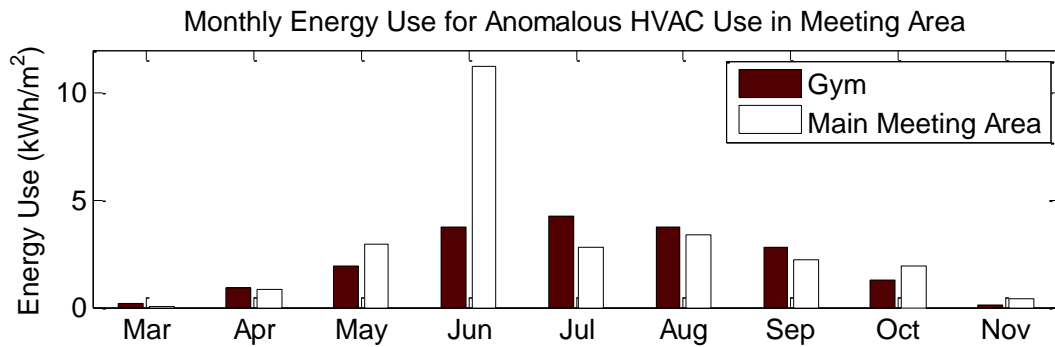


Figure 44. Comparison between HVAC usage for the two large meeting areas. With the exception of May and June (abnormal months for the main meeting area), the gym shows an increase in energy intensity in the summer months due to the limited time with temperature setbacks.

Anomalous System #3 – Incorrect Thermostat Setting

The last observed anomalous condition occurred in the main meeting area in the month of June. The system power and space temperature is shown for the second half of June in Figure 45. The beginning of this time period shows the constant temperature setpoint as discussed previously. The end of this block of time shows the normal operational condition with temperature setbacks and normal HVAC usage. The anomalous condition occurred between the two blocks of time. During this time, the system ran at full capacity for days with both A/C units running. Even in the second half of this block of time, the system ran nearly continuously in conditioning the space. However, in looking at the temperature data, the space temperature during the anomalous condition doesn't correspond well to the HVAC system. The initial temperature drop with the continuously running system is expected, but the system follows a more stochastic pattern afterwards.

The full cause for this disconnection is unknown. Prior to the study, when gathering information at the College Station church, one system was operating with simultaneous heating and cooling. Both the furnace and the condenser unit were running, causing the incoming air to be heated and then cooled. The conditioned space was generally muggy and uncomfortable, despite the running system. A similar condition may have been created when the temperature setbacks were initially implemented, which condition was later corrected to create the normal operating condition found at the end of the month.

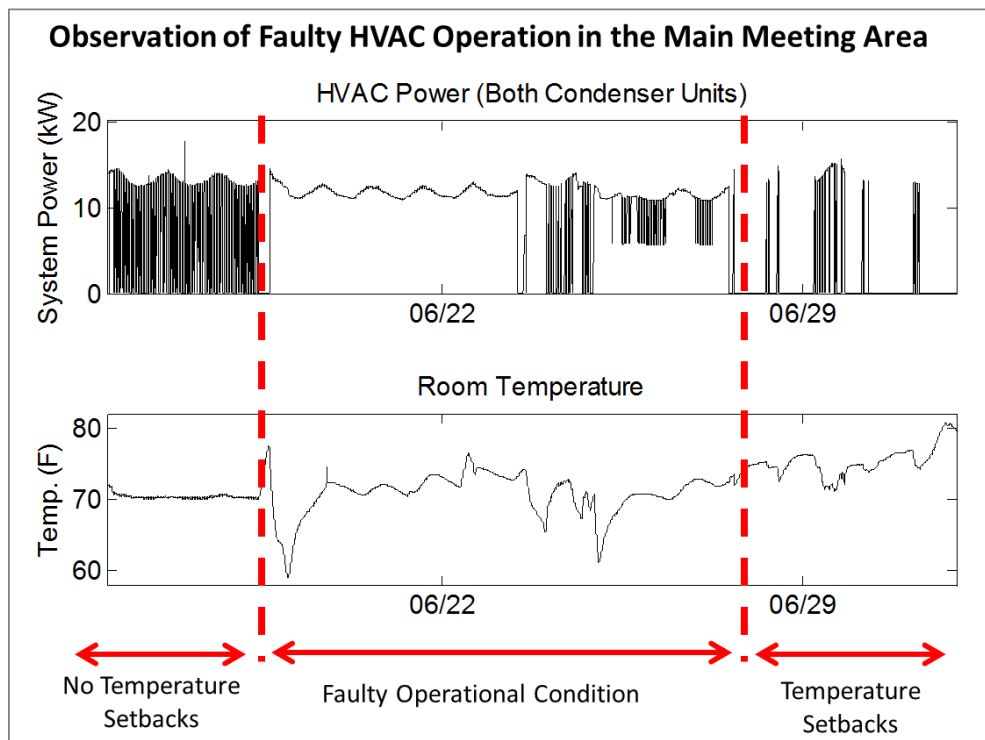


Figure 45. Evaluation for the faulty HVAC usage in June for the main meeting area. The time period without temperature setbacks is shown on the left (discussed previously), and the time period with temperature setbacks (normal operation) is shown on the right. The faulty condition is presented in the center section.

The energy use for this faulty operational month is shown in June in Figure 44. Note that the first half of this month included the time period with a constant temperature setpoint (mid-May to mid-June) and so the energy usage will be elevated from this operational condition. However, the energy use for the total month is several times the expected use for the system based on usage for the other summer months. This once again demonstrates the large energy saving potential for maintaining equipment in a fault-free state.

Dependence on HVAC Compressor Use with Outdoor Air Temperature (OAT)

Several avenues of research on HVAC control employ model predictive control with some sort of energy storage to optimize energy usage and cost while still maintaining a comfortable space. This energy storage may be a complex system involving ice storage or another phase change, or it may be simpler and involve building precooling using the thermal mass of the building. In some cases, different rate schedules based on time of day may be used to minimize cost while assuming the same power draw occurs at all times. In reality, the energy consumed by the A/C unit depends on the outdoor air temperature. The lower power requirements during cooler time periods can be leveraged to store energy during these times to offset usage during the peak temperature.

With detailed data available from twelve condenser units in a warm climate, reasonable estimation on the power requirements from increasing outdoor air temperature can be made. This section attempts to generalize this average increase of

power based on the twelve systems. A scatter plot depicting of instances of data when the A/C unit was running is shown below in Figure 46. This scatter plot is plotted against the outdoor air temperature in Fahrenheit to give a general idea of the trend between power and outdoor air temperature. There is considerable spread in the data. Factors affecting the power draw include wind conditions, cloud cover, shade (from time of day), and humidity. However, there is a definite increasing trend of power with outdoor air temperature. An approximate trendline is drawn on the figure to show the average increase with temperature.

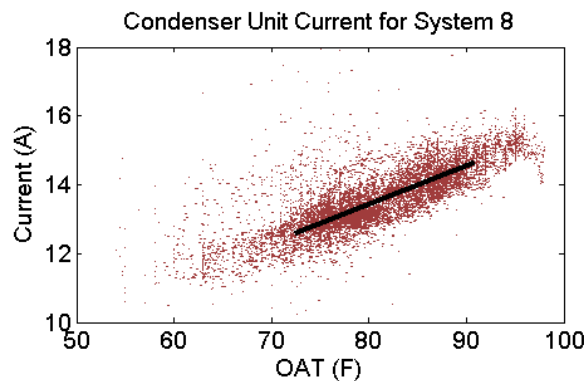


Figure 46. Dependence of power on the outdoor air temperature (OAT) for a specific system. An approximate trendline is shown indicating the general relationship.

The same scatter plots were created for each of the twelve systems and similar data were seen. For each system, there is a definite increasing trend that depends on outdoor air temperature. A couple of interesting systems are displayed in Figure 47. In both systems, there appears to be a second operating condition in which the power (and likely cooling capacity) is significantly lower than the average power. There are no

specific indicators suggesting the reason for this second operating condition. The second point of interest is the nonlinear increase of power seen for System 9 (rightmost plot of Figure 47). The majority of systems show a more linear relationship, similar to System 7 and 8. However, a couple of the systems showed this nonlinear relationship.

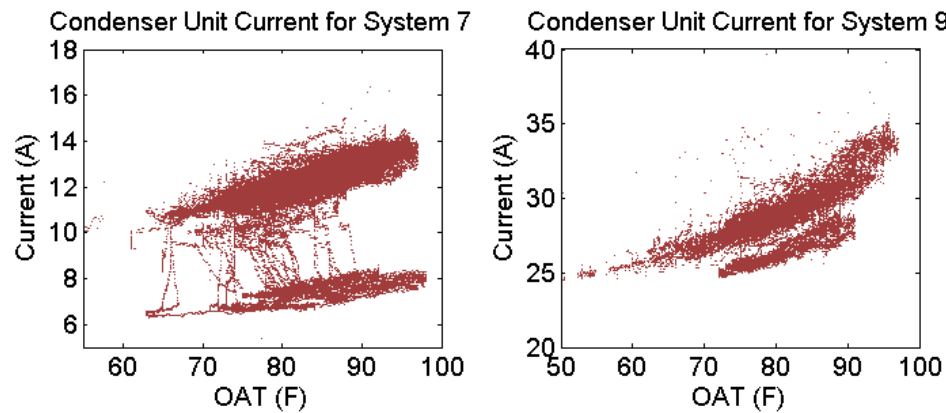


Figure 47. Correlation of system power with outdoor air temperature (OAT) for two different systems. Both systems exhibit a dual operational state. The system on the right shows a nonlinear increase of power with temperature.

In estimating the increase in power consumption, trendlines were drawn for each system, similar to what was shown in Figure 46. Even for those systems with a nonlinear increase in power, an approximate linear trend was drawn to try and provide an estimate of average increase of power. The percent increase of power per degree (°F) outdoor air temperature was calculated and is displayed in Figure 48. These same data are tabulated in Table 8. Even with considerable spread in the data for each system and large variation between systems, the average increase in required power is consistent across all systems. As seen in Table 8, the average increase is almost exactly 1% / °F with a standard

deviation of 0.14%. These data provide a useful guideline to those seeking to determine the relationship between HVAC system power with outdoor air temperature if no system-specific data are available.

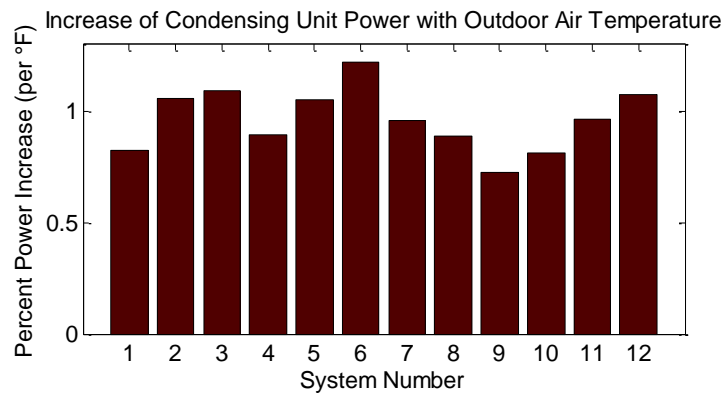


Figure 48. Average increase of system power per degree Fahrenheit for each system in the College Station church.

Table 8. Increase of system power with outdoor air temperature

System	Average Percent Increase (per °F OAT)
1	0.82%
2	1.06%
3	1.09%
4	0.90%
5	1.05%
6	1.22%
7	0.96%
8	0.89%
9	0.73%
10	0.81%
11	0.96%
12	1.07%
Average Increase	0.96%
Standard Deviation	0.14%

Summary

This chapter discussed experimentally-measured HVAC usage in the two churches. Initially, the general heating and cooling trends were identified and were found to be consistent with expected operational conditions. A 4-week instance in one of the systems was discovered where temperature setbacks were not implemented, and this block of data was compared to other instances with temperature setbacks to estimate the energy savings from implementing temperature setbacks. Several different anomalous conditions in HVAC usage were discovered and discussed in regards to the wasted energy and cause of the faulty conditions. Finally, the increase in required condensing unit power with outdoor air temperature was quantified and discussed.

CHAPTER VI

THERMAL COMFORT AND CO₂ LEVELS

This chapter analyzes comfort at a basic level in the two buildings. There are many elements that contribute to thermal comfort, and this chapter analyzes some straightforward methods to understand at a high level comfort in the building. The chapter begins by discussing ASHRAE Standard 55 and Predicted Mean Vote as a means to estimate thermal comfort. An overall estimation of comfort building wide is then presented for both buildings. The main meeting area in both churches is analyzed with regards to the ASHRAE Standard 55 and Predicted Mean Vote. A brief analysis on the estimated time required to condition the main meeting area to its steady state operating condition is then presented. The chapter concludes by analyzing CO₂ levels in the building with regard to occupant comfort.

ASHRAE Standard 55 and Predicted Mean Vote

The American Society of Heating and Air Conditioning Engineers (ASHRAE) publishes standards on minimum building requirements to maintain thermal comfort to occupants. One of the most common figures related to this standard is given in Figure 49. This image is based on Fanger's Predicted Mean Vote (PMV) model [6]. The predicted mean vote varies from -3 to +3 and is a measure of the average comfort level of occupants based on certain environmental conditions. A lower number results in a larger number of people finding the space uncomfortably cool. In the figure, the humidity ratio is shown on the axis. The relative humidity, the value most often

recorded, is shown with the curving lines. The values of relative humidity increase with increasing absolute humidity and decreasing temperature on the graph.

In the figure, the boxes outline the ASHRAE Standard 55 limits for two different clothing levels. These levels are typically seen by occupants in winter and summer months. The limits on the left and right of the boxes outline a PMV of ± 0.5 for the given clothing levels, assuming the other factors relating PMV are typical of an office building. The upper limit is a humidity limit set by ASHRAE Standard 55.

Thermal comfort (and corresponding PMV) for occupants depends on six different parameters: air temperature, relative humidity, mean radiant temperature, air velocity, clothing level and metabolic rate. As the purpose of the study was an overall energy study and not an in-depth study on comfort, the only consistent data available are the air temperature and relative humidity. The other values will be assumed based on expected building usage as is commonly done when evaluating thermal comfort.

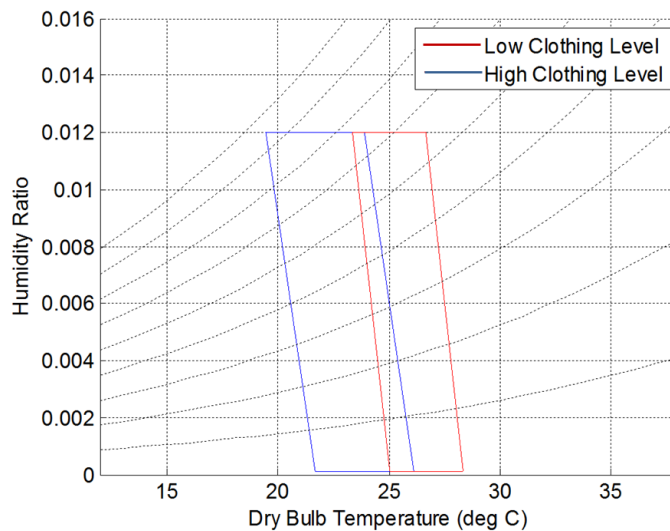


Figure 49. ASHRAE Standard 55 limits for both high and low clothing levels.

Overall Building Comfort

In looking at overall building conditions and comfort from a high level, the average PMV was calculated for each building over the course of the study. The values over all rooms of the building were averaged at every point in time to give an estimation of comfort of the building as a whole. This overall building comfort is displayed in Figure 50 for the Orem church and Figure 51 for the College Station church. In the calculations for PMV, a clothing level of 1.0 was used, which is approximately the clothing level of someone in trousers and a long shirt. The actual clothing level will vary significantly, which will have a significant value on the PMV. However, this value was chosen as a median value to gauge overall comfort levels.

As seen in Figure 50, the PMV generally decreases with the change in seasons with obvious spikes in a higher PMV. These spikes correspond to Sunday usage when

the building is heavily conditioned. There is a similar trend in the College Station church with rising PMV values in the summer months and lower values during the cooler months. The spikes in the cooler months for this church aren't nearly as pronounced. In both churches, during times with lower occupancy in the winter months, the percent of people dissatisfied in regards to thermal comfort is high. If there are periods of occupancy during these instances with temperature setbacks, the occupants will likely be thermally uncomfortable.

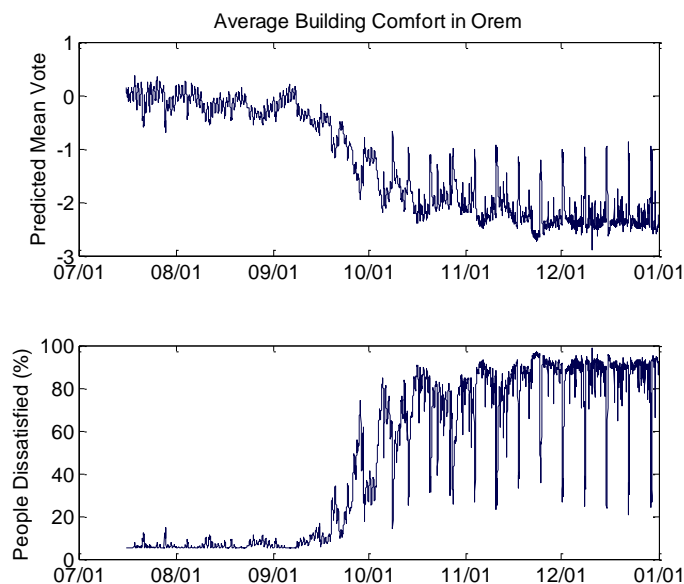


Figure 50. Predicted Mean Vote (PMV) over all rooms in the Orem church. Note the spikes in PMV during the latter half of the study during Sundays when the building is heavily conditioned. Values relating the percent people dissatisfied based on the PMV are shown in the bottom plot.

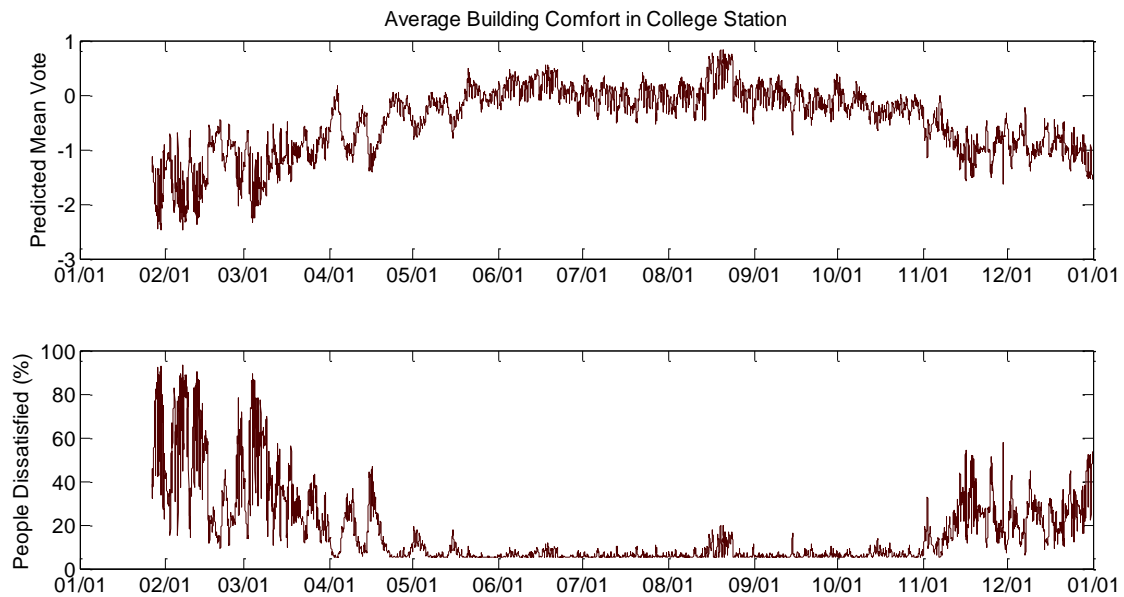


Figure 51. Predicted Mean Vote (PMV) over all rooms in the College Station church. Values relating the percent people dissatisfied based on the PMV are shown in the bottom plot.

These same data were compiled and averaged based on a typical week during data collection. Figure 52 and Figure 53 shows the average PMV of the building over a representative week for the Orem and College Station churches, respectively. As can be seen in Figure 52, there is a definite rise in PMV during Sunday to a more comfortable level. The remaining week shows fluctuations typical of weather patterns. An overall similar trend is seen in the College Station church in Figure 53. The principal difference for the average PMV in this church is the overall higher levels for PMV throughout the week. This comes from the warmer climate, as this week is the average over all weeks of data collection. The peak on Sunday is much less pronounced as the average PMV is already similar to the setpoint building conditions during occupied times.

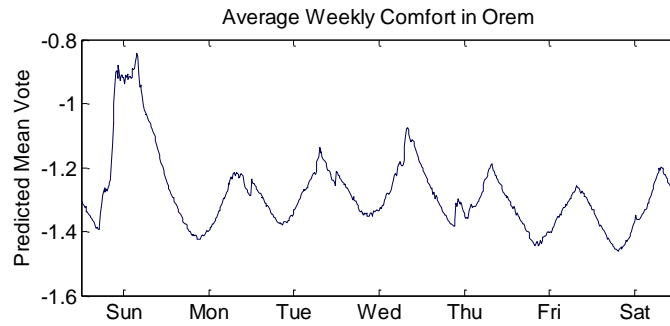


Figure 52. Average Predicted Mean Vote over a representative week for the Orem church. There is a notable increase in thermal comfort during Sunday.

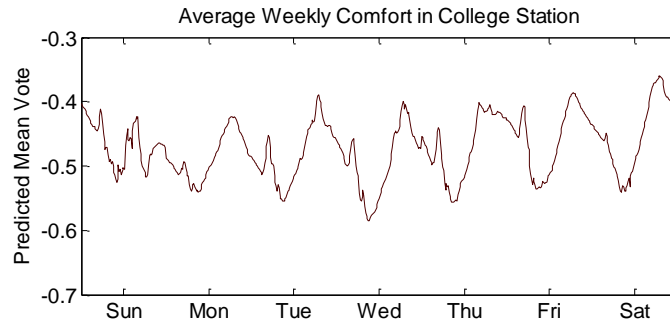


Figure 53. Average Predicted Mean Vote (PMV) over a representative week for the College Station church. The spike in PMV is much less pronounced in this church, likely due to the higher overall values of PMV during the week.

Thermal Comfort in the Main Meeting Area

In analyzing thermal comfort, the main meeting area is chosen specifically for analysis due to the long meeting times with heavy occupancy. The overall thermal comfort based on Figure 49 for the main meeting area in both churches is presented in the following figures.

The thermal comfort for the main meeting area in the Orem church is shown in Figure 54. This shows the thermal comfort in relation to ASHRAE Standard 55 for the two different clothing levels. The figure plots all instances when the meeting area is occupied for the different months of data collection in 2013. As seen in the figure, the space is never outside the standards in regards to high humidity. Instead, instances outside of the standard occur from the space being too cold in the colder months. The overall comfort profile consistently migrates to cooler values with decreasing outdoor temperatures.

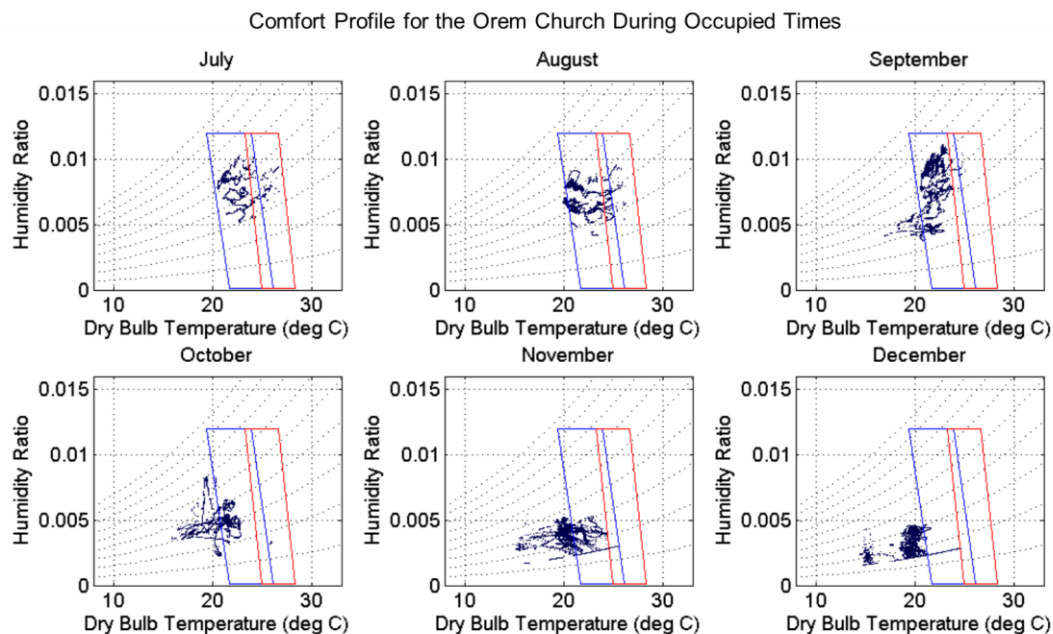


Figure 54. Thermal comfort profile in the main meeting area in the Orem church based on ASHRAE Standard 55.

The same comfort profile in the main meeting area is shown for the College Station church in Figure 55 and Figure 56. These figures show a similar trend to the Orem church in that the cooler months are characterized by instances outside of the standard because of cold air temperatures. In the summer months, in large part because of an upper temperature setback of 80°F (27 °C), the standard is not exceeded from high temperatures. Instead, the most common instances of failure to comply with the standard during summer months come from high humidity levels in the main meeting area. Note that in May, the month that had no temperature setbacks for the entire month, all instances of occupancy are located within a tight region. This shows that one potential benefit, at the cost of higher energy usage, of not implementing temperature setbacks is a higher overall comfort level from maintaining the temperature during all times. However, that statement is difficult to verify, as the natural evolution of comfort conditions in the space from March through June migrate through the values seen in May.

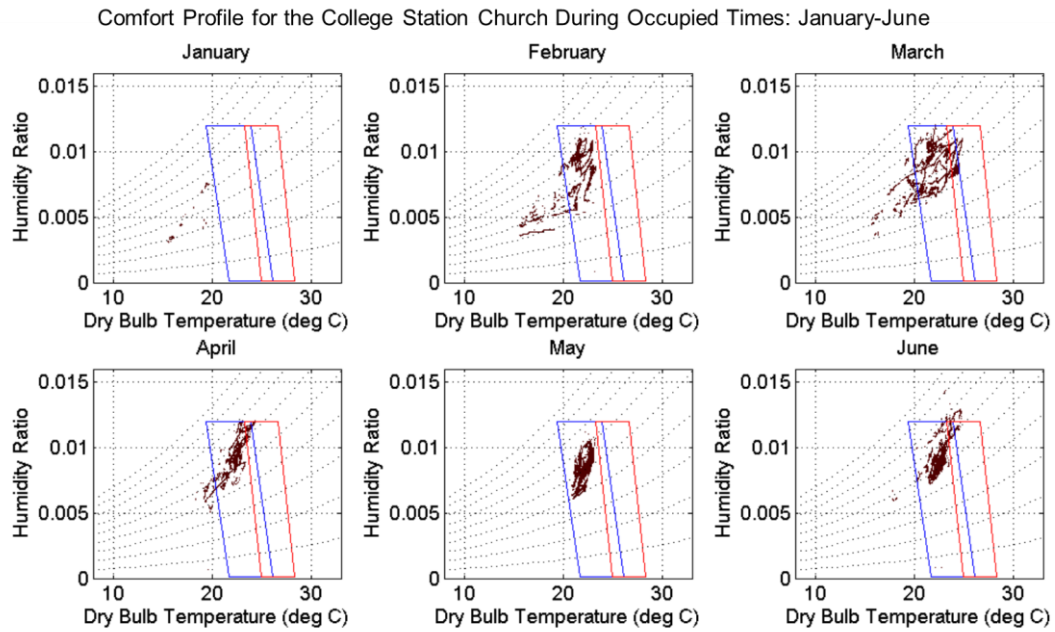


Figure 55. Thermal comfort profile in the main meeting area in the College Station church based on ASHRAE Standard 55 for the first six months in the year.

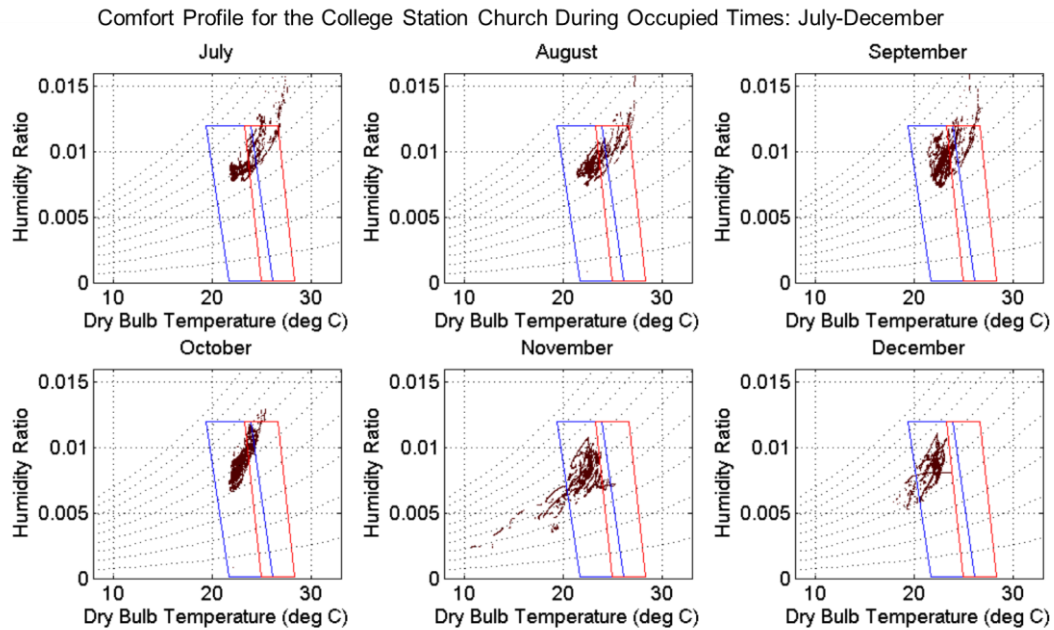


Figure 56. Thermal comfort profile in the main meeting area in the College Station church based on ASHRAE Standard 55 for the last six months in the year.

In analyzing the main meeting areas for thermal comfort, the evolution of comfort during occupancy is presented in Figure 57. This figure shows all longer instances of occupancy in the main meeting area in the College Station church. The same data for the Orem church are presented in Figure 58. The period of time prior to occupancy and after occupancy is shown to show how the conditions change dependent on occupancy. The average value for PMV is shown along with bounds of ± 2 standard deviations away from the mean. As seen in the figure for College Station, the overall comfort in the meeting area converges to its final value (and minimum standard deviation) after around 80 minutes of occupancy. Similar trends are seen in the Orem church but with a longer time to converge to the minimum standard deviation. The

average time to reduce the standard deviation is approximately 180 minutes (3 hours).

These plots highlight the potential to increase the degree of precooling in order to ensure comfort of occupants during periods of occupancy.

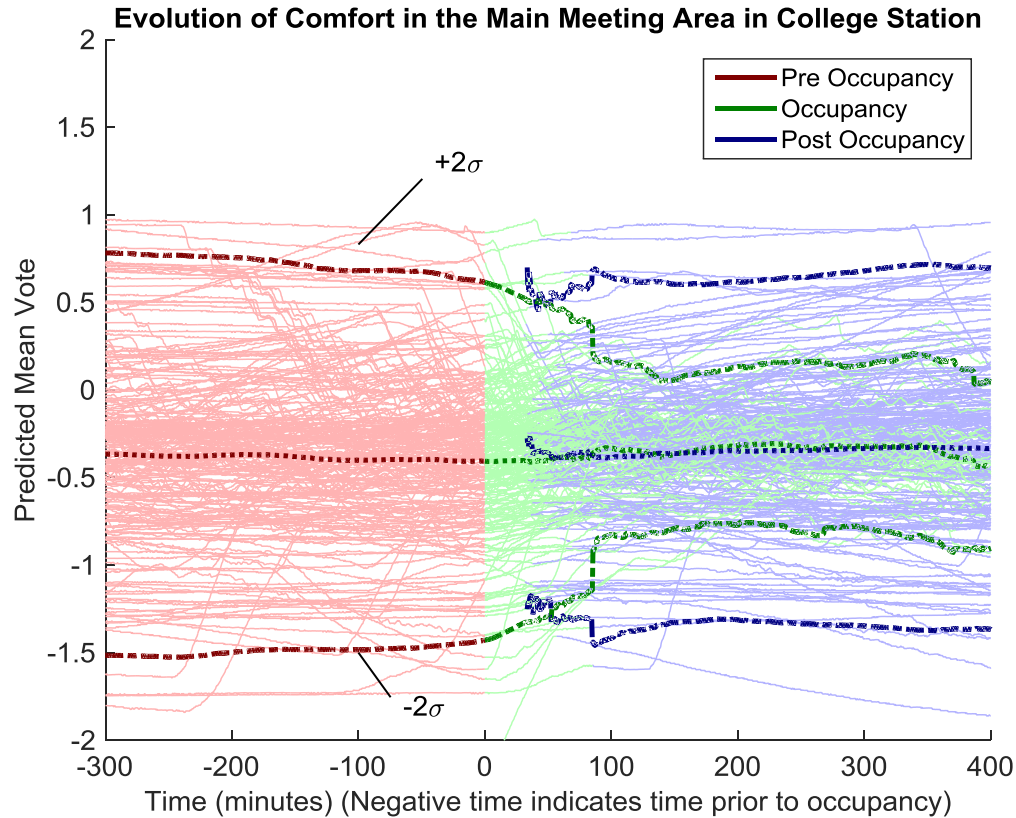


Figure 57. Evolution of comfort for the main meeting area in College Station. This shows thermal comfort for all instances of occupancy greater than 30+ minutes before, during, and after occupancy.

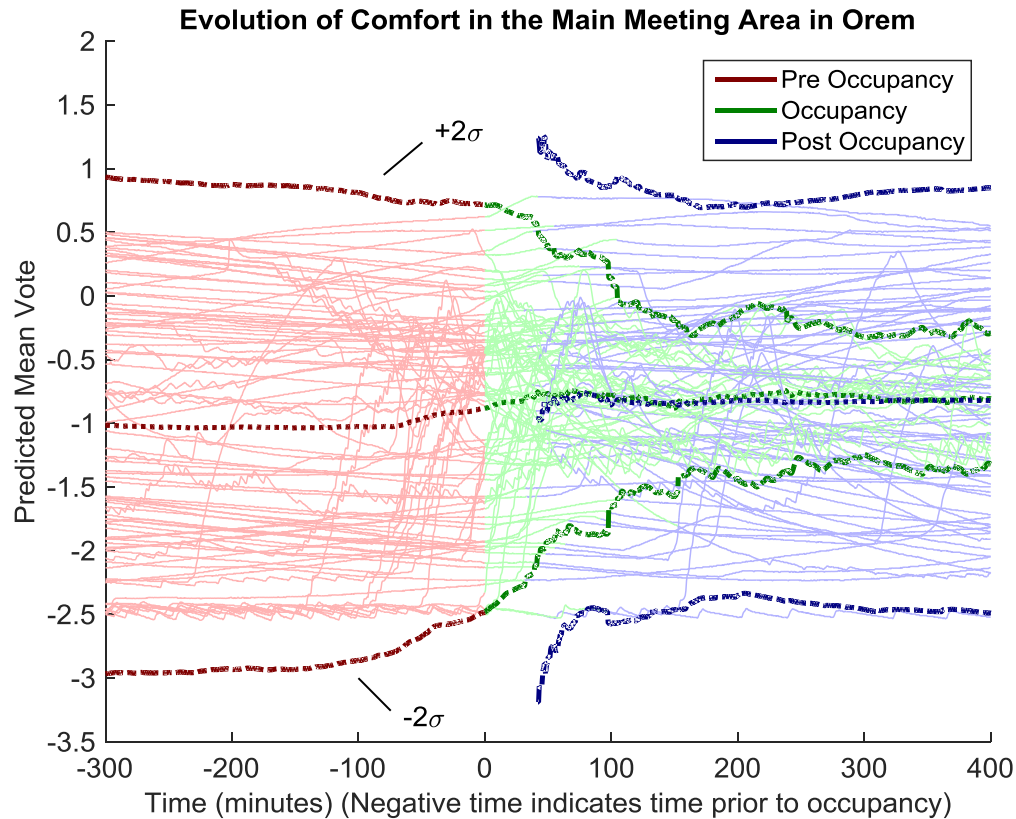


Figure 58. Evolution of comfort for the main meeting area in Orem. This shows thermal comfort for all instances of occupancy greater than 30+ minutes before, during, and after occupancy.

Building CO₂ Levels

One common area of interest in building performance is maintaining acceptable CO₂ levels. ASHRAE sets acceptable limits for CO₂ to maintain a comfortable environment for occupants. The recommended limit for CO₂ levels is 700 ppm above normal background levels. In evaluating CO₂ levels throughout the building, a single CO₂ sensor was rotated to three different areas of interest: 1.) the main meeting area, 2.) one of the offices, 3.) a children's meeting area.

Figure 59 shows the CO₂ levels of one of the offices from mid-May to mid-July in 2014. The background level for CO₂ is approximately 500 ppm, resulting in an acceptable limit of 1,200 ppm. As seen in the figure, the CO₂ levels rise significantly above the recommended 1,200 ppm consistently through the time period. Many of the peaks correspond to Sundays when the building has a high intensity of usage.

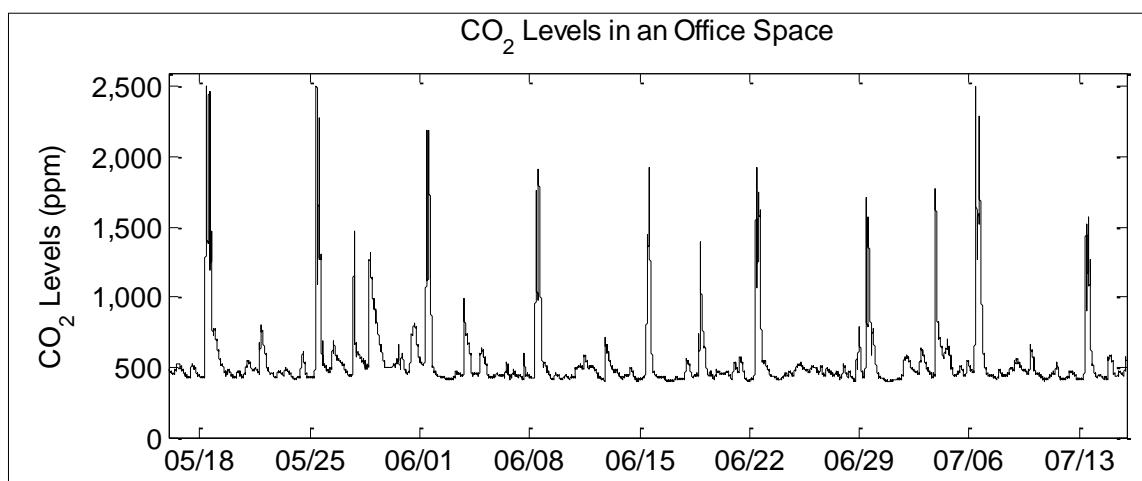


Figure 59. CO₂ levels in an office space over approximately one month of data collection. Large spikes occur during heavy occupancy and exceed the recommended CO₂ levels.

Similar high CO₂ levels were found in the other areas of the building as well. Each area experienced large peaks in CO₂ levels during time periods of heavy occupancy. These levels exceed the recommended limits for CO₂ and present an opportunity for improving building operation. A summary of the CO₂ levels for each Sunday of data collection is given in Table 9. The average maximum CO₂ value was calculated by taking the maximum CO₂ value for each Sunday of data collection and averaging these values over all Sundays. The average CO₂ value was calculated by

averaging the CO₂ levels for each Sunday between 8:00 am and 6:00 pm. Of particular interest is the maximum sensor capability of the CO₂ sensor. The sensor limit was 2,500 ppm, and the CO₂ levels in the children's meeting area exceeded this value each week during data collection. Therefore, the actual maximum CO₂ value and average CO₂ value will be larger than those listed in the table.

Table 9. CO₂ values for different areas of the building during data collection

Area	Average Maximum CO ₂ Value	Average CO ₂ Value
Main Meeting Area	1,725 ppm	1,120 ppm
Children's Meeting Area	2,500 ppm*	1,540 ppm*
Office	2,080 ppm	1,300 ppm

* Note that 2,500 ppm is the sensor limit, so the actual values will be higher than those listed.

Figure 60 shows the CO₂, occupancy, and HVAC data for the main meeting area on a particular Sunday. The CO₂ levels rise above the acceptable limit of 1,200 ppm. In general, many buildings will experience high CO₂ levels when the space is occupied but not conditioned. However, occupancy and HVAC data reveal that the CO₂ levels still rise above acceptable limits, even when the space is conditioned. The time period between 9:00 AM and 10:30 AM illustrates rising CO₂ levels even when the space is conditioned. This reveals the need to bring in additional outside air when space conditioning to maintain acceptable CO₂ levels.

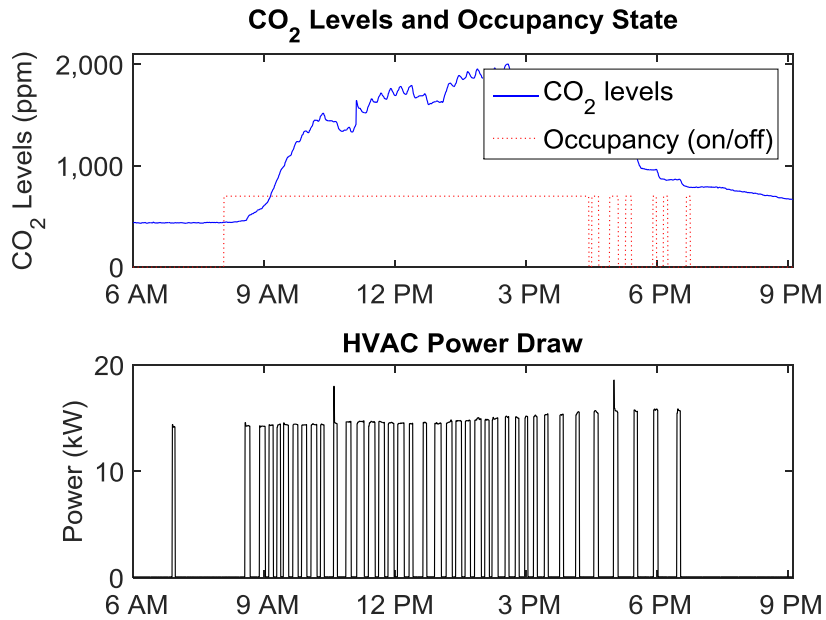


Figure 60. Analysis of CO₂ levels during one Sunday for the main meeting area. Despite conditioning throughout the day, CO₂ levels still exceed recommended limits.

Summary

This chapter investigated thermal comfort in both church buildings based on ASHRAE Standard 55 and Predicted Mean Vote. Both churches have extended periods of time with a low PMV throughout the building. Even during periods of occupancy, the average conditions in the main meeting area for both churches are cold during the cooler months. Evolution of thermal comfort with occupancy shows the long time necessary to converge on steady PMV conditions. Analysis of CO₂ levels in the building illustrate the need for additional outside air for ventilation.

CHAPTER VII

CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

This chapter, although brief, serves to highlight potential future avenues for data analysis that have the potential to yield significant results. The chapter starts by discussing extensions of current effort that can be explored. The chapter then explores the potential to model the building and use that model for optimal temperature control strategies. The chapter concludes by discussing the potential avenues in regards to building energy simulation.

Extensions on Current Analysis

Although this thesis attempted to perform a complete analysis on all systems that are typically analyzed in the literature, there are likely specific instances in which the analysis could be extended. This thesis specifically looked at basic analysis for building energy usage, occupancy lighting, space conditioning, and thermal comfort. In each of these areas, there are potential future analyses that are available through the depth and breadth of data. For example, investigation of the additional energy requirements on space conditioning from humidity could be explored. The analysis performed in the thesis were not intended to be exhaustive; rather the attempt was to sufficiently analyze each system to understand how these unique buildings operate and detect obvious operational changes or potential retrofits that yield large energy savings.

Future Modeling and Control Efforts

Often the use of advanced control strategies on HVAC systems is explored to reduce the energy use for heating and cooling. A first step in this effort is the inclusion of temperature setbacks to reduce space conditioning requirements when the space is unoccupied. Additional control strategies can be employed to determine the optimum amount of preheating or precooling to ensure thermal comfort while generating energy savings. With occupancy data, model predictive control can be used to determine the optimal control strategy.

These advanced control strategies require a model to predict the energy use and building conditions with changes in disturbances. There is a significant amount of research performed on automated building modeling using experimental data, including research in our research laboratory group. Data from the church can be used to create these models. An example of this is shown in Figure 61 below. This plot on top was shown previously in the thesis to illustrate the large thermal mass of the building. The bottom plot shows the same data as the top plot but with normalized temperature profiles to highlight the relationship between the space temperature and the outdoor temperature.

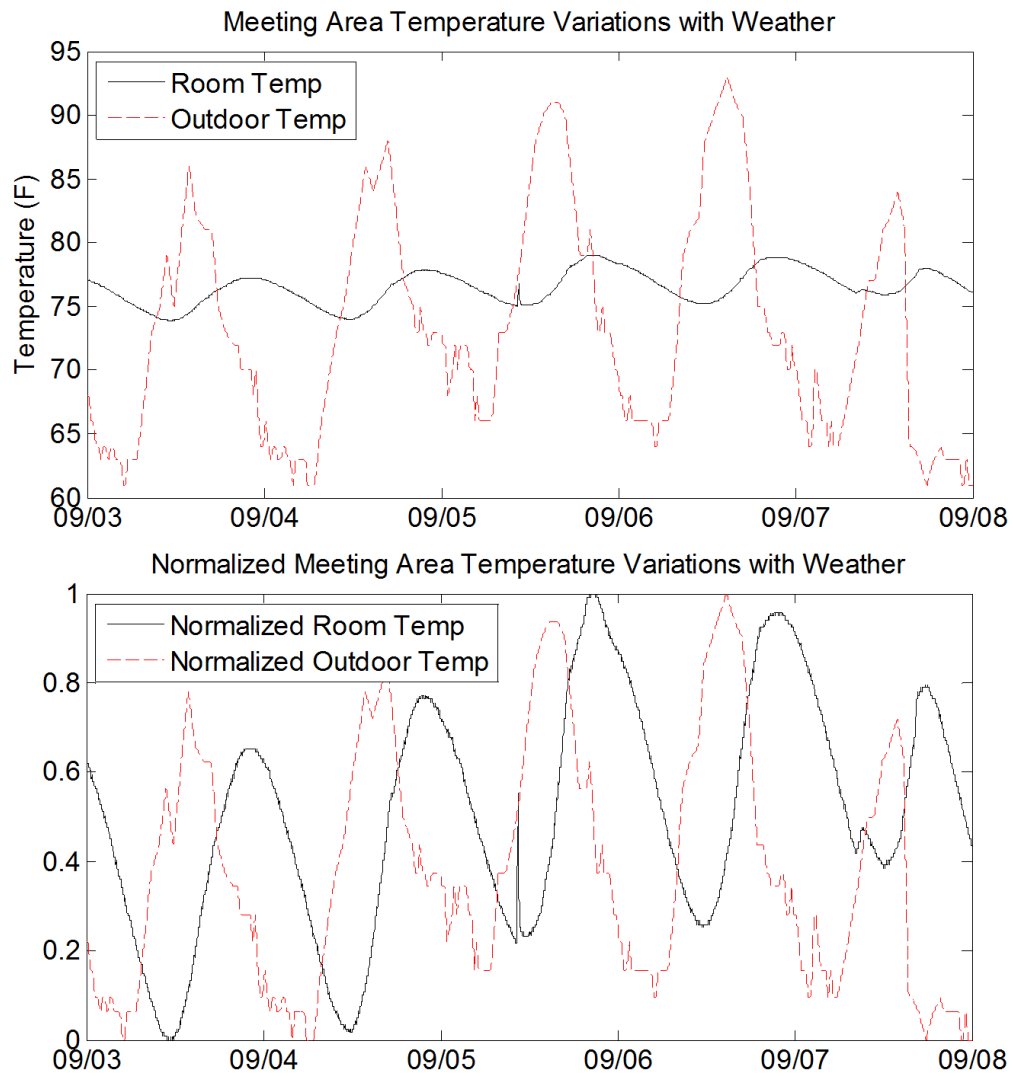


Figure 61. Variation of room temperature as a function of outdoor air temperature. The bottom plot normalizes the temperature data to show the relationship more clearly.

The data between the room and outdoor temperature can be correlated through a first-order model. Higher orders may also be explored, but for this simple example a first order system is sufficient. Once the model is created, the room temperature based on

initial conditions and the outdoor weather is predicted in simulation. The weather data act as the disturbance (input) to the model and the room temperature is the output. The resulting estimated temperature profiles are then compared to actual temperature profiles to judge to validity of the model, as seen in Figure 62. Using the available data from the HVAC system, weather conditions, occupancy, and neighboring rooms, accurate models can be created that will allow for sophisticated analysis on energy savings from advanced control strategies.

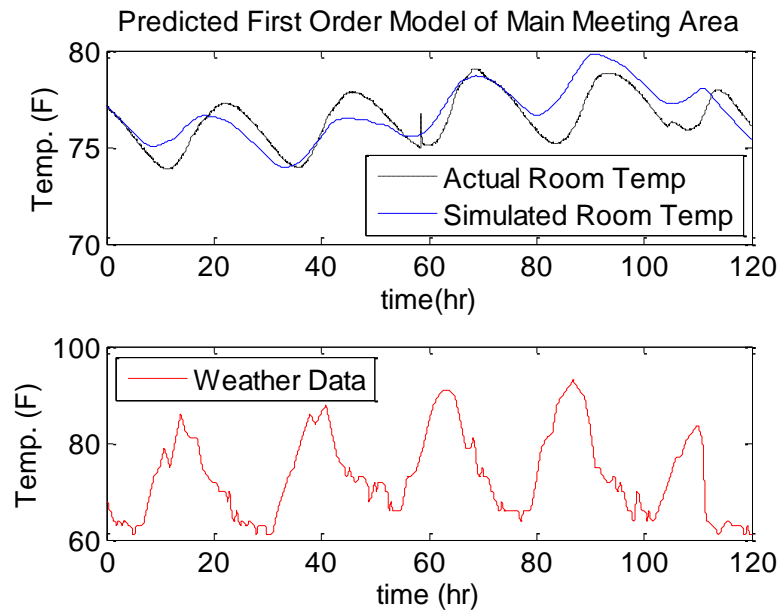


Figure 62. Preliminary validation of a first order model of the main meeting area.

Building Energy Simulation

Many papers related to energy efficiency in buildings, including those studying mosques, obtain their predicted energy savings through simulation. Building energy simulation is a popular technique to evaluate a building because of the low cost and relative ease to setup building models and run simulations. Many different energy simulation programs exist, including several free programs through the Department of Energy. Building simulation programs provide a simple avenue to compare many different retrofits, including upgrades to windows, insulation, or other materials. Additionally, different operational schedules for equipment can be evaluated very quickly. Also, the geographic location and orientation of the building can be rapidly changed, allowing for a straightforward comparison between different climates.

One of the more difficult aspects of building energy simulation is correctly predicting from the simulation the correct building energy use. If experimental or utility data are available, the total usage can be matched to simulated data in the ground truth case. With a large range of potential data available, the models built to simulate energy usage in the churches can be matched to data to provide a reliable estimate of total energy usage and potential energy reductions.

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APPENDIX

ESTIMATION OF ELECTRICAL LOADS FOR THE ENERGY BALANCE

The major loads used in predicting the total electricity usage in the churches include indoor lighting, parking lot lighting, HVAC usage, and peripheral loads (plug loads, unsensored lighting, routers, etc.). In the College Station church, data loggers were installed on the routers, refrigerator, and other small plug loads to measure the average usage over time. These values were used to obtain representative uses from different appliances.

The majority of the interior lighting was measured with data loggers. Each logger was correlated to the total number of associated watts. Once the total time with lighting was measured, the corresponding power was calculated. For lights without loggers, the amount of time the lighting was on was estimated to estimate the total power from these fixtures. As mentioned earlier, these typically were closets and other rarely-used areas and constitute a minor fraction of the total electricity usage. The additional estimated energy from this lighting was added on to the measured lighting usage. For outdoor lighting, the total power from all fixtures was determined. The outdoor lights are set on timers or photocells, so the estimated time on was approximated at 12 hours each day. Although this number likely is a little larger during the summer and shorter during the winter, this provides a reasonable approximation for the energy balance.

The power from the HVAC system was measured with current loggers installed on the condensing units for each system. The approximate power draw from the air

handler fan was measured with a portable current logger. Each time the compressor was on, the measured power was augmented with the estimated power from the air handler. During heating, when the furnace is on, the fan power is the only major contributor to the electricity usage. There is a small pump/compressor for the natural gas, and the average power was recorded with a portable data logger. This electricity usage is also added during heating, but the total contribution is small.

There are several computers in offices and in a room used for researching genealogy and family history in the Orem church. In the College Station church, computers were found in several of the offices. During each downloading period every two weeks, the number of computers that were running was recorded. This was used to provide an estimated average on the number of computers left on at a given time, since the power draw from running computers is higher. Although this will be subject to estimation errors, the total contribution of the peripheral loads constitutes a small percentage of the total. Therefore, errors from estimation to the total energy balance will be minimal.