THESIS

USE OF BIM-BASED ENERGY SIMULATIONS TO ANALYZE THE IMPACT OF OCCUPANT BEHAVIOR ON ENERGY PERFORMANCE OF COMMERCIAL BUILDINGS

Submitted by

Sanjeev Yogi

Department of Construction Management

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Master's Committee:

Advisor: Svetlana Olbina

Kelly Strong
Laura Malinin

ABSTRACT

USE OF BIM-BASED ENERGY SIMULATIONS TO ANALYZE THE IMPACT OF OCCUPANT BEHAVIOR ON ENERGY PERFORMANCE OF COMMERCIAL BUILDINGS

The impact of occupant behavior on the energy performance of a building has been studied for a very long time. However, despite many studies, occupant behavior is difficult to understand due to its complex and unpredictable nature. Usually, occupant behavior is oversimplified and poorly represented; hence, one fails to make the correct assessment of the impact of occupant behavior on building energy performance. To make a precise prediction of the impact of occupant behavior on building energy consumption, it is imperative to develop better techniques in terms of analyzing occupant behavior and methods of research.

Occupant behavior is stochastic in nature and varies widely depending on the characteristics of the building. Some occupants are proactive in saving energy while others are wasteful. Based on the workstyles of the occupants, occupant workstyles can be divided into three categories: austerity, standard and wasteful. As building characteristics influence both occupant behavior and energy performance of buildings, it is important to incorporate building characteristics into any building energy analysis to make the correct assessment of the impact of occupant behavior on the energy performance of the building. This can be achieved by using the building information modeling (BIM) based energy simulation for different categories of occupant behavior.

This research used BIM to study and analyze the effect of different categories of occupant behavior on the energy performance of the building. To achieve this goal, most influential building characteristics and parameters of occupant behavior were identified; case study of occupant behavior on commercial building at Colorado.

State University (CSU) was performed and guidelines to minimize the impact of wasteful workstyle on energy performance of the commercial buildings were developed. The identified most influential building characteristics of commercial buildings in this research were used to create the building information models in Revit which were then exported to DesignBuilder for simulations of annual building energy consumption. The identified parameters of occupant behavior for different types of workstyles were inputted in DesignBuilder before performing energy simulations. The simulation procedure was also illustrated in one of the commercial building at Colorado State University.

The analysis of the simulation results showed that energy performance of the building is affected by the occupant behavior. The change of occupant workstyle from wasteful to austerity decreased the annual energy consumption between 41% and 58% while change of occupant workstyle from wasteful to standard decreased the annual energy consumption between 9% and 19%. Similarly, the decrease of annual energy consumption was between 33% and 45% due to change of workstyle from standard to austerity.

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1 CHAPTER 1- INTRODUCTION

The building sector consumes nearly half of the world's energy and thus offers significant potential for energy savings. Residential and commercial buildings are of primary consideration in the discussion about energy consumption in the building sector as 40% of the energy used in the United States is associated with residential and commercial buildings alone (*U.S. Environmental Protection Agency*, 2009; Alfakara & Croxford, 2014). In both developed and developing countries, building energy consumption in the residential sector forms a large part of total national energy consumption. In developed countries like the US and Japan, it accounts for 25% and 26% of total domestic energy consumption respectively; in developing countries like China and Thailand, it ranges from 11.3% to 15.4% (Richardson, Thomson, & Infield, 2008).

Energy consumption in residential buildings is rapidly increasing because of the rapid growth of the economy and living standard of people (Van Ruijven, De Vries, Van Vuuren, & Van Der Sluijs, 2010). In the US, the energy demand in both the residential sector and commercial sector has been growing rapidly since 1990; a, the rate of growth of energy demand in the commercial sector is 2.9% higher than the rates of other energy end-use sectors (*Energy Information Administration*, 2015). To address this growing energy demand of buildings, design standards for the energy performance of buildings and appliances have, likewise, become increasingly stricter (Chen, Yang, Yoshino, Levine, Newhouse, & Hinge, 2015). Chen et al. (2015) have further suggested that building energy use depends on several factors like climate, the building envelope, building services and energy systems and the occupant's activities and behavior. Among these several factors, user behavior and lifestyle choices are either ignored or inadequately addressed when estimating the energy consumption of a building (Bourgeois, Reinhart, & Macdonald, 2006). Research reveals that, to optimize the building design for the actual users and their peculiarities, buildings features must be examined in more detail. This approach helps to create better working and living environments for occupants inside buildings, which consequently enhances the building energy performance (Nguyen & Aiello, 2013).

There are many factors in the building that influence occupant behavior, and building characteristics play one of the most important roles in influencing occupant behavior (Azar & Menassa, 2012). Thus, it is necessary to include building characteristics while analyzing the impact of occupant behavior on building energy performance. However, very little work has been done on the impact of building characteristics on energy consumption from a statistical perspective (Guerra Santin, Itard, & Visscher, 2009). Moreover, there is also a gap in the literature regarding the effects of occupant behavior that takes building characteristics into account (Guerra Santin et al., 2009). One of the ways to incorporate building characteristics in a building performance assessment is to use a building information modeling (BIM) in integration with energy simulation tools (Peeraya, Hisn, Long, Chen & Yimin, 2014).

A building information modeling (BIM) offers great flexibility in building energy performance assessments, as most of the input parameters required by most of the energy simulation programs (such as weather data, 3D geometry information, construction and material definitions, space types, space loads, HVAC systems and its components) and some additional simulation-specific parameters can be defined within the building information models (Aksamija, 2012). Previously, a BIM has been used to analyze the impact of occupant behavior or impact of building characteristics on the energy consumption of the building (Peeraya et al., 2014). However, a building information model has never been used to analyze the combined effect of building characteristics and occupant behavior on the energy performance of the building (Hoes, Hensen, Loomans, de Vries, & Bourgeois, 2009). Autodesk Revit is one of the common tools used to build the building information model of a building. Alternately, DesignBuilder provides a wide range of simulations that are suitable for analyzing the impact of occupant behavior on building energy performance. DesignBuilder can also create partial geometry models from building information models and link them directly to control design tools. Furthermore, DesignBuilder also has the additional features (e.g. specific HVAC components and strategies), which – when compared to other simulation tools – make it more accurate and reliable. DesignBuilder therefore is the most suitable tool for building energy simulation in this research. One additional advantage of DesignBuilder is that a building information model created in Revit can be easily imported to DesignBuilder in gbXML and XML formats ("http://www.designbuilder.co.uk/," n.d.).

1.1 Problem statement

Over the last 40 years, occupant behavior has been identified as one of the major contributing factors on building energy performance. Regardless of the many studies on the subject, occupant behavior in a building is not well understood and is oversimplified. Building characteristics also play a major role in influencing occupant behavior inside a building. However, very little is known about the impact of occupant behavior on energy consumption that also takes into account the role of these building characteristics. Thus, it is necessary to include building characteristics while analyzing the impact of occupant behavior on building energy performance. BIM-based energy simulation is one of the best method in terms of ease and accuracy that can incorporate both occupant behavior and building characteristics while analyzing the impact of occupant behavior on the energy performance of buildings (Peeraya et al., 2014).

1.2 Research objectives

The objectives of this research were to:

1. Identify the most influential building characteristics and parameters of occupant behavior that affect the energy performance of the building.
2. Determine the impact of each category of occupant behavior and building characteristics on the energy performance of buildings.
3. Verify the results obtained from the analysis of the impact of occupant behavior on the energy performance of the building.
4. Develop guidelines to minimize the energy consumption in building due to occupant behavior.

2 CHAPTER 2- LITERATURE REVIEW

In this chapter, several topics and theories are presented to explain the impact of occupant behavior on the energy performance of building and the use of BIM-based energy simulations for the analysis of impact of occupant behavior on building energy performance. In this regard, four main topics remain central to the discussion throughout this literature review: occupant behavior, building characteristics, use of BIM to study occupant behavior and building energy performance and energy simulation software (like DesignBuilder).

2.1 Impact of occupant behavior on building energy performance

Occupant behavior can be defined as the presence of people inside a building and their actions that influence the indoor environment (Hoes, Hensen, Loomans, Vries, & Bourgeois, 2009); meanwhile, behavioral patterns can be defined as distinct patterns that categorize similar behaviors into groups (Peeraya et al., 2014). Energy use in buildings is therefore closely linked to the building's operational and space-utilization characteristics and the behavior of its occupants (Pfafferott & Herkel, 2007).

Some studies emphasized the role of building occupants in building energy performance and the anticipated savings in energy if occupant behavior were modified (Blom, Itard, & Meijer, 2011). Alfakara and Croxford (2014) suggested that the changes in occupant behavior can result in a saving of up to 40% in energy consumption in a building. Emery and Kippenhan (2006) further showed that correctly modeling a building's occupancy can improve the required capacity of the ventilation system by approximately 43%. Such savings can foster economic and environmental benefits by improving building energy efficiency. Hoes, Hensel, Loomans, De Vries and Bourgeois (2009) also revealed that occupant behavior has a much larger influence on the energy performance of a building than the thermal process within the building façade. Furthermore, research has shown that building occupants who actively seek daylighting can save more than 40% of primary energy expenditure compared to occupants who systematically rely on artificial lighting (Pfafferott & Herkel, 2007). It was also found that household electricity consumption can be reduced by (on average) more than 10% through active promotion of energy-conscious behavior (Yu, Haghighat, Fung, Morofsky, & Yoshino, 2011). For example, energy consumption can be reduced by 39% by improving occupant behavior; for example, by setting the air conditioner thermostat to a higher temperature in cooling-dependent climates in summer and turning off the lights when rooms are empty (Al-Mumin, Khattab, & Sridhar, 2003). The research conducted by Azar and Menassa (2012) demonstrated that, by simulating occupancy usage patterns, HVAC energy usage can be reduced by approximately 14%. Hence, research on occupant behavior and building energy performance showed that there is a need of early identification of influential occupant behaviors in the building design process for the allocation of adequate resources required for enhanced building performance (Azar & Menassa, 2012).

Azar and Menassa (2012) identified some of the benefits of incorporating occupant behavior in energy simulation processes for the prediction of energy consumption in a building. Such benefits were:

- High sensitivity parameters related to occupant behavior and energy use can be identified and modeled with extreme care for better energy estimates.
- Stakeholders can predict the impact of particular behavioral patterns on building energy performance, depending on the characteristics of building.
- Policy makers can be motivated to address the effects of the behavioral pattern of the energy use of building and invest in the occupant's energy education.

2.2 Complexity of human behavior

The aforementioned research showed that occupant behavior is an important aspect of building performance assessment. However, the simple approaches used nowadays for design assessments of buildings that have close interaction with users are found to be inadequate (Hoes et al., 2009). Hoes et al. (2009) further suggested that building occupants affect total energy consumption levels mainly through their actions and interactions and, hence, make assessment a very complex and unpredictable procedure.

Occupants might change their energy usage characteristics by adopting more energy efficient practices or, on the contrary, adopting bad consumption habits: some of these may be attributable to the often-called rebound effect (Sorrell, Dimitropoulos, & Sommerville, 2009). One example of the rebound effect might be when occupants use more electric lighting than required after the installation of energy saving light bulbs, assuming that their actions will have less impact on the environment. Such type of behavior change negatively affects energy consumption by increasing energy use. A numerical example, developed by Azar and Menassa (2012) to test the effect of user patterns, revealed that energy consumption patterns might change considerably over time. The more the occupants control the energy-consuming elements of their immediate environment, the more their behavioral change affects total energy use. It is, therefore, also essential to model and predict change of occupant behavior over time and the resulting impact on energy consumption while also modeling occupants with different energy consumption patterns (Azar & Menassa, 2012). However, the influence of behavioral parameters on energy consumption varies with building characteristics and weather conditions (Azar & Menassa, 2012b). However, buildings with the same activities, in the same geographic area and occupied by people that share the same cultural background are expected to have similar energy usage patterns (van Ruijven, de Vries, van Vuuren, & van der Sluijs, 2010). Yalcintas (2008) found that even the outcome of building retrofitting projects is often unpredictable due to the uncertainty surrounding occupant behavior. Therefore, it is crucial to consider the influence of occupant behavior early in the design stage to obtain a model that accurately creates the desired building usage patterns once the building is occupied.

2.3 Occupant-behavior parameters

Occupant behavior mainly refers to the occupant's interaction with operable windows, lights, blinds, thermostats and plugin appliances (Heydarian, Carneiro, Gerber, & Becerik-Gerber, 2015). In this regard, an occupant interacts with building energy and systems to achieve the desired comfort inside the building: this directly affects the operation of buildings and their energy use. Typical energy-related occupant behavior variables include cooling set points, heating set points, adaptive comfort, occupancy control, daylight control, HVAC operation time and cooling startup control (Hong, 2014). Hong (2014) categorized the energy-related occupant behavior in private offices into three workstyles based on potential impact on energy consumption that are named accordingly as austerity, standard, and wasteful. Occupants with an austerity workstyle are dedicated to saving energy, occupants with the standard workstyle represent those who have average energy-use behavior, and occupants with the wasteful workstyle tend to use energy at will with no incentive for energy-use reduction.

Thermal comfort is the state of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation (Hoes et al., 2009). Depending upon the HVAC control strategy, energy consumption can vary in accordance with the primary physical behavioral forces; for example, ventilation, thermostat set point and indoor thermal environment (Tanner & Henze, 2013). According to the observations of occupant window opening behavior, carried out by Humphreys and Nicol (1998), occupants only interact with windows when the temperature reaches 2° C over the upper limit or below the lower limit of the adaptive comfort temperature. This finding from Humphrey's observation can be used in a building simulation model (Rijal, 2008). According to the American Society of Heating, Refrigerating and Air-Conditioning Engineers Standard 55 (ASHRAE, 2010), standard conditions must be acceptable to least 80 % of the occupants within the space. Regarding standard temperature conditions, ASHRAE Standard 55 specifies the operative temperature range for building occupants in typical winter clothing as 0.8 clo to 1.2 clo as 68°F to 74°F (20° to 23.5°C). Likewise, for the occupants dressed in summer clothes: 0.35 clo to 0.6 clo is 73°F to 79°F (22.5° to 26°C) (clo is a measure of clothes thermal insulation). These values are specified for the relative humidity of 60%, an activity level of approximately 1.2 met, and an airspeed low enough to avoid drafts. Furthermore, ASHRAE Standard 55 also specifies the lowest acceptable operative temperature for sedentary occupancy, which is 65°F (18°C). Table 1 summarizes the operative temperature ranges in winter and summer conditions for different types of building spaces.

Table 1 Guideline for room air temperature (ASHRAE, 2004)

	Indoor Air Temperature			
	°F		**°C**	
Type of Space	**Summer**	**Winter**	**Summer**	**Winter**
Residences, apartments, classrooms, offices	74-78	68-72	23-26	20-22
School dining and lunch rooms	75-78	65-70	24-26	18-21

Occupants adjust their thermal and visual comfort through interaction with window, shades and blinds; nonetheless, there is considerable variability associated with such interaction, which is subject to the energy-use workstyle of occupants in buildings (Gunay, O'Brien, & Beausoleil-Morrison, 2013). For instance, energy-conscious occupants interact responsibly with windows, shades and blinds in a way that saves energy. Conversely, occupants lacking motivation for energy saving can cause energy wastage (Li, Li, Fan, & Jia, 2015).

The study showed that energy saving of more than 9% was achieved by making occupants aware of their energy-use behavior, providing them with systematic energy visualization and use of real-time monitoring of electrical equipment (D'Oca, Corgnati, & Buso, 2014). User behavior is also an important factor for the overall increase in plug load. Plug loads refer to any equipment powered by an ordinary AC plug and is typically unique to the building, such as computers, localized fans/heaters, toasters, etc. The study carried out by Carrie, Judy, Richard, Christopher, Bruce, and Jonathan (2014) on offices in Washington DC and San Francisco showed that only 44% of computers, 32% of monitors and 25% of printers were turned off at night. Another study by Hong (2014) revealed that the occupants who were proactive in energy saving reduced plug load by 30% when the space was unoccupied.

The research carried out by Parys, Saelens, and Hens (2009) indicated that energy use in individual offices can be decreased by 10% by employing a daylight dimming system that depends on the presence and movement of the occupants. This result is fairly independent of boundary conditions such as orientation, blind type, window size, glazing type, etc. Again, Hong's research (2014) showed that occupants, who are dedicated to energy saving, dim lights to 50% or completely turn them off if daylight meets the visual comfort; in contrast, occupants who lack the motivation to save energy do not respond at all.

Occupant presence and movement are major factors that affect lighting, thermostat settings, plug loads, HVAC equipment, and other such variables related to building energy performance (Duarte, Van Den Wymelenberg, & Rieger, 2013; Feng, Yan, & Hong, 2015). Consequently, occupancy has a significant role in building energy consumption and is the basis of building energy simulation tools like EnergyPlus (Crawley, Lawrie, Winkelmann, Buhl, Huang, Pedersen, Strand, Liesen, Fisher, Witte & Glazer, 2001). Occupancy also gives the basic information of location or presence of occupants required for the energy simulation of a building (Yan et al., 2015). The occupancy schedule is, therefore, the deciding factor in the operating schedule of HVAC, lighting, plug loads and many other components that affect the building energy performance (ASHRAE, 2004). Standard HVAC and lighting schedules according to ASHRAE Standard 55 for different types of spaces are summarized in Table 2.

Table 2 HVAC and occupancy schedule for different types of occupancy (ASHRAE, 2004)

Types of occupancy	**Occupancy Schedule**			**HVAC schedule**		
	Weekdays	**Saturday**	**Sunday**	**Weekdays**	**Saturday**	**Sunday**
Assembly occupancy	8 am – 11 pm	8 am – 11 pm	8 am – 11 pm	6 am – 11 pm	7 am – 11 pm	7 am – 11 pm
Health occupancy	7 am – 10 pm	7 am – 7 pm	8 am – 4 pm	24 hours	24 hours	24 hours
Hotel/Motel Occupancy	24 hours	24 hours	24 hours	24 hours	24 hours	24 hours
School Occupancy	7 am – 10 pm	6 am – 7 pm	0 hours	7 am – 10 pm	6 am – 7 pm	0 hours
Office Occupancy	6 am – 10 pm	8 am – 1 pm	0 hours	6 am – 10 pm	6 am – 7 pm	0 hours

Despite the clear relationship between occupancy and operating schedules in regard to building energy performance, data collected by Duarte et al. (2013) showed variations of occupancy diversity factors in private offices for the time of day, the day of the week, holidays and month of the year which differ by up to 46% compared to those recommended by ASHRAE Standard 90.1.2004.

2.4 Relationship between building characteristics and occupant behavior

The relationship between building characteristics and occupant behavior is vital for the understanding of building energy use. In their study, Gaetani, Hoes and Hensen (2016) acknowledged that gap between the predicted and actual building energy performance is results of the unrealistic representation of the occupant behavior in building energy simulations. According to the Gaetani et al. (2016), there are not any available guidelines based on which the appropriate occupant behavior model can be selected with respect to different phases of the building lifecycle, type of buildings and other building related factors. Gaetani et al. (2016) further suggested that the selection of appropriate occupant behavior model for any building energy simulation is strongly case-specific. The most appropriate occupant behavior model for any specific case is characterized by the lowest complexity while maintaining its validity with respect to the objective of the simulation.

Azar and Menassa (2012) also discussed the relationship between building characteristics and occupant behavior revealing that factors like building size, location or weather conditions have a considerable impact on the sensitivity of building behavioral parameters. Depending upon such factors, the impact of behavioral parameters on building energy performance can differ. Even a change of only one factor, such as change of the insulative properties of a building, might result in a 40% change of the estimated energy consumption. This rate of energy consumption in buildings is a function of not only the design, but also occupancy-related actions such as the frequency of opening of doors and windows, which are typically not accounted for in energy-simulation tools (Hoes et al., 2009).

Several limiting factors, such as the complexity of buildings, weather and variations in building schedule and occupancy, affect the accuracy of building energy simulations. These deviations can mainly be attributed to misunderstanding and underestimating the important role of occupants' energy-use habits in determining energy consumption levels. Similarly, according to Wei, Jones, and de Wilde (2014), four underlying factors that influence space-heating occupant behavior are environmental factors, occupant-related factors, building- and system-related factors. Guerra Santin et al. (2009) showed that occupant characteristics and behavior affect energy use in buildings by up to 4.2%, while building characteristics are still the most important factors, which can affect the same by up to 42%. This study also revealed that some occupant behaviors in a building are determined by the type of dwelling and HVAC systems. Azar and Menassa (2012) performed a comprehensive sensitivity analysis on parameters of occupant behavior in office buildings with different sizes and locations. Their study has shown that parameters of occupant behavior are influenced by building sizes and locations. Azar and Menassa (2012) also identified other influential building characteristics that affect the energy performance of commercial buildings. Such characteristics include type of building, gross floor area, number of floors, construction materials used in walls, construction materials in roofs, number of equipment used, weekly building schedule, number of occupants, HVAC system type and type of exterior wall.

In their study, Heydarian, Carneiro, Gerber, and Becerik (2015) carried out an experiment to explore the influence of human behavior on lighting use. This study investigated the manual control system as well as the both manual and semi-automated control systems to control either interior shades or artificial lights or both. The result of the experiment indicated that building occupants are likely to use natural light if a semi-automated system is used to control shades. Nonetheless, occupants are less likely to use natural light if a semi-automated system is employed to control both shades and interior artificial lights. Thus, the study proved that energy consumption by lighting use can be improved by integrating suitable control systems that minimize the use of artificial lighting.

Limited research has been done on the effect of occupant behavior on building energy consumption in relation to building characteristics (Santin et al., 2009; Hoes et al., 2009). One exception is Santin's research (2012) which statistically examined the variation in occupant behavior in relation to building characteristics and its effect on space heating of the building. Here, Santin suggested that, due to the rebound effect, occupants tend to set the thermostats to higher temperatures in energy-efficient buildings than in normal buildings. Occupants therefore tend to use more energy in energy-efficient buildings; nevertheless, the improved thermal properties and system efficiency in these energy-efficient buildings decreases the energy required for space heating. Santin (2012) used different variables of building characteristics like construction period, dwelling type, the presence of insulation, ventilation system and type of temperature control for the statistical analysis of the impact of building characteristics on variation of occupant behavior.

Another study done by Santin, Itard and Visscher (2009) aimed at determining the extent of effect of building characteristics, household characteristics and occupant behavior on energy use for space and water heating in the Netherlands. The building characteristics accounted for this study included the age of building, design of dwelling, insulation, heating system and energy type. This research showed that, while occupant behavior can affect energy use by 4.2%, building characteristics can affect energy use by as much as 42%. Azar and Menassa (2012a) performed a similar study to analyze the impact of occupant behavior on the energy performance of a building, collecting data required for building characteristics from the 2003 Commercial Building Energy Consumption Survey (CBES) in the US. Buildings included in the study were divided into 30 types, based on their size and climate. Building characteristics, such as number of floors, area, number of occupants, wall construction materials, roof construction materials, percentage of exterior glass, main heating equipment, main cooling equipment, and hours of operation per week, were used in a building energy simulation for this study. Based on their statistical analysis, it was concluded that the "heating temperature set point" parameter in small-size commercial buildings is the most influential characteristic that affects the building energy performance.

Based on this literature review and the 2003 Commercial Building Energy Consumption Survey in the US, general building characteristics and data required for general building energy simulation have been summarized in Table 3.

Table 3 Types of building characteristics and corresponding data per CBES (Azar & Menassa, 2012b) c

Type	Building size	Number of floors (ft^2)	Area (m^2)	Wall construction materials	Roof construction materials	Percentage exterior glass	Main heating equipment	Main cooling equipment	Hours of operation	Number of occupants
1	Small	2	303.3	Siding, shingles, tiles or shakes	Asphalt, fiberglass, or other shingles	16%	Furnaces	Central (residential type)	51	6
2	Small	2	256.5	Siding, shingles, tiles or shakes	Asphalt, fiberglass, or other shingles	21%	Furnaces	Central (residential type)	51	**8**
3	Small	2	279.0	Brick, stone, or stucco	Asphalt, fiberglass, or other shingles	19%	Furnaces	Central (residential type)	51	**6**
4	Small	2	279.0	Brick, stone, or stucco	Asphalt, fiberglass, or other shingles	19%	Furnaces	Central (residential type)	51	**6**
5	Small	1	242.9	Brick, stone, or stucco	Slate or tile shingles	17%	Packaged Units	Central	51	**6**
6	Medium	2	1446.0	Brick, stone, or stucco	Built-up	23%	Boilers	Packaged units	66	35
7	Medium	2	1446.0	Brick, stone, or stucco	Plastic, rubber or synthetic sheeting	19%	Furnaces	Packaged units	57	33
8	Medium	3	1400.8	Brick, stone, or stucco	Built-up	21%	Packaged units	Packaged units	58	37

Table 3 Types of building characteristics and corresponding data per CBES (Azar & Menassa, 2012b) cont'd

Type	Building size	Number of floors (ft^2)	Area (m^2)	Wall construction materials	Roof construction materials	Percentage exterior glass	Main heating equipment	Main cooling equipment	Hours of operation	Number of occupants
9	Medium	2	13666.2	Brick, stone, or stucco	Built-up	24%	Packaged units	Packaged units	58	33
10	Medium	2	1779.80	Brick, stone, or stucco	Built-up	31%	Other	Packaged units	50	49
11	Large	4	11072.2	Brick, stone, or stucco	Plastic, rubber or synthetic sheeting	33%	Boilers	Packaged units	72	349
12	Large	6	14078.4	Brick, stone, or stucco	Plastic, rubber or synthetic sheeting	41%	Boilers	Packaged units	74	358
13	Large	6	13840.4	Brick, stone, or stucco	Built-up	33%	Boilers	Packaged units	79	353
14	Large	7	14105.3	Brick, stone, or stucco	Built-up	45%	Boilers	Central Chillers	62	354
15	Large	6	14131.8	Pre-cast concrete panels	Built-up	51%	Packaged units	Packaged units	71	291

Based on research conducted by Hong (2014) and the literature review, occupant behavior and its characteristics for different types of workstyles are summarized in Table 4.

Table 4 Occupant behavior categorized into workstyles

Occupant behavior characteristics	Austerity workstyle	Standard workstyle	Wasteful workstyle
Cooling set points (ºC)	26	24	22
Heating set points (ºC)	18	21	23
Occupancy Control	If unoccupied, turns off lights and HVAC, turn down plug load 30%	Scheduled	Leave everything on: lights, HVAC and plug loads
Adaptive comfort	Yes	No	No
Daylight control	Dimming	None	None
HVAC operation time	Turn on 1 hour late and turn off 1 hour early: 9 am to 4 pm	As scheduled	Same as whole building schedule
Cooling startup control	Occupied – Turns on when the temperature reaches 28°C to maintain 24°C. Unoccupied – Turns off (from Humphrey's observation)	As scheduled	Same as whole building schedule

2.5 Data collection method

There has been a great deal of progress made regarding data collection techniques in the areas of (a) occupant movement and presence, (b) thermal comfort (c) window shades and blinds and, (d) lighting and electrical equipment (Hong, Taylor-Lange, D'Oca, Yan, & Corgnati, 2015). Data related to these areas are used to measure the degree of influence of occupant behavior on the energy performance of buildings through energy simulation. Gathering data to investigate these factors requires a host of information from the weather stations, building energy and lighting management systems and from the custom sensors. Hong et al. (2015) identified the data needed to complete the study on occupant behavior related to occupancy, shading, lighting, window closing/opening, thermal comfort, plug load, and HVAC; this is summarized in Table 5.

Table 5 A mapping of the data needed for the study of occupant behavior (Hong et al., 2015) c

Variables/ Behaviors		Window opening	Occupancy	Shading	Lighting	Thermal Comfort	Plug Loads	HVAC	Occupancy Survey	Device/ System
Weather data	Outdoor air temperature	M	N/A	N/A	N/A	M	N/A	M	N/A	Weather Station
	Outdoor air humidity	M	N/A	N/A	N/A	M	N/A	M	N/A	Weather Station
	Wind direction	M	N/A	N/A	N/A	M	N/A	N/A	N/A	Weather Station
	Solar irradiance	O	N/A	M	M	O	N/A	O	N/A	Weather Station
	Illuminance	O	N/A	M	M	O	N/A	O	N/A	LMS
	Rain (event)	O	N/A	N/A	N/A	N/A	N/A	O	N/A	Weather Station
Space data	Indoor Air Temperature	M	N/A	M	N/A	M	O	M	N/A	BMS
	Indoor Air Humidity	O	N/A	N/A	N/A	M	O	M	N/A	BMS
	CO_2	M	M	N/A	N/A	M	N//A	M	N/A	BMS
	Occupancy	M	M	M	M	M	M	M	N/A	BMS/Custom Sensor
	Light level	N/A	O	M	M	O	O	N/A	N/A	BMS/LMS
	Window State	M	O	O	N/A	M	N/A	O	N/A	BMS/LMS
	Shading State	N/A	O	M	M	O	N/A	O	N/A	EMS
	Plug loads	N/A	O	N/A	O	N/A	O	M	N/A	EMS

Table 5 A mapping of the data needed for the study of occupant behavior (Hong et al., 2015) cont'd

Variables/ Behaviors		Window opening	Occupancy	Shading	Lighting	Thermal Comfort	Plug Loads	HVAC	Occupancy Survey	Device/ System
	Thermostat setting (heating and cooling)	N/A	O	N/A	N/A	M	O	M	N/A	BMS
	Heating/Cooling state	N/A	O	N/A	N/A	O	O	M	N/A	EMS
Energy Data	Total energy use	O	O	O	O	O	O	M	M	EMS/survey
	Sub-metering (lighting, HVAC, plug loads, etc.)	N/A	N/A	N/A	O	O	O	O	N/A	EMS
	Energy production (renewable)	N/A	N/A	N/A	O	O	O	O	N/A	EMS
Occupants data	Age	O	O	O	O	O	O	O	M	Management/Survey
	Gender	O	O	O	O	O	O	O	M	Management/Survey
	Weather profiles	O	O	O	O	O	O	O	M	Management/Survey

BMS = Building Management System
EMS = Energy Management System
LMS = Lighting Management System
M= Mandatory
O = Optional
N/A = Non-Applicable

2.6 DesignBuilder software

DesignBuilder is software for creating and assessing building designs that also performs various types of BIM-based energy simulations. DesignBuilder has been developed in such a way that it can be used at any stage of the design process: either at the conceptual stage or at much more advanced stages that require detailed building models. A data template in DesignBuilder can be used to load common building geometries, constructions, usage patterns, HVAC and lighting systems in a design. Furthermore, this attribute of DesignBuilder, when combined with data inheritance, means that global changes can be made at building, block or zone level. Such features of the DesignBuilder make it very user-friendly ("DesignBuilder Software Ltd", 2016).

DesignBuilder uses EnergyPlus as its simulation engine ("DesignBuilder Software Ltd", 2016). EnergyPlus is a powerful energy simulation program that has new capabilities along with the combined features and capabilities of DOE-2 and BLAST. EnergyPlus can perform a wide range of simulations that can be used to analyze the impact of the occupant on building energy performance. Some of these widely used simulations include integrated simultaneous solution, user-definable time steps, combined heat and mass transfer, thermal comfort models and daylight controls (EnergyPlus, 2013). However, EnergyPlus is standalone software and lacks the user-friendly graphical interface. DesignBuilder has integrated EnergyPlus as its simulation engine and is more user-friendly because it has an elegant and easy-to-use interface for different kinds of energy simulations. Building models and data can be easily defined in the DesignBuilder environment and the detailed simulation outputs can also be obtained by using the EnergyPlus simulation engine, thanks to this integration of DesignBuilder and EnergyPlus. ("http://www.designbuilder.co.uk/," n.d.). Additionally, DesignBuilder has passed the validation test indicating the agreement of temperatures and energy flow with other simulation software. Thus, results obtained from the simulations performed in DesignBuilder are accurate and are suitable for research ("http://www.designbuilder.co.uk/helpv3/Content/Standards.htm.," n.d.).

Some of the features of DesignBuilder are:

i. A wide range of simulation data can be shown in annual, monthly, daily, hourly or sub-hourly intervals.

ii. Design weather data can be used to calculate heating and cooling equipment.

iii. 3D building models created in Revit can be imported using a gbXML import feature. Additionally, building geometry can be imported from scanned drawings or by using CAD data.

iv. DesignBuilder comes with ASHRAE worldwide design, weather data and locations. Furthermore, it also includes 2100 EnergyPlus hourly weather files that can be automatically downloaded.

v. Detailed analysis of commonly used heating and cooling systems can be easily conducted using compact HVAC descriptions that come with the DesignBuilder software.

vi. Natural ventilation can be modeled with the option for ventilation openings to be based on a ventilation set point temperature along with the option for mixed-mode operation in “change-over” with HVAC.

vii. The computational fluid dynamics (CFD) function is integrated with the simulation model and can be easily used and, optionally, one can use EnergyPlus outputs to define CFD boundary conditions.

viii. OpenGL geometric modeler allows building models to be assembled by positioning ‘blocks’ in 3D space. Such blocks can be easily edited to model any required geometry.

The simulation input and output of DesignBuilder are summarized in Table 6.

Table 6 Simulation inputs and outputs in DesignBuilder ("DesignBuilder Software Ltd", 2016)

Input	**Output**
The weather data	Heating design output
3D geometry information	Cooling design output
Construction and material definitions	Simulation output
Space types	Summary annual report
Space loads	LEED summary
HVAC systems	Annual building utility summary
Simulation-specific parameters	Demand end-use component summary
Occupants behavior	Sensible heat gain summary
Environmental control	Input verification and results summary
Cooling set point	Source energy end-use component summary
Heating set point	Adaptive comfort summary
HVAC schedule	Zone comfort load summary
Plug loads	Standard 62.1 summary
Cooling startup control	Climatic data summary
Lighting control	Equipment summary
	Envelope summary
	Surface shadowing summary
	Shading summary
	Lighting summary
	HVAC sizing summary
	System summary
	Component sizing summary
	Outdoor air summary

Table 6 Simulation inputs and outputs in DesignBuilder ("DesignBuilder Software Ltd", 2016) cont'd

Input	Output
	Object count summary Component cost economics summary Summary monthly report Zone heating and cooling summary End use energy consumption Peak energy end use Others Detailed daylight output and other miscellaneous output

Along with many variables of the building characteristics, all the input parameters of occupant behavior with different workstyles identified in the literature review can be easily used as input parameters in DesignBuilder to perform the different types of energy simulation. However, the terminology used in DesignBuilder for input parameters of occupant behavior can vary. The comparison of the terminologies used in DesignBuilder for parameters of occupant behavior is shown in Table 7.

Table 7 Terminology used for input parameters of occupant behavior in DesignBuilder

Input parameters of occupant behavior identified in literature review	Terminology used in DesignBuilder
Cooling set points	Cooling set points
Heating set points	Heating set points
Daylight control	Light control – Stepped
HVAC operation time	HVAC operation schedule
Occupancy control	Does not have the exact terminology for occupancy control but occupancy control can be easily managed in DesignBuilder using various methods
Cooling startup control	Does not have the exact terminology for cooling startup control but cooling startup control can be easily managed in DesignBuilder using various methods

Crawley, Hand, Kummert, and Griffith, (2008) compared the functionality and differences of the 20 most commonly used energy simulation software programs. Of these 20, EnergyPlus, eQUEST, TRNSYS, ESP-r, IDA ICE, TRACE, and IES are programs that consider the whole building and have comparable functionality with each other Based on the study done by Crawley et al. (2008) and a literature review, different features of these software programs are compared with DesignBuilder in Table 8.

Table 8 Simulation tool comparison based on features (Crawley et al., 2008)

	EnergyPlus	eQuest (DOE)	TRNSYS	ESP-r	IDA ICE	TRACE	IES	DesignBuilder
Supports high level of detail	No	No	No	No	No	No	No	No
User adjustable component equations	Yes	No	Yes	No	Yes	Yes	Yes	No
BIM-based geometry import	Yes	Yes	Yes	No (IFC)	No (gbXML)	No (gbXML)	No (gbXML)	No (gbXML)
Multisided polygons	No	Yes	No	No	Yes	Yes	No	No
Integrated simulation (feedback to space temps)	Yes	No	No	No	No	No	No	No
Automated routines to import measured data	Yes	Yes	No	Yes	Yes	Yes	Partial	No
Overriding of system variables	Some	Some (input functions)	No	No	Yes	Yes	Yes	Some
HVAC system flexibility	No	Yes	No	No	No	Yes	Yes	No
Complete water side simulation	No	No	No	No	No (partial)	No	No	No
Links to other control tools	No	Yes	Yes	Yes	Yes	Yes	Yes	No
Time step (min)	1 min	1 hour	0.1 sec	1 min	<0.1 sec	1 hour	1 hour	1 min

The output of energy simulation obtained by the DesignBuilder is categorized by total energy consumed by plug loads, heating, cooling, lighting, and electricity used for domestic hot water (DHW) ("DesignBuilder Software Ltd", 2016). In this study, the energy consumed by the occupant for heating, cooling, lighting and plugin loads was taken into account while evaluating the total energy consumed by the occupant with the particular workstyle.

2.7 BIM-based energy simulation

According to the US National Institute of Building Sciences (2015), a building information modeling (BIM) is the digital representation of the physical and functional properties of a facility, which acts as a reliable resource of information for any kind of decision making during its life cycle from its inception to end. A building information model can be used to conduct structural analyses, HVAC simulations, solar and energy analyses, and other crucial analyses through its export to third-party software like EnergyPlus and DesignBuilder. Hence, a BIM is beneficial to developers, facility managers, architects, engineers and contractors alike. The integration of human behavior simulation with BIM can significantly enable owners and facility managers to better understand user behavior and predict energy use and carbon emissions (Ioannidis, Tropios, & Krinidis, 2016). Using a building information model can help with the visualization of data, thus making energy simulation for future prediction easier. Building information models can also be used to conduct engineering analyses; however, human behavior simulation using building information models is still lacking (Cheng & Gan, 2013).

Inyim, Ha, Phan, Zhu, and Chen (2014) successfully used BIM-based energy simulations to identify the impact of occupant behavior on energy simulation. The building that houses the School of International and Public Affairs (SIPA) at Florida State University (FIU) was taken as a case study for BIM-based energy simulation: this building has received the Sustainable Design Award from the American Institute of Architects (AIA) and was also awarded a Leadership in Energy and Environmental Design (LEED) gold certification from the US Green Building Council. EnergyPlus (Version 8.1.0), was used as energy simulation software and Autodesk Revit 2013 was used to build a building information model. A building information model built in Revit can be used for space and zone volume calculations. Revit files can be exported to an XML file and a gbXML file with UTS coding (Inyim et al., 2014). The XML file and gbXML file generated from the building information model in Revit can be imported to DesignBuilder without any loss of information to perform different types of energy simulations (“http://www.designbuilder.co.uk/,” n.d.).

2.8 Summary of literature review

The research presented in this literature review revealed that building energy performance depends on several factors. First, occupant behavior is one of the important aspects of building performance assessment. However, occupant behavioral patterns are complex and unpredictable, and the effect of occupant behavior on building energy performance has not been acknowledged properly. This factor has led to the enormous gap between the predicted energy consumption of a building and the actual energy consumed by the building.

The second factor deals with types of occupant behavior. Based on the level of energy consumption, the three types being the austerity workstyle, the standard workstyle and the wasteful workstyle. The third factor that building energy performance depends on is the seven energy-related occupant behavior parameters. These include cooling set points, heating set points, adaptive comfort, occupancy control, daylight control, HVAC operation time and cooling startup control. Data related to these parameters need to be collected to perform any BIM-based energy simulations. The potential sources of data for the parameters of occupant behavior are building management systems, energy management systems, surveys, case studies and interviews with occupants in buildings.

Occupant behavior depends upon several factors such as climate, age, gender, the lifestyle of the occupant and income of the family. However, as building characteristics influence occupant behavior in a building, it is essential to include them in any analysis of the impact of occupant behavior on building energy performance. However, the gap in the literature on this subject reflects the fact that very little work has been done to understand the impact of occupant behavior on energy consumption in relation to building characteristics. To be able to include building characteristics in the analysis of the impact of occupant behavior on building energy performance, BIM can be used in conjunction with energy simulation software like DesignBuilder. Such a combination of BIM and energy simulations has several advantages compared to traditional methods of analyzing the impact of occupant behavior on energy use. These advantages include efficient data input, accurate representation of building characteristics, the possibility of using dynamic energy simulation and many others. Autodesk Revit is one of the most commonly used tools for to creating a building information model; however, DesignBuilder provides a wide range of simulations that are suitable for analyzing the impact of occupant behavior on building energy performance. Furthermore, a building information model created in Revit can be exported as gbXML file to DesignBuilder for energy simulations. Hence, by using Autodesk Revit and DesignBuilder together, BIM-based energy simulation can be performed if required data for the parameters of occupant behavior are available.

3 CHAPTER 3- RESEARCH METHODOLOGY

The research objectives and methods used in this thesis are summarized in Table 9. As shown in Table 9, the research was conducted in four stages. In the first stage, the influential building characteristics that affected the occupant behavior and energy performance of the building were identified based on the literature review. In the second stage, the impact of occupant behavior and building characteristics on building energy performance was determined by analyzing their relationship with the annual energy consumption of the 15 types of commercial buildings obtained from the literature review. All the information on occupant behavior and building characteristics, including numerical values for different variables of both occupant behavior and building characteristics, were also obtained from the literature review.

Based on the information collected from literature review, annual energy consumptions by commercial buildings were obtained by performing BIM-based energy simulations. For this study, 153 building information models for 15 types of commercial buildings were created in Revit and exported to DesignBuilder for energy simulations. The results obtained from the BIM-based energy simulations were analyzed to measure the impact of occupant behavior and building characteristics on building energy performance. In the third stage, the case study of Alder Hall, one of the commercial buildings at Colorado State University at CSU was conducted to illustrate the energy simulations by using the real data and information for parameters of occupant behavior in the building. More simulations were performed for Alder Hall using the information and numerical values obtained from the literature review for austerity, standard and wasteful occupant workstyles. In the fourth and last stage, the guidelines were developed based on an analysis of BIM-based energy simulations from stage 2 and the results of the case study from stage 3.

Table 9 Research objectives and methods c

Research Objectives	**Research Methods/Stages**
1. Identify the most influential building characteristics that affect occupant behavior and energy performance of the commercial buildings.	Stage 1. Conduct literature review.
2. Determine the impact of each category of occupant behavior and building characteristics on energy performance of the building. i. Identify three categories of occupant	Stage 2. i. Conduct literature review.

Table 9 Research objectives and methods cont'd

Research Objectives	Research Methods/Stages
behavior based on occupant's workstyle. ii. Collect the numerical values and the information on the variables of building characteristics and parameters of occupant behavior for three different workstyles required to perform energy simulations.	ii. a. Perform 153 BIM-based energy simulations of abstract buildings to collect the data on annual energy consumed by the commercial buildings. Use Revit 2016 and DesignBuilder to perform BIM-based energy simulations. b. Analyze the results obtained from the BIM-based energy simulations to measure the impact of occupant behavior and building characteristics on energy performance of buildings.
3. Illustrate the impact of occupant behavior on energy performance of building by performing energy simulations of a real building.	Stage 3. i. Conduct the case study of a commercial building, Alder Hall at Colorado State University. ii. Perform energy simulations of Alder Hall for three types of occupant workstyles. Also perform the energy simulation using actual value/information of parameters of occupant behavior observed in Alder Hall. iii. Find abstract building among 153 building information models that has the same or the closest building characteristics to those of Alder Hall. Perform the energy simulations for three types of occupant workstyles for this building. Also perform the energy simulation by using the actual values or information collected for the parameters of occupant behavior in Alder Hall. iv. Analyze the similarities and differences of impact of occupant behavior on energy performance of building from the simulations results obtained from Alder Hall and the abstract building.
4. Develop the guidelines for changing the	Stage 4. Based on the simulation results and case study

Table 9 Research objectives and methods cont'd

Research Objectives	Research Methods/Stages
occupant behavior to improve the building energy performance.	results, develop recommendations for: i. Providing incentives for occupants to change their behavior to save energy. ii. Developing different control strategies to minimize energy consumption. iii. Identifying the techniques that increase the energy awareness among the building occupants. iv. Identifying the techniques and strategies to discourage the wasteful workstyle of occupants. v. Identifying the building characteristics that affect the occupant behavior and devise a plan to improve them for energy saving. vi. Identifying bad behavioral practices and implementing new policies to enhance energy saving.

3.1 Identification of influential building characteristics

In the first stage, the most influential building characteristics and parameters of occupant behavior that affect the building energy performance were identified through a literature review. The identified building characteristics from the literature review were building size, number of floors, floor area of building, wall construction material, roof construction material, main heating equipment, main cooling equipment, hours of operation and number of occupants. In addition, shortlisted parameters of energy-related occupant behavior consisted of the cooling set point, heating set point, adaptive comfort, occupancy controls, daylight controls, HVAC operation time and cooling startup control.

3.2 Determining impact of occupant behavior and building characteristics on building energy performance

In the second stage, occupant behavior was categorized into three types, austerity, standard and wasteful workstyles - based on the amount of energy used by the occupants to achieve the desired comfort inside the buildings. Occupants with an austerity workstyle are motivated to save energy and tend to consume less energy; occupants with standard workstyle have average energy-consuming behavior, and the occupants with a wasteful workstyle are not motivated at all to save energy and tends to consume energy at will (Hong & Lin, 2012).

3.2.1 Collection of data on parameters of building characteristics and occupant behavior

In the second stage, information on parameters of occupant behavior and building characteristics required for energy simulations were also obtained from the literature review. The information of each parameter of occupant behavior depends upon the workstyle of the occupant. The numerical values and the description of each parameter of occupant behavior for three occupant workstyles are summarized in Table 10.

Table 10 Values of parameters of three categories of occupant behavior based on literature review (Hong & Lin, 2012)

Occupant behavior parameters from literature review	**Austerity**	**Standard**	**Wasteful**
Cooling set point (°C)	26	24	22
Heating set point (°C)	18	21	23
Adaptive comfort	Yes	No	No
Occupancy controls	If unoccupied, turn off lights and HVAC, turn down plug load 30%	Scheduled	Leave everything on: lights, HVAC, and plug load
Daylight controls	Dimming	None	None
HVAC operation time	Turn on 1 hour late and turn off 1 hour early: 9 am to 4 pm	Scheduled	Same as whole building schedule
Cooling startup control	Occupied – turns on when the temperature reaches 28°C to maintain 24°C. Unoccupied – turns off	Follow HVAC Operation schedule to maintain 24°C	Same as whole building schedule

All the data and information regarding the identified building characteristics were also collected from the literature review. In the literature review, commercial buildings in the US were categorized into 15 types based on their distinct characteristics. Among these 15 types of commercial buildings, five types are small-size, five types are medium-size and the remaining five types are large-size (Azar & Menassa, 2012a).

Azar and Menassa (2012) developed this database on the characteristics of small, medium and large-size commercial buildings in the US by combining the results of the 20 Commercial Building Energy Consumption Survey (CBECS) data files. The smallest commercial building had an average area of 2,391 ft^2, while the largest commercial building had an average area of 152,105 ft^2. The area of small buildings ranged between 2,391 ft^2 and 3261 ft^2; the areas of the medium-size buildings varied from 15,565 ft^2 to 147,099 ft^2, and the areas of the large-size buildings varied between 119,180 ft^2 and 152,113 ft^2. The number of floors of these commercial buildings ranged from one to seven. Commercial buildings in the US are also characterized by the extensive use of glass on their exterior walls. Consequently, buildings that were categorized as small-size commercial buildings had an exterior glass percentage that ranged between 16% and 17%. Exterior glass percentage of medium-size buildings ranged between 19% and 31% while that of large-size buildings varied between 33% and 51%. These three types of buildings were further categorized based on other building characteristics, such as roof construction materials, wall construction materials and cooling and heating systems. A typical commercial building could, for example, use one to five different materials for roof and wall: such materials had their own typical thermal mass and thermal resistance. Thermal mass could be defined as the property of the material that enabled it to absorb, store and release significant amounts of heat, while thermal resistance referred to the ability of the material to resist heat flow (ANSI/ASHRAE, 2004). Taking all such variations into consideration and ignoring the weather zone, there were 15 types of buildings as shown in Table 3.

Type 1 to type 5 buildings in this study were small-size commercial buildings. Type 1 buildings had siding, tiles and shingles as the wall construction material and shingles and asphalt as roof construction material. The exterior glass percentage of type 1 buildings was 16%. Heating and cooling systems used for such buildings were a furnace and central residential type respectively. To satisfy the heating and cooling requirement of such buildings – district heating and cooling: FCU-4 pipe system – was used in the building information models. The average number of occupants in type 1 commercial buildings was six, as shown in Table 3. The thermal resistance of wall construction materials for type 1 buildings varied between 26.72 hr·ft2·°F/Btu and 47.51 hr·ft2·°F/Btu in this study while thermal mass for wall construction materials varies from 7.89 Btu/^{0}F to 25.67 Btu/^{0}F.

Type 2 commercial buildings had the same number of floors as type 1 commercial buildings. The area of the building for this type was 2761 ft^2. The types of wall materials used in type 2 buildings were shingles, siding and tiles and fiberglass asphalt and shingles for the roof. The thermal resistance of the wall construction materials varied between 26.72 hr·ft2·°F/Btu and 47.51 hr·ft2·°F/Btu and for roof construction material it ranged between 32.01 hr·ft2·°F/Btu to 59.68 hr·ft2·°F/Btu. The thermal mass of the wall construction materials, however, varied between 7.89 Btu/^{0}F and 25.67 Btu/^{0}F, while that for roof construction material ranged between 0.89 Btu/^{0}F to 1.41 Btu/^{0}F. The average number of occupants was six (0.023 per square meter) as shown in Table 3.

As summarized in Table 3, type 3 commercial buildings were two-story with 19% exterior glass. Brick, stone, and stucco comprise the wall construction materials; fiberglass, shingles, and asphalt are used for the roof construction materials. Additionally, the heating and cooling systems were identical to the first and second type of commercial buildings. An average number of occupants in type 3 buildings was also six.

Type 4 commercial buildings were almost identical to type 3. The average area of type 4 buildings was 3143 ft^2 which was slightly smaller than the type 3 commercial buildings. Likewise, the exterior glass percentage was smaller than that of type 3 commercial buildings, averaging at 16% for this type of commercial building. The wall construction material and roof construction materials were identical to those of the type 3 commercial building. Based on Table 3, the average number of occupants is eight (0.032 per square meter).

Type 5 commercial buildings were the smallest of all the small-size commercial buildings with an average area of 2391 ft^2. The wall construction materials for this type of commercial buildings were identical to type 3 and type 4 commercial buildings, and roof construction materials used for type 5 commercial building consist of slates, shingles and tiles. Heating and cooling systems were also identical to the previous two types of commercial buildings. Exterior glass percentage is 17 % and the average number of occupants was six (0.027 per square meter).

The HVAC system used for all the small-sized commercial buildings was identical: district heating and cooling: FCU-4 pipe system.

Based on the study carried out by Azar and Menassa (2014), type 6 to type 10 buildings in this study were medium-size buildings. The area of the medium-size buildings varies between 15,565 ft^2 and 147,100 ft^2. The percentage of exterior glass in medium-size commercial buildings was similarly greater than small-size buildings and varied between 23% and 31%, depending on the type of medium-size buildings. In medium-size commercial buildings, the main heating systems used were packaged units or boilers and the main cooling systems were packaged units. In this study, PTAC HW heating was used for type 6 and type 7 commercial buildings. For other types of commercial buildings such as type 8, 9 and 10, PTAC electric heating was used. The least number of occupants in medium-size commercial buildings was 33, while the maximum was 49. Hence, the number of occupants was larger than that of small-size commercial buildings.

Type 6 commercial buildings were two-story with stucco, stone and brick as exterior wall construction materials and rubber and plastic as roof construction materials: the roof of some of the medium-size buildings could be built up as well. The exterior percentage glass of type 6 building was 23%. Other medium-size commercial buildings like type 7, 8, 9 and 10 all had brick, stone and stucco as exterior wall construction materials and plastic and rubber as roof construction materials. Type 9 had the largest area of 13666.2 m^2 (147100 ft^2). With three floors, type 9 was also the tallest medium-size building. All other medium-size commercial buildings were two-story buildings. Type 10 buildings used the most glass in their exterior walls – 31% – compared to 23%, 19%, 21% and 24% for types 6, 7, 8 and 9 respectively.

Large-size commercial buildings were taller than medium and small-size commercial buildings. The number of floors of these varied between four for type 11 buildings and seven (the highest number of floors) for type 14 buildings. The rest of the large-size buildings had six floors. Large-size commercial buildings used stone, brick, and concrete as exterior wall construction material. Plastic and rubber were mostly used for roof construction. Built-up roofs were also a popular option for large-size commercial buildings. In this study, one of the type 11 buildings used plastic as roof construction material; type 12 had plastic and rubber as roof construction material, while all the other types of large-size commercial-building had built-up roofs. Large-size commercial buildings used a larger percentage of glass in their exterior walls compared to medium- and small-size commercial buildings. Type 11 and type 13 had the least glass in their exterior walls with 33%: type 12 had 41%, type 14 had 45% and type 15 had more than half (51%) of its exterior covered with glass. Boilers, central chillers, and packaged units were used as heating and cooling systems in large-size commercial buildings. In this study, PTAC HW heating was used as the HVAC system for building types 11 to 14; PTAC electric heating was used as the HVAC system for type 15 buildings. Regarding occupants, there were more occupants in large-size commercial buildings compared to medium and small-size commercial buildings. Type 15 had the least number of occupants with 291 while other types had over 300 occupants: type 12 had the highest number of occupants with 358.

The thermal resistance of the roofing materials used for the large-size commercial buildings ranged between 26.18 hr·ft2·°F/Btu and 54.08 hr·ft2·°F/Btu and thermal mass varied between 7.18 Btu/°F and 44.62 Btu/°F. Conversely, the thermal resistance of the roof construction material ranged between 66.29 hr·ft2·°F/Btu and 113.18 hr·ft2·°F/Btu and thermal mass varied between 2.01 Btu/°F and 4.42 Btu/°F.

3.2.2 Collection of data on annual building energy consumption

To collect the data on annual energy consumption, building information model-based energy simulations were performed. Autodesk Revit was used to create the building information models of commercial buildings while DesignBuilder was used to conduct energy simulations.

Multiple building information models were created for each type of building based on the variation of the properties of their roofing and exterior wall construction materials. In this study, 51 building information models were used for energy simulation, and each building information model was used with three different types of occupant behavior for energy simulation; altogether, 153 simulations were performed in this study.

Depending upon the variation of building characteristics, multiple models were created for each type of building. Twenty-four building information models were created for small-size commercial buildings in Revit. In total, 72 energy simulations were performed in DesignBuilder for small-size commercial buildings. Twenty building information models were created for medium-size commercial buildings and seven building information models were created for large-size commercial buildings. Subsequently, 60 energy simulations were performed for medium-size commercial buildings, and 21 energy simulations were performed for large-size commercial buildings in this study.

Figures 1, 2 and 3 show the typical small, medium and large-size commercial buildings used in this study; Figures 4, 5 and 6 illustrate the typical floor plans of small, medium and large-size commercial buildings. The building information models used in this research for energy simulations were developed according to the building characteristics identified in the literature review. The shape, orientation and placement of openings were kept identical (as much as possible) among the small, medium and large-size commercial buildings. The floor plans of all sizes of buildings were kept square to avoid non-uniformity among the shapes of the buildings. The internal partitions that could influence the energy consumption of the buildings were also avoided in all sizes of the buildings. The shape of the roof of the buildings were designed based on the materials used for roofing. As such, the building information models of small-size commercial buildings had mostly pyramidal roofs, the medium-size commercial buildings had flat as well as sloped roof and the large-size-commercial buildings had flat roofs. The openings were kept on all four sides of the buildings. The size of the openings was based on exterior glass percentage of the buildings. The distance between the openings was also uniform in all sizes of the buildings. Overall, the building information models of small, medium and large-size commercial buildings were created based on the information obtained from the literature review. Any inclusion of additional information or designs that could affect the energy consumption of the buildings was thus avoided.

Figure 1 Building Information Model of typical small-size commercial building

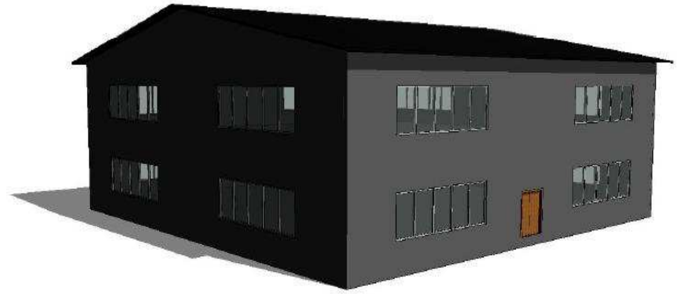

Figure 2 Building Information Model of typical medium-size commercial building

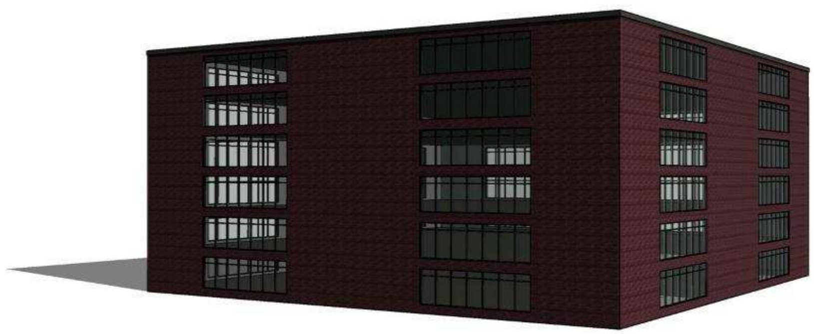

Figure 3 Building Information Model of typical medium-size commercial building

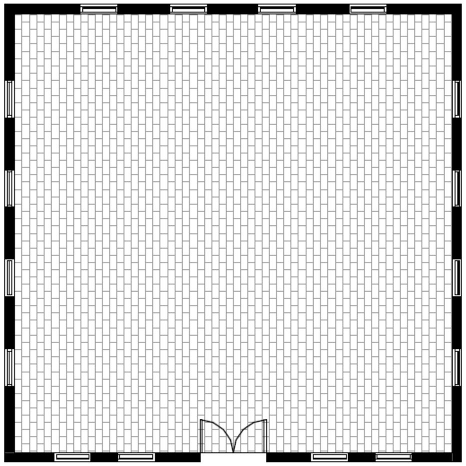

Figure 4 Typical floor plan of small-size commercial buildings

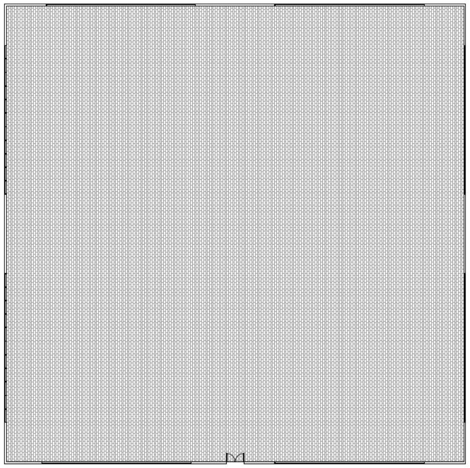

Figure 5 Typical floor plan of medium-size commercial buildings

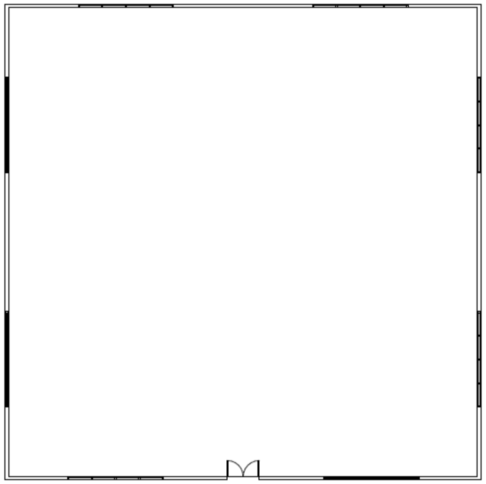

Figure 6 Typical floor plan of large-size commercial buildings

Once the building information models of 15 types of commercial buildings were created in Revit, they were exported as gbXML files, which could then be imported in DesignBuilder. In this study, all the building characteristics, with the exception of the heating and cooling systems, were defined in Revit. These building characteristics were retained when the gbXML files created using Revit were imported into DesignBuilder. In DesignBuilder, HVAC systems that were used in a typical commercial building could be easily defined. Such HVAC systems were already available in DesignBuilder's library or could be modified to suit the cooling and heating system requirements of the building. For the purpose of this study, existing HVAC systems in the DesignBuilder library were used for all the building information models for energy simulations. The HVAC systems used in this study were: a) district heating and cooling: FCU- 4 pipe; b) PTAC HW heating; and c) PTAC electric heating.

Aside from the heating and cooling system, DesignBuilder was also used to define the parameters of three types of occupant behavior. The parameters of occupant behavior were obtained from the literature review (see chapter 2) and comprised of the cooling set point, heating set point, adaptive control, daylight control, HVAC operation time and cooling startup up control. The values of these parameters for the different types of occupant behavior based on their workstyles (austerity, standard and wasteful) were defined in DesignBuilder.

3.2.2.1 Heating and cooling set points

The different activities of the occupants, such as environmental control, lighting control, control of plug loads and other environmental controls can be easily defined in DesignBuilder. This allows one to assign the values of heating and cooling set points for occupants with different types of occupant behavior.

3.2.2.2 HVAC operation time

The HVAC operation time is different for occupants with different types of workstyle. There are numerous templates in DesignBuilder designed for the HVAC operation time in DesignBuilder. Some of these templates were manually modified to match them with the HVAC operation requirements of occupants with the three workstyles used in this study.

3.2.2.3 Daylight control

The occupants with an austerity workstyle control their daylight requirements by dimming whenever it is necessary. DesignBuilder provides the option in which light can be controlled by means of stepped dimming. Other occupants with standard and wasteful workstyle do not use daylight control.

3.2.2.4 Adaptive comfort and cooling startup control

The theory of adaptive comfort states that a human can adapt to a wider range of thermal conditions than are generally accepted as comfortable when the occupant has control over his or her immediate environment (Santamouris, 2006). Occupants with an austerity workstyle contribute to energy saving through such adaptive thermal comfort. In contrast, occupants with standard and wasteful workstyles do not have any adaptive characteristics in their behavior that they could use to achieve the desired level of thermal comfort in the buildings. Moreover, only occupants with an austerity workstyle have cooling startup control. Based on the literature review, occupants with an austerity workstyle do not start to use cooling devices until the temperature reaches 28^{o}C. According to ASHRAE 55, 24^{o} C is the ideal temperature at a relative humidity of 60%, air velocity of 0.5 m/s, activity rate 1 and clothing level (Clo) 1. Thus, in this research, cooling startup control starts when the indoor temperature reaches 28^{o}C to maintain 24^{o}C when the building is occupied. The cooling startup control is turned off when the building is unoccupied. ASHRAE 55 uses the predicted mean value (PMV) to calculate the percentage of people dissatisfied with a given temperature. The recommended PMV for thermal comfort is -0.5 to +0.5. As noted above, occupants with an austerity workstyle do not turn on the cooling system until 28^{o}C: at this point, the PMV is 0.9, given that all other conditions remain constant. In DesignBuilder, the cooling startup control can be controlled by assigning the appropriate numerical value to the PMV set points and setbacks.

3.2.2.5 Occupancy control

Occupants with an austerity workstyle turn off the lights and HVAC when the room is unoccupied, thus turning down 30% of the plug loads. Conversely, occupants with a standard workstyle use lighting and HVAC as scheduled, while occupants with wasteful workstyles leave everything on. There are several ways to address these occupancy control matters in DesignBuilder.

Figure 7 summarizes the simulation process used in this research. It is evident from Figure 7 that most of the building characteristics (number of floors, area, wall construction material, roof construction material, number of occupants and exterior percentage glass) were defined in Revit. The files were then exported to DesignBuilder in gbXML file format. The remaining building characteristics, such as heating and cooling systems, were defined in DesignBuilder. DesignBuilder was also used to define the parameters of occupant behavior. The building characteristics and parameters of occupant behavior were the input used for energy simulations in DesignBuilder in this study to obtain the output; for example, annual energy consumption, heating load, cooling load, lighting load and plug load.

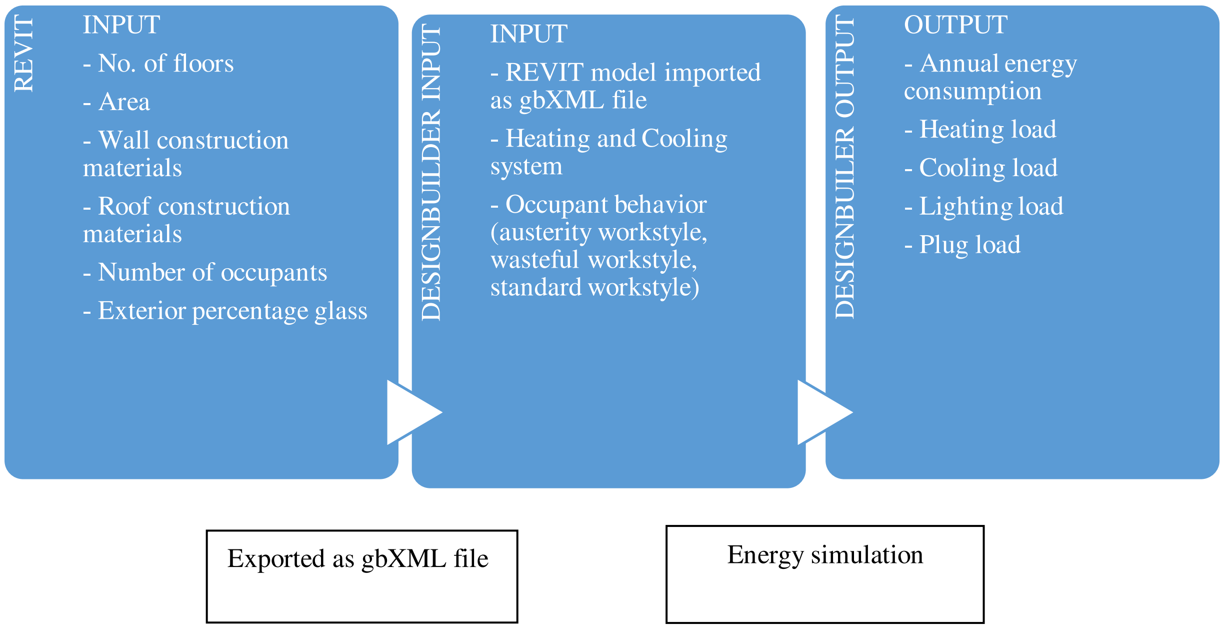

Figure 7 Simulation stepwise procedure

3.2.3 Analysis of results of BIM-based energy simulations

As the last part of the second stage, the data obtained from the literature review and BIM-based energy simulations were analyzed to measure the impact of occupant behavior and building characteristics on the energy performance of the commercial buildings. The percentage difference in annual energy consumption was calculated for each of the 153 commercial buildings for occupants with austerity, standard and wasteful workstyles.

3.3 Case study of Alder Hall

In the third stage, Alder Hall at CSU was selected to conduct the case study. Alder Hall was chosen because of its size, building characteristics and the interaction between the plug loads and occupants in the building. The data on the building characteristics of Alder Hall were collected from multiple site visits, working drawings and the information provided by the Facilities Management Department at CSU. Site visits were also used to study the occupants and their behavior in the building. Following the data collection on building characteristics, a building information model was developed for Alder Hall using Revit; BIM-based annual simulations were performed using DesignBuilder for occupants with austerity, standard and wasteful workstyles and for actual values and information of the parameters of occupant behavior in Alder Hall. Once all the required data on building characteristics and annual energy consumptions were available, the percentage differences in annual energy consumption due to occupant behavior (according to the three types of workstyles) were calculated. Based on the percentage differences of annual energy consumption by occupants with three types of workstyles, the impact of occupant behavior on Alder Hall energy performance was studied and analyzed. Additionally, the information on the six parameters (cooling set point, heating set point, adaptive comfort, occupancy control, daylight controls, HVAC operation time and cooling startup control) of occupant behavior in Alder Hall were examined to learn about the types of workstyle of the occupants in Alder Hall. The data on actual annual energy consumed by Alder Hall in 2014, 2015 and 2016 were also collected from the Facilities Management at CSU. Additionally, an abstract building was selected from 153 buildings that had the same or similar building characteristics to Alder Hall, and BIM-based energy simulations were performed using the actual values/information on parameters of occupant behavior in Alder Hall. The annual energy consumption for this abstract building, adjusted to occupants with three workstyles (austerity, standard and wasteful), were already available from previous BIM-based energy simulations performed for 153 buildings. Based on all the information available at this stage and the results obtained from the analysis of BIM-based energy simulations of buildings, three types of analysis were subsequently performed.

i. The impact of the three types of occupant behavior on annual energy consumption of Alder Hall was compared with the impact of the three types of occupant behavior on annual energy consumptions obtained from BIM-based energy simulation of the selected abstract building.
ii. The simulation results of Alder Hall and the selected abstract building that were obtained using the actual values of the seven parameters of occupant behavior in Alder Hall were compared and analyzed.
iii. The seven parameters of occupant behavior in Alder Hall were studied to ascertain the type of workstyle that occupants in Alder Hall had. Additionally, the values of the actual annual energy consumed by the Alder Hall in 2014, 2015 and 2016 were compared with simulation results of Alder Hall and analyzed.

3.4 Development of guidelines

In the fourth stage of this study, guidelines were developed to help minimize the energy consumption in the building by discouraging the wasteful workstyle of occupants. The simulation results and results obtained from the case study were used to develop these guidelines, which included policies, techniques and strategies to discourage a wasteful workstyle, and to promote awareness programs and incentives policies.

4 CHAPTER 4- RESULTS

In this chapter, the results of the BIM-based energy simulations were analyzed to show the impact of occupant behavior on the energy performance of commercial buildings. An analysis of the results began with medium-size commercial buildings because of their wider variation of building properties, compared to small and large-size commercial buildings. The results of simulations were also compared among the three sizes of the buildings. Following the analysis presented in this chapter, guidelines to improve the occupant behavior to minimize the energy consumption in the building were developed.

4.1 Analysis of results of BIM-based energy simulations

Out of ten building characteristics, seven building characteristics of the commercial buildings used in this study were defined in their building information models, which were created in Revit. These seven building characteristics were size, number of floors, percentage of exterior glass, number of occupants, wall construction materials (thermal resistance and thermal mass of wall construction materials), roof construction materials (thermal resistance and thermal mass of roof construction materials) and area of building. The remaining three building characteristics (hours of operation, heating system and cooling system) were defined in DesignBuilder after importing the building information models from Revit. The three variables, building size, heating system and cooling system, were categorical variables: the remaining seven variables were numerical variables.

The seven parameters of occupant behavior (cooling set point, heating set point, adaptive comfort, occupancy control, daylight controls, HVAC operation time and cooling startup control) were defined in DesignBuilder. The numerical and descriptive information of these parameters varied according to the workstyles of the occupants living in the buildings. Altogether, 153 energy simulations were performed in DesignBuilder for small-, medium- and large-size commercial buildings.

4.1.1 Medium-size buildings

In this study, the area of the medium-size commercial building ranged between 15,564 ft^2 and 147,102 ft^2. Based on variations of the building characteristics, such as wall construction materials and roof construction materials, 20 building information models were created for medium-size commercial buildings. Each model was used to perform three energy simulations for three types of occupant workstyles: austerity, standard and wasteful. Thus, 60 building information model-based energy simulations were performed for medium-size commercial buildings. Two types of HVAC systems were used in energy simulations of the medium-size commercial buildings: these were packaged terminal air conditioner hot water (PTAC HW) heating and packaged terminal air conditioner (PTAC) hot water electric heating.

The thermal resistance of the wall construction materials of medium-size commercial buildings used in the energy simulations varied between 20.56 hr·ft^2·°F/Btu and 74.77 hr·ft^2·°F/Btu whereas that of roof construction material between 66.29 hr·ft2·°F/Btu and 113.28 hr·ft2·°F/Btu. The thermal mass of wall construction materials ranged between 14.33 Btu/°F and 26.65 Btu/°F and for roof construction materials, it ranged between 2.01 Btu/°F and 4.42 Btu/°F. The thermal resistance of the wall construction materials as well as roof construction materials had more variation than the thermal mass. The thermal mass of both wall construction and roof construction materials had a small range in terms of numerical values. To study the effect of change of roof and wall construction materials, annual energy simulations number 87 and 88 were performed using two identical building information models for the small-size commercial buildings with wasteful workstyle. All the variables except the thermal resistance of wall-construction materials were kept identical. The thermal resistance of the wall-construction materials was changed from 74.77 hr·ft2·°F/Btu to 53.41 hr·ft2·°F/Btu by changing the wall-construction material. The resulting change of energy consumption due to change of the thermal resistance of the wall was only 0.34%.

4.1.1.1 Energy simulation results for medium-size commercial buildings

The results obtained from BIM-based energy simulations in DesignBuilder showed that the energy consumed by the medium-size commercial buildings ranged between 416,996 kBtu and 7,903,109 kBtu. In addition to that, the occupants in the building with the highest annual energy consumption had wasteful workstyles and the occupants with least annual energy consumption had austerity workstyles.

Sixty BIM-based energy simulations were performed for medium-size commercial buildings, 20 for each workstyle. Table 11 shows that the highest annual energy consumption by medium-size commercial buildings for wasteful workstyle was 7,903,109 kBtu and the lowest was 881,406 kBtu. For the standard workstyle, the annual energy consumption ranged between 6,994,528 kBtu and 747,858 kBtu, while the range for austerity workstyle was 4,676,347 kBtu to 416,996 kBtu. The difference between the highest and the lowest annual energy consumption by occupants with a wasteful workstyle in medium-size commercial building was 7,021,703 kBtu: a difference of 89%. For the standard and austerity workstyles, the difference between the highest and the lowest were 6,246,670 kBtu (89%) and 4,259,351 (91%) respectively. In summary, these results showed that the change of annual energy consumption due to change of building characteristics in medium-size commercial building ranged between 89% and

91%. Such a significant change of annual energy consumption could be attributed to the large variation of the building characteristics in medium-size commercial buildings compared to small and large-size commercial buildings. Moreover, this significant change of energy consumption due to variation of building characteristics further indicated that building characteristics were a very important factor in building energy performance, irrespective of the occupant behavior in the buildings.

Table 11 Change of energy consumption for different workstyles of occupants in medium-size commercial buildings

Occupant workstyle	Highest energy consumed (kBtu)	Lowest energy consumed (kBtu)	Difference in energy consumption due to change of building characteristics (kBtu)	Percentage difference in energy consumption due to change of building characteristics (%)
Austerity Workstyle	4,676,347	416,996	4,259,351	91%
Standard Workstyle	6,994,528	747,858	6,246,670	89%
Wasteful Workstyle	7,903,109	881,406	7,021,703	89%

4.1.1.2 Impact of occupant behavior on the energy performance of medium-size commercial buildings

To measure the impact of occupant behavior on building energy consumption, the characteristics of the buildings were kept intact in the building information models of medium-size commercial buildings and energy simulations were performed in DesignBuilder by altering the numerical and descriptive value of the parameters of occupant behavior for three different types of occupant workstyles. The parameters of occupant behavior were the cooling set point, the heating set point, HVAC operation time, cooling startup control, daylight control and adaptive comfort. The results obtained from the energy simulations in DesignBuilder were used to compare the differences in energy consumed by occupants with three types of workstyles. The difference in annual energy consumption by occupants with wasteful and austerity workstyles is shown in Table 12. Table 13 shows the difference in annual energy consumption between wasteful and standard workstyles of occupants while Table 14 shows the difference in annual energy consumption between standard and austerity workstyles.

Table 12 Comparison of energy consumed by medium-size commercial buildings for occupants with Wasteful and Austerity Workstyle

HVAC type	Simulation Number		Annual Energy Consumed (kBtu)		Decrease in energy use (kBtu)	Percentage Decrease (%)
	Workstyle		Workstyle			
	Wasteful	Austerity	Wasteful	Austerity	Wasteful – Austerity (From -To)	Wasteful – Austerity (From -To)
PTAC HW Heating	73	113	968785	445431	523354	54
	74	114	978145	450258	527887	54
	75	115	968783	450258	518525	54
	76	116	978127	450258	527869	54
	77	117	978145	450258	527887	54
	78	118	968759	445431	523328	54
	79	119	968783	445431	523352	54
	80	120	968053	454460	513593	53
	81	121	968053	454460	513593	53
	82	122	968042	454460	513582	53
	83	123	958732	449586	509146	53
PTAC Electric Heating	84	124	881406	416996	464410	53
	85	125	891942	422643	469299	53
	86	126	891942	422643	469299	53
	87	127	7876266	4655403	3220863	41
	88	128	7903109	4676347	3226762	41
	89	129	7903109	4676347	3226762	41

Table 12 Comparison of energy consumed by medium-size commercial buildings for occupants with Wasteful and Austerity Workstyle cont'd

HVAC type	Simulation Number		Annual Energy Consumed (kBtu)		Decrease in energy use (kBtu)	Percentage Decrease (%)
	Workstyle		Workstyle			
	Wasteful	Austerity	Wasteful	Austerity	Wasteful – Austerity (From -To)	Wasteful – Austerity (From -To)
	90	130	4717674	2264831	2452843	52
	91	131	4746032	2280122	2465910	52
	92	132	4746032	2280122	2465910	52

Table 13 Comparison of energy consumed by medium-size commercial buildings for occupants with Wasteful and Standard Workstyle

HVAC	Simulation Model		Annual Energy Consumed (kBtu)		Decrease in Energy use (kBtu)	Percentage Decrease (%)
	Workstyle		Workstyle			
	Wasteful	Standard	Wasteful	Standard	Wasteful - Standard (From -To)	Wasteful - Standard (From -To)
PTAC HW Heating	73	93	968785	784628	184157	19
	74	94	78145	792457	184157	19
	75	95	968783	792457	176326	18
	76	96	978127	792457	185670	19
	77	97	978145	792457	185688	19
	78	98	968759	784628	184131	19

Table 13 Comparison of energy consumed by medium-size commercial buildings for occupants with Wasteful and Standard Workstyle cont'd

HVAC	**Simulation Model**		**Annual Energy Consumed (kBtu)**		**Decrease in Energy use (kBtu)**	**Percentage Decrease (%)**
	Workstyle		**Workstyle**			
	Wasteful	**Standard**	**Wasteful**	**Standard**	**Wasteful - Standard (From -To)**	**Wasteful - Standard (From -To)**
	79	99	968783	784628	184155	19
	80	100	968053	786105	181948	19
	81	101	968053	786105	181948	19
	82	102	968042	786105	181937	19
	83	103	958732	778303	180429	19
PTAC Electric Heating	84	104	881406	747858	133548	15
	85	105	891942	757316	134626	15
	86	106	891942	757316	134626	15
	87	107	7876266	6970701	905565	12
	88	108	7903109	6994528	908581	12
	89	109	7903109	6994528	908581	12
	90	110	4717674	4076353	641321	14
	91	111	4746032	4101681	644351	14

Table 13 Comparison of energy consumed by medium-size commercial buildings for occupants with Wasteful and Standard Workstyle cont'd

HVAC	Simulation Model		Annual Energy Consumed (kBtu)		Decrease in Energy use (kBtu)	Percentage Decrease (%)
	Workstyle		Workstyle			
	Wasteful	Standard	Wasteful	Standard	Wasteful - Standard (From -To)	Wasteful - Standard (From -To)
	92	112	4746032	4101681	644351	14

Table 14 Comparison of energy consumed by building information models of medium-size commercial buildings for occupants with Standard and Austerity Workstyle cont'd

HVAC	Simulation Number		Annual Energy Consumed (kBtu)		Decrease in energy use (kBtu)	Percentage Decrease (%)
	Workstyle		Workstyle			
	Standard	Austerity	Standard	Austerity	Standard – Austerity (From -To)	Standard – Austerity (From -To)
PTAC HW Heating	93	113	784628	445431	339197	43
	94	114	792457	450258	342199	43
	95	115	792457	450258	342199	43
	96	116	792457	450258	342199	43
	97	117	792457	450258	342199	43
	98	118	784628	445431	339197	43
	99	119	784628	445431	339197	43
	100	120	786105	454460	331645	42
	101	121	786105	454460	331645	42
	102	122	786105	454460	331645	42

Table 14 Comparison of energy consumed by building information models of medium-size commercial buildings for occupants with Standard and Austerity Workstyle cont'd

HVAC	**Simulation Number**		**Annual Energy Consumed (kBtu)**		**Decrease in energy use (kBtu)**	**Percentage Decrease (%)**
	Workstyle		**Workstyle**			
	Standard	**Austerity**	**Standard**	**Austerity**	**Standard – Austerity (From -To)**	**Standard – Austerity (From -To)**
	103	123	778303	449586	328717	42
PTAC Electric Heating	104	124	747858	416996	330862	44
	105	125	757316	422643	334673	44
	106	126	757316	422643	334673	44
	107	127	6970701	4655403	2315298	33
	108	128	6994528	4676347	2318181	33
	109	129	6994528	4676347	2318181	33
	110	130	4076353	2264831	1811522	44
	111	131	4101681	2280122	1821559	44
	112	132	4101681	2280122	1821559	44

Table 15 was developed based on Tables 12-14, which further shows that when the workstyle of occupants was changed from wasteful to austerity, the annual energy consumption decreased by 41%-54% for medium-size commercial buildings. Similarly, when the workstyle of occupants changed from wasteful to standard, the reduction of annual energy consumption was between 11% and 19%, and the reduction was between 33% and 44% for the change of workstyle from standard to austerity. This result indicated that occupant behavior, along with building characteristics, had a major role in the energy performance of medium-size commercial buildings. The annual energy consumption can be decreased by up to 54% in medium-size commercial building by changing the workstyle from wasteful to austerity.

Table 15 Decrease in energy consumption in medium-size commercial building due to change of workstyles

Change of occupant workstyles (From – To)	Range of Percent decrease in energy consumption due to change of workstyles
Wasteful – Austerity	41% to 54%
Wasteful – Standard	11% to 19%
Standard – Austerity	33% to 44%

4.1.1.3 Energy use intensity in medium-size commercial buildings

Table 16 compares the change of energy use intensity due to the change of workstyle of the occupants in medium-size commercial buildings. The results in this table show that the energy use intensity for occupants with a wasteful workstyle ranged between 54 kBtu and 248 kBtu. For standard and austerity workstyles, the ranges of energy use intensity varied between 47 kBtu to 214 kBtu and 28 kBtu to 119 kBtu respectively. The decrease in energy use intensity due to change of workstyle from wasteful to austerity varied between 41% and 54%, whereas a decrease in energy use intensity ranged from 33% to 44% for a change of workstyle from wasteful to standard. Similarly, the decrease in energy use intensity was 12% to 19% for the change of workstyle from standard to austerity. The results of this analysis of energy use intensity in medium-size commercial buildings indicated that occupant behavior had a significant impact on building energy performance. The results also showed that energy use intensity in medium-size commercial buildings could vary by up to 54% due to occupant behavior.

Table 16 Change of energy use intensity due to change of occupant workstyles in medium-size commercial buildings

Simulation Number			Energy use intensity (kBtu/ft^2)			Decrease in energy use intensity due to change of workstyle (%)		
W	S	A	W	S	A	W-S	W-A	S-A
73	93	113	62	50	29	19	54	43
74	94	114	63	51	29	19	54	43
75	95	115	62	51	29	18	54	43

Table 16 Change of energy use intensity due to change of occupant workstyles in medium-size commercial buildings cont'd

Simulation Number			**Energy use intensity (kBtu/ft^2)**			**Decrease in energy use intensity due to change of workstyle (%)**		
W	**S**	**A**	**W**	**S**	**A**	**W-S**	**W-A**	**S-A**
76	96	116	63	51	29	19	54	43
77	97	117	63	51	29	19	54	43
78	98	118	62	50	29	19	54	43
79	99	119	62	50	29	19	54	43
80	100	120	62	50	29	19	53	42
81	101	121	62	50	29	19	53	42
82	102	122	62	50	29	19	53	42
83	103	123	61	49	29	19	53	42
84	104	124	58	50	28	15	53	44
85	105	125	59	50	28	15	53	44
86	106	126	59	50	28	15	53	44
87	107	127	54	47	32	12	41	33
88	108	128	54	48	32	12	41	33
89	109	129	54	48	32	12	41	33
90	110	130	246	213	118	19	52	44
91	111	131	248	214	119	19	52	44
92	112	132	248	214	119	18	52	44

W= Wasteful Workstyle
S= Standard Work Style
A= Austerity Workstyle

4.1.2 Small-size commercial buildings

The area of small-size commercial buildings varied between 2,761 ft^2 and 3265 ft^2. Like medium-size commercial buildings, small-size commercial buildings were defined by 10 numerical variables and two categorical variables. Altogether, 72 building information models were created for small-size commercial buildings: 24 models for occupants with austerity workstyles, 24 for occupants with standard workstyles and 24 for the wasteful workstyle. Only one HVAC system was used for the annual energy simulations of small-size commercial buildings which was district heating and cooling: FCU-pipe.

In small-size commercial buildings, the thermal resistance of the wall construction materials varied between 20.56 hr·ft2·°F/Btu and 74.77 hr·ft2·°F/Btu whereas that of roof construction materials varied between 32.01 hr·ft2·°F/Btu and 59.68 hr·ft2·°F/Btu. The thermal mass of wall construction materials ranged between 7.89 Btu/°F and 26.65 Btu/°F: for roof construction materials, it ranged between 0.81 Btu/°F and 0.71 Btu/°F. The range of the numerical value for thermal resistance and thermal mass of the wall construction materials and roof construction materials in small-size commercial buildings was smaller than that of medium-size commercial buildings. Such a small variation in the numerical values of thermal resistance and thermal mass of wall and roof construction materials was due to the fewer varieties of materials that are used in the US for roof and wall construction in small-size commercial buildings compared to medium-size commercial buildings. Thus, the results showed that wall and roof construction materials did not have a significant effect on annual energy consumption of the small-size commercial buildings. Likewise, other features like the number of floors, number of occupants and area of the building also presented a smaller variation in small-size commercial buildings compared to medium-size commercial buildings.

4.1.2.1 Energy simulation results for small-size commercial buildings

The results of BIM-based energy simulations performed in DesignBuilder showed that the energy consumed by the small commercial buildings ranged between 107,616 kBtu and 265,120 kBtu. The energy consumption pattern in small-size commercial buildings was similar to medium-size commercial buildings: the building with the highest area had the highest amount of energy consumption and that with the lowest area had the lowest amount of energy consumption. However, because of the smaller variation of building characteristics in small-size commercial buildings (in comparison to medium-size commercial buildings), the percentage difference between the highest and the lowest annual energy consumption was smaller than for medium-size commercial buildings. The effect of occupant behavior on energy consumption in small-size commercial buildings also revealed a similar energy consumption pattern to that of medium-size commercial buildings, with results indicating that, for identical buildings, occupants with austerity workstyles consumed the lowest amount of energy annually and occupants with wasteful workstyles consumed the highest amount of energy annually.

Table 17 shows the change of energy consumption due to the change of building characteristics of small-size commercial buildings. To measure the impact of building characteristics on energy consumption of small-size buildings, the workstyles of the occupants were kept identical. This allowed one to identify the difference in energy consumption due to variation of building characteristics: these results are shown in Table 18-20. The lowest annual energy consumption by occupants with wasteful workstyles in small commercial buildings was 250,144 kBtu and the highest was 296,021 kBtu. The annual energy consumed by the occupants with austerity workstyles ranged between 107,616 kBtu and 128,760 kBtu. The range for occupants with standard workstyles was 192,985 kBtu to 231,630 kBtu. The results in these tables show that the variations in energy consumption in small-size commercial buildings for identical workstyles were due to changes in building characteristics. The difference in annual energy consumption due to changes in building characteristics of small commercial buildings with occupants with wasteful workstyles was 15% and, for occupants with austerity and standard workstyles, the difference in energy consumption was 17%. To make the point of comparison, this difference in energy consumption due to change of building characteristics in medium-size commercial buildings was 89% to 91% which was much greater than the 15%-17% difference in small-size commercial buildings. This variance in annual energy consumption between small and medium-size commercial building could be attributed to the larger variation of the building characteristics in medium-size commercial buildings than in small-size commercial building.

Table 17 Change of energy consumption for different workstyles of occupants in small-size commercial buildings

Occupant workstyle	**Highest energy consumed (kBtu)**	**Lowest energy consumed (kBtu)**	**Range of change of energy consumption due to change of building characteristics (kBtu)**	**Percentage change of energy consumption due to change of building characteristics (%)**
Austerity Workstyle	129580	107616	21,964	17
Standard Workstyle	231630	192985	38645	17
Wasteful Workstyle	296021	250144	45,877	15

4.1.2.2 Impact of occupant behavior on the energy performance of small-size commercial buildings

Table 18-20 compares the change of energy consumption due to change of occupant workstyle in small-size commercial buildings. To calculate the change of energy consumption due to the change of occupant workstyles, the building characteristics of small-size commercial buildings were kept identical and energy simulations were performed for the three types of workstyles of occupants. The results presented in Table 18 shows the decrease in annual energy use due to the change of workstyle from wasteful to austerity; Table 19 shows the decrease in annual energy use due to the change of workstyle from wasteful to standard and Table 20 shows the decrease of annual energy consumption due to the change of workstyle from standard to austerity in small-size commercial buildings.

Table 18 Comparison of energy consumed by small-size commercial buildings for occupants with Wasteful and Austerity workstyles

HVAC	Simulation Number		Annual Energy Consumed (kBtu)		Decrease in energy use (kBtu)	Percentage Decrease (%)
	Workstyles		Workstyle		Wasteful – Austerity (From – To)	Wasteful – Austerity (From – To)
	Wasteful	Austerity	Wasteful	Austerity		
District Heating, FCU-4 Pipe	1	25	287524	125820	161704	56
	2	26	294222	128760	165462	56
	3	27	296021	129580	166441	56
	4	28	294222	128760	165462	56
	5	29	257557	109666	147891	57
	6	30	250522	107616	142906	57
	7	31	256031	108920	147111	58
	8	32	256031	108920	147111	58
	9	33	256031	108920	147111	58
	10	34	276389	116990	159399	58
	11	35	276389	116990	159399	58
	12	36	276389	116990	159399	58
	13	37	281262	119097	162165	58
	14	38	281262	119097	162165	58
District	15	39	260407	110221	150186	58

Table 18 Comparison of energy consumed by small-size commercial buildings for occupants with Wasteful and Austerity workstyles cont'd

HVAC	**Simulation Number**		**Annual Energy Consumed (kBtu)**		**Decrease in energy use (kBtu)**	**Percentage Decrease (%)**
	Workstyles		**Workstyle**		**Wasteful – Austerity (From – To)**	**Wasteful – Austerity (From – To)**
	Wasteful	**Austerity**	**Wasteful**	**Austerity**		
Heating, FCU-4 Pipe	16	40	265120	112275	152845	58
	17	41	260407	110221	150186	58
	18	42	265120	112275	152845	58
	19	43	265120	112275	152845	58
	20	44	254758	107918	146840	58
	21	45	254758	107918	146840	58
	22	46	250141	107740	142401	57
	23	47	250144	107740	142404	57
	24	48	254758	107918	146840	58

Table 19 Comparison of energy consumed by small-size commercial buildings for occupants with Wasteful and Standard workstyles

HVAC	**Simulation Model**		**Annual Energy Consumed (kBtu)**		**Decrease in energy use (kBtu)**	**Percentage Decrease (%)**
	Workstyle		**Workstyle**			
	Wasteful	**Standard**	**Wasteful**	**Standard**	**Wasteful – Standard (From – To)**	**Wasteful – Standard (From – To)**
District Heating, FCU-4 Pipe	1	49	287524	224799	62725	22
	2	50	294222	230142	64080	22
	3	51	296021	231630	64391	22
	4	52	294222	230142	64080	22
	5	53	257557	200978	56579	22
	6	54	250522	194425	56097	22

Table 19 Comparison of energy consumed by small-size commercial buildings for occupants with Wasteful and Standard workstyles

HVAC	Simulation Model		Annual Energy Consumed (kBtu)		Decrease in energy use (kBtu)	Percentage Decrease (%)
	Workstyle		Workstyle			
	Wasteful	Standard	Wasteful	Standard	Wasteful – Standard (From – To)	Wasteful – Standard (From – To)
	7	55	256031	199553	56478	22
	8	56	256031	199553	56478	22
	9	57	256031	199553	56478	22
	10	58	276389	213938	62451	23
	11	59	276389	213938	62451	23
	12	60	276389	213938	62451	23
	13	61	281262	217397	63865	23
District Heating, FCU-4 Pipe	14	62	281262	217397	63865	23
	15	63	260407	201165	59242	23
	16	64	265120	205051	60069	23
	17	65	260407	201165	59242	23
	18	66	265120	205051	60069	23
	19	67	265120	205051	60069	23
	20	68	254758	196793	57965	23
	21	69	254758	196793	57965	23
	22	70	250141	192985	57156	23
	23	71	250144	196793	53351	21

Table 19 Comparison of energy consumed by small-size commercial buildings for occupants with Wasteful and Standard workstyles

HVAC	Simulation Model Workstyle		Annual Energy Consumed (kBtu) Workstyle		Decrease in energy use (kBtu)	Percentage Decrease (%)
	Wasteful	Standard	Wasteful	Standard	Wasteful – Standard (From – To)	Wasteful – Standard (From – To)
	24	72	254758	192985	61773	24

Table 20 Comparison of energy consumed by small-size commercial buildings for occupants with Standard and Austerity workstyles cont'd

HVAC	Simulation Model Workstyle		Annual Energy Consumed (kBtu) Workstyle		Decrease in energyuse (kBtu)	Percentage decrease (%)
	Standard	Austerity	Standard	Austerity	Standard – Austerity (From – To)	Standard – Austerity (From – To)
District Heating, FCU-4 Pipe	49	25	287524	125820	98979	44
	50	26	294222	128760	101382	44
	51	27	296021	129580	102050	44
	52	28	294222	128760	101382	44
	53	29	257557	109666	91312	45
	54	30	250522	107616	86809	45
	55	31	256031	108920	90633	45
	56	32	256031	108920	90633	45
	57	33	256031	108920	90633	45
	58	34	276389	116990	96948	45
	59	35	276389	116990	96948	45

Table 20 Comparison of energy consumed by small-size commercial buildings for occupants with Standard and Austerity workstyles cont'd

HVAC	**Simulation Model**		**Annual Energy Consumed (kBtu)**		**Decrease in energyuse (kBtu)**	**Percentage decrease (%)**
	Workstyle		**Workstyle**		**Standard – Austerity (From – To)**	**Standard – Austerity (From – To)**
	Standard	**Austerity**	**Standard**	**Austerity**		
	60	36	276389	116990	96948	45
	61	37	281262	119097	98300	45
	62	38	281262	119097	98300	45
	63	39	260407	110221	90944	45
District Heating, FCU-4 Pipe	64	40	265120	112275	92776	45
	65	41	260407	110221	90944	45
	66	42	265120	112275	92776	45
	67	43	265120	112275	92776	45
	68	44	254758	107918	88875	45
	69	45	254758	107918	88875	45
	70	46	250141	107740	85245	44
	71	47	250144	107740	89053	45
	72	48	254758	107918	85067	44

Table 21 summarizes the decrease in energy consumption in small-size commercial buildings due to the change of workstyles. The range of percentage decrease in energy consumption for the change of workstyle from wasteful to austerity in small-size buildings was between 56 % and 58%; between 21% and 24% for the change of workstyle from wasteful to standard and between 44% and 45% for the change of workstyle from standard to austerity.

These data showed that occupant behavior plays a very important role in the energy performance of the small-size commercial buildings. Around 57% of the energy can be saved if the occupants adopt the austerity workstyle as compared to the wasteful workstyle. This result suggests that the behavior of occupants in small-size commercial buildings has a slightly greater effect on the energy consumption than in the medium-size commercial building for the same change of workstyles from wasteful to austerity, wasteful to standard and standard to austerity.

Table 21 Decrease in energy consumption in small-size commercial building due to change of workstyles

Change of occupant workstyles (From – To)	**Percentage decrease in energy consumption due to change of workstyles**
Wasteful – Austerity	56 % to 58%
Standard – Austerity	44% to 45%
Wasteful -Standard	21% to 24%

4.1.2.3 Energy use intensity in small-size commercial buildings

Table 22 shows the energy use intensity for occupants with different workstyles. The energy use intensity for occupants with wasteful workstyles varied between 88 kBtu and 107 kBtu. Energy use intensity for occupants with standard and austerity workstyles varied between 69 kBtu and 89 kBtu and between 39 kBtu and 45 kBtu respectively. The percentage decrease in energy use intensity due to change of workstyle from wasteful to austerity varied between 56% and 58%, whereas the range of percentage decrease in energy use intensity was between 21% and 24% for change of workstyles from wasteful to standard. The decrease in energy use intensity varied between 44% and 45% for the change of workstyle from standard to austerity. According to these results, the effect of a changed occupant workstyle on energy use intensity in small-size commercial building is slightly greater than in medium-size commercial buildings for the same change of workstyles.

Table 22 Comparison of energy use intensity in small-size buildings for occupants with different workstyles l

Energy simulation Number			**Energy use Intensity ($kBtu/ft^2$)**			**Decrease in Energy use intensity due to change of workstyle (%)**		
W	**S**	**A**	**W**	**S**	**A**	**W-S**	**W-A**	**S-A**
1	49	25	88	69	39	22	56	44
2	50	26	90	70	39	22	56	44

Table 22 Comparison of energy use intensity in small-size buildings for occupants with different workstyles cont'd

Energy simulation Number			Energy use Intensity ($kBtu/ft^2$)			Decrease in Energy use intensity due to change of workstyle (%)		
W	**S**	**A**	**W**	**S**	**A**	**W-S**	**W-A**	**S-A**
3	51	27	91	71	40	22	56	44
4	52	28	90	70	39	22	56	44
5	53	29	93	73	40	22	57	45
6	54	30	91	70	39	22	57	45
7	55	31	93	72	39	22	58	45
8	56	32	93	72	39	22	58	45
9	57	33	93	72	39	22	58	45
10	58	34	92	71	39	23	58	45
11	59	35	92	71	39	23	58	45
12	60	36	92	71	39	23	58	45
13	61	37	94	72	40	23	58	45
14	62	38	94	72	40	23	58	45
15	63	39	100	77	42	23	58	45
16	64	40	101	78	43	23	58	45
17	65	41	100	77	42	23	58	45
18	66	42	101	78	43	23	58	45
19	67	43	101	78	43	23	58	45
20	68	44	107	82	45	23	58	45
21	69	45	107	82	45	23	58	45

Table 22 Comparison of energy use intensity in small-size buildings for occupants with different workstyles cont'd

Energy simulation Number			**Energy use Intensity ($kBtu/ft^2$)**			**Decrease in Energy use intensity due to change of workstyle (%)**		
W	**S**	**A**	**W**	**S**	**A**	**W-S**	**W-A**	**S-A**
22	70	46	105	81	45	23	57	44
23	71	47	105	82	45	21	57	45
24	72	48	107	81	45	24	58	44
W= Wasteful Workstyle S= Standard Workstyle A= Austerity Workstyle								

4.1.3 Large-size commercial buildings

In this study, 21 building information models were created in Revit 2016 for the large-size commercial buildings: seven models for each workstyle of occupants. The area of the large-size commercial building varied between 119,180.2ft^2 and 152,113 ft^2. Two types of HVAC systems were used for energy simulations in large-size commercial buildings which were packaged terminal air conditioner (PTAC) hot water heating and packaged terminal air conditioner (PTAC) electric heating.

The thermal resistance of the wall construction materials of large-size commercial buildings used in the energy simulations varied between 26.18 hr·ft^2·°F/Btu and 54.08 hr·ft^2·°F/Btu: whereas that of roof construction materials varied between 66.29 hr·ft2·°F/Btu and 113.28 hr·ft2·°F/Btu. The thermal mass of wall construction materials ranged between 7.18 Btu/°F and 44.62 Btu/°F and, for roof construction materials, it ranged between 2.01 Btu/°F and 4.42 Btu/°F. Similar to the medium-size commercial buildings, the thermal resistance of the wall construction materials and roof construction materials in large-size commercial buildings had more variation than thermal mass. The thermal mass of both wall construction and roof construction materials also had a small range in terms of numerical values.

4.1.3.1 Energy simulation results of large-size commercial buildings

The results obtained using the BIM-based energy simulations of large-size commercial buildings showed that the highest annual energy consumption in large-size commercial building for occupants with wasteful workstyles was 8,435,895 kBtu: the lowest annual energy consumption was 6,541,518 kBtu. For the occupants with austerity workstyles, the highest and the lowest annual energy consumptions were 4,268,591 kBtu and 3,375,702 kBtu respectively. For occupants with standard workstyles, the energy consumption varied between 5,844,580 kBtu and 7,453,953 kBtu. The results of energy simulations for the different types of workstyles in large-size commercial buildings are summarized in Tables 24-26.

Table 23 further summarizes the change of annual energy consumption due to the change of building characteristics in large-size commercial buildings. The variation in energy consumption in large-size commercial buildings for occupants with wasteful workstyles was 22%, for standard workstyles it was 22%, and for austerity workstyles it was 21%. The effect of the variation of building characteristics on energy consumption was greater in large-size commercial buildings, compared to small-size commercial buildings, but smaller than medium-size commercial buildings. The range of variation of energy consumption in small and medium-size commercial buildings for occupants with three different types of workstyles due to change of building characteristics was between 15% and 17% and between 89% and 91% respectively compared to a variation of between 21% and 22% in large-size commercial buildings.

Such differences in the range of variation of energy consumption due to building characteristics among the three different sizes of the commercial buildings could be attributed to the greater fluctuation of building properties in medium-size commercial buildings compared to the building properties of small and large-size commercial buildings in this study. In other words, the results here revealed that the numerical values of the parameters of building characteristics of medium-size commercial buildings in this study had a larger range than numerical values of the parameters of building characteristics of small and large-size commercial buildings. This further indicated that building properties play a predominant role in building energy performance irrespective of occupant behavior.

Table 23 Change of energy consumption for different workstyles of occupants in large-size commercial buildings

Occupant workstyle	**Highest energy consumed (kBtu)**	**Lowest energy consumed (kBtu)**	**Range of change of energy consumption due to change of building characteristics (kBtu)**	**Percentage change of energy consumption due to change of building characteristics (%)**
Austerity Workstyle	4,268,591	3,375,702	892,889	21
Standard Workstyle	7,453,953	5,844,580	1,609,373	22
Wasteful Workstyle	8,435,895	6,541,518	1,894,377	22

4.1.3.2 Impact of occupant behavior on energy performance of large-size commercial building

Table 24-26 compare the change of annual energy consumption by occupants due to change of their workstyles. To evaluate the impact of occupant behavior on energy performance of large-size commercial buildings, building characteristics were kept identical and energy simulations were performed for three types of occupant workstyles. Table 24 compares the annual energy consumptions between wasteful and austerity workstyles. Similarly, Table 25 compares the annual energy consumption between wasteful and standard workstyles while the comparison of annual energy consumption between standard and austerity workstyles is shown in Table 26.

Table 24 Comparison of energy consumed by large-size commercial buildings for occupants with Wasteful and Austerity workstyles

HVAC	**Energy Simulation Number**		**Annual Energy Consumed (kBtu)**		**Decrease in energy use (kBtu)**	**Percentage Decrease (%)**
	Workstyle		**Workstyle**		**Wasteful – Austerity (From – To)**	**Wasteful – Austerity (From – To)**
	Wasteful	**Austerity**	**Wasteful**	**Austerity**		
PTAC HW Heating	147	140	6541518	3375702	3165816	48
PTAC HW Heating	148	141	8109035	4268591	3840444	47
PTAC HW Heating	149	142	8109035	4268591	3840444	47
PTAC HW Heating	150	143	8109035	4268591	3840444	47
PTAC HW Heating	151	144	8130301	4197104	3933197	48
PTAC HW Heating	152	145	8435895	4153602	4282293	51
PTAC Electric Heating	153	146	8411470	4071310	4340160	52

Table 25 Comparison of energy consumed by large-size commercial buildings for occupants with Wasteful and Standard workstyles

HVAC	**Energy Simulation Number**		**Annual Energy Consumed (kBtu)**		**Decrease in energy use (kBtu)**	**Percentage decrease (%)**
	Workstyle		**Workstyle**		**Wasteful – Standard (From – To)**	**Wasteful - Standard (From – To)**
	Wasteful	**Standard**	**Wasteful**	**Standard**		
PTAC HW Heating	147	133	6541518	5844580	696938	11
PTAC HW Heating	148	134	8109035	7372838	736197	9

Table 25 Comparison of energy consumed by large-size commercial buildings for occupants with Wasteful and Standard workstyles cont'd

HVAC	Energy Simulation Number		Annual Energy Consumed (kBtu)		Decrease in energy use (kBtu)	Percentage decrease (%)
	Workstyle		Workstyle		Wasteful – Standard (From – To)	Wasteful - Standard (From – To)
	Wasteful	Standard	Wasteful	Standard		
PTAC HW Heating	149	135	8109035	7372838	736197	9
PTAC HW Heating	150	136	8109035	7372838	736197	9
PTAC HW Heating	151	137	8130301	7330134	800167	10
PTAC HW Heating	152	138	8435895	7453953	981942	12
PTAC Electric Heating	153	139	8411470	7361106	1050364	12

Table 26 Comparison of energy consumed by large-size commercial buildings for occupants with Standard and Austerity workstyles

HVAC	Energy Simulation Number		Annual Energy Consumed (kBtu)		Decrease in energy use (kBtu)	Percentage decrease (%) From - To
	Workstyle		Workstyle		Standard - Austerity (From – To)	Standard - Austerity (From – To)
	Standard	Austerity	Standard	Austerity		
PTAC HW Heating	133	140	5844580	3375702	2468878	42
PTAC HW Heating	134	141	7372838	4268591	3104247	42
PTAC HW Heating	135	142	7372838	4268591	3104247	42
PTAC HW Heating	136	143	7372838	4268591	3104247	42
PTAC HW Heating	137	144	7330134	4197104	3133030	43
PTAC HW Heating	138	145	7453953	4153602	3300351	44
PTAC Electric Heating	139	146	7361106	4071310	3289796	45

Table 27 shows the decrease in energy consumption due to the change of occupant workstyle in large-size commercial building from wasteful to austerity varied between 48% and 52%. The range of percentage decrease due to change of workstyle from wasteful to standard was between 9% and 11% and it was between 42% and 45% due to change of workstyle from standard to austerity. The results of the BIM-based energy simulations of large-size commercial buildings complied with the results obtained by BIM-based energy simulations of small and medium-size commercial buildings. The occupants with austerity workstyle consumed the lowest amount of energy annually while occupants with wasteful workstyle had the highest annual energy consumption for all building sizes.

Table 27 Decrease in energy consumption in large-size commercial buildings due to change of workstyles

Change of occupant workstyles (From – To)	**Range of percentage decrease in energy consumption due to change of workstyles**
Wasteful – Austerity	48 % to 52%
Wasteful – Standard	9% to 11%
Standard – Austerity	42% to 45%

4.1.3.3 Energy use intensity in large-size commercial buildings

Table 28 shows that the energy use intensity for occupants with wasteful workstyles ranged between 54 kBtu/ft^2 and 56 kBtu/ft^2; for occupants with standard workstyles, it ranged between 48 kBtu/ft^2 and 49 kBtu/ft^2 and between 27 kBtu/ft^2 to 28 kBtu/ft^2 for occupants with austerity workstyles. The decrease of energy use intensity varied between 9% and 12% when the workstyle changed from wasteful to standard. The variation was between 47% and 52% for change of workstyle from wasteful to austerity and it was between 42% and 45% for a change of workstyle from standard to austerity.

Table 28 Comparison of energy use intensity in large-size commercial buildings for occupants with different workstyles (

Simulation Number			**Energy use intensity (kBtu/ft^2)**			**Decrease in Energy use intensity due to change of workstyle (%)**		
W	**S**	**A**	**W**	**S**	**A**	**W-S**	**W-A**	**S-A**
147	133	140	55	49	28	11	48	42
148	134	141	54	49	28	9	47	42

Table 28 Comparison of energy use intensity in large-size commercial buildings for occupants with different workstyles cont'd

Simulation Number			Energy use intensity (kBtu/ft^2)			Decrease in Energy use intensity due to change of workstyle (%)		
149	135	142	54	49	28	9	47	42
150	136	143	54	49	28	9	47	42
151	137	144	55	49	28	10	48	43
152	138	145	56	49	27	12	51	44
153	139	146	55	48	27	12	52	45
W= Wasteful Workstyle S= Standard Workstyle A= Austerity Workstyle								

4.1.4 Comparison of results of BIM-based energy simulations among the three building sizes

Table 29 compares the results of BIM-based energy simulations among the three sizes of buildings. The different types of comparison shown in Table 29 are:

i. Comparison of percentage change of annual energy consumption due to change of workstyle.

ii. Comparison of energy use intensity for three types of workstyles.

iii. Comparison of change of energy use intensity due to change of workstyle.

iv. Comparison of change of energy use intensity due to variation of building properties.

Table 29 Comparison of the results of BIM-based energy simulations among small, medium and large-size buildings

Metrics	Occupant workstyles	Small-size commercial buildings		Medium-size commercial buildings		Large-size commercial buildings	
Range of percentage change of annual energy consumption due to change of Occupant workstyles	Wasteful to Austerity	56% - 58%		41% - 54%		47% - 52%	
	Wasteful to Standard	21% - 24%		12% - 19%		9% - 12%	
	Standard to Austerity	44% - 45%		33% - 44%		42% - 45%	
Range of energy use intensity	Austerity	(39-45) kBtu/ft^2		(28-119) kBtu/ft^2		(27-28) kBtu/ft^2	
	Standard	(69-82) kBtu/ft^2		(47-214) kBtu/ft^2		(48-49) kBtu/ft^2	
	Wasteful	(88-107) kBtu/ft^2		(58-248) kBtu/ft^2		(54-55) kBtu/ft^2	
Range of change of annual	Wasteful to Austerity	(53-61) kBtu/ft^2	56% - 58%	(22-129) kBtu/ft^2	41% - 54%	(5-7) kBtu/ft^2	47% - 52%

Table 29 Comparison of the results of BIM-based energy simulations among small, medium and large-size buildings cont'd

Metrics	Occupant workstyles	Small-size commercial buildings		Medium-size commercial buildings		Large-size commercial buildings	
energy use intensity	Wasteful to Standard	(20-26) kBtu/ft^2	21% - 24%	(6-34) kBtu/ft^2	12% - 19%	(25-29) kBtu/ft^2	9% - 12%
	Standard to Austerity	(32-37) kBtu/ft^2	44% - 45%	(16-95) kBtu/ft^2	33% - 44%	(20-22) kBtu/ft^2	42% - 45%
Range of change of annual energy consumption due to change of building characteristics		15% -17%		89 - 91%		21% - 22%	

The comparison of BIM-based energy simulations for the three sizes of buildings revealed that:

- The lower limit and the upper limit of the range of energy use intensity was slightly larger in small-size commercial buildings compared to large-size commercial buildings for all types of occupant workstyles (see Table 29). The results of this study suggested that occupant behavior had more impact on energy consumption in small-size commercial buildings compared to large-size commercial buildings. However, in medium-size commercial buildings, although the lower limit of energy use intensity was smaller than in small-size commercial buildings, the upper limit of energy use intensity was much larger than for both small and large-size commercial buildings. The lower limits for both medium and large-size commercial buildings were almost similar. This could be attributed to large variations of building characteristics, especially the area of medium-size commercial buildings compared to small and large-size commercial buildings in the US. Based on Table 3, 15,565 ft^2 was the smallest medium-size commercial building while the largest medium-size commercial building was 147,102 ft^2. Similarly, the areas of smallest small-size commercial building and the largest small-size commercial building were 2,614 ft^2 and 3,265 ft^2 respectively. The areas of the smallest large-size building and the largest large-size building were 119,178 ft2 and 152,113 ft2 respectively. Thus, the difference in area between the largest and the smallest medium-size commercial building was 128,306 ft2. Similarly, the difference in area between the smallest small-size and the largest small-size commercial building was 651 ft2. Furthermore, the difference in area between the smallest large-size and the largest large-size commercial building was 32,935 ft2.
- The simulation results showed that occupant behavior is a very important factor in energy performance of commercial buildings regardless of the size of buildings. In small-size commercial buildings, 56% to 58% of the total energy can be saved annually by changing the wasteful workstyle to an austerity workstyle in ideal

conditions. For the same wasteful to austerity change of workstyles, 41% to 54% of the total energy can be saved in medium-size commercial buildings and 47% to 52% of the total energy can be saved in large-size commercial buildings. The range of energy use intensity was the largest in medium-size commercial buildings and it was the smallest in large-size commercial buildings for each type of workstyles.

- The effect of building characteristics on annual energy consumption is greater in medium-size commercial buildings compared to other sizes of commercial buildings due to the larger range of area of medium-size commercial buildings. Based on the literature review, some of the medium-size commercial buildings used in this study have a larger area than even some of the large-size commercial buildings. Furthermore, a change of 89%-91% in annual energy consumption in medium-size commercial buildings is the result of the larger range of numerical values of parameters of the building characteristics in medium-size commercial buildings compared to small and large-size commercial buildings. This suggests that building characteristics, along with occupant behavior, have an important role in building energy performance.

4.2 Case Study

The purpose of the case study performed as a part of this research was to illustrate the energy simulation procedure using a real building, Alder Hall, located on the CSU campus (also mentioned in stage 3 of the research methodology). To meet this objective, the building information model of Alder Hall was first created in Revit based on information collected from multiple site visits to Alder Hall and from the Facilities Management Department at CSU. Secondly, the annual energy consumption of Alder Hall was simulated using DesignBuilder for the three types of occupant workstyles and for the values of seven parameters of occupant behavior observed in Alder Hall (see Table 31). The values of parameters of occupant workstyle listed in Table 31 were obtained based on the study of occupant behavior in Alder Hall during site visits. Additionally, a commercial building that had the closest building characteristics to Alder Hall was selected from 15 types of commercial buildings and energy simulations were performed for this building for the three types of workstyles and for the same values of parameters of occupant behavior shown in Table 31. This building is referred to as a “type-7 selected” building in this research. Data on the annual energy consumption of Alder Hall in years 2014, 2015 and 2016 were also collected from the Facilities Management Department at CSU for this case study.

Finally, the results obtained from the energy simulations performed for Alder Hall, type-7 selected building and data obtained from Facilities Management at CSU on annual energy consumption by Alder Hall in 2014, 2015 and 2016 were analyzed to identify the impact of occupant behavior on building energy performance. The analysis showed that there are similarities in the way occupant behavior affects the energy performance of commercial buildings. The occupants with wasteful workstyles consumed the largest amount of energy annually while occupants with austerity workstyles consumed the least amount. Occupants with standard workstyles consumed a moderate amount of energy annually as expected. These results also confirmed that the simulation procedure used in this study was appropriate.

Figure 8 presents a perspective view of Alder Hall. The north and west face of the building, curtain wall, typical windows and new addition to the original Alder Hall are visible in the figure.

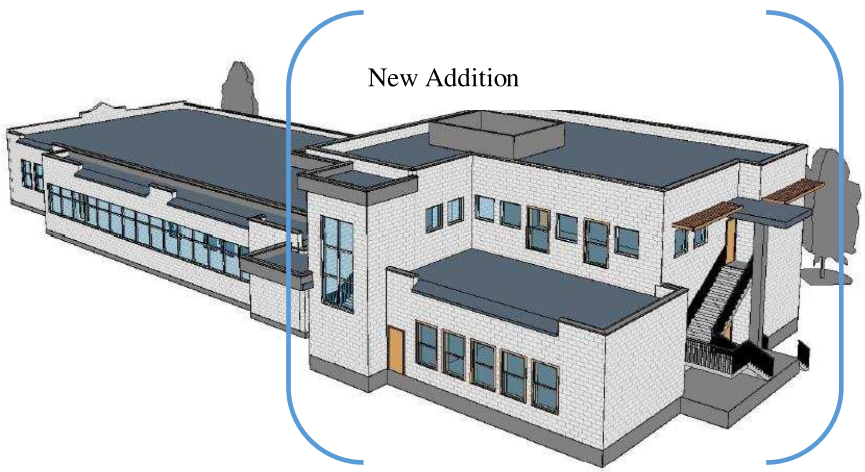

Figure 8 Perspective view of Alder Hall

4.2.1 Introduction

Alder Hall is a multi-purpose building opened for international students at Colorado State University. The building is occupied throughout the year and it is open 24 hours a day for students. It is a two-story building with 10 classrooms, café, lounge, study area, computer lab and four restrooms. The total area of the building is 12,963 square feet. Each classroom has a computer, projector, and document camera. The café and lounge are also frequently occupied during the day and include five desktop computers, refrigerators, coffee machines, microwave, TV and other equipment with plug loads. In addition to that, there are 27 desktop computers, one television and four printers in the computer lab and study area.

Alder Hall can be categorized as a medium-size commercial building because of its area and other building characteristics. If the minimum required area for a person is 45.06 square feet according to the ASHRAE 55 standard, then the maximum number of occupants inside the building when fully occupied can be found by dividing total rentable area by the minimum area required for a person: this calculation results in around 23 occupants. Overall, the nature of its building characteristics, its size and its occupants who frequently interact with the plug loads available in the building, made Alder Hall an appropriate case study for this research.

4.2.2 Methodology of case study

The building information model of Alder Hall was created in Revit 2016 software. The information on the parameters of building characteristics of Alder Hall were collected from the Facilities Management Department at CSU. All the building characteristics, except the heating and cooling system used in the building, were defined in Revit 2016. The gbXML file created using Revit 2016 was then exported to DesignBuilder. In DesignBuilder, the HVAC system used in the building was subsequently defined. In total, four simulations were performed in DesignBuilder for Alder Hall. Three simulations were performed for occupant behavior with austerity workstyle, standard workstyle and wasteful workstyle. The fourth simulation was performed for the values of the parameters of observed occupant behavior listed in Table 31.

One commercial building that had the closest building characteristics to Alder Hall was selected to make the comparison with Alder Hall in terms of the impact of occupant behavior on annual building energy performance. This was the type-7 commercial building (see Table3). The building characteristics of the type-7 commercial buildings are compared to those of Alder Hall in Table 34. Three energy simulations were performed for Alder Hall in DesignBuilder for three types of workstyles and one simulation was performed using the values of the parameters for the observed occupant behavior (Table 31). The results obtained from the energy simulations performed in Alder Hall and the selected commercial building (type-7) were then compared and analyzed to understand the impact of occupant behavior on building energy performance.

The data on annual energy consumed by Alder Hall in 2014, 2015 and 2016 were compared to the annual energy consumption by Alder Hall that was simulated using the values of parameters of observed occupant behavior in Table 31. The goal of this comparison was to verify the accuracy of the simulations performed by DesignBuilder. Figure 9 summarizes the five steps involved in this case study which were: (1) site visits to Alder Hall and data collection; (2) creating of building information model of Alder Hall in Revit; (3) Energy simulations of Alder Hall in

DesignBuilder and collection of data on actual energy consumption by Alder Hall in 2014,2015 and 2016; (4) Selection of commercial building with similar building characteristics to Alder Hall and energy simulations in DesignBuilder; and (5) Analysis of results obtained from the energy simulations and other data.

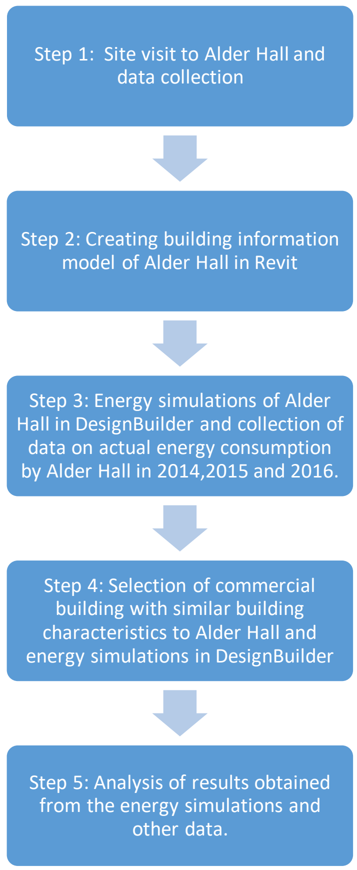

Figure 9 Case study steps

4.2.2.1 Site visits to Alder Hall and data collection

The site visits to Alder Hall were carried out to collect information on its building characteristics and parameters of its occupant behavior. The occupant behavior in Alder Hall is referred to as "observed occupant behavior" in this study.

4.2.2.1.1 Building characteristics of Alder Hall

Alder Hall represents a typical commercial building built in the US. Alder Hall has similar characteristics to other commercial buildings that were used in this study for energy simulations and analysis of occupant behavior. As shown in Figures 10 and 11, Alder Hall is a two-story building whose characteristics match the medium-size commercial buildings used in this study. The ground floor has several multipurpose rooms, and the upper floor has a few rooms ideally designed for study and conference. Additionally, the use of exterior glass, the construction materials of wall and roof, types of wall, the construction style and size of the building makes it an appropriate subject for a case study in this research.

Figures 10 and 11 show the first and second floor plans of Alder Hall. The first floor plan illustrates the new addition to the original building on the left. The first floor is a split level that separates the original building and new addition. The new addition has two floors.

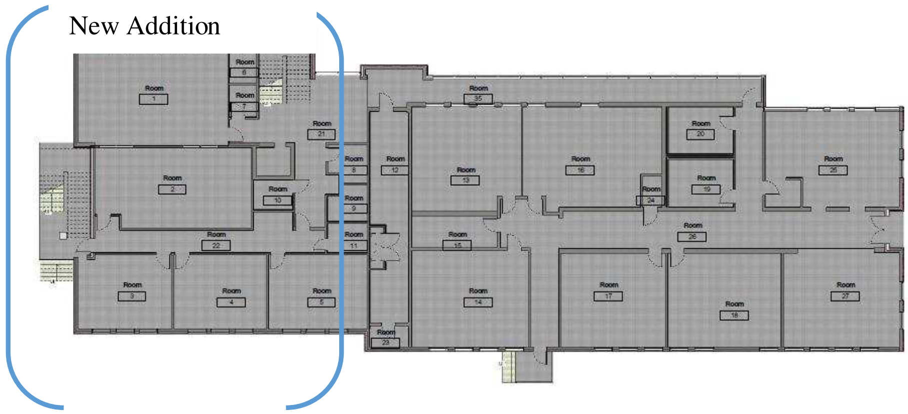

Figure 10 Alder Hall's First Floor

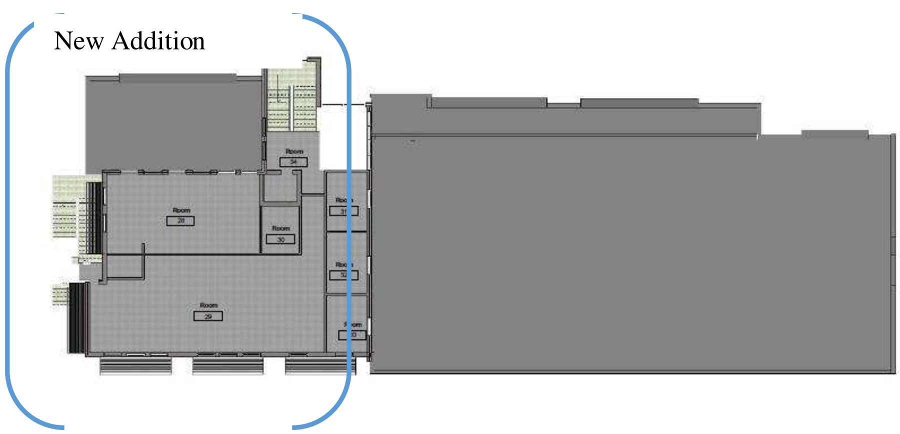

Figure 11 Alder Hall's Second Floor

i. Wall structure of Alder Hall and its characteristics

The exterior wall of Alder Hall consists of five layers. The total thickness of the exterior wall is 12 inches. The outermost layer consists of three inches of brick veneer followed by two and a half inches of air and weather barrier, a half inch of oriented strand board, five and a half inches of wood stud, vapor retarder, and a half inch of gypsum board. Two types of wall are used in the building. The thermal resistance of these walls is 48 hr·ft^2·°F/Btu and 68 Btu/°F. The interior walls are 1-hour fire rated partition walls. The thickness of these partition walls varies throughout the building from five inches to 12 inches. Figure 12 shows the typical wall detail of Alder Hall.

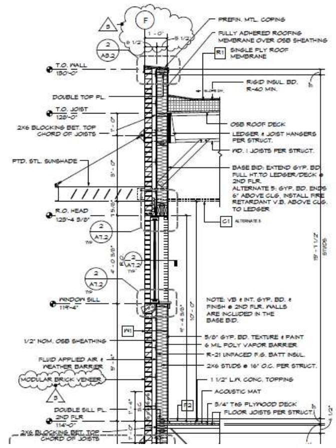

Figure 12 Wall section and roofing details of Alder Hall

ii. Roof of Alder Hall

Alder Hall is a building with a split level. The old part on the east side and the new addition on the west side are separated by split-level floors. The old part is only single-story while the new part is double-story. Thus, old and new part of Alder Hall does not share the same roof. Alder Hall has a typical roof with six layers. The outermost layer is the fully adhered TPO membrane on half an inch of DensDeck prime glass mat gypsum cover board, followed by polyisocyanurate R-42 min flat insulation board, ¾ inches of plywood sheathing, fiberglass batt with varying thickness and half an inch of oriented stranded board as finish underneath. The roof has a varying thickness with a minimum thickness of one foot and one and a half inches. The thermal insulation of the roof is 87 hr·ft^2·°F/Btu and thermal mass is 3 Btu/°F.

iii. Exterior glass percentage

The percentage of exterior glass in Alder Hall is 16.33%. The total area of the glazing present in the exterior wall amounts to 2100 square feet. Table 30 summarizes the size and number of all the glass openings in Alder Hall.

Table 30 Glass openings in Alder Hall cont'd

Type of openings	**Opening label**	**Number of openings**	**Area of an opening (ft^2)**	**Total area of openings (ft^2)**
Windows	W1	14	26.64	372.96
	W2	5	26.64	133.2
	W3	17	16	272
	T (Window)	18.5	26.64	492.84
Curtain Wall	AL1	1	115.2	115.2

Table 30 Glass openings in Alder Hall cont'd

Type of openings	Opening label	Number of openings	Area of an opening (ft^2)	Total area of openings (ft^2)
	AL2	1	109.45	109.45
	AL3	1	56.76	56.76
	AL4	1	114	114
	AL5	1	98	98
	AL6	2	168.7	337.4
	Total area of exterior openings (ft^2)			2101.81

iv. HVAC system

For heating, the building steam is used and circulated around the building. Packaged terminal air conditioner hot water (PTAC HW) heating has been used as the HVAC system for annual energy simulation of Alder Hall in DesignBuilder.

v. Number of occupants

In this case study, the number of occupants in Alder Hall was calculated based on the number of occupants per square foot in a type-7 medium-size commercial building. The area of the type-7 commercial building was 15,725 ft^2 and the number of occupants per square foot in a type-7 commercial building was 0.0021. Using 0.0021 as occupant per unit area, the total number of occupants in Alder Hall was calculated at 27.

4.2.2.1.2 Occupant behavior in Alder Hall

The occupant behavior in Alder Hall was observed to identify the nature of workstyle in the building. Detailed information on most of the parameters of occupant behavior like adaptive comfort, occupancy controls, daylight controls, HVAC operation time, and cooling startup control were collected from the site visits. The information on other parameters, such as cooling and heating set points, were collected from the Facilities Management Department at CSU.

Site visits were accompanied by two other research participants to avoid the subjective bias of the researcher. The information on adaptive comfort, occupancy controls, daylight controls, HVAC operation time, and cooling startup control were collected separately by these three research participants and then later compared for uniformity. The information on adaptive comfort, occupancy controls and daylight controls were first collected from the building occupants, which was then later confirmed by the Facilities Management Department at CSU. The information on HVAC operation time, cooling set point, heating set point, and cooling startup control was collected directly from the

Facilities Management Department at CSU. The information collected for each parameter is discussed in the following subsections:

i. Cooling set point and heating set point:

The cooling set point in Alder Hall was 71.6°F and the heating set point was 69.8°F.

ii. Adaptive Comfort:

Theory of adaptive comfort states that a human can adapt to a wider range of thermal conditions than generally accepted as comfortable when it has control over its immediate environment (Santamouris, 2006). Based on the information collected from the occupants, the occupants in Alder Hall interacted with the windows and blinds to adjust the room temperature. Most of the employees and students wore seasonally appropriate clothing to achieve the desired level of comfort inside the building. These activities suggested that occupants were used to adaptive comfort in Alder Hall.

iii. Occupancy controls:

The employees in Alder Hall turned off the lights and turned down the plug loads before leaving the buildings. However, they did not have access to heating and cooling control. HVAC operation time was automatic and controlled by the Facilities Management Department at CSU.

iv. Daylight controls:

Occupants in Alder Hall used the automatic stepped dimming for daylight control.

v. HVAC operation time:

The HVAC operation time followed the whole building schedule.

vi. Cooling startup control:

The occupants in Alder Hall did not have access to cooling startup control. Cooling set point followed the HVAC operation schedule and was controlled by the Facilities Management Department at CSU.

Based on the information available, the parameters of occupant behavior in Alder Hall were categorized into different workstyles as shown in Table 31.

Table 31 Observed values of parameters of occupant behavior based on observation of workstyle of occupants in Alder Hall c

Parameters of occupant behavior	**Values/Description**	**Workstyle**
Cooling set point	22°C	Wasteful
Heating set point	21°C	Standard

Table 31 Observed values of parameters of occupant behavior based on observation of workstyle of occupants in Alder Hall cont'd

Parameters of occupant behavior	**Values/Description**	**Workstyle**
Adaptive Comfort	Yes	Austerity
Occupancy Control	Yes	Austerity
Daylight Controls	Yes	Austerity
HVAC operation time	Whole building schedule	Wasteful
Cooling Startup Control	No	Standard

Out of the seven parameters of occupant behavior in Alder Hall, two parameters indicated a wasteful workstyle of occupants, two indicated a standard workstyle and the remaining three indicated an austerity occupant workstyle.

4.2.2.2 Building information model in Revit

The building information model for Alder Hall was created in Revit. The information on building characteristics collected from site visits in Step 1 of the case study was used to create the building information model for Alder Hall.

4.2.2.3 Energy simulations of Alder Hall in DesignBuilder and collection of data on energy consumption by Alder Hall in 2014, 2015 and 2016

The annual energy simulations were performed for Alder Hall for the three types of occupant workstyles and for the values of the seven parameters of observed occupant behavior listed in Table 31 obtained from the case study of Alder Hall. The energy simulation for Alder Hall was performed using DesignBuilder after importing its building information model from Revit 2016 as a gbXML file. Table 32 shows the energy consumed by Alder Hall for the different types of workstyles along with the energy consumed for observed occupant behavior in Alder Hall.

The annual energy consumptions of Alder Hall for the wasteful, standard and austerity workstyles simulated using the values of parameters from the literature review (see Table 10) were 797,188 kBtu, 617,546 kBtu and 367,269 kBtu respectively; the energy use intensities were 61 kBtu/ft^2, 48 kBtu/ft^2 and 28 kBtu/ft^2 respectively (see Table 32). The simulated annual energy consumption for the listed values of parameters of observed occupant behavior in Table 31 was 614,482 kBtu and energy use intensity was 47 kBtu/ft^2.

Table 32 Energy consumption in Alder Hall for different types of occupant behavior

Occupant Behavior type		**Annual energy consumed (kBtu)**	**Energy use intensity (kBtu/ft^2)**
Values of parameters	Wasteful	797,188	61
	Standard	617,546	48

Table 32 Energy consumption in Alder Hall for different types of occupant behavior cont'd

Occupant Behavior type		Annual energy consumed (kBtu)	Energy use intensity (kBtu/ft^2)
based on literature review	Austerity	367,269	28
Values of parameters based on observed occupant behavior		614,482	47

Table 32 reveals that the effect of observed occupant behavior on energy performance in Alder Hall was very close to the effect of occupant behavior with a standard workstyle. The effect of wasteful workstyle was the largest and the austerity workstyle had the smallest effect. The results signify that, unlike the occupants with wasteful and austerity workstyles, the effect of observed occupant behavior in Alder Hall was smaller than the effect of wasteful workstyle and the effect was larger than the effect of austerity workstyle.

Table 33 shows the actual energy consumed by Alder Hall in 2014, 2015 and 2016, which was obtained from the Facilities Management Department at CSU. The data on actual energy consumption by Alder Hall in 2014, 2015 and 2016 were also collected from the Facility Management Department at CSU: these were 580,224 kBtu, 614,604 kBtu and 614,602 kBtu respectively. Energy use intensities for Alder Hall in 2014, 2015 and 2016 were 45 kBtu/ft^2, 47 kBtu/ft^2 and 42 kBtu/ft^2 respectively.

Table 33 Annual energy consumed by Alder Hall in 2014, 2015 and 2016 based on data by Facilities Management Department of Colorado State University

Year	Annual energy consumed (kBtu)	Energy use intensity (kBtu/ft^2)
2014	580,224	45
2015	614,602	47
2016	542,302	42

Table 33 shows that the actual energy consumed by Alder Hall in 2015 was the largest and the actual energy consumed by Alder Hall in 2016 was the smallest. The energy use intensities in Alder Hall in 2014, 2015 and 2016 obtained from Facility Management at CSU were close to the energy use intensity for standard workstyle in Alder Hall which was 48 kBtu/ft^2 as shown in Table 32.

4.2.2.4 Selection of commercial building with similar building characteristics to Alder Hall and energy simulations in DesignBuilder

Of the 15 types of abstract commercial buildings (see Table 3), the type-7 commercial building had the closest characteristics to the Alder Hall was thus selected for comparison of the impact of occupant behavior on building energy performance. Both Alder Hall and the type-7 commercial building were medium-size commercial buildings. The area of Alder Hall was 12,963 ft^2 and for type-7, it was 15,725 ft^2. The type-7 was also a two-story building like Alder Hall with a 19% of exterior glass compared to 16.33% for Alder Hall. The exterior wall construction material was brick in both buildings. Similarly, the roof construction material in the abstract building was plastic and thermoplastic polyolefin (TPO) membrane in Alder Hall. The packaged terminal air conditioner hot water (PTAC HW) heating was used in both the abstract building and Alder Hall as the HVAC system. The comparison of building characteristics of Alder Hall and the selected abstract building is shown in Table 34.

Table 34 Comparison of building characteristics between Alder Hall and selected type-7 commercial building

Building characteristics	**Alder Hall**	**Type-7 commercial building**
1. Floors	Two	Two
2. Roof construction material	Plastic	Thermoplastic polyolefin (TPO)membrane
3. Wall construction material	Brick	Brick
4. HVAC system	Packaged terminal air conditioner hot water (PTAC HW) heating	Packaged terminal air conditioner hot water (PTAC HW) heating
5. Area	12,963 ft^2	15,725 ft^2
6. Percentage exterior glass	16.33%	19%

Table 35 shows the simulated annual energy consumption by the selected type-7 commercial building. The energy consumed by type-7 commercial buildings for wasteful, standard and austerity workstyles were 968,053 (kBtu), 786,160 (kBtu) and 454,460 (kBtu) respectively. The energy consumed by type-7 commercial buildings for the values of parameters of occupant behavior listed in Table 31 was 706,705 kBtu. The energy-use intensities for wasteful, standard and austerity workstyles were 62 ($kBtu/ft^2$), 50 ($kBtu/ft^2$) and 29 ($kBtu/ft^2$) respectively. For the parameters of observed occupant behavior listed in Table 31, the energy use intensity was 45 $kBtu/ft^2$.

Table 35 Simulated energy consumption of type-7 commercial buildings shown in Table 3

Occupant Behavior		Annual energy consumed (kBtu)	Energy use intensity (kBtu/ft^2)
Values of parameters based on literature review	Wasteful	968,053	62
	Standard	786,160	50
	Austerity	454,460	29
Observed occupant behavior		706,705	45

Table 35 also shows a similar pattern to Table 32, which compared the annual energy consumption in Alder Hall by occupants with different types of workstyles. In Table 35, the observed occupant behavior and the occupant behavior with standard workstyle had a similar impact on annual energy consumption. There was a difference of 5 kBtu/ft^2 between the energy-use intensities of occupants with standard workstyles and occupants with observed behavior in type-7 buildings. This result, shown in Table 35, verified the result shown in Table 32 and confirmed that the impact of observed occupant behavior and occupants with standard workstyles on energy performance of the Alder Hall was similar.

4.2.2.5 Analysis of results obtained from the energy simulations and other data.

Table 32 shows that, as expected, occupants with wasteful workstyles had the largest annual energy consumption and occupants with austerity workstyles had the smallest annual energy consumption in Alder Hall. The simulation results were presented in separate tables to analyze the impact of occupant behavior on energy performance of the building. Table 36 shows the percentage change of energy consumption due to change of workstyles in Alder Hall. The bar chart in Figure 13 is the visual representation of data presented in Table 36. Table 37 thus compares the impact of occupant behavior with parametric values based on the literature review for the three types of workstyles on the energy performance of Alder Hall and medium-size commercial buildings used in this research.

Table 36 Decrease in energy consumption due to change of occupant workstyles (Austerity, Standard and Wasteful) characteristics from literature review in Alder Hall

Change of occupant workstyle	Percentage Decrease in annual energy consumption (%)	Decrease in energy use intensity (kBtu/ft^2)
From Wasteful to Austerity	54	33
From Wasteful to Standard	23	14

Table 36 Decrease in energy consumption due to change of occupant workstyles (Austerity, Standard and Wasteful) characteristics from literature review in Alder Hall cont'd

Change of occupant workstyle	Percentage Decrease in annual energy consumption (%)	Decrease in energy use intensity (kBtu/ft^2)
From Standard to Austerity	41	19

Table 37 Comparison of change of annual energy consumption due to change of workstyles in Alder Hall and medium-size commercial buildings (using occupant behavior data obtained from literature review)

Change of occupant workstyle	Percentage decrease in annual energy consumption in Alder Hall (%)	Percentage decrease in annual energy consumption for medium-size commercial building (%)
From Wasteful to Austerity	54	41 to 54
From Wasteful to Standard	23	12 to 19
From Standard to Austerity	41	33 to 44

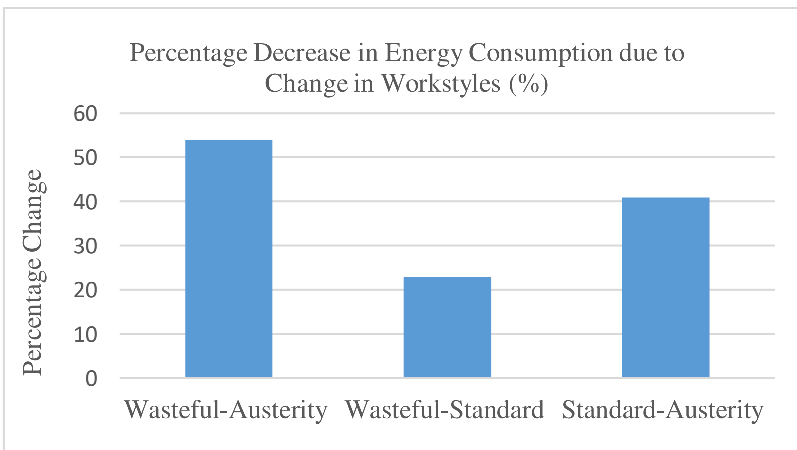

Figure 13 Change of energy consumption due to change of occupant workstyles (Austerity, Standard and Wasteful) in Alder Hall

In Alder Hall, the percentage decrease in annual energy consumption due to change of workstyle from wasteful to austerity was 54%; for the change of workstyle from wasteful to standard, this figure was 23% and for the change of workstyle from standard to austerity it was 41% (as shown in Table36). Table 37 compares the percentage change of annual energy consumption between Alder Hall and medium-size commercial buildings using occupant behavior data obtained from the literature review due to change of occupant workstyles (standard, austerity and wasteful). Unlike Alder Hall, the percentage change of annual energy consumption in medium-size commercial buildings due to change of occupant workstyles varied as there were numerous types of medium-size commercial buildings, based on the variation of their characteristics (as summarized in the literature review). If the percentage decreases in annual energy consumption in Alder Hall due to change of workstyles are compared with percentage decreases in energy consumption in medium-size commercial buildings used in this study, the values are close.

In medium-size commercial buildings the percentage decrease in annual energy consumption due to change of workstyle from wasteful to austerity ranged between 41% and 54% (see Table 37). The range of percentage decrease was between 12% and 19% for the change of workstyle from wasteful to standard and between 33% and 44% for the change of workstyle from standard to austerity. The comparison shows that a change of annual energy consumption due to change of workstyle from wasteful to austerity and standard to austerity in Alder Hall were within the range of decrease of annual energy consumption in medium-size commercial buildings for the same change of workstyles. The decrease in annual energy consumption due to change of workstyle from wasteful to standard in Alder Hall (23%) was also close to a range of decrease in annual energy consumption (12% to 19%) in the medium-size commercial buildings due to change of workstyle from wasteful to standard. For the change of workstyle from standard to austerity, the decrease in energy consumption in Alder Hall was 41% compared to the range of 33% to 44% for medium-size commercial buildings. These results confirmed that the simulation results of Alder Hall closely matched the simulation results of medium-size commercial buildings. Hence, the impact of occupant behavior on energy performance of Alder Hall is similar to the impact of occupant behavior on energy performance of medium-size commercial buildings used in this study.

Table 38 Comparison of annual energy consumption by Alder Hall in 2014, 2015 and 2016 with simulated energy for Alder Hall (using the observed values of parameters of occupant behavior shown in Table 31

Comparison of simulated energy and actual energy consumption in different years	Percentage change of energy consumption (%)	Change of energy use intensity (kBtu/ft2)
Simulated (observed) - Actual in 2014	6	3
Simulated (observed) - Actual in 2015	-0.02	0
Simulated (observed) - Actual in 2016	12	6

Simulated (observed): Simulated annual energy consumed by Alder Hall for the observed values of parameters of occupant behavior listed in Table 31.
Actual in 2014: The energy consumption recorded by Facilities Management at CSU in Alder Hall in 2014
Actual in 2015: The energy consumption recorded by Facilities Management at CSU in Alder Hall in 2015
Actual in 2016: The energy consumption recorded by Facilities Management at CSU in Alder Hall in 2016

Table 38 compares the simulated annual energy used by Alder Hall for the values of seven parameters of observed occupant behavior (see Table 31) with the actual annual energy consumed by Alder Hall in 2014, 2015 and 2016 based on data provided by Facilities Management Department at CSU. The simulated energy consumption for the parameters of observed occupant behavior listed in Table 31 was 6% higher than the annual energy consumed by Alder Hall in 2014; it was 0.02% lower than recorded energy consumed by Alder Hall in 2015 and it was 12% higher than the annual energy consumed by Alder Hall in 2016. These values show that the energy simulation results from DesignBuilder for Alder Hall were close to the actual values of energy consumption in Alder Hall in 2014 and 2015. Two of these differences are in accordance with the guidelines of the American Society of Heating, Air-conditioning and Refrigerating Engineers Guide 14 (ASHRAE, 2002), where the recommended error margin as per Cumulative Variation of Root Mean Squared Error (CVRMSE) for building energy simulation software is below 10%.

Table 39 shows the impact of the change of workstyle on energy consumption of the selected type-7 commercial building by comparing the percentage change of annual energy consumption and change of energy use intensity due to change of workstyles. The decrease in energy consumption in type-7 commercial buildings due to change of workstyle from wasteful to austerity was 53%, wasteful to standard was 19% and standard to austerity was 42%. Similarly, the decrease in energy use intensity for the change of workstyle from wasteful to austerity was 33 kBtu/ft^2, wasteful to standard was 12 kBtu/ft^2 and standard to austerity was 21 kBtu/ft^2. The results show that up to 53% of energy can be saved in ideal conditions in a type-7 building by changing the occupant behavior.

Table 39 Impact of occupant behavior on energy performance of a type-7 commercial building (using occupant behavior data obtained from literature review)

Occupant workstyle	**Percentage decrease in energy consumption (%)**	**Decrease in energy use intensity (kBtu/ft^2)**
From Wasteful to Austerity	53	33
From Wasteful to Standard	19	12
From Standard to Austerity	42	21

Table 40 provides the comparison of energy consumed by Alder Hall and a type-7 commercial building according to the three types of workstyles and for observed occupant behavior shown in Table 31. From the comparison of energy-use intensities shown in Table 40, it was found that the impact of the change of occupant behavior on annual energy consumption of both buildings was close. The differences in energy use intensity in Alder Hall and the type-7 commercial building for the changes in workstyles from wasteful to austerity, wasteful to standard and standard to austerity were 0.016%, 0.04% and 0.034% respectively. The difference in energy-use intensities was -0.04% for the observed occupant behavior in Alder Hall.

Table 40 Comparison of energy- use intensity between a type-7 commercial building and Alder Hall (using occupant behavior data obtained from literature review and Table 31)

Occupant workstyle	**Energy use intensity in Type-7 commercial building ($kBtu/ft^2$)**	**Energy use intensity in Alder Hall ($kBtu/ft^2$)**	**Difference in energy use intensity between Type-7 commercial building and Alder Hall ($kBtu/ft^2$)**	**Percentage Difference in energy use intensity between Type-7 commercial building and Alder Hall (%)**
Wasteful	62	61	1	0.016
Standard	50	48	2	0.04
Austerity	29	28	1	0.034
Observed occupant behavior (Table 31)	45	47	-2	-0.04
Observed occupant behavior (Table 31): The occupant behavior in Alder Hall with values of the parameters listed in Table 31.				

The case study of Alder Hall was performed to illustrate the energy simulations procedure used in this study. Based on the case study, the following findings can be given:

- The annual energy consumption in Alder Hall for the observed values of parameters of occupant behavior was close to recorded annual energy consumption in Alder Hall in 2014 and 2015. This proves that simulations obtained for Alder Hall were accurate based on error margin for simulation software of 10% recommenced by ASHARE (2002).
- Fifty-four percent of the annual energy can be saved when the workstyle of the occupant is changed from wasteful to austerity in Alder Hall. Hence, occupant behavior plays very crucial role in building energy performance.
- The comparison of the simulation results of Alder Hall and medium-size commercial buildings used in this study showed that the simulation procedure used for abstract buildings in this research was appropriate.
- The comparison of simulation results of Alder Hall and the selected medium-size commercial building (type-7) showed that the difference between simulation results in this study was small.
- Based on the simulation results obtained from the observed occupant behavior in Alder Hall (as shown in Table 31), findings indicate that the workstyle of the occupants in Alder Hall is close to the standard workstyle.

4.3 Guidelines for changing the occupant behavior to improve the building energy performance

Based on the analysis of the energy simulation results and the case study of Alder Hall, the following measures to minimize energy consumption of the commercial buildings were developed:

- Raising energy awareness among the occupants is very important for bringing behavioral change. Information and outreach plans regarding the impact of occupant behavior on the energy performance of a building can be the first step to raise awareness among building occupants. There are several information and outreach techniques that can be used, such as websites, public surveys, direct mail, videos, workshops and mass media campaigns. It might also be necessary to conduct information and outreach programs on a continual basis to instigate a change of wasteful workstyles that are well-established.
- The impact of occupant behavior is the highest in small commercial buildings. These small commercial buildings usually have six to eight occupants. Due to the small-size of the buildings, it can be inferred that occupants in such buildings have more flexibility in interacting with the energy-consuming elements of buildings. As simulation results show, a change of occupant behavior in small commercial buildings can alter the annual energy consumption of small commercial buildings by up to 58%, so it is important to educate occupants about good energy saving habits. Additionally, other incentives, like annual reward programs for energy-conscious occupants, can be implemented. Such practices are already implemented at Colorado State University.
- In the larger commercial buildings, reward programs or other financial incentives might not be very appealing. In these buildings, therefore, strict rules that would discourage a wasteful occupant workstyle can be implemented. For example, turning off the plug loads and interior lighting whenever the building is unoccupied or turning on the heating and cooling devices only when the building is occupied and so on. Such measures can save the building's energy consumption by 50% annually in ideal conditions, as was shown by the simulation results.
- Most of the commercial buildings built in the US have a good barrier between conditioned (indoor) and unconditioned environment (outdoor). There may be slight variations in the thermal properties of the materials used in the building envelope of such commercial buildings. As the energy simulation results show, such small variations in building characteristics do not have much impact on the overall energy consumption of the buildings if materials used in the building envelope have good insulative properties. The thermal comfort of the occupants can be enhanced by improving the insulation between the conditioned and unconditioned environment in the building. As occupant comfort increases, the energy consumed by the occupants decreases. Hence, it is important

to use the right materials for the wall and roof construction with the correct set of thermal properties to enhance occupant comfort and minimize building energy consumption.

- As shown by the analysis of simulation results and case study, adaptive comfort is an important factor in the energy performance of the building. The occupants in the building can maintain comfort in a wide range of conditions. The building characteristics and technologies inside the building should be developed in such a way that adaptive comfort in the building is enabled. One example is the use of technologies that offer occupants immediate control over the lighting devices and ventilation. Another example would be to introduce mobility options that enable occupants to move to a more comfortable place within the building so that they do not need to interact with plug loads that eventually increase the energy consumption.
- When the occupants of a building cannot feel comfortable because of temperature, lighting, noise or any other factors in the building, they often take alternative means to achieve that comfort inside the building, for example, using an additional heater or cooler in the room, using additional light sources and interacting more with other plug loads: this eventually increases the energy consumption in the building. Such occupant behavior can cause greater energy consumption than energy consumed by typical heating, cooling, ventilation and air-conditioning systems and must therefore be minimized by providing ideal building characteristics. These would include improving sound and thermal insulation by using the suitable building materials, allowing the right amount of daylight inside the building (by ensuring the suitable amount of exterior glass on exterior walls), enhancing the combination of natural and artificial ventilation and making sure to provide the minimum area required by an occupant for comfort.
- Default settings used in the building for cooling, heating and ventilation are very important to enhance the energy performance of commercial buildings. Some of the examples of default settings are thermostat settings, automatic light settings, automatic ventilation settings etc. Default settings should be selected in such a way as to encourage occupants to make the correct choices to save energy in the building and avoid a wasteful workstyle. Nonetheless, these default settings should also offer occupants the flexibility to adapt. Hence, it might be challenging to identify the ideal default settings that discourage the wasteful workstyle and, at the same time, enable adaptive comfort.
- Feedback about the energy habits of occupants is essential to bring behavioral change. Using feedback, occupants can learn about their progress in moving away from a wasteful workstyle. Feedback should not only inform occupants about their behavior but should also motivate them to change their habits towards more energy-saving

behavior. The selection of effective feedback techniques is, consequently, also important to consider.

- Bad policies that hinder the energy performance of the building must be identified, discarded and replaced with better policies.

In summary, increasing energy awareness among occupants (by using e.g. incentives, rules, feedback, good policies and education) to discourage a wasteful workstyle and using appropriate building characteristics to improve occupant comfort play key roles in a building's energy conservation.

5 CHAPTER 5- CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Regardless of many studies on the subject over the decades, a gap remains between the predicted energy consumed in a building and the actual energy consumed. One of the reasons for this gap between predicted and actual energy consumption is that, in most of the methods and approaches used for building energy simulation, the impact of occupant behavior on energy performance of the building is either ignored or inaccurately represented. Furthermore, one of the reasons for challenges with measuring the impact of occupant behavior on energy performance of the buildings is the unpredictable and stochastic nature of occupant behavior. Other influences too, affect the behavior of the occupant in the building; this study has shown that building characteristics are one of the main factors that affect occupant behavior. Thus, as this thesis has shown, it is imperative to include the building characteristics for the correct representation of occupant behavior while analyzing the impact of occupant behavior on energy performance of building. The use of BIM-based energy simulations is one of the methods that can predict energy consumption of a building by accurately incorporating both building characteristics and occupant behavior.

Based on workstyles and level of energy consumption by the occupant, occupant behavior was divided into three types: austerity, standard and wasteful. The occupants with austerity workstyles consumed the least amount of energy; occupants with wasteful workstyles had the highest energy consumption and occupants with standard workstyles had an average annual energy consumption. The parameters of occupant behavior and influential variables of building characteristics that played a role in energy performance of the building were identified and the numerical values and other information required for energy simulations for such parameters and variables were collected from the literature review.

The BIM-based energy simulations were performed using Revit and DesignBuilder. The building information models of commercial buildings were created in Revit and exported to DesignBuilder as gbXML file. In DesignBuilder the type of workstyles of occupants and HVAC systems were defined and energy simulations were performed. The simulation results were analyzed and the simulation procedure was further illustrated by doing the case study of the office building, Alder Hall, at Colorado State University. The results of the energy simulations of Alder Hall and other commercial buildings used in this study were compared and analyzed.

The analysis of the energy simulation results shows that building characteristics are important factors that affect the energy consumption of the building regardless of the size of the building. Nonetheless, the slight variations in the building characteristics within the small, medium and large commercial buildings do not have a large impact on the energy consumptions of the commercial buildings. The simulation results show that the annual energy consumed by the typical small commercial building is around 190,000 kBtu to 290,000 kBtu. On the other hand, for the large commercial buildings, it is around 400,000 kBtu to 850,000 kBtu. For the small-size building, the range of percentage differences in energy consumption between austerity and wasteful workstyles was 56% to 57% and 21% to 24% between standard and wasteful workstyles respectively. Similarly, in medium-size commercial buildings, the range of percentage difference was 40% to 54% between austerity and wasteful workstyles and 11% to 19% between standard and wasteful workstyles. In large commercial buildings, the range of percentage differences in energy consumption was 40% to 50% for the change of workstyle from austerity and wasteful and 9% to 11% for the change of workstyle from standard and wasteful.

Hence, the effect of occupant behavior on the energy performance of the small-size commercial buildings is greater than the effect of occupant behavior on the energy performance of medium and large-size commercial buildings. The variation of energy consumption of medium-size commercial buildings was larger compared to that of small and large commercial buildings. This is due to the wider range of parametric numerical values of building characteristics in medium-size commercial buildings compared to small and large commercial buildings.

Moreover, the case study of Alder Hall showed that the building characteristics used to create building information models for energy simulations in this study reflected a correct representation of the actual medium-size commercial buildings in the US, as the error margins between measured and simulated annual energy in Alder Hall in 2014 and 2015 were within the error margin of 10% recommended by ASHRAE (2002).

Furthermore, this study also establishes that a BIM-based energy simulation is an appropriate and useful method to analyze the impact of occupant behavior on the energy performance of buildings. Based on the results of BIM-based energy simulations and the case study, it can be concluded that occupants can save a large amount of building energy annually by changing their energy-related habits and becoming more energy conscious.

5.2 Research limitations

This research had the following limitations:

- The occupant schedules used in the BIM-based energy simulations for Alder Hall and building information model were predetermined. However, the occupant schedules are stochastic in nature and it is difficult to emulate them perfectly in energy simulation software like DesignBuilder. This may cause a difference in simulated/predicted energy and actual energy consumed by the commercial buildings.

- The climate information used in this study for energy simulation was based on the climate of Fort Collins, Colorado. Since the US has very wide range of climatic conditions that vary from state to state, the outcomes of the energy simulations performed in this study might vary slightly for places with different weather conditions.
- There are interoperability issues between the Revit 2016 and DesignBuilder, which could slightly affect the outcome of the simulations. However, the comparison of simulated energy with actual energy consumed by the building in this study showed that the simulation of energy by DesignBuilder is accurate.
- Although DesignBuilder uses EnergyPlus as the simulation engine, the energy simulation capabilities of DesignBuilder are limited compared to EnergyPlus. EnergyPlus provides more flexibility in terms of variable input compared to DesignBuilder, which in return gives a more precise representation of the occupant behavior for energy simulation in EnergyPlus. However, due to the ability of DesignBuilder to perform different types of energy simulations accurately and easily in relatively short span of time, DesignBuilder was selected for energy simulations in this study.
- Previous research shows that occupant behavior is greatly influenced by building characteristics. However, this research does not address the relationship between building characteristics and occupant behavior.

5.3 Recommendations for future research

The energy prediction model for the commercial buildings using occupant behavior and building characteristics can be a good topic for future research. Such models can be used to predict the annual, monthly and hourly energy consumption of any given commercial building with distinct building characteristics and occupant behavior.

Another possible area for future research might be to find a way to emulate more realistically the stochastic nature of the occupant behavior in an energy analysis of the commercial buildings. This research might reduce the difference in the predicted energy and actual energy consumed by the commercial buildings.

The integration of occupant behavior and BIM-based energy simulation is a new topic; thus, there are several shortcomings related to integrating BIM with occupant behavior and energy simulating tools. The integrated methodology that addresses such shortcomings can be another topic for future research which would serve to improve the energy simulation process by reducing the simulation time and providing more detailed and accurate results.

This research did not address the relationship between the building characteristics and occupant behavior while analyzing its impact on the energy performance of the buildings. Thus, development of the methodology that incorporates the impact of building characteristics on occupant behavior while analyzing the impact of occupant behavior on building energy performance could be a useful research because it will help designers, planners and building managers to make the accurate decisions during the design and operation phase of the buildings to reduce the impact of occupant behavior on building energy performance.

In general, occupant behavior and BIM-based energy simulation are important topics for future research. Study on these subjects can play an essential role in making energy-related decisions in the early stage of the building design and during the life cycle of the building. The selection of the right type of materials, the ways to increase occupant comfort, the plans to discourage occupant’s wasteful workstyles, encourage energy-saving habits of occupants, making a more precise prediction of the building energy consumption are some of the expected contributions from future research in occupant behavior and BIM-based energy simulation.

6 REFERENCES

Al-Mumin, A., Khattab, O., & Sridhar, G. (2003). Occupants' behavior and activity patterns influencing the energy consumption in the Kuwaiti residences. *Energy and Buildings*, *35*(6), 549–559. https://doi.org/10.1016/S0378-7788(02)00167-6

Aksamija, A. (2012). BIM-Based Building Performance Analysis: Evaluation and Simulation of Design Decisions. *2012 ACEEE Summer Study on Energy Efficiency in Buildings*, (Aksamija 2010), 12.1-12.12. Retrieved from http://www.aceee.org/files/proceedings/2012/data/papers/0193-000367.pdf

Alfakara, A., & Croxford, B. (2014). Using agent-based modelling to simulate occupants' behaviours in response to summer overheating, 13. Retrieved from http://dl.acm.org/citation.cfm?id=2664323.2664336

Annual Energy Outlook 2015 - Energy Information Administration. (2015). Retrieved from http://www.eia.gov/forecasts/aeo/

ASHRAE, Guideline 14-2002: Measurement of Energy and Demand Savings, ASHRAE, Atlanta, Georgia, 2002.

ASHRAE Standard 55-2010. Thermal Environmental Conditions for Human Occupancy. Atlanta: American Society of Heating Refrigerating and Air Conditioning Engineers; 2010.

Azar, E., & Menassa, C. C. (2011). Agent-based modeling of occupants and their impact on energy use in commercial buildings. *Journal of Computing in Civil Engineering*. Retrieved from http://www.esrc.ac.uk/my-esrc/grants/RES-332-27-0001/outputs/read/a19ee7e8-6fff-49f9-9767-48f30ef6b8b4

Azar, E., & Menassa, C. C. (2012). A comprehensive analysis of the impact of occupancy parameters in energy simulation of office buildings. *Energy and Buildings*, *55*, 841–853. https://doi.org/10.1016/j.enbuild.2012.10.002

Azar, E., & Menassa, C. C. (2012). Agent-Based Modeling of Occupants and Their Impact on Energy Use in Commercial Buildings. *Journal of Computing in Civil Engineering*, *26*(4), 506–518. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000158

Azar, E., & Menassa, C. C. (2014). A comprehensive framework to quantify energy savings potential from improved operations of commercial building stocks. *Energy Policy*, *67*, 459–472. https://doi.org/10.1016/j.enpol.2013.12.031

Blom, I., Itard, L., & Meijer, A. (2011). Environmental impact of building-related and user-related energy consumption in dwellings. *Building and Environment*, *46*(8), 1657–1669. https://doi.org/10.1016/j.buildenv.2011.02.002

Bourgeois, D., Reinhart, C., & Macdonald, I. (2006). Adding advanced behavioural models in whole building energy simulation: A study on the total energy impact of manual and automated lighting control. *Energy and Buildings*, *38*(7), 814–823. https://doi.org/10.1016/j.enbuild.2006.03.002

Brown, R. E., Payne, C. T., Webber, C. A., Roberson, J. A., Brown, R. E., Payne, C. T., … Koomey, J. G. (n.d.). Field surveys of office equipment operating patterns Field Surveys of Office Equipment Operating Patterns, (May 2014). https://doi.org/10.2172/791184

Cheng, J., & Gan, V. (2013). Integrating Agent-Based Human Behavior Simulation with Building Information Modeling for Building Design. *Ijetch.Org*, *5*(4), 473–477. https://doi.org/10.7763/IJET.2013.V5.600

Crawley, D. B., Lawrie, L. K., Winkelmann, F. C., Buhl, W. F., Huang, Y. J., Pedersen, C. O., … Glazer, J. (2001). EnergyPlus: creating a new-generation building energy simulation program. *Energy and Buildings*, *33*(4), 319–331. https://doi.org/10.1016/S0378-7788(00)00114-6

Crawley, D. B., Hand, J. W., Kummert, M., & Griffith, B. T. (2008). Contrasting the capabilities of building energy performance simulation programs. *Building and Environment*, *43*(4), 661–673. https://doi.org/10.1016/j.buildenv.2006.10.027

Duarte, C., Wymelenberg, K. Van Den, & Rieger, C. (2013). Revealing occupancy patterns in an office building through the use of occupancy sensor data. *Energy & Buildings*, *67*, 587–595. https://doi.org/10.1016/j.enbuild.2013.08.062

Gaetani, I., Hoes, P., & Hensen, J. L. M. (2016). Occupant behavior in building energy simulation : Towards a fit-for-purpose modeling strategy. *Energy & Buildings*, *121*, 188–204. https://doi.org/10.1016/j.enbuild.2016.03.038

Gunay, H. B., O'Brien, W., & Beausoleil-Morrison, I. (2013). A critical review of observation studies, modeling, and simulation of adaptive occupant behaviors in offices. *Building and Environment*, *70*, 31–47. https://doi.org/10.1016/j.buildenv.2013.07.020

Hoes, P., Hensen, J. L. M., Loomans, M. G. L. C., de Vries, B., & Bourgeois, D. (2009). User behavior in whole building simulation. *Energy and Buildings*, *41*(3), 295–302. https://doi.org/10.1016/j.enbuild.2008.09.008

Hong, T., D'Oca, S., Taylor-Lange, S. C., Turner, W. J. N., Chen, Y., & Corgnati, S. P. (2015). An ontology to represent energy-related occupant behavior in buildings. Part II: Implementation of the DNAS framework using an XML schema. *Building and Environment*, *94*, 196–205. https://doi.org/10.1016/j.buildenv.2015.08.006

Hong, T., & Lin, H. (2012). Occupant Behavior : Impact on Energy Use of Private Offices. *Asim IBSPA Asia Conference*, (January).
http://www.designbuilder.co.uk/. (n.d.). Retrieved from http://www.designbuilder.co.uk/
Humphreys, M. A., & Nicol, J. F. (1998). Understanding the adaptive approach to thermal comfort. *ASHRAE Transactions*, 991–1004.
Heydarian, A., Carneiro, J. P., Gerber, D., & Becerik-Gerber, B. (2015). Immersive virtual environments, understanding the impact of design features and occupant choice upon lighting for building performance. *Building and Environment*, *89*, 217–228. https://doi.org/10.1016/j.buildenv.2015.02.038
Inyim, P., Yu Ha, H., Phan, L., Zhu, Y. & Chen, S. (2014). *Integration of Video Image Processing and BIM-Based Energy Simulation for Analyzing the Impact of Dynamic User Patterns on Building Energy Consumption (ASCE)*. Retrieved from http://ascelibrary.org/doi/abs/10.1061/9780784413777.062
Ioannidis, D., Tropios, P., & Krinidis, S. (2016). ScienceDirect Occupancy driven building performance assessment. *Journal of Innovation in Digital Ecosystems*, *3*(2), 57–69. https://doi.org/10.1016/j.jides.2016.10.008
Li, N., Li, J., Fan, R., & Jia, H. (2015). Probability of occupant operation of windows during transition seasons in of fi ce buildings. *Renewable Energy*, *73*, 84–91. https://doi.org/10.1016/j.renene.2014.05.065
Nguyen, T. A., & Aiello, M. (2013). Energy intelligent buildings based on user activity: A survey. *Energy and Buildings*, *56*, 244–257. https://doi.org/10.1016/j.enbuild.2012.09.005
Parys, W., Saelens, D., & Hens, H. (2009). Laboratory of Building Physics , K . U . Leuven , Kasteelpark Arenberg 40 – bus 2447 , 3001 Heverlee , Belgium Corresponding e-mail address : wout.parys@bwk.kuleuven.be, (Dc), 1143–1150.
Pfafferott, J., & Herkel, S. (2007). Statistical simulation of user behaviour in low-energy office buildings. *Solar Energy*, *81*(5), 676–682. https://doi.org/10.1016/j.solener.2006.08.011
Rijal H.B., Tuohy P., Nicol J.F., Humphreys M.A., Samuel A., & Clarke J. (2008). Development of an adaptive window-opening algorithm to predict the thermal comfort, energy use and overheating in buildings, *Journal of Building Performance Simulation*. 1(1): 17–30.
Santamouris, M. (2006). Ventilation I nformation Adaptive Thermal Comfort and Ventilation, (June), 1–8.
Santin, O. G. (2012). Occupant behaviour in energy efficient dwellings : evidence of a rebound effect. https://doi.org/10.1007/s10901-012-9297-2
Santin, O. G., Itard, L., & Visscher, H. (2009). The effect of occupancy and building characteristics on energy use for space and water heating in Dutch residential stock, *41*, 1223–1232. https://doi.org/10.1016/j.enbuild.2009.07.002
Sorrell, S., Dimitropoulos, J., & Sommerville, M. (2009). Empirical estimates of the direct rebound effect: A review. *Energy Policy*, *37*(4), 1356–1371. https://doi.org/10.1016/j.enpol.2008.11.026
Tanner, R. A., & Henze, G. P. (2013) Stochastic control optimization for a mixed mode building considering occupant window opening behavior, *Journal of Building Performance Simulation*, 427-444
Van Ruijven, B., de Vries, B., Van Vuuren, D. P., & Van der Sluijs, J. P. (2010). A global model for residential energy use: Uncertainty in calibration to regional data. *Energy*, *35*(1), 269–282. https://doi.org/10.1016/j.energy.2009.09.019
Wei, S., Jones, R., & De Wilde, P. (2014). Driving factors for occupant-controlled space heating in residential buildings. *Energy and Buildings*, *70*, 36–44. https://doi.org/10.1016/j.enbuild.2013.11.001
Yan, D., Brien, W. O., Hong, T., Feng, X., Gunay, H. B., Tahmasebi, F., & Mahdavi, A. (2015). Occupant behavior modeling for building performance simulation : Current state and future challenges, *107*, 264–278.
Yalcintas, M. (2008). Energy-savings predictions for building-equipment retrofits. *Energy and Buildings*, *40*(12), 2111–2120. https://doi.org/10.1016/j.enbuild.2008.06.008
Yu, Z. (Jerry), Haghighat, F., Fung, B. C. M., Morofsky, E., & Yoshino, H. (2011). A methodology for identifying and improving occupant behavior in residential buildings. *Energy*, *36*(11), 6596–6608. https://doi.org/http://dx.doi.org/10.1016/j.energy.2011.09.0

7 APPENDIX A- ENERGY SIMULATION RESULTS OF SMALL-SIZE COMMERCIAL BUILDINGS

Simulation No.	Occupant behavior Type	HVAC System	Building size	Number of floors	Area (m^2)	Percentage exterior glass (%)	Number of occupants	Thermal resistance of Wall construction materials($hr \cdot ft^2 \cdot {}^\circ F/Btu$)	Thermal resistance of Roof construction materials($hr \cdot ft^2 \cdot {}^\circ F/Btu$)	Thermal mass of wall ($Btu/{}^0F$)	Thermal mass of roof ($Btu/{}^0F$)	Energy Consumed (kBtu)
1	Wasteful	District Heating and Cooling, FCU- 4 pipe	Small	2	303.3	16	6	35.01	57.85	25.67	1.41	287524
2	Wasteful	District Heating and Cooling, FCU- 4 pipe	Small	2	303.3	16	6	47.51	57.85	9.91	1.41	294222
3	Wasteful	District Heating and Cooling, FCU- 4 pipe	Small	2	303.3	16	6	26.72	57.85	7.89	1.41	296021
4	Wasteful	District Heating and Cooling, FCU- 4 pipe	Small	2	303.3	16	6	47.51	32.01	9.91	1.35	294222

Simulation No.	Occupant behavior Type	HVAC System	Building size	Number of floors	Area (m^2)	Percentage exterior glass (%)	Number of occupants	Thermal resistance of Wall construction materials(hr·ft²·°F/Btu)	Thermal resistance of Roof construction materials(hr·ft²·°F/Btu)	Thermal mass of wall ($Btu/^0F$)	Thermal mass of roof ($Btu/^0F$)	Energy Consumed (kBtu)
5	Wasteful	District Heating and Cooling, FCU- 4 pipe	Small	2	256.5	21	8	26.72	59.68	7.89	0.89	257557
6	Wasteful	District Heating and Cooling, FCU- 4 pipe	Small	2	256.5	21	8	35.01	59.68	25.67	0.89	250522
7	Wasteful	District Heating and Cooling, FCU- 4 pipe	Small	2	256.5	21	8	47.51	59.68	9.91	0.89	256031
8	Wasteful	District Heating and Cooling, FCU- 4 pipe	Small	2	256.5	21	8	47.51	57.85	9.91	1.41	256031
9	Wasteful	District Heating and Cooling, FCU- 4 pipe	Small	2	256.5	21	8	47.51	32.01	9.91	1.35	256031

Simulation No.	Occupant behavior Type	HVAC System	Building size	Number of floors	Area (m^2)	Percentage exterior glass (%)	Number of occupants	Thermal resistance of Wall construction materials(hr·ft²·°F/Btu)	Thermal resistance of Roof construction materials(hr·ft²·°F/Btu)	Thermal mass of wall (Btu/^{0}F)	Thermal mass of roof (Btu/^{0}F)	Energy Consumed (kBtu)
10	Wasteful	District Heating and Cooling, FCU- 4 pipe	Small	2	279	19	6	74.77	59.68	14.33	0.89	276389
11	Wasteful	District Heating and Cooling, FCU- 4 pipe	Small	2	279	19	6	74.77	57.85	14.33	1.41	276389
12	Wasteful	District Heating and Cooling, FCU- 4 pipe	Small	2	279	19	6	74.77	32.01	14.33	1.35	276389
13	Wasteful	District Heating and Cooling, FCU- 4 pipe	Small	2	279	19	6	53.41	32.01	22.13	1.35	281262
14	Wasteful	District Heating and Cooling, FCU- 4 pipe	Small	2	279	19	6	20.56	32.01	26.65	1.35	281262

Simulation No.	Occupant behavior Type	HVAC System	Building size	Number of floors	Area (m^{2})	Percentage exterior glass (%)	Number of occupants	Thermal resistance of Wall construction materials(hr·ft^{2}·°F/Btu)	Thermal resistance of Roof construction materials(hr·ft^{2}·°F/Btu)	Thermal mass of wall (Btu/^{0}F)	Thermal mass of roof (Btu/^{0}F)	Energy Consumed (kBtu)
15	Wasteful	District Heating and Cooling, FCU- 4 pipe	Small	1	242.9	16	6	74.77	59.68	14.33	0.89	260407
16	Wasteful	District Heating and Cooling, FCU- 4 pipe	Small	1	242.9	16	6	20.56	57.85	26.65	1.43	265120
17	Wasteful	District Heating and Cooling, FCU- 4 pipe	Small	1	242.9	16	6	74.77	43.76	14.33	1.43	260407
18	Wasteful	District Heating and Cooling, FCU- 4 pipe	Small	1	242.9	16	6	53.41	32.01	22.13	1.35	265120
19	Wasteful	District Heating and Cooling, FCU- 4 pipe	Small	1	242.9	16	6	20.56	57.08	26.65	1.71	265120

Simulation No.	Occupant behavior Type	HVAC System	Building size	Number of floors	Area (m^{2})	Percentage exterior glass (%)	Number of occupants	Thermal resistance of Wall construction materials(hr·ft²·°F/Btu)	Thermal resistance of Roof construction materials(hr·ft²·°F/Btu)	Thermal mass of wall (Btu/^{0}F)	Thermal mass of roof (Btu/^{0}F)	Energy Consumed (kBtu)
20	Wasteful	District Heating and Cooling, FCU- 4 pipe	Small	1	222.1	17	6	53.41	43.76	22.13	1.43	254758
21	Wasteful	District Heating and Cooling, FCU- 4 pipe	Small	1	222.1	17	6	20.56	43.76	26.65	1.43	254758
22	Wasteful	District Heating and Cooling, FCU- 4 pipe	Small	1	222.1	17	6	74.77	43.76	14.33	1.43	250141
23	Wasteful	District Heating and Cooling, FCU- 4 pipe	Small	1	222.1	17	6	74.77	32.01	14.33	1.35	250144
24	Wasteful	District Heating and Cooling, FCU- 4 pipe	Small	1	222.1	17	6	20.56	57.08	26.65	1.71	254758

Simulation No.	Occupant behavior Type	HVAC System	Building size	Number of floors	Area (m^2)	Percentage exterior glass (%)	Number of occupants	Thermal resistance of Wall construction materials($hr \cdot ft^2 \cdot °F/Btu$)	Thermal resistance of Roof construction materials($hr \cdot ft^2 \cdot °F/Btu$)	Thermal mass of wall ($Btu/^0F$)	Thermal mass of roof ($Btu/^0F$)	Energy Consumed (kBtu)
25	Austerity	District Heating and Cooling, FCU- 4 pipe	Small	2	303.3	16	6	35.01	57.85	25.67	1.41	125820
26	Austerity	District Heating and Cooling, FCU- 4 pipe	Small	2	303.3	16	6	47.51	57.85	9.91	1.41	128760
27	Austerity	District Heating and Cooling, FCU- 4 pipe	Small	2	303.3	16	6	26.72	57.85	7.89	1.41	129580
28	Austerity	District Heating and Cooling, FCU- 4 pipe	Small	2	303.3	16	6	47.51	32.01	9.91	1.35	128760
29	Austerity	District Heating and Cooling, FCU- 4 pipe	Small	2	256.5	21	8	26.72	59.68	7.89	0.89	109666

Simulation No.	Occupant behavior Type	HVAC System	Building size	Number of floors	Area (m^2)	Percentage exterior glass (%)	Number of occupants	Thermal resistance of Wall construction materials(hr·ft²·°F/Btu)	Thermal resistance of Roof construction materials(hr·ft²·°F/Btu)	Thermal mass of wall (Btu/^{0}F)	Thermal mass of roof (Btu/^{0}F)	Energy Consumed (kBtu)
30	Austerity	District Heating and Cooling, FCU- 4 pipe	Small	2	256.5	21	8	35.01	59.68	25.67	0.89	107616
31	Austerity	District Heating and Cooling, FCU- 4 pipe	Small	2	256.5	21	8	47.51	59.68	9.91	0.89	108920
32	Austerity	District Heating and Cooling, FCU- 4 pipe	Small	2	256.5	21	8	47.51	57.85	9.91	1.41	108920
33	Austerity	District Heating and Cooling, FCU- 4 pipe	Small	2	256.5	21	8	47.51	32.01	9.91	1.35	108920
34	Austerity	District Heating and Cooling, FCU- 4 pipe	Small	2	279	19	6	74.77	59.68	14.33	0.89	116990

Simulation No.	Occupant behavior Type	HVAC System	Building size	Number of floors	Area (m^2)	Percentage exterior glass (%)	Number of occupants	Thermal resistance of Wall construction materials(hr·ft²·° F/Btu)	Thermal resistance of Roof construction materials(hr·ft²·° F/Btu)	Thermal mass of wall (Btu/^{0}F)	Thermal mass of roof (Btu/^{0}F)	Energy Consumed (kBtu)
35	Austerity	District Heating and Cooling, FCU- 4 pipe	Small	2	279	19	6	74.77	57.85	14.33	1.41	116990
36	Austerity	District Heating and Cooling, FCU- 4 pipe	Small	2	279	19	6	74.77	32.01	14.33	1.35	116990
37	Austerity	District Heating and Cooling, FCU- 4 pipe	Small	2	279	19	6	53.41	32.01	22.13	1.35	119097
38	Austerity	District Heating and Cooling, FCU- 4 pipe	Small	2	279	19	6	20.56	32.01	26.65	1.35	119097
39	Austerity	District Heating and Cooling, FCU- 4 pipe	Small	1	242.9	16	6	74.77	59.68	14.33	0.89	110221

Simulation No.	Occupant behavior Type	HVAC System	Building size	Number of floors	Area (m^2)	Percentage exterior glass (%)	Number of occupants	Thermal resistance of Wall construction materials(hr·ft²·°F/Btu)	Thermal resistance of Roof construction materials(hr·ft²·°F/Btu)	Thermal mass of wall (Btu/^{0}F)	Thermal mass of roof (Btu/^{0}F)	Energy Consumed (kBtu)
40	Austerity	District Heating and Cooling, FCU- 4 pipe	Small	1	242.9	16	6	20.56	57.85	26.6	1.43	112275
41	Austerity	District Heating and Cooling, FCU- 4 pipe	Small	1	242.9	16	6	74.77	43.76	14.33	1.43	110221
42	Austerity	District Heating and Cooling, FCU- 4 pipe	Small	1	242.9	16	6	53.41	32.01	22.13	1.35	112275
43	Austerity	District Heating and Cooling, FCU- 4 pipe	Small	1	242.9	16	6	20.56	57.08	26.65	1.71	112275
44	Austerity	District Heating and Cooling, FCU- 4 pipe	Small	1	222.1	17	6	53.41	43.76	22.13	1.43	107918

Simulation No.	Occupant behavior Type	HVAC System	Building size	Number of floors	Area (m^2)	Percentage exterior glass (%)	Number of occupants	Thermal resistance of Wall construction materials(hr·ft²·°F/Btu)	Thermal resistance of Roof construction materials(hr·ft²·°F/Btu)	Thermal mass of wall (Btu/^{0}F)	Thermal mass of roof (Btu/^{0}F)	Energy Consumed (kBtu)
45	Austerity	District Heating and Cooling, FCU- 4 pipe	Small	1	222.1	17	6	20.56	43.76	26.65	1.43	107918
46	Austerity	District Heating and Cooling, FCU- 4 pipe	Small	1	222.1	17	6	74.77	43.76	14.33	1.43	107740
47	Austerity	District Heating and Cooling, FCU- 4 pipe	Small	1	222.1	17	6	74.77	32.01	14.33	1.35	107740
48	Austerity	District Heating and Cooling, FCU- 4 pipe	Small	1	222.1	17	6	20.56	57.08	26.65	1.71	107918
49	Standard	District Heating and Cooling, FCU- 4 pipe	Small	2	303.3	16	6	35.01	57.85	25.67	1.41	224799

Simulation No.	Occupant behavior Type	HVAC System	Building size	Number of floors	Area (m^2)	Percentage exterior glass (%)	Number of occupants	Thermal resistance of Wall construction materials(hr·ft²·°F/Btu)	Thermal resistance of Roof construction materials(hr·ft²·°F/Btu)	Thermal mass of wall (Btu/⁰F)	Thermal mass of roof (Btu/⁰F)	Energy Consumed (kBtu)
50	Standard	District Heating and Cooling, FCU- 4 pipe	Small	2	303.3	16	6	47.51	57.85	9.91	1.41	230142
51	Standard	District Heating and Cooling, FCU- 4 pipe	Small	2	303.3	16	6	26.72	57.85	7.89	1.41	231630
52	Standard	District Heating and Cooling, FCU- 4 pipe	Small	2	303.3	16	6	47.51	32.01	9.91	1.35	230142
53	Standard	District Heating and Cooling, FCU- 4 pipe	Small	2	256.5	21	8	26.72	59.68	7.89	0.89	200978
54	Standard	District Heating and Cooling, FCU- 4 pipe	Small	2	256.5	21	8	35.01	59.68	25.67	0.89	194425

Simulation No.	Occupant behavior Type	HVAC System	Building size	Number of floors	Area (m^2)	Percentage exterior glass (%)	Number of occupants	Thermal resistance of Wall construction materials(hr·ft²·°F/Btu)	Thermal resistance of Roof construction materials(hr·ft²·°F/Btu)	Thermal mass of wall (Btu/^{0}F)	Thermal mass of roof (Btu/^{0}F)	Energy Consumed (kBtu)
55	Standard	District Heating and Cooling, FCU- 4 pipe	Small	2	256.5	21	8	47.51	59.68	9.91	0.89	199553
56	Standard	District Heating and Cooling, FCU- 4 pipe	Small	2	256.5	21	8	47.51	57.85	9.91	1.41	199553
57	Standard	District Heating and Cooling, FCU- 4 pipe	Small	2	256.5	21	8	47.51	32.01	9.91	1.35	199553
58	Standard	District Heating and Cooling, FCU- 4 pipe	Small	2	279	19	6	74.77	59.68	14.33	0.89	213938
59	Standard	District Heating and Cooling, FCU- 4 pipe	Small	2	279	19	6	74.77	57.85	14.33	1.41	213938

Simulation No.	Occupant behavior Type	HVAC System	Building size	Number of floors	Area (m^2)	Percentage exterior glass (%)	Number of occupants	Thermal resistance of Wall construction materials(hr·ft²·°F/Btu)	Thermal resistance of Roof construction materials(hr·ft²·°F/Btu)	Thermal mass of wall (Btu/^{0}F)	Thermal mass of roof (Btu/^{0}F)	Energy Consumed (kBtu)
60	Standard	District Heating and Cooling, FCU- 4 pipe	Small	2	279	19	6	74.77	32.01	14.33	1.35	213938
61	Standard	District Heating and Cooling, FCU- 4 pipe	Small	2	279	19	6	53.41	32.01	22.13	1.35	217397
62	Standard	District Heating and Cooling, FCU- 4 pipe	Small	2	279	19	6	20.56	32.01	26.65	1.35	217397
63	Standard	District Heating and Cooling, FCU- 4 pipe	Small	1	242.9	16	6	74.77	59.68	14.33	0.89	201165
64	Standard	District Heating and Cooling, FCU- 4 pipe	Small	1	242.9	16	6	20.56	57.85	26.65	1.43	205051

Simulation No.	Occupant behavior Type	HVAC System	Building size	Number of floors	Area (m^2)	Percentage exterior glass (%)	Number of occupants	Thermal resistance of Wall construction materials(hr·ft²·°F/Btu)	Thermal resistance of Roof construction materials(hr·ft²·°F/Btu)	Thermal mass of wall (Btu/^{0}F)	Thermal mass of roof (Btu/^{0}F)	Energy Consumed (kBtu)
65	Standard	District Heating and Cooling, FCU- 4 pipe	Small	1	242.9	16	6	74.77	43.76	14.33	1.43	201165
66	Standard	District Heating and Cooling, FCU- 4 pipe	Small	1	242.9	16	6	53.41	32.01	22.13	1.35	205051
67	Standard	District Heating and Cooling, FCU- 4 pipe	Small	1	242.9	16	6	20.56	57.08	26.65	1.71	205051
68	Standard	District Heating and Cooling, FCU- 4 pipe	Small	1	222.1	17	6	53.41	43.76	22.13	1.43	196793
69	Standard	District Heating and Cooling, FCU- 4 pipe	Small	1	222.1	17	6	20.56	43.76	26.65	1.43	196793

Simulation No.	Occupant behavior Type	HVAC System	Building size	Number of floors	Area (m^2)	Percentage exterior glass (%)	Number of occupants	Thermal resistance of Wall construction materials(hr·ft^2·°F/Btu)	Thermal resistance of Roof construction materials(hr·ft^2·°F/Btu)	Thermal mass of wall (Btu/^{0}F)	Thermal mass of roof (Btu/^{0}F)	Energy Consumed (kBtu)
70	Standard	District Heating and Cooling, FCU- 4 pipe	Small	1	222.1	17	6	74.77	43.76	14.33	1.43	192985
71	Standard	District Heating and Cooling, FCU- 4 pipe	Small	1	222.1	17	6	20.56	57.08	26.65	1.71	196793
72	Standard	District Heating and Cooling, FCU- 4 pipe	Small	1	222.1	17	6	74.77	32.01	14.33	1.35	192985

8 APPENDIX B- ENERGY SIMULATION RESULTS OF MEDIUM-SIZE COMMERCIAL BUILDINGS

Simulation No.	Occupant Behavior Type	HVAC System	Building size	Number of floors	Area (m^2)	Percentage exterior glass (%)	Number of occupants	Thermal resistance of Wall construction materials($hr·ft^2·°F/Btu$)	Thermal resistance of Roof construction materials($hr·ft^2·°F/Btu$)	Thermal Mass of wall ($Btu/^0F$)	Thermal mass of roof ($Btu/^0F$)	Energy Consumed (kBtu)
73	Wasteful	PTAC HW Heating	Medium	2	1446	23	35	74.77	101.07	14.33	2.79	968785
74	Wasteful	PTAC HW Heating	Medium	2	1446	23	35	53.41	113.18	22.13	2.01	978145
75	Wasteful	PTAC HW Heating	Medium	2	1446	23	35	53.41	66.29	22.13	4.42	968783
76	Wasteful	PTAC HW Heating	Medium	2	1446	23	35	20.56	113.18	26.65	2.01	978127
77	Wasteful	PTAC HW Heating	Medium	2	1446	23	35	20.56	66.29	26.65	4.42	978145
78	Wasteful	PTAC HW Heating	Medium	2	1446	23	35	74.77	113.18	14.33	2.01	968759
79	Wasteful	PTAC HW Heating	Medium	2	1446	23	35	74.77	66.29	14.33	4.42	968783
80	Wasteful	PTAC HW Heating	Medium	2	1460.9	19	33	53.41	101.07	22.13	2.79	968053
81	Wasteful	PTAC HW Heating	Medium	2	1460.9	19	33	20.56	101.07	26.65	2.79	968053

Simulation No.	Occupant Behavior Type	HVAC System	Building size	Number of floors	Area (m^2)	Percentage exterior glass (%)	Number of occupants	Thermal resistance of Wall construction materials($hr\cdot ft^2\cdot °F/Btu$)	Thermal resistance of Roof construction materials($hr\cdot ft^2\cdot °F/Btu$)	Thermal Mass of wall ($Btu/^0F$)	Thermal mass of roof ($Btu/^0F$)	Energy Consumed (kBtu)
82	Wasteful	PTAC HW Heating	Medium	2	1460.9	19	33	20.56	66.29	26.65	4.42	968042
83	Wasteful	PTAC HW Heating	Medium	2	1460.9	19	33	74.77	101.07	14.33	2.79	958732
84	Wasteful	PTAC Electric Heating	Medium	3	1400.8	21	37	74.77	113.18	14.33	2.01	881406
85	Wasteful	PTAC Electric Heating	Medium	3	1400.8	21	37	53.41	113.18	22.13	2.01	891942
86	Wasteful	PTAC Electric Heating	Medium	3	1400.8	21	37	20.56	113.18	26.65	2.01	891942
87	Wasteful	PTAC Electric Heating	Medium	2	13666.2	24	33	74.77	113.18	14.33	2.01	7876266
88	Wasteful	PTAC Electric Heating	Medium	2	13666.2	24	33	53.41	113.18	22.13	2.01	7903109
89	Wasteful	PTAC Electric Heating	Medium	2	13666.2	24	33	20.56	113.18	26.65	2.01	7903109
90	Wasteful	PTAC Electric Heating	Medium	2	1779.8	31	49	74.77	113.18	14.33	2.01	4717674
91	Wasteful	PTAC Electric Heating	Medium	2	1779.8	31	49	53.41	113.18	22.13	2.01	4746032

Simulation No.	Occupant Behavior Type	HVAC System	Building size	Number of floors	Area (m^2)	Percentage exterior glass (%)	Number of occupants	Thermal resistance of Wall construction materials($hr \cdot ft^2 \cdot °F/Btu$)	Thermal resistance of Roof construction materials($hr \cdot ft^2 \cdot °F/Btu$)	Thermal Mass of wall (Btu/^{0}F)	Thermal mass of roof (Btu/^{0}F)	Energy Consumed (kBtu)
92	Wasteful	PTAC Electric Heating	Medium	2	1779.8	31	49	20.56	113.18	26.65	2.01	4746032
93	Standard	PTAC HW Heating	Medium	2	1446	23	35	74.77	101.07	14.33	2.79	784628
94	Standard	PTAC HW Heating	Medium	2	1446	23	35	53.41	113.18	22.13	2.01	792457
95	Standard	PTAC HW Heating	Medium	2	1446	23	35	53.41	66.29	22.13	4.42	792457
96	Standard	PTAC HW Heating	Medium	2	1446	23	35	20.56	113.18	26.65	2.01	792457
97	Standard	PTAC HW Heating	Medium	2	1446	23	35	20.56	66.29	26.65	4.42	792457
98	Standard	PTAC HW Heating	Medium	2	1446	23	35	74.77	113.18	14.33	2.01	784628
99	Standard	PTAC HW Heating	Medium	2	1446	23	35	74.77	66.29	14.33	4.42	784628
100	Standard	PTAC HW Heating	Medium	2	1460.9	19	33	53.41	101.07	22.13	2.79	786105
101	Standard	PTAC HW Heating	Medium	2	1460.9	19	33	20.56	101.07	26.65	2.79	786105

Simulation No.	Occupant Behavior Type	HVAC System	Building size	Number of floors	Area (m^2)	Percentage exterior glass (%)	Number of occupants	Thermal resistance of Wall construction materials($hr \cdot ft^2 \cdot °F/Btu$)	Thermal resistance of Roof construction materials($hr \cdot ft^2 \cdot °F/Btu$)	Thermal Mass of wall ($Btu/^0F$)	Thermal mass of roof ($Btu/^0F$)	Energy Consumed (kBtu)
102	Standard	PTAC HW Heating	Medium	2	1460.9	19	33	20.56	66.29	26.65	4.42	786105
103	Standard	PTAC HW Heating	Medium	2	1460.9	19	33	74.77	101.07	14.33	2.79	778303
104	Standard	PTAC Electric Heating	Medium	3	1400.8	21	37	74.77	113.18	14.33	2.01	747858
105	Standard	PTAC Electric Heating	Medium	3	1400.8	21	37	53.41	113.18	22.13	2.01	757316
106	Standard	PTAC Electric Heating	Medium	3	1400.8	21	37	20.56	113.18	26.65	2.01	757316
107	Standard	PTAC Electric Heating	Medium	2	13666.2	24	33	74.77	113.18	14.33	2.01	6970701
108	Standard	PTAC Electric Heating	Medium	2	13666.2	24	33	53.41	113.18	22.13	2.01	6994528
109	Standard	PTAC Electric Heating	Medium	2	13666.2	24	33	20.56	113.18	26.65	2.01	6994528
110	Standard	PTAC Electric Heating	Medium	2	1779.8	31	49	74.77	113.18	14.33	2.01	4076353
111	Standard	PTAC Electric Heating	Medium	2	1779.8	31	49	53.41	113.18	22.13	2.01	4101681

Simulation No.	Occupant Behavior Type	HVAC System	Building size	Number of floors	Area (m^2)	Percentage exterior glass (%)	Number of occupants	Thermal resistance of Wall construction materials($hr \cdot ft^2 \cdot °F/Btu$)	Thermal resistance of Roof construction materials($hr \cdot ft^2 \cdot °F/Btu$)	Thermal Mass of wall ($Btu/^0F$)	Thermal mass of roof ($Btu/^0F$)	Energy Consumed (kBtu)
112	Standard	PTAC Electric Heating	Medium	2	1779.8	31	49	20.56	113.18	26.65	2.01	4101681
113	Austerity	PTAC HW Heating	Medium	2	1446	23	35	74.77	101.07	14.33	2.79	445431
114	Austerity	PTAC HW Heating	Medium	2	1446	23	35	53.41	113.18	22.13	2.01	450258
115	Austerity	PTAC HW Heating	Medium	2	1446	23	35	53.41	66.29	22.13	4.42	450258
116	Austerity	PTAC HW Heating	Medium	2	1446	23	35	20.56	113.18	26.65	2.01	450258
117	Austerity	PTAC HW Heating	Medium	2	1446	23	35	20.56	66.29	26.65	4.42	450258
118	Austerity	PTAC HW Heating	Medium	2	1446	23	35	74.77	113.18	14.33	2.01	445431
119	Austerity	PTAC HW Heating	Medium	2	1446	23	35	74.77	66.29	14.33	4.42	445431
120	Austerity	PTAC HW Heating	Medium	2	1460.9	19	33	53.41	101.07	22.13	2.79	454460
121	Austerity	PTAC HW Heating	Medium	2	1460.9	19	33	20.56	101.07	26.65	2.79	454460

Simulation No.	Occupant Behavior Type	HVAC System	Building size	Number of floors	Area (m^2)	Percentage exterior glass (%)	Number of occupants	Thermal resistance of Wall construction materials(hr·ft^2·°F/Btu)	Thermal resistance of Roof construction materials(hr·ft^2·°F/Btu)	Thermal Mass of wall (Btu/^{0}F)	Thermal mass of roof (Btu/^{0}F)	Energy Consumed (kBtu)
122	Austerity	PTAC HW Heating	Medium	2	1460.9	19	33	20.56	66.29	26.65	4.42	454460
123	Austerity	PTAC HW Heating	Medium	2	1460.9	19	33	74.77	101.07	14.33	2.79	449586
124	Austerity	PTAC Electric Heating	Medium	3	1400.8	21	37	74.77	113.18	14.33	2.01	416996
125	Austerity	PTAC Electric Heating	Medium	3	1400.8	21	37	53.41	113.18	22.13	2.01	422643
126	Austerity	PTAC Electric Heating	Medium	3	1400.8	21	37	20.56	113.18	26.65	2.01	422643
127	Austerity	PTAC Electric Heating	Medium	2	13666.2	24	33	74.77	113.18	14.33	2.01	4655403
128	Austerity	PTAC Electric Heating	Medium	2	13666.2	24	33	53.41	113.18	22.13	2.01	4676347
129	Austerity	PTAC Electric Heating	Medium	2	13666.2	24	33	20.56	113.18	26.65	2.01	4676347
130	Austerity	PTAC Electric Heating	Medium	2	1779.8	31	49	74.77	113.18	14.33	2.01	2264831
131	Austerity	PTAC Electric Heating	Medium	2	1779.8	31	49	53.41	113.18	22.13	2.01	2280122

Simulation No.	Occupant Behavior Type	HVAC System	Building size	Number of floors	Area (m^2)	Percentage exterior glass (%)	Number of occupants	Thermal resistance of Wall construction materials(hr·ft^2·°F/Btu)	Thermal resistance of Roof construction materials(hr·ft^2·°F/Btu)	Thermal Mass of wall (Btu/^{0}F)	Thermal mass of roof (Btu/^{0}F)	Energy Consumed (kBtu)
132	Austerity	PTAC Electric Heating	Medium	2	1779.8	31	49	20.56	113.18	26.65	2.01	2280122

9 APPENDIX C-ENERGY SIMULATION RESULTS OF LARGE-SIZE COMMERCIAL BUILDINGS

Simulation No.	Occupant Behavior Type	HVAC System	Building size	Number of floors	Area (m^2)	Percentage exterior glass (%)	Number of occupants	Thermal resistance of Wall construction materials(hr·ft²·°F/Btu)	Thermal resistance of Roof construction materials(hr·ft²·°F/Btu)	Thermal Mass of wall (Btu/^{0}F)	Thermal mass of roof (Btu/^{0}F)	Energy Consumed (kBtu)
133	Wasteful	PTAC HW Heating	Large	4	11072.2	33	349	74.77	101.07	14.33	2.79	6541518
134	Wasteful	PTAC HW Heating	Large	6	14078.4	41	358	54.08	101.07	7.18	2.79	8109035
135	Wasteful	PTAC HW Heating	Large	6	14078.4	41	358	53.41	101.07	22.13	2.79	8109035
136	Wasteful	PTAC HW Heating	Large	6	14078.4	41	358	53.41	66.29	22.13	4.42	8109035
137	Wasteful	PTAC HW Heating	Large	6	13840.4	33	353	54.08	113.18	7.18	2.01	8130301
138	Wasteful	PTAC HW Heating	Large	7	14105.3	45	354	31.15	113.18	29.58	2.01	8435895
139	Wasteful	PTAC Electric Heating	Large	6	14131.8	51	291	26.18	113.18	44.62	2.01	8411470
140	Standard	PTAC HW Heating	Large	4	11072.2	33	349	74.77	101.07	14.33	2.79	5844580
141	Standard	PTAC HW Heating	Large	6	14078.4	41	358	54.08	101.07	7.18	2.79	7372838

Simulation No.	Occupant Behavior Type	HVAC System	Building size	Number of floors	Area (m^2)	Percentage exterior glass (%)	Number of occupants	Thermal resistance of Wall construction materials(hr·ft^2·°F/Btu)	Thermal resistance of Roof construction materials(hr·ft^2·°F/Btu)	Thermal Mass of wall (Btu/^{0}F)	Thermal mass of roof (Btu/^{0}F)	Energy Consumed (kBtu)
142	Standard	PTAC HW Heating	Large	6	14078.4	41	358	53.41	101.07	22.13	2.79	7372838
143	Standard	PTAC HW Heating	Large	6	14078.4	41	358	53.41	66.29	22.13	4.42	7372838
144	Standard	PTAC HW Heating	Large	6	13840.4	33	353	54.08	113.18	7.18	2.01	7330134
145	Standard	PTAC HW Heating	Large	7	14105.3	45	354	31.15	113.18	29.58	2.01	7453953
146	Standard	PTAC Electric Heating	Large	6	14131.8	51	291	26.18	113.18	44.62	2.01	7361106
147	Austerity	PTAC HW Heating	Large	4	11072.2	33	349	74.77	101.07	14.33	2.79	3375702
148	Austerity	PTAC HW Heating	Large	6	14078.4	41	358	54.08	101.07	7.18	2.79	4268591
149	Austerity	PTAC HW Heating	Large	6	14078.4	41	358	53.41	101.07	22.13	2.79	4268591
150	Austerity	PTAC HW Heating	Large	6	14078.4	41	358	53.41	66.29	22.13	4.42	4268591
151	Austerity	PTAC HW Heating	Large	6	13840.4	33	353	54.08	113.18	7.18	2.01	4197104

Simulation No.	Occupant Behavior Type	HVAC System	Building size	Number of floors	Area (m^2)	Percentage exterior glass (%)	Number of occupants	Thermal resistance of Wall construction materials(hr·ft²·°F/Btu)	Thermal resistance of Roof construction materials(hr·ft²·°F/Btu)	Thermal Mass of wall (Btu/^{0}F)	Thermal mass of roof (Btu/^{0}F)	Energy Consumed (kBtu)
152	Austerity	PTAC HW Heating	Large	7	14105.3	45	354	31.15	113.18	29.58	2.01	4153602
153	Austerity	PTAC Electric Heating	Large	6	14131.8	51	291	26.18	113.18	44.62	2.01	4071310

10 APPENDIX D- END-USE ENERGY – SAMPLES

Table 41 Energy simulation result for building information model number 1; (Simulation number -1)

End Uses

	Electricity [kBtu]	Natural Gas [kBtu]	Additional Fuel [kBtu]	District Cooling [kBtu]	District Heating [kBtu]	Water [gal]
Heating	0.00	0.00	0.00	0.00	97100.40	0.00
Cooling	0.00	0.00	0.00	73750.55	0.00	0.00
Interior Lighting	55898.04	0.00	0.00	0.00	0.00	0.00
Exterior Lighting	0.00	0.00	0.00	0.00	0.00	0.00
Interior Equipment	46581.72	0.00	0.00	0.00	0.00	0.00
Exterior Equipment	0.00	0.00	0.00	0.00	0.00	0.00
Fans	13355.17	0.00	0.00	0.00	0.00	0.00
Pumps	838.24	0.00	0.00	0.00	0.00	0.00
Heat Rejection	0.00	0.00	0.00	0.00	0.00	0.00
Humidification	0.00	0.00	0.00	0.00	0.00	0.00
Heat Recovery	0.00	0.00	0.00	0.00	0.00	0.00
Water Systems	0.00	0.00	0.00	0.00	0.00	0.00
Refrigeration	0.00	0.00	0.00	0.00	0.00	0.00
Generators	0.00	0.00	0.00	0.00	0.00	0.00
Total End Uses	116673.16	0.00	0.00	73750.55	97100.40	0.00

Note: District heat appears to be the principal heating source based on energy usage.

Table 42 Simulation result for building information model number 2; (Simulation number -5)

End Uses

	Electricity [kBtu]	Natural Gas [kBtu]	Additional Fuel [kBtu]	District Cooling [kBtu]	District Heating [kBtu]	Water [gal]
Heating	0.00	0.00	0.00	0.00	73463.07	0.00
Cooling	0.00	0.00	0.00	80042.05	0.00	0.00
Interior Lighting	49091.76	0.00	0.00	0.00	0.00	0.00
Exterior Lighting	0.00	0.00	0.00	0.00	0.00	0.00
Interior Equipment	40909.82	0.00	0.00	0.00	0.00	0.00
Exterior Equipment	0.00	0.00	0.00	0.00	0.00	0.00
Fans	13302.68	0.00	0.00	0.00	0.00	0.00
Pumps	748.04	0.00	0.00	0.00	0.00	0.00
Heat Rejection	0.00	0.00	0.00	0.00	0.00	0.00
Humidification	0.00	0.00	0.00	0.00	0.00	0.00
Heat Recovery	0.00	0.00	0.00	0.00	0.00	0.00
Water Systems	0.00	0.00	0.00	0.00	0.00	0.00
Refrigeration	0.00	0.00	0.00	0.00	0.00	0.00
Generators	0.00	0.00	0.00	0.00	0.00	0.00
Total End Uses	104052.30	0.00	0.00	80042.05	73463.07	0.00

Note: District heat appears to be the principal heating source based on energy usage.

Table 43 Simulation result for building information model number 3; (Simulation number -10)

End Uses

	Electricity [kBtu]	Natural Gas [kBtu]	Additional Fuel [kBtu]	District Cooling [kBtu]	District Heating [kBtu]	Water [gal]
Heating	0.00	0.00	0.00	0.00	92795.70	0.00
Cooling	0.00	0.00	0.00	75296.52	0.00	0.00
Interior Lighting	51319.03	0.00	0.00	0.00	0.00	0.00
Exterior Lighting	0.00	0.00	0.00	0.00	0.00	0.00
Interior Equipment	42765.88	0.00	0.00	0.00	0.00	0.00
Exterior Equipment	0.00	0.00	0.00	0.00	0.00	0.00
Fans	13387.77	0.00	0.00	0.00	0.00	0.00
Pumps	824.53	0.00	0.00	0.00	0.00	0.00
Heat Rejection	0.00	0.00	0.00	0.00	0.00	0.00
Humidification	0.00	0.00	0.00	0.00	0.00	0.00
Heat Recovery	0.00	0.00	0.00	0.00	0.00	0.00
Water Systems	0.00	0.00	0.00	0.00	0.00	0.00
Refrigeration	0.00	0.00	0.00	0.00	0.00	0.00
Generators	0.00	0.00	0.00	0.00	0.00	0.00
Total End Uses	108297.21	0.00	0.00	75296.52	92795.70	0.00

Note: District heat appears to be the principal heating source based on energy usage.

Table 44 Simulation result for building information model number 4; (Simulation number -15)

End Uses

	Electricity [kBtu]	Natural Gas [kBtu]	Additional Fuel [kBtu]	District Cooling [kBtu]	District Heating [kBtu]	Water [gal]
Heating	0.00	0.00	0.00	0.00	89205.13	0.00
Cooling	0.00	0.00	0.00	71014.97	0.00	0.00
Interior Lighting	47263.37	0.00	0.00	0.00	0.00	0.00
Exterior Lighting	0.00	0.00	0.00	0.00	0.00	0.00
Interior Equipment	39386.16	0.00	0.00	0.00	0.00	0.00
Exterior Equipment	0.00	0.00	0.00	0.00	0.00	0.00
Fans	12749.47	0.00	0.00	0.00	0.00	0.00
Pumps	787.58	0.00	0.00	0.00	0.00	0.00
Heat Rejection	0.00	0.00	0.00	0.00	0.00	0.00
Humidification	0.00	0.00	0.00	0.00	0.00	0.00
Heat Recovery	0.00	0.00	0.00	0.00	0.00	0.00
Water Systems	0.00	0.00	0.00	0.00	0.00	0.00
Refrigeration	0.00	0.00	0.00	0.00	0.00	0.00
Generators	0.00	0.00	0.00	0.00	0.00	0.00
Total End Uses	100186.59	0.00	0.00	71014.97	89205.13	0.00

Note: District heat appears to be the principal heating source based on energy usage.

Table 45 Simulation result for building information model number 5; (Simulation number -20)

End Uses

	Electricity [kBtu]	Natural Gas [kBtu]	Additional Fuel [kBtu]	District Cooling [kBtu]	District Heating [kBtu]	Water [gal]
Heating	0.00	0.00	0.00	0.00	88137.56	0.00
Cooling	0.00	0.00	0.00	69208.57	0.00	0.00
Interior Lighting	45888.82	0.00	0.00	0.00	0.00	0.00
Exterior Lighting	0.00	0.00	0.00	0.00	0.00	0.00
Interior Equipment	38240.70	0.00	0.00	0.00	0.00	0.00
Exterior Equipment	0.00	0.00	0.00	0.00	0.00	0.00
Fans	12508.52	0.00	0.00	0.00	0.00	0.00
Pumps	774.26	0.00	0.00	0.00	0.00	0.00
Heat Rejection	0.00	0.00	0.00	0.00	0.00	0.00
Humidification	0.00	0.00	0.00	0.00	0.00	0.00
Heat Recovery	0.00	0.00	0.00	0.00	0.00	0.00
Water Systems	0.00	0.00	0.00	0.00	0.00	0.00
Refrigeration	0.00	0.00	0.00	0.00	0.00	0.00
Generators	0.00	0.00	0.00	0.00	0.00	0.00
Total End Uses	97412.30	0.00	0.00	69208.57	88137.56	0.00

Note: District heat appears to be the principal heating source based on energy usage.

Table 46 Simulation result for building information model number 5; (Simulation number -20)

End Uses

	Electricity [kBtu]	Natural Gas [kBtu]	Additional Fuel [kBtu]	District Cooling [kBtu]	District Heating [kBtu]	Water [gal]
Heating	25.35	361013.66	0.00	0.00	0.00	0.00
Cooling	97565.33	0.00	0.00	0.00	0.00	0.00
Interior Lighting	273547.92	0.00	0.00	0.00	0.00	0.00
Exterior Lighting	0.00	0.00	0.00	0.00	0.00	0.00
Interior Equipment	227956.69	0.00	0.00	0.00	0.00	0.00
Exterior Equipment	0.00	0.00	0.00	0.00	0.00	0.00
Fans	6779.05	0.00	0.00	0.00	0.00	0.00
Pumps	1897.28	0.00	0.00	0.00	0.00	0.00
Heat Rejection	0.00	0.00	0.00	0.00	0.00	0.00
Humidification	0.00	0.00	0.00	0.00	0.00	0.00
Heat Recovery	0.00	0.00	0.00	0.00	0.00	0.00
Water Systems	0.00	0.00	0.00	0.00	0.00	0.00
Refrigeration	0.00	0.00	0.00	0.00	0.00	0.00
Generators	0.00	0.00	0.00	0.00	0.00	0.00
Total End Uses	607771.63	361013.66	0.00	0.00	0.00	0.00

Note: Natural gas appears to be the principal heating source based on energy usage.

Table 47 Simulation result for building information model number 7; (Simulation number -32)

End Uses

	Electricity [kBtu]	Natural Gas [kBtu]	Additional Fuel [kBtu]	District Cooling [kBtu]	District Heating [kBtu]	Water [gal]
Heating	25.81	359144.63	0.00	0.00	0.00	0.00
Cooling	93499.65	0.00	0.00	0.00	0.00	0.00
Interior Lighting	276494.97	0.00	0.00	0.00	0.00	0.00
Exterior Lighting	0.00	0.00	0.00	0.00	0.00	0.00
Interior Equipment	230412.58	0.00	0.00	0.00	0.00	0.00
Exterior Equipment	0.00	0.00	0.00	0.00	0.00	0.00
Fans	6600.13	0.00	0.00	0.00	0.00	0.00
Pumps	1875.06	0.00	0.00	0.00	0.00	0.00
Heat Rejection	0.00	0.00	0.00	0.00	0.00	0.00
Humidification	0.00	0.00	0.00	0.00	0.00	0.00
Heat Recovery	0.00	0.00	0.00	0.00	0.00	0.00
Water Systems	0.00	0.00	0.00	0.00	0.00	0.00
Refrigeration	0.00	0.00	0.00	0.00	0.00	0.00
Generators	0.00	0.00	0.00	0.00	0.00	0.00
Total End Uses	608908.19	359144.63	0.00	0.00	0.00	0.00

Note: Natural gas appears to be the principal heating source based on energy usage.

Table 48 Simulation result for building information model number 8; (Simulation number -36)

End Uses

	Electricity [kBtu]	Natural Gas [kBtu]	Additional Fuel [kBtu]	District Cooling [kBtu]	District Heating [kBtu]	Water [gal]
Heating	28.05	301796.92	0.00	0.00	0.00	0.00
Cooling	98831.61	0.00	0.00	0.00	0.00	0.00
Interior Lighting	263587.59	0.00	0.00	0.00	0.00	0.00
Exterior Lighting	0.00	0.00	0.00	0.00	0.00	0.00
Interior Equipment	219656.41	0.00	0.00	0.00	0.00	0.00
Exterior Equipment	0.00	0.00	0.00	0.00	0.00	0.00
Fans	6769.82	0.00	0.00	0.00	0.00	0.00
Pumps	1370.03	0.00	0.00	0.00	0.00	0.00
Heat Rejection	0.00	0.00	0.00	0.00	0.00	0.00
Humidification	0.00	0.00	0.00	0.00	0.00	0.00
Heat Recovery	0.00	0.00	0.00	0.00	0.00	0.00
Water Systems	0.00	0.00	0.00	0.00	0.00	0.00
Refrigeration	0.00	0.00	0.00	0.00	0.00	0.00
Generators	0.00	0.00	0.00	0.00	0.00	0.00
Total End Uses	590243.51	301796.92	0.00	0.00	0.00	0.00

Note: Natural gas appears to be the principal heating source based on energy usage.

Table 49 Simulation result for building information model number 9; (Simulation number -39)

End Uses

	Electricity [kBtu]	Natural Gas [kBtu]	Additional Fuel [kBtu]	District Cooling [kBtu]	District Heating [kBtu]	Water [gal]
Heating	2329929.40	0.00	0.00	0.00	0.00	0.00
Cooling	700909.05	0.00	0.00	0.00	0.00	0.00
Interior Lighting	2624160.94	0.00	0.00	0.00	0.00	0.00
Exterior Lighting	0.00	0.00	0.00	0.00	0.00	0.00
Interior Equipment	2186801.72	0.00	0.00	0.00	0.00	0.00
Exterior Equipment	0.00	0.00	0.00	0.00	0.00	0.00
Fans	34464.41	0.00	0.00	0.00	0.00	0.00
Pumps	0.00	0.00	0.00	0.00	0.00	0.00
Heat Rejection	0.00	0.00	0.00	0.00	0.00	0.00
Humidification	0.00	0.00	0.00	0.00	0.00	0.00
Heat Recovery	0.00	0.00	0.00	0.00	0.00	0.00
Water Systems	0.00	0.00	0.00	0.00	0.00	0.00
Refrigeration	0.00	0.00	0.00	0.00	0.00	0.00
Generators	0.00	0.00	0.00	0.00	0.00	0.00
Total End Uses	7876265.53	0.00	0.00	0.00	0.00	0.00

Note: Electricity appears to be the principal heating source based on energy usage.

Table 50 Simulation result for building information model number 10; (Simulation number - 42)

End Uses

	Electricity [kBtu]	Natural Gas [kBtu]	Additional Fuel [kBtu]	District Cooling [kBtu]	District Heating [kBtu]	Water [gal]
Heating	1414704.08	0.00	0.00	0.00	0.00	0.00
Cooling	558063.40	0.00	0.00	0.00	0.00	0.00
Interior Lighting	1482780.32	0.00	0.00	0.00	0.00	0.00
Exterior Lighting	0.00	0.00	0.00	0.00	0.00	0.00
Interior Equipment	1235650.80	0.00	0.00	0.00	0.00	0.00
Exterior Equipment	0.00	0.00	0.00	0.00	0.00	0.00
Fans	26475.23	0.00	0.00	0.00	0.00	0.00
Pumps	0.00	0.00	0.00	0.00	0.00	0.00
Heat Rejection	0.00	0.00	0.00	0.00	0.00	0.00
Humidification	0.00	0.00	0.00	0.00	0.00	0.00
Heat Recovery	0.00	0.00	0.00	0.00	0.00	0.00
Water Systems	0.00	0.00	0.00	0.00	0.00	0.00
Refrigeration	0.00	0.00	0.00	0.00	0.00	0.00
Generators	0.00	0.00	0.00	0.00	0.00	0.00
Total End Uses	4717673.84	0.00	0.00	0.00	0.00	0.00

Note: Electricity appears to be the principal heating source based on energy usage.

Table 51 Simulation result for building information model number 11; (Simulation number - 45)

End Uses

	Electricity [kBtu]	Natural Gas [kBtu]	Additional Fuel [kBtu]	District Cooling [kBtu]	District Heating [kBtu]	Water [gal]
Heating	21.22	2338394.21	0.00	0.00	0.00	0.00
Cooling	955965.95	0.00	0.00	0.00	0.00	0.00
Interior Lighting	2680373.26	0.00	0.00	0.00	0.00	0.00
Exterior Lighting	0.00	0.00	0.00	0.00	0.00	0.00
Interior Equipment	2233645.35	0.00	0.00	0.00	0.00	0.00
Exterior Equipment	0.00	0.00	0.00	0.00	0.00	0.00
Fans	58000.58	0.00	0.00	0.00	0.00	0.00
Pumps	13272.29	0.00	0.00	0.00	0.00	0.00
Heat Rejection	0.00	0.00	0.00	0.00	0.00	0.00
Humidification	0.00	0.00	0.00	0.00	0.00	0.00
Heat Recovery	0.00	0.00	0.00	0.00	0.00	0.00
Water Systems	0.00	0.00	0.00	0.00	0.00	0.00
Refrigeration	0.00	0.00	0.00	0.00	0.00	0.00
Generators	0.00	0.00	0.00	0.00	0.00	0.00
Total End Uses	5941278.66	2338394.21	0.00	0.00	0.00	0.00

Note: Natural gas appears to be the principal heating source based on energy usage.

Table 52 Simulation result for building information model number 12; (Simulation number - 46)

End Uses

	Electricity [kBtu]	Natural Gas [kBtu]	Additional Fuel [kBtu]	District Cooling [kBtu]	District Heating [kBtu]	Water [gal]
Heating	21.27	2232538.80	0.00	0.00	0.00	0.00
Cooling	893157.08	0.00	0.00	0.00	0.00	0.00
Interior Lighting	2696338.55	0.00	0.00	0.00	0.00	0.00
Exterior Lighting	0.00	0.00	0.00	0.00	0.00	0.00
Interior Equipment	2246949.76	0.00	0.00	0.00	0.00	0.00
Exterior Equipment	0.00	0.00	0.00	0.00	0.00	0.00
Fans	54403.60	0.00	0.00	0.00	0.00	0.00
Pumps	12712.92	0.00	0.00	0.00	0.00	0.00
Heat Rejection	0.00	0.00	0.00	0.00	0.00	0.00
Humidification	0.00	0.00	0.00	0.00	0.00	0.00
Heat Recovery	0.00	0.00	0.00	0.00	0.00	0.00
Water Systems	0.00	0.00	0.00	0.00	0.00	0.00
Refrigeration	0.00	0.00	0.00	0.00	0.00	0.00
Generators	0.00	0.00	0.00	0.00	0.00	0.00
Total End Uses	5903583.19	2232538.80	0.00	0.00	0.00	0.00

Note: Natural gas appears to be the principal heating source based on energy usage.

Table 53 Simulation result for building information model number 13; (Simulation number -49)

End Uses

	Electricity [kBtu]	Natural Gas [kBtu]	Additional Fuel [kBtu]	District Cooling [kBtu]	District Heating [kBtu]	Water [gal]
Heating	20.30	2134327.49	0.00	0.00	0.00	0.00
Cooling	962148.16	0.00	0.00	0.00	0.00	0.00
Interior Lighting	2696338.55	0.00	0.00	0.00	0.00	0.00
Exterior Lighting	0.00	0.00	0.00	0.00	0.00	0.00
Interior Equipment	2246949.76	0.00	0.00	0.00	0.00	0.00
Exterior Equipment	0.00	0.00	0.00	0.00	0.00	0.00
Fans	57033.97	0.00	0.00	0.00	0.00	0.00
Pumps	12216.49	0.00	0.00	0.00	0.00	0.00
Heat Rejection	0.00	0.00	0.00	0.00	0.00	0.00
Humidification	0.00	0.00	0.00	0.00	0.00	0.00
Heat Recovery	0.00	0.00	0.00	0.00	0.00	0.00
Water Systems	0.00	0.00	0.00	0.00	0.00	0.00
Refrigeration	0.00	0.00	0.00	0.00	0.00	0.00
Generators	0.00	0.00	0.00	0.00	0.00	0.00
Total End Uses	5974707.23	2134327.49	0.00	0.00	0.00	0.00

Note: Natural gas appears to be the principal heating source based on energy usage.

Table 54 Simulation result for building information model number 14; (Simulation number -50)

End Uses

	Electricity [kBtu]	Natural Gas [kBtu]	Additional Fuel [kBtu]	District Cooling [kBtu]	District Heating [kBtu]	Water [gal]
Heating	21.03	2438558.58	0.00	0.00	0.00	0.00
Cooling	1020247.81	0.00	0.00	0.00	0.00	0.00
Interior Lighting	2692236.62	0.00	0.00	0.00	0.00	0.00
Exterior Lighting	0.00	0.00	0.00	0.00	0.00	0.00
Interior Equipment	2243531.48	0.00	0.00	0.00	0.00	0.00
Exterior Equipment	0.00	0.00	0.00	0.00	0.00	0.00
Fans	61547.99	0.00	0.00	0.00	0.00	0.00
Pumps	13937.73	0.00	0.00	0.00	0.00	0.00
Heat Rejection	0.00	0.00	0.00	0.00	0.00	0.00
Humidification	0.00	0.00	0.00	0.00	0.00	0.00
Heat Recovery	0.00	0.00	0.00	0.00	0.00	0.00
Water Systems	0.00	0.00	0.00	0.00	0.00	0.00
Refrigeration	0.00	0.00	0.00	0.00	0.00	0.00
Generators	0.00	0.00	0.00	0.00	0.00	0.00
Total End Uses	6031522.66	2438558.58	0.00	0.00	0.00	0.00

Note: Natural gas appears to be the principal heating source based on energy usage.

Table 55 Simulation result for building information model number 15; (Simulation number - 51)

End Uses

	Electricity [kBtu]	Natural Gas [kBtu]	Additional Fuel [kBtu]	District Cooling [kBtu]	District Heating [kBtu]	Water [gal]
Heating	2439605.48	0.00	0.00	0.00	0.00	0.00
Cooling	1031875.55	0.00	0.00	0.00	0.00	0.00
Interior Lighting	2680106.04	0.00	0.00	0.00	0.00	0.00
Exterior Lighting	0.00	0.00	0.00	0.00	0.00	0.00
Interior Equipment	2233422.67	0.00	0.00	0.00	0.00	0.00
Exterior Equipment	0.00	0.00	0.00	0.00	0.00	0.00
Fans	48261.41	0.00	0.00	0.00	0.00	0.00
Pumps	0.00	0.00	0.00	0.00	0.00	0.00
Heat Rejection	0.00	0.00	0.00	0.00	0.00	0.00
Humidification	0.00	0.00	0.00	0.00	0.00	0.00
Heat Recovery	0.00	0.00	0.00	0.00	0.00	0.00
Water Systems	0.00	0.00	0.00	0.00	0.00	0.00
Refrigeration	0.00	0.00	0.00	0.00	0.00	0.00
Generators	0.00	0.00	0.00	0.00	0.00	0.00
Total End Uses	8433271.15	0.00	0.00	0.00	0.00	0.00

Note: Electricity appears to be the principal heating source based on energy usage.