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Potential energy savings and benefits to thermal comfort from the effective use of window blinds

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POTENTIAL ENERGY SAVINGS AND BENEFITS TO THERMAL COMFORT FROM THE EFFECTIVE USE OF WINDOW BLINDS

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ABSTRACT

Sudhakaran, Saurabh. M.S.,B.C.M. Purdue University, May 2016. Potential Energy Savings and Benefits to Thermal Comfort from the Effective Usage of Venetian Window Blinds. Major Professor: Mark Shaurette.

This research work involves the study of usage patterns of window blinds by the occupants of a multi-story apartment buildings in Lafayette, IN. The goal of this study is to understand the processes of enhancing comfort by changing window blind positioning through various times of the day. To achieve this the researcher studied the actual window blind usage pattern of the building under consideration. The researcher also surveyed the occupants of the building to record comfort preferences and its effect on window blind usage. The window pattern is simulated into an energy model and its predicted energy consumption is compared with the predicted energy consumption under optimum window blind usage to maximize energy savings. To conclude the study, the researcher will quantify the energy that can be saved by proper positioning of window blinds.

CHAPTER 1. INTRODUCTION

In this study the researcher talks about the need for a research in the area of window blinds and comfort. Since there is a severe need for reduction of energy consumption in buildings the researcher would be studying the window blinds and how Venetian window blinds can help reduce energy consumption of buildings in the U.S.

1.1 Statement of Purpose

EIA (U.S. Energy Information Administration) is an organization that has collected and analyzes energy associated data for several decades. EIA's 2014 annual energy review talks about the energy consumption for the year 2014 and the energy consumption figures are shocking. EIA has broken down the total consumption into four major sectors. These sectors are transportation, industrial processes, commercial buildings and residential buildings. (Figure 1.1) shows residential, and commercial buildings are responsible for consumption of almost 40% of all the energy produced in the US. (Figure 1.1) also indicates that overtime there is a huge increase in the amount of energy that our buildings are using. This increase in consumption of energy is massive and the numbers are quite disturbing

(Figure 1.2) shows a steady increase in the energy consumption during the winter months. This is because of the increase in heating energy consumption.

Recent technological advances in the area of building energy performance offers promising solutions to the problem of ever-increasing energy consumption of buildings. Increasing the energy retaining capacity of the building envelope, use of more efficient electrical equipment, and energy education are some of the obvious solutions to this problem.

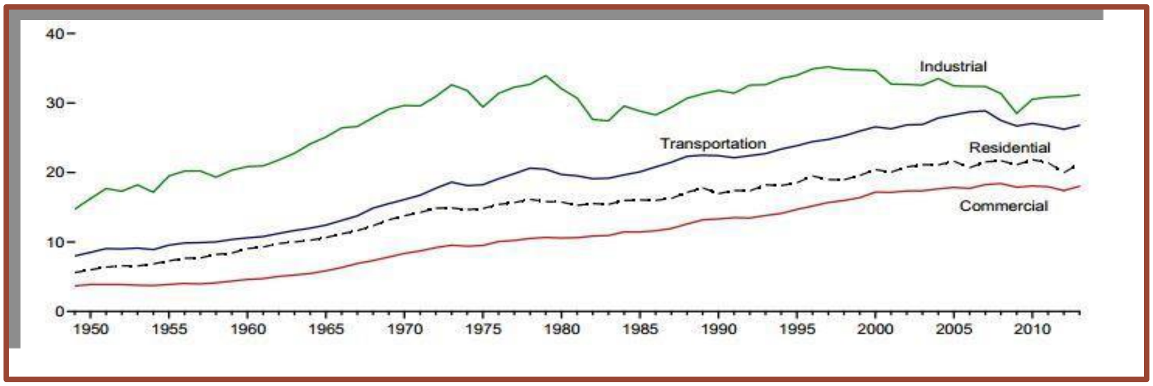


Figure 1.1 Consumption by End Use, Sector (Quadrillion Btu)

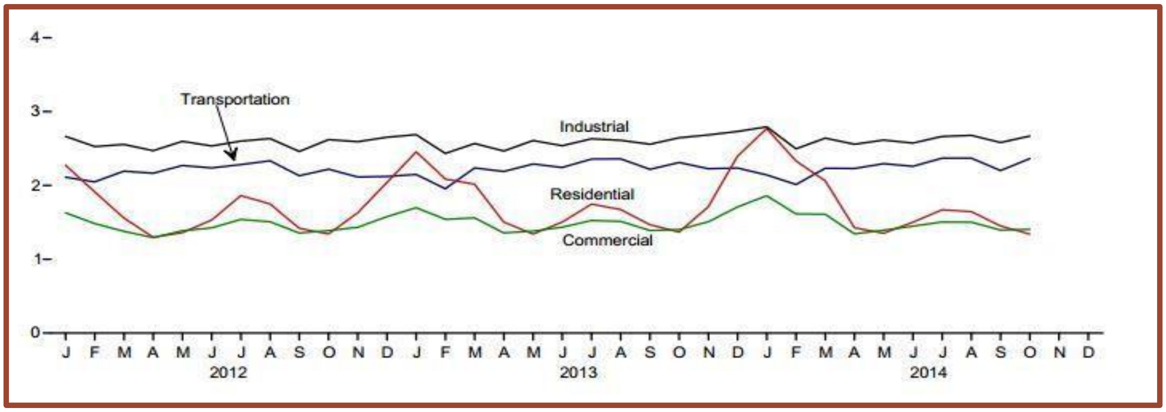


Figure 1.2 Consumption by End Use, Monthly (Quadrillion Btu)

1.2 Research Questions

What is the Venetian window blind usage pattern of occupants of a multi-story residential apartment building in Lafayette, IN during the heating season?

What is the effect of façade orientation, cloud cover and exterior temperature on window blind usage?

What are the possible energy savings from keeping the window blinds completely open from 8AM to 5PM and completely closed during the heating season, for a multi- family residential building?

1.3 Scope

For this research the researcher will study the effect of window blinds on the heat loss and heat gain through windows in multi-story apartment buildings. The research will analyze the effect of various positions of window blinds and the angle of slats on energy gain or loss of buildings. The anticipated target of this research project is to study the usage patterns of window blinds by the occupants of multi-story apartment buildings and to develop recommendations that will reduce heating or cooling requirement of these buildings hence reducing energy consumption. Finally, the researcher will study the changes in the window blind usage pattern and related energy and comfort benefits to the occupants after the recommendations are made.

1.4 Significance

Reducing the energy consumption of buildings is of utmost importance. The buildings in United States consume almost 40% of all the energy produced. Also the annual increase in the energy consumption by buildings is massive and the numbers are quite disturbing. There are several driving factors that contribute to this trend of increase in energy consumption. Lack of awareness is one of the primary reasons behind this increased energy consumption.

The requirement for reducing energy consumption in buildings is accentuated by the increasing cost of energy in the United States and the detrimental effect of greenhouse gas emissions during energy production. In the residential sector, the cost of retail electricity has increased by a factor of 1.5 over the last 20 years. The cost of energy prior to 20 years was even less. Based on these trends, it can be predicted that the cost of energy will continue to increase. This increase in the cost of energy is because of our dependence on fossil fuels for energy production. The market forces of demand and supply are effecting the cost energy production. Demand is increasing as populations grow and the supply of fossil fuels used as energy sources are finite (U.S. Energy Information Administration, 2011a). Because 40% of US energy consumption is invested in the operation of buildings, large savings in energy use and greenhouse gas emissions can be realized through implementing building efficiency measures (Wierzba, Morgenstern, Meyer, Ruggles, & Himmelreich, 2011). There is significant development in building technology, application of these technologies can reduce the energy consumption of new and upcoming buildings. However, discontinuing the use of existing buildings in order to reduce energy consumption is not a practical alternative. On the other hand, upgrading the energy performance of existing buildings is a practical technique to decrease their energy consumption.

The building envelop is responsible for maintaining a comfortable atmosphere within a building. Even though windows are an essential part of any building, they act as cavity in the overall building envelope. There are several researchers that identify windows as the crucial source of heat loss and heat gain in buildings. The removal and sealing of window in order to increase energy performance is a theoretical but not a practical solution. Windows can be used for ventilative cooling of the building structure and, also help in the attainment of comfort (Brager, Paliaga and de Dear, 2004). Some other advantages associated with windows are increase in productivity of occupants and serving as a source of natural light (Leaman and Bordass, 1994).

Researchers of energy efficient buildings have come up with several critical techniques that will assist in the reduction of unwanted heat loss and heat gain through windows. By some estimates the combined heating, cooling and lighting energy can be reduced by over 30% by employing an optimal controller for shading systems (Lee, DiBartolomeo, & Selkowitz, 1998; Tzempelikos & Athienitis, 2007). However, the reality of the situation is different. In the real-world, the conditions in which the windows operate are not always ideal. What make matters worse is that there are numerous extraneous human factors that affect the overall energy efficiency of the windows. These human factors have an unfavorable influence on the energy efficiency of the windows and building operations.

1.5 Assumptions

Assumptions are items that researcher is not able to verify or monitor due to time and other constraints:

- The researcher is not able to collect data on the inside temperatures and the artificial lighting arrangements of the apartment units
- All the window blinds installed in all the apartment units under consideration are similar
- All the windows are perfectly air sealed
- The size and shape of all the windows under consideration are similar
- The glass installed in all the windows is double paneled
- The angle at which sunlight hits the apartment building is constant throughout the week when the blind usage data is being collected
- Residents of the apartment units are same throughout the time period when the data is being collected

1.6 Limitations

As will be seen in the literature review, there are several factors that impact the control pattern of window blinds. These factors include:

- Interaction of heat, light, and ventilation between interior and exterior environment

- Regulation of view and privacy, and the individual aesthetic preferences
- Individual preferences of lighting and temperature
- Ability of an individual to adapt to a change in the physical environment
- Occupants of different age and gender have different preferences
- Contextual factors such as orientation of seating, orientation of the façade under consideration, lighting requirement of the task being performed by the occupants

It is not possible to examine all factors at once. From the literature review, the most promising variables are mainly related to the visual and thermal environment.

Therefore, this study focuses on just the transfer of heat and light to and from the apartment units under consideration.

1.7 Delimitations

The purpose of delimitations presented in this research is to narrow the scope and identify items that were not analyzed:

- Since this study focuses on a residential setting, the researcher will not include any data on window blind usage pattern by occupants in a commercial, industrial or institutional buildings
- The research will not include study of window blinds in individual detached housing

- The research focuses on traditional venetian blinds and does not include any data on other types of window blinds
- The researcher will not include the effect of objects with high thermal mass inside the apartment on the comfort of occupants
- For this study the researcher will be neglecting the temperature differential between different apartment within the building
- The researched will not model the effect of angle of slat of window blinds.

1.8 Definitions

The purpose of providing definitions was to educate the audience regarding certain terms used in this research that may not be part of a normal lexicon. Definitions used in this research included:

ASHRAE – American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE, 2010)

building envelope – exterior walls and roof of a building; all parts of a building through which air can pass to the outdoors (Gadgil, Price, Shehabi, & Chan, 2006)

CFM – cubic feet per minute

conditioned space – the part of a building that is capable of being thermally conditioned for the comfort of occupants (ASHRAE, 2010)

HVAC system – heating, ventilating, and air conditioning system (Gadgil, Price, Shehabi,

& Chan, 2006)

infiltration – uncontrolled inward leakage of air through cracks and interstices in any building element and around windows and doors of a building (ASHRAE, 2010)

natural ventilation – ventilation occurring as a result of only natural forces, such as wind pressure or differences in air density, through intentional openings such as open windows and doors (ASHRAE, 2010)

ventilation – process of supplying outdoor air to or removing indoor air from a dwelling by natural or mechanical means (ASHRAE, 2010)

slat – a thin, narrow piece of wood, plastic, or metal, especially one of a series that overlap or fit into each other, as in a fence or a venetian blind

1.9 Summary

This chapter outlines the statement of purpose of the study. It also talks about the scope, significance and research question. The assumptions, limitations and delimitations identified by the researcher arte also mentioned in this chapter. In the end this chapter provides definitions in order to educate audience regarding certain terms.

CHAPTER 2. LITERATURE REVIEW

Window blinds have been used to cover windows for several years. In addition to their intended use of controlling visibility, the window blind serves several purposes.

Window blinds are available in different shapes, materials and types. They can be located inside, outside or within the building envelope.

2.1 Perception of Comfort

Previous studies have identified that the productivity of the occupants of any building is largely dependent on how comfortable the indoor environment is. This makes comfort or discomfort of the occupants a major concern when designing an interior environment. It is logical to say that the interior environment should be designed in order to achieve maximum productivity of its occupants while moderating the energy requirements of the building. But, the question "what is comfort?" does not have one correct answer. Comfort can be defined in more than one way. While all the major definitions of comfort are precise, it is almost impossible to generalize the single- dimensional concept of comfort for every built environment. Using an onion with overlapping layers as a metaphor, the notion of comfort can be seen as evolving through time in which new meanings, shaped by culture, add additional layers to the previous ones (Rybczynski, 1986).

2.2 Development of controlled environments for physical comfort

Studies on human comfort and improvement of interior environment have led to the development of interior environment control systems. These control systems have several advantages they tend to improve the comfort levels of the occupants of the buildings and at the same time they are effective in reducing the energy consumed in maintaining such environments. In the eighteenth and the nineteenth century prior to the development of mechanical systems, the interior environments were maintained passively by elements of the building envelope. Industrial development in the past centuries has brought along electricity. This is the major reason behind the development of other systems such as electric lighting, air conditioning and mechanical ventilation systems. Heating/cooling devices freed architects from the constraints of climate and the restriction of passive methods (Baird, 2001).

Olgyay (1963) worked towards understanding the relationship between “climatology” and “biology”. He concluded that the relation between these factors was intermediated by the mutual processes of “architecture” and the new element “technology”. Figure 1 illustrates Olgyay’s model of environmental processes.

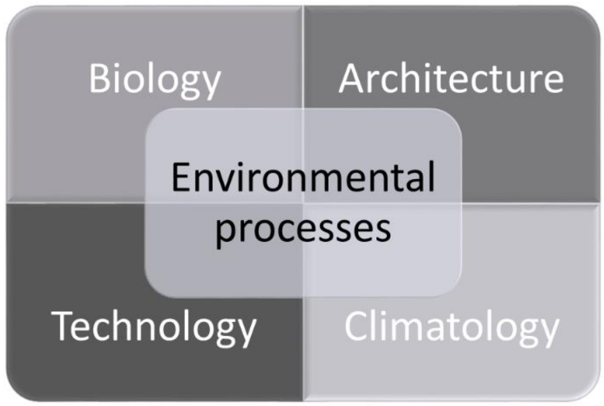


Figure 2.1 Model of environmental processes (Olgay, 1963).

Today, almost all the buildings constructed in the United States make use of active interior environment control systems. The occupants of these buildings heavily rely on numerous electrical and mechanical systems such as lighting, air-conditioning, heating and ventilation to retain an optimal indoor environment. As a result of advancements in control and automation of interior environment control, occupants of most of the buildings in United States are capable of fine tuning their immediate environment. Window blinds are one such system that can be found on most of the commercial, institutional and residential buildings.

2.3 Adaptive Controls

The general perception of indoor comfort is always related to physical factors of the built environment. Most people consider physical factors such as lighting, heating, ventilation, air quality etc. to be the only aspects that govern the perception of comfort. Using thermal comfort as an example, the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) defines comfort as the condition of mind that expresses satisfaction with the thermal environment (ASHRAE, 1992). This definition of comfort, however, does not convey the complexity of comfort and all of its contextual and cultural influences (Brager & De Dear, 2003).

Building science researchers are increasingly researching on adaptive building controls, especially in the areas of thermal comfort and illumination control. This trend has led to the development of several automatic indoor climate control systems. The algorithms of some of these contemporary adaptive controls are not only based on the indoor climate but also the expectation and usage patterns. In the automation of interior window shading devices, a control system that relies on a prediction of environmental conditions and a building's thermal response can provide savings to space-conditioning loads beyond what can be achieved using a reactive approach (Huchuk et al., 2015).

Review of window blind usage literature suggests that a window blind acts like a system that the building occupants interact with in order to attain a more comfortable indoor environment. Therefore, in this research, the researcher will study the window blind usage pattern of occupants of residential buildings. This will be followed by a subjective survey that will ask participants about the stimulus that leads to the act of change of blind position. Finally, a building energy simulation will be used to compare the actual energy consumption of a residential apartment building with the reduced energy consumption as a result of optimal window blind usage. There is very limited research on window blind usage pattern of residential buildings in order to develop a relation between the window blind usage patterns and the perception of comfort.

The review of literature has helped in the identification of comfort as a complex sensation. There are several identified and unidentified factors that stimulate the perception of comfort. Inkarojrit's 2005 study of window blinds has acknowledged that occupant comfort within a built environment is effected by several factors other than the physical elements of the building. Growing evidence shows that there is an association between perceived productivity and factors such as comfort, health, and satisfaction of staff in office organizations (Leaman & Bordass, 1999). Comfort is a complex perception that reflects the interaction between objective stimuli and cognitive/emotional processes in which the general perception of comfort is a result of the overall comfort appraisal through human senses (Elzeyadi, 2002). Figure 2.2 shows an example model of this complex interactions.

Figure 2.1 The relationship of environmental parameters of indoor comfort (Elzeyadi, 2002)

Unfortunately, previous studies in the area of the window blind usage and comfort like Rea's, 1984 study Window blind occlusion: a pilot study, Reinhart's, 2001 Daylight availability and manual lighting control in office buildings: Simulation studies and analysis of measurement and Rubin, et al's 1978 study Window blinds as a potential energy saver - A case study are mostly one-dimensional. Even though the researchers have identified that the window blind usage depends on several factors, the studies are usually focused on a one sub-system (i.e., visual comfort or thermal comfort). These studies have successfully established that in indoor environment is effected by various attributes of having a window. The presence of a window effects the indoor air temperature, radiant temperature, quality of view, may add outdoor noise and a sense of spatial comfort by letting the occupant being connected by the outdoor environment. It is the researcher's opinion that all the above mentioned factors that were established by these one-dimensional studies may have either constructive or destructive effect on the comfort of the occupants. These previous studies have also established that change in some of the parameters related to window or window blinds may result in a weighty reduction on the energy consumed for maintaining comfortable temperatures inside of the building, but fail to study the effect of these changes on comfort of the occupant. There are limited studies that have attempted a cross-examination of data from two or more sub-systems of comfort within the built environment.

2.4 Venetian Blinds

Most windows in commercial buildings have some type of internal shading to give varying degrees of sun control and to provide privacy and aesthetic effects (ASHRAE, 1997; Littlefair, 1999; Ozisik & Schutrum, 1960). Window attachments represent a wide range of products that are commonly attached to windows in a house as an “add-on” device. The most common and widely used types of attachments are window coverings and fashions that are typically used to control glare, to provide privacy, and for aesthetic purposes (Curcija et al., 2013). In a study conducted by Bader, 2011 it was established that in the United States, overhangs are the most common type of external shading devises and Venetian blinds have evolved to be the most common form of internal shading devices for windows. The availability of window blinds in a wide range of materials, colors and patterns, along with its ease of installation and usage, make it the most preferred interior shading systems. Also, due to their low cost compared to other types of interior shading devices, manually controlled Venetian blinds are perhaps the most common type of interior shading devices in contemporary office buildings (Inkarojrit, 2005). The Venetian blinds have two degrees of motion. They can be closed, opened or adjusted such that a part of the window is open and the rest is covered. Also, the slats in the Venetian blinds can be adjusted (i.e., they can be rotated in their axis), which allows the occupants to further customize the occlusion from the system. When the occupants of a building want an outside view, they can bring the window blind to a fully open position. Just like a fabric roller in this position there is absolutely no occlusion caused by the system. But the advantage of using a Venetian blind is that when the window blind is in a completely or partially closed position, the occlusion can be controlled by adjusting the angle of the slats. The use of fabric rollers, or other internal shading systems does not provide the occupants with so much flexibility over the control of the shading system.

If properly used, the Venetian blinds are capable of blocking the entry of sunlight and reflecting the direct solar radiation towards the ceiling, hence providing a glare free illumination and an outside view all at the same time. Utilization of daylight in buildings may result in significant savings in electricity consumption for lighting while creating a higher quality indoor environment. The benefits of using natural light within office buildings results in higher productivity and reduced absenteeism of office workers and may result in considerable energy savings (Athienitis & Tzempelikos, 2002).

2.5 Physical Properties

In order to understand the energy savings from the use of the window blind system, it is crucial to understand its performance in the regulation of thermal radiation and visible light.

2.6 Optical Properties

A dynamic building envelope increases the quality of built environment in commercial, residential and institutional buildings. Innovative daylighting systems aim to increase daylight levels and improve the daylight uniformity within a space, while controlling sunlight and reducing glare and discomfort for the occupants (Lorenz, 2000). Energy usage for interior illumination of a building can be significantly reduced if both the lighting system and the conventional components of building envelope are used simultaneously (Athienitis & Tzempelikos, 2002).

There are several advantages of using natural light for illumination, but it is also very important to control the glare and contrast caused by direct sunlight. Achieving visual comfort refers primarily to the elimination of visual discomfort (Boyce, 2014). The phenomenon of glare is one of the primary causes of visual discomfort. After several decades of continuous research on this topic, researchers have identified four factors that cause the perception of discomfort or glare: Luminance of the glare source, size of the glare source, position of the source in the field of view and luminance of the background (DiLaura, Houser, Mistrick, & Steffy, 2010).

Venetian window blinds can be multi-purpose. They can effectively block the direct solar radiation thus reducing the solar gains in the cooling season. They can be used to maximize daylighting and heat gain during the heating season. Positive angle of slats (slats point upwards) can allow the deflection of maximum amount of sunlight towards the ceiling, which diffuses it and reduces the glare. Also, on an overcast day, they are capable of letting in most of the daylight available through windows.

In order to keep the window blind system performing at its maximum efficiency, the position of the window blinds and the angle of the slats have to be constantly adjusted throughout the day. If the position of blinds and angle of slats are not adjusted to adapt to the external lighting conditions, the shading system can cause constant disruption of visual comfort. Optimum performance from the system requires constant manual control.

2.7 Thermal Properties

In order to calculate the building energy performance, architects, engineers and designers make use of the tables provided in the *ASHRAE Handbook of Fundamentals* (ASHRAE, 1997). The Solar Heat Gain Coefficient (SHGC) describes the solar heat blocking capacity of any material (its value is between 0 and 1). This fractional number represents the percentage of solar radiation that entered the window. It should be noted that the SHGC for Venetian blinds are listed in the ASHRAE tables; the values were limited to only one blind type and a few blind slat angles as shown in table 2.1.

Table 2.1 SHGC for window blinds

	Blind Position/Color	Solar Reflect	Solar Absorb.	Solar Trans. Summer (Default)	Solar Trans. Winter	Optical Trans. Diffuse (Cloudy)	Optical Trans. (Sunny)
Stephenson (1964) +	0	-	-	-	-	0.3	-
	22.5	-	-	-	-	0.14	-
	45	-	-	-	-	0.08	-
ASHRAE (1997)++	Light	0.55	0.40	(0.05)	-	-	-
	Medium	0.35	0.60	(0.05)	-	-	-
Littlefair (1999)*	Shut	-	-	0.57	0.58	0.03	-
	Open	-	-	-	-	0.32	-
Athienitis (2002)**	-60	-	-	-	-	(0.14)	0.1
	-30	-	-	-	-	(0.38)	0,35
	-15	-	-	-	-	(0.33)	0.48
	-0	-	-	-	-	(0.25)	0.42
	-30	-	-	-	-	(0.11)	0.15
	60	-	-	-	-	(0.03)	0.03

+ A typical lighted-color Venetian blind
++ Ratio of slat width to slat spacing 1.2, slay angle 45, normal incidence
* Venetian blind
** 35mm wide mid-plane highly reflective Venetian blind between double glazed low-E coating.

For a more complex building energy performance calculation, previous research (Lee & Selkowitz, 1995) used the thermal performance derived from a mathematical model created for a between-pane louver system with diffused blind surface reflectance. Alternatively, one may consider using the interpolation of blind properties based on small sets of characteristic SHGCs that was proposed by Klems and Warner (1997).

2.8 Control Studies on Window Blinds

Researchers in the past have collected and studied data on the window blind usage patterns. The method of collection of data has been simple observation, photography and video recordings. The studies have successfully identified patterns of blind usage between window orientation, position of sun in the sky and condition of sky. The researchers have come up with simple predictors that have been used to accurately develop rules for window blind automation.

Inkarojrit (2005) observed that the blind positions are the result of actions of the office occupants. The occupants come to a conclusion about the optimum window blind position after analyzing all the positive and negative stimulus of natural illumination. Once the window blind is brought to this position, no more changes are done to its position or angles.

Rea (1984) studied the occupant blind behavior on three facades of a 16-story office building in Ottawa, Canada. He studied the patterns and interaction of external factors such as orientation of façade, angle of solar radiation, sky conditions on the window blind usage pattern. Just like Rubin, Collins and Tibbott (1978), Rea took photographs that were analyzed for collection of data on window blind usage patterns of the three building façade. These photographs were taken at three times during a day, first at 9:30 then at 12:00 and finally at 14:00. These photos were taken on one cloudy day and a clear day in April and May, 1982. A total of 3,330 windows were observed for their blind position. The angle of slats was not considered in this study. The proportion of the window opening covered by blinds was given a value from 0-10 for the purpose of the study.

Inoue, Kawase, Ibamoto, Takakusa, and Matsuo (1988) studied window blind usage, analyzed photographs of four buildings in Tokyo, Japan. They also collected the direct and diffused values of solar radiation for the purpose of their study. Inoue et al. identified that the change in the rate of blind operation was dependent on the orientation of the buildings and weather conditions. They also reported that the pattern of control of the window blind was particularly crucial in the determining the rate of blind modifications. On the eastern façade, the window blinds were closed by the occupants on their entry into the office, but gradually through the day, these blinds were opened fully or partially to allow the entry of natural light, as there was no incident direct sunlight. On the west façade the window blinds were completely opened during the morning times when there was no direct solar radiation, but during the afternoon as the amount and intensity of radiation increased these blinds were closed gradually. They also reported that in both the above mentioned conditions the position of the blinds were not changed throughout an overcast day, when the values of solar radiation were low.

Foster and Oreszczyn (2001) recorded a video capturing the window blind movement of three offices in London, England. In this study, the average sunshine index and the average occlusion index were plotted for regression analysis. The occlusion index included the angle of the slats of the window blinds. The positions of each window blind was given a value that ranged from zero to five, zero being fully open and five being fully closed. The angle of slats were also give a value, which ranged from one to three, one being horizontal, two represented everything between horizontal and three being vertical. To obtain the proportion of occlusion, both the values were divided by their maximum.

The occlusion index was obtained by multiplying blind position values with the respective slat angle values. The sunshine index was obtained by multiplication of the factor for weather. These factors were one for overcast, two for slightly cloudy and three for sunny. Also, a time code was added to the study, which was one for early morning or late afternoon, two for midafternoon and three for midday.

Foster and Oreszczyn (2001) reported that there was a very small influence of solar availability on the window blind usage pattern. Hence, there is a very weak relation between the occlusion index and degree of sunshine. However, they found that the orientation of the façade had huge influence on the blind usage pattern. Facades that had south orientation had the highest occlusion value. The study also reported that the western façade had lower occlusion value than the northern façade. The authors acknowledged that the proximity of the northern façade of the building under consideration to another building may have caused privacy issues, which resulted in higher occlusion values of this façade.

A prominent function of any shading device is to cut off the direct solar heat entering the building in warm or hot weather. Raja, Nicol, McCartney, and Humphreys (2001) found that the usage of shading devices was proportional to indoor temperature. They reported that there was an increase in the blind use pattern whenever there was an increase in indoor temperature, outdoor air temperature, and thermal comfort sensation vote. They acknowledged that the increase of window blind usage was prominent but the rate of change was small. Raja et al. speculated that this change in the rate of blind usage might have been because of glare caused by direct solar radiation.

To summarize, all the previously conducted studies point out that the primary usage of window blind by occupants of office buildings was to regulate the penetration of direct sunlight into workspace. The studies show that reduction of glare was the major driving factor behind the window blind usage behavior. Heat gain was a relatively less evident factor in modification of window blind control pattern. Similarly, orientation of façade played an important role in determining the occlusion of the shading system. It was noted that, in general the occlusion values on the northern façades were lower than the occlusion values on the southern façades.

2.9 Subjective Surveys

After conducting the literature review the researcher has identified that not many surveys and interviews study the subjective reasons for window blind control have been conducted. A subjective survey is important because it allows the researcher to understand the stimulus that causes the occupants to change the position of blinds.

For their study of automated blinds, Inoue et al. (1988) conducted 336 questionnaire asking “how do you control your nearest blind?” They reported that 60-70% of the population did not alter the position of the blind as long as possible if it was open. Only 20- 30 of the sample was found to adjust the blind position to adjust to the changes in external factors. Furthermore, they reported that the awareness among the population of the use of window blinds in modification natural illumination was 90 %, but the awareness of its effect on the thermal environment accounted for 50-80%. Eighty percent of the sample preferred a location near windows as it offered better illumination. Between70% and 80% were inclined towards being closer to windows because of views, and 50% - 60% because of the visual range. Inoue et al. concluded that the stimulus for changing the occlusion of window blinds are the negative factors. These are the factors that were identified near most of the window seats. The major negative factors reported by them were heat and glare caused by direct solar radiation.

2.10 Stimulus for Adjusting Window Blinds

There are many other physical, physiological, psychological, and social factors that influence window blind control behavior. Inkarojrit (2005) identified several independent variables that directly influenced the frequency of the window blind adjustment. These variables were identified as visual comfort, luminance ratios, thermal comfort, interior luminance, vertical solar radiation at the window and subjective factors. He identified, direct solar penetration, orientation of façade, sky condition, age and gender of occupants as the major confounding factors that affects the window blind usage pattern. For occupant productivity luminance ratios are used in most lighting standards, the "1:3:10" is one of the commonly used luminance ratios. The principle is based on the idea that the luminance in the visual field of someone who's doing a static task, must remain in reasonable ratios in order to prevent glaring situations caused by a heavy contrast, hence impairing visual performances. The recommended luminance ratios are:

3:1 or 1:3 between paper and computer/laptop screen,

3:1 or 1:3 between the visual task (paper or screen) and the adjacent surfaces,

10:1 or 1:10 between the visual task and the non-adjacent surfaces.

The adjacent and non-adjacent surfaces can be delimited by two cones of 60 and 120 degrees respectively. It has been found that a strong correlation exists between the preferred luminance ratios and the visual interest of a scene [Loe, 1994]

2.11 Gaps in the Literature

The review of literature has helped in identification of several gaps in the research conducted on window blind control:

1. Previous research identifies the significant effect of physical factors, such as visual and thermal comfort on the control patterns of window blinds (Lindsay & Littlefair, 1993; Newsham, 1994; Rea, 1984; Reinhart, 2001; Rubin et al., 1978). The review of literature shows that, in addition to these physical factors, social factors, physiological factors and psychological factors are also responsible for

altering the general perception of comfort, eventually effecting the window blind control. The effect of one or a combination of these factors on window blind control is not fully understood. Therefore, in order to entirely understand the effect of these factors on window blind control, a qualitative study of the window blind usage patterns has to be conducted alongside subjective surveys that studies cause and effect of these factors.

2. The previous studies on window blind usage patterns do not have conclusions. The studies are focused on a single façade of buildings. There is no research that examines all the façade orientations in a single study. This makes it difficult to quantify the heat gained or heat lost by the building through fenestrations.
3. Even though several researchers have acknowledged the effects that the angle of slats have on the occlusion of window blinds, the studies conducted in the past have either ignored the angle of slats completely, or identified them as closed or open for the sake of convenience. Different window blind slat angles can drastically increase or decrease workplace illuminance for workspaces near the window opening (Christoffersen, 1995).
4. Several previous studies have used visual examination to record the window blind usage pattern. In recent studies, researchers have made use of high resolution photographs, and videos to collect data. In both these cases the angle of observation makes it difficult to accurately determine the position of slats in the window blind. Furthermore, the angles of the blind slats are usually ignored because of the different relative camera angles on different floors of tall buildings

(Rea, 1984). In order to accurately determine the angle of slats and the position of window blind, studies have yet to come up with a more reliable method of measurement.

5. All the previous research on window blind control has commercial, educational and institutional buildings as a sample; no study on the window blind usage pattern of residential buildings has been conducted.
6. Only few window blind control models were based on actual field studies. The studies have made use of models that have been constructed theoretically. While these models moderate the variables, their application to real life settings are limited.
7. Studies on the window blind usage pattern, perception of comfort and productivity in workspace are conducted to support the development of automated shading systems which will reduce the energy consumption of buildings without decreasing the quality of indoor environment, comfort, and productivity of occupants. There is a need for research on automated external blinds or shading systems, as these have a tremendous potential for reducing heat gain in warmer climates. These external systems can work either independently or in combination with the automated interior blinds. Further research is needed about the potential energy and peak demand reductions from external automated blinds (Wymelenberg, 2012).
8. The quality of view is a confounding variable in the study of the window blind usage patterns. There are no known techniques for quantifying the outside view

quality from a window. Development of a view quality rating system would support researchers since there is a correlation between the window blind usage and the quality of view from the window.

2.12 Summary

This chapter outlines research studies in the field of venetian blinds and provides context and background details associated with this paper. It also uses the evidence from scholarly reviews and field data to support the methodology of this paper. Several key topics are identified as being relevant to this research. These topics include: residential building energy consumption trend, perception of comfort, window blind usage patterns and adaptive settings for window blinds.

CHAPTER 3. METHODOLOGY

3.1 Introduction

Traditionally, human comfort studies within a built environment focus on only one domain of the physical environment: the lighting domain or the thermal domain. The literature review establishes that window blind control behaviors are influenced by many factors, including physical, physiological, psychological and social variables. A variety of methods have been used by researchers to collect data about the physical environment, and the window blind usage pattern in the past. Photography, video recording and sensors attached to the window blinds are all techniques that have been used successfully by, Foster and Oreszczyn (2001) and Rea (1988) to record the changes made to window blinds. Inoue et al. (1984) and Inkarojrit (2005) used interviews of occupants of buildings to understand their window blind usage patterns and preferences. In order to assess the performance of Venetian window blinds in a residential setting, the researcher will integrate the physical environment data (window blind usage) with subjective opinion on window blind usage and preferences. This will project a better picture of Venetian window blind usage and their effect on occupant comfort.

This chapter can be broken into three sections, the first section describes the process used to conduct investigation, the study variables, equipment used and the process of collection of window blind usage data. The second section describes how occupants of the building would be interviewed. The last section covers all the data analysis techniques used in the study.

3.2 Research Questions

What is the Venetian window blind usage pattern of occupants of a multi-story residential apartment building in Lafayette, IN during the heating season?

What is the effect of façade orientation, cloud cover and exterior temperature on window blind usage?

What are the possible energy savings from keeping the window blinds completely open between 8AM to 5PM and completely closed every time else during heating season(12/21-3/20), completely closed all the time during summer season (6/21 – 9/20) and 50 percent open between 8AM and 5PM and completely closed every other time during fall and spring season?

3.3 Research Framework

The principle research in this project is aimed at collecting and analyzing the window blind usage patterns of occupants living in a residential apartment building in Lafayette, IN. The rate of change of window blind position primarily depends on occupant's comfort preferences, interior & exterior temperature but lighting or glare is reported to be the major reason behind changes made to the window blind position. There are several models that predict visual discomfort, like American Visual Comfort Probability (The Illuminating Engineering Society of North America, 2000), and the Unified Glare Rating (Eindhorn, 1969, 1979, 1998; CIE, 1995). These models have presented glare as the primary reason for visual discomfort. Hence it is important to design a research method which can integrate personal preferences and exterior conditions with actual window blind occlusion data to answer the research questions.

To begin the study, the researcher will take high resolution photographs of all the four façades of the residential building to study the rate of change in the window blind position. After calculating the usage pattern the occupants of the building who are willing to participate in this study will be interviewed for subjective responses.

3.4 Pilot Study

Prior to the main experiment a pilot study was conducted in which photographs of all four façades of the multi-story building were captured at an interval of 2 hours starting 7AM ending 3PM on 12/05/2015. These photographs helped in validation of research methods as the researcher was able to identify the position of window blinds and the angle of slats. These photographs also helped in testing of the preliminary research hypothesis- “What is the effect of cloud cover on window blind occlusion?” The pilot study also helped the researcher understand the frequency of changes made to window blinds and occlusion values between façade orientations.

3.5 Study Variables

Table 3.1 provides a list of all the variables that the study will measure. The dependent variables in the study are related to window blind movements and the independent variables are selected based on their effect on thermal or visual comfort. In this study, the independent variables are classified into three types, stimulus factors, personal preferences and confounding factors. Stimulus factors are the variables that cause a direct sensation of discomfort to the occupant that results in the event of closure of window blinds. Confounding variables on the other hand are factors that affect both dependent and independent variables but may or may not be the reason behind the changes made to the position of window blinds.

3.6 Dependent Variables

Changes made to the position of window blinds is the primary variable analyzed by this study. This change is identified as a dependent variable since it is caused by the occupant’s response to the independent variables. This study defines three dependent variables 1. A change made to the position of the Venetian window blind itself. 2. A change made to the position of angle of slats of window blinds. 3. The frequency with which changes are made to the system of window blinds.

The researcher will collect data in the form of photographs of all the four facades of the building under consideration and the changes to the position of window blind will be analyzed in steps of 0 to 10 (0 = completely open, 10 = completely closed). High resolution images enable the researcher to detect the angle of slats of the window blinds. These images provide the researcher, opportunity to categorize the angle of slats in blinds into three categories 1) facing up 2) horizontal and 3) Facing down. For the purpose of this study the angle of slats have been distinctly classified as completely open (horizontal) and closed (facing down or facing up). The frequency with which changes are made to the system of window blinds is the third dependent variable identified by the study. For the purpose of this study this variable has been identified into 4 distinct sets, 1) More than once a day, 2) once every day, 3) more than once but less than seven times every week 4) less than once every week.

3.7 Independent Variables

Independent variables in this study are the factors that cause the dependent variables. These variables have been identified by previous researchers as the factors that cause the occupants to make changes to the position of window blinds and the angle of slats. For the purpose of this study the independent factors have been categorized into four types, 1) solar radiation 2) external thermal conditions 3) subjective opinion and 4) confounding factors.

Previous research conducted by Inkarojrit, Inoue et al and Rea in the area of window blind usage have established several visual and thermal stimulus that effect the rate of usage of window blinds. Some prominent visual stimuli are average window luminance, background luminance, daylight glare index, maximum window luminance, luminance ratio's, vertical solar radiation at window, etc. Similarly some thermal stimuli that effect window blind usage which have been established by previous studies are air temperature, mean radiant temperature, relative humidity, predicted mean vote, predicted percentage dissatisfied etc. This study will be focusing on stimuli that the researcher can measure with available equipment. Table 3.1 provides a list of all the variables, measured by the study.

Table 3.1. List of variables in the study

Type of variables	List
Dependent variables	1. Window blind position change 2. Slat angle change 3. Frequency of window blind/slat adjustment
Independent variables	1. Solar Radiation (stimulus factors) 1.1. Cloud cover 2. Exterior Thermal Condition (stimulus factors) 2.1. Air temperature 3. Subjective opinion 3.1. Brightness Preference 3.2. Thermal Preference 3.3. Self-reported sensitivity to brightness 3.4. Self-reported sensitivity to temperature 4. Confounding factors 4.1. Privacy 4.2. Direct solar penetration 4.3. Façade Orientation 4.4. Sky condition 4.5. Age 4.6. Gender

Subjective opinion, as mentioned in Table 3.1 is an independent variable that will not remain constant for all occupants participating in this study. This study aims to analyze how occupant comfort is effected by window blind usage. Hence it is important to account for personal preferences for occupant's comfort in the study. To achieve this the researcher will be conducting interviews with occupants of the building under consideration to record subjective opinion of occupant comfort.

In a residential setting the occupants of apartment can control interior air temperatures and lighting levels which is used for modifying the interior environment. In a preliminary survey conducted, it was observed that the interior temperatures, relative humidity, lighting levels (brightness) and window blind occlusion levels in various apartment units were different. That these dissimilarities in the interior environments are a result of occupant preferences, lack of awareness about energy efficient task lighting and comfortable temperature/humidity levels as defined by ASHRAE. To study the effect of personal preferences on the rate of change of window blind position the occupant's will be interviewed, their personal preferences and opinion on interior comfort will be recorded in the survey. These subjective responses collected during the interview will be later compared with actual window blind usage data and observations will be presented.

3.8 Data Recorded

This section explains in detail all the form of data that will be recorded by researcher in the course of this study.

3.9 Time Lapse Photography

During the pilot study period, window blind movements were monitored from outside the building through photography. Pictures were manually taken with a digital camera to study the percentage occlusion of window blinds. The angle of slat and the position of blind itself were identified as the two variables. High resolution of photographs assisted in identification of slat angles as "horizontal/open" or "non-horizontal/closed". The position of window blind could be identified into ten different steps. (See Images 3.1 and Image 3.2.)

For the final study the researcher will manually capture time lapse pictures at an interval of 2 hours between 8AM and 6PM for a duration of one week staring 3rd February and ending 9th February. This interval of 2 hours was chosen in order to record in detail the rate of change of window blind position. The two-hour interval between captured photographs, was chosen to decrease the chances of missing an event of changes made to the position of window blinds. At the end of data collection process there will be total of 42 images captured per façade of the building. These images will be used to calculate the percentage occlusion of windows as described above, and the researcher will comment on any trends that are visible in the usage patterns of window blinds.

Figure 3.1. Window on left has 60% occlusion from blinds with slats closed, whereas window on the right has its blinds 100% closed, with slats open.

Figure 3.2. Left side window has 100% occlusion whereas window on the right has 20% occlusion.

3.10 Survey

The survey will ask participants to rate their satisfaction with the environmental quality of their residence. Majority of the questions will be multiple-choice, with a few open-ended questions. The questions will be divided into three major sections. 1) Background Information: This section will measure characteristics of participant's apartment such as occupancy of apartment (number of people), orientation of windows, type of internal shading device used, etc. 2) Window Blind Usage: This section will measure the frequency of window blind usage and the reasons for operating window blinds. 3) Personal Preference: This section will enquire about personal preferences and sensitivity to temperature and brightness.

3.11 Procedure

Prior to conducting survey and field study, the research methods would be submitted to Purdue Institutional Review Board (IRB). The researcher will submit sample photographs, survey questions and occupancy log to the IRB. Once permission is granted to conduct the field study and survey the researcher will proceed with research.

After conducting the survey and field study, the researcher will interpret the similarities and trends in the window blind usage patterns of the occupants. The window occlusion data will be compared to cloud cover data and researcher will comment on prominent behavior patterns that are observed. The survey data will help the researcher identify other factors that may stimulate the occupants to make changes to the position of window blinds that have not been mentioned in the literature review.

3.12 The Energy Model

Once the researcher has established the actual window blind usage pattern of the residents of the building, an energy model of the apartment building will be created on e-Quest. The researcher will use the software to calculate the simulated energy consumption of the apartment with actual occlusion values that were collected earlier in the process. This energy consumption will be compared with the simulated energy consumption of the same building but with blinds completely open between 8AM to 5PM and completely closed every time else during heating season (12/21-3/20). During the summer season the building will be modeled to have all windows closed all the time (6/21 – 9/20). Also, 50 percent open between 8AM and 5PM and completely closed every other time during fall and spring season. The difference in energy consumption of both the models will quantify the possible energy that can be saved with suggested usage of window blinds.

3.13 Population and Sample

The population of this research are occupants of multi-story residential apartment buildings. The sample for this research are the occupants of The Bluffs Apartments in Lafayette, IN. The Bluffs is a three story residential building, with over 60 apartments.

3.14 Summary

This chapter outlines the method and procedure that will be used to conduct this study. It gave details of how the research was designed, the population and sample was selected, and the sampling approach. It also outlined the study of variables that will be used in the research.

CHAPTER 4. DATA ANALYSIS AND RESULTS

This chapter presents the data that was collected for the purpose of this study. The chapter also discusses the details of the analysis of the collected data.

4.1 Data Collection

Since the study involved human subjects, the collection of data was started only after the study was categorized as an exempt research by IRB. For this study, the data was collected primarily in five forms. The first form of data was high resolution images captured from a distance of 50 feet from each façade of the building. Six such images were captured every day per façade of the building, allowing the author to study changes made to the position of the window blinds. Figure 4.1 is one of the images captured for the purpose of this study.

Figure 4.1. South-West façade of the building under consideration

The second set of data collected for this study was outside temperatures, this was recorded using a hand held temperature monitor. The temperature was recorded by the author in a manner similar to the images, six times a day for a week. Overall for the purpose of the study, 42 temperature readings were collected which represent the outside temperatures when the images were captured.

The third and fourth form of data collected for this study was light intensity and direct sun light incident on the surface of the building façade. The intensity of light was measured by a mobile device app “Light Meter”. This app allowed the author to capture the intensity of natural light at the times when images were captured. The presence of direct sunlight was data that was generated during the data analysis. This data is binary and identifies whether or not a façade has direct sunlight incident, when the images were captured. Overall the light intensity and direct sunlight readings allowed the author to quantify cloud cover which is studied in this research.

The fifth form of data collect was in the form of an occupant survey. This survey was designed to extract information about occupancy, window blind usage, thermal and lighting preference and some biographical information from the occupants of the building under consideration. This survey questionnaire was color coded and numbered to identify the apartment unit which the represented, but after extracting required information all identifiable information about any of the survey participants was carefully removed by the author. Figure 4.2 is an image of the survey questionnaire used for the purpose of this study.

SURVEY

1. Please enter your age and gender in the space provided__________ ____________.
2. What is your preferred temperature setting within your apartment?
   a. 56 °F - 60 °F
   b. 61 °F – 65 °F
   c. 66 °F – 70 °F
   d. 71 °F – 75 °F
   e. None of the above
3. What is your indoor brightness preference?
   a. Low brightness (equivalent to one light bulb/tube light)
   b. Moderate brightness (equivalent to 2 or more light bulbs/light sources within the room)
   c. High brightness
4. Within your apartment you prefer
   a. Natural light (prefer open window blinds/window shades)
   b. Artificial light (prefer closed blinds)
5. How many hours in a day do you spend in your apartment on a normal day?
   a. Weekdays _____/24 hours
6. Why do you make changes to the position of window blinds in your apartment?
   a. ____
   b. ____
   c. ____

Figure 4.2. Survey Questionnaire

4.2 Window Blind Positions and Usage Patterns

A total of 42 pictures were captured for the purpose of this study. The author extracted the required information from these pictures which was made into an excel worksheet. Details of the conversion process has been discussed in chapter 3. The building under consideration has a total of 62 apartment units and each apartment has two windows and an additional 2 windows for storage and lobby. Hence a total of 126 windows that were monitored for the study. Figure 4.3 shows a segment of the excel file that was created for the study.

The North façade of the building had a total of 34 windows, 12 on the third floor, 12 on the second and 10 on the first floor. The South façade of the building had a total of 24 windows, 8 on the third floor, 8 on the second and 8 on the first floor. The East façade of the building had a total of 36 windows, 12 on the third floor, 12 on the second and 12 on the first floor. The West façade of the building had a total of 30 windows, 10 on the third floor, 10 on the second and 10 on the first floor. There were a total of 42 readings for each window mentioned in the study, which gave the researcher a total of 5292 data points. Each data point had 9 variables, which were:

1. Façade Orientation
2. Window Level
3. Day of The Week
4. Time of Image Capture
5. Occlusion Value (10-Closed to 1-Open)

6. Angle of Slats (Open / Closed)
7. Outside Temperature (Fahrenheit °F)
8. Outside Light Intensity (LUX)
9. Incident Direct Sunlight (Yes / No)

Observation	Façade	Level	Day	Time	Oclussion(1-10)	Pitch (0-1)	Termpertature °F	Light Reading(LUX)	Direct sunlinght
10	North	2	7	14	2	0	20	4823	0
10	North	2	7	16	2	0	19	2873	0
10	North	2	7	18	2	0	18	7	0
11	North	2	1	8	1	0	39	1168	0
11	North	2	1	10	1	0	38	11780	0
11	North	2	1	12	1	0	38	5148	0
11	North	2	1	14	1	0	37	1617	0
11	North	2	1	16	1	0	34	1383	0
11	North	2	1	18	1	0	32	68	0
11	North	2	2	8	1	0	24	285	0
11	North	2	2	10	1	0	23	6287	0
11	North	2	2	12	1	0	24	8632	0
11	North	2	2	14	10	0	29	6775	0
11	North	2	2	16	1	0	30	5491	0
11	North	2	2	18	1	0	28	191	0
11	North	2	3	8	0	0	22	1446	0

Figure 4.3. Survey Questionnaire

4.3 Occlusion and Slat Angle Values

Figure 4.4 is a bar graph that shows the frequency of window blind position. This graph shows all the data points with the respective window blind occlusion values. Of the 5292 window readings, 3796 readings had an occlusion value of 10 (completely closed). The second most common occlusion value was 0, a total of 561 readings had occlusion value as 0 (completely open).

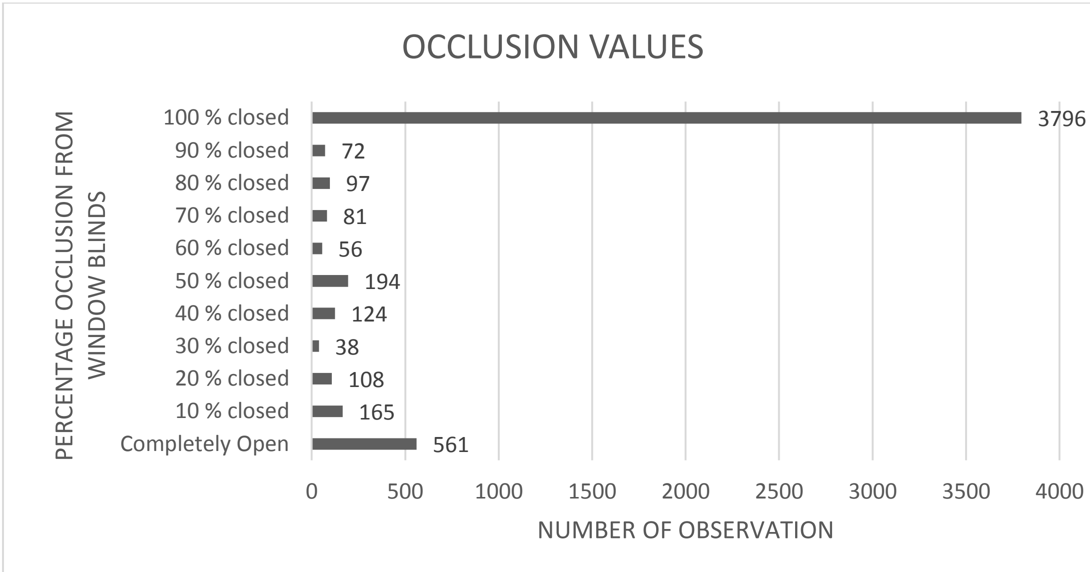


Figure 4.4. Occlusion Values

In the literature review section of this research the angle of slats was identified as one of the important factors that was not captured by studies conducted in the past. This study was successful in capturing the angle of slats of all the window blinds. Table 4.1 shows the frequency of the readings measured as open or closed.

Table 4.1. List of variables in the study

Angle of Slat	Frequency
Closed	4892
Open	400

This research only identifies angle of slats as open or closed, of the 5292 readings that were analyzed only 400 readings showed that the angle of slats was partially or completely open. Four thousand eight hundred and ninety-two windows were recorded with their slat angle closed. Overall less than 10 percent of the windows in the study showed open slat positions, and the total number of changes made to the angle of slats in the study was just 17 times in all of the 5292 readings. It was noted that the occupants of the building under consideration, did not make a significant number of changes to the position of slats of the window blinds, and the author has not used the angle of slats in any further analysis for the same reason.

4.4 Sub-Sets

As mentioned earlier, this study has 5292 data points, with each point having 9 variables. In order to understand the window blind usage pattern, it was important to classify the data into subsets. For the purpose of this study, the researcher has broken down the data into 12 subsets. Each of these 12 subsets represent a specific floor on a specific façade of the building. Table 4.2 shows the number of windows and readings on each of these sub-sets.

Table 4.2. Number of windows and Readings per subset

	Number of Windows	Number of Observations
North 3rd Floor	9	378
North 2nd Floor	9	378
North 1st Floor	8	336
South 3rd Floor	10	420
South 2nd Floor	10	420
South 1st Floor	10	420
East 3rd Floor	12	504
East 2nd Floor	12	504
East 1st Floor	12	504
West 3rd Floor	12	504
West 2nd Floor	12	504
West 1st Floor	10	420

After the window blind position was coded onto excel, the researcher was able to calculate the number of times the position of window blinds changed during the week. As mentioned in chapter 3, this study captured changes that were made to the position of window blinds in intervals of 10 percent. Hence even a slight change in blind position has been recorded and presented categorically in Table 4.2. Table 4.2. presents the total number of changes that were observed within various subsets, various floors and various facades. Figure 4.5 is a bar graph that categorizes sub-sets in increasing order of changes observed during the study. Figure 4.6 is a bar graph categorizing sub-sets in increasing order of percentage of windows that showed changes made to the position of window blinds.

Table 4.3. Number of changes in occlusion values observed per subset

	North	South	East	West	Total/Floor
2nd Floor	6	20	65	115	206
1st Floor	14	39	44	76	173
Main	1	22	7	22	52
Total/Facade	21	81	116	213	

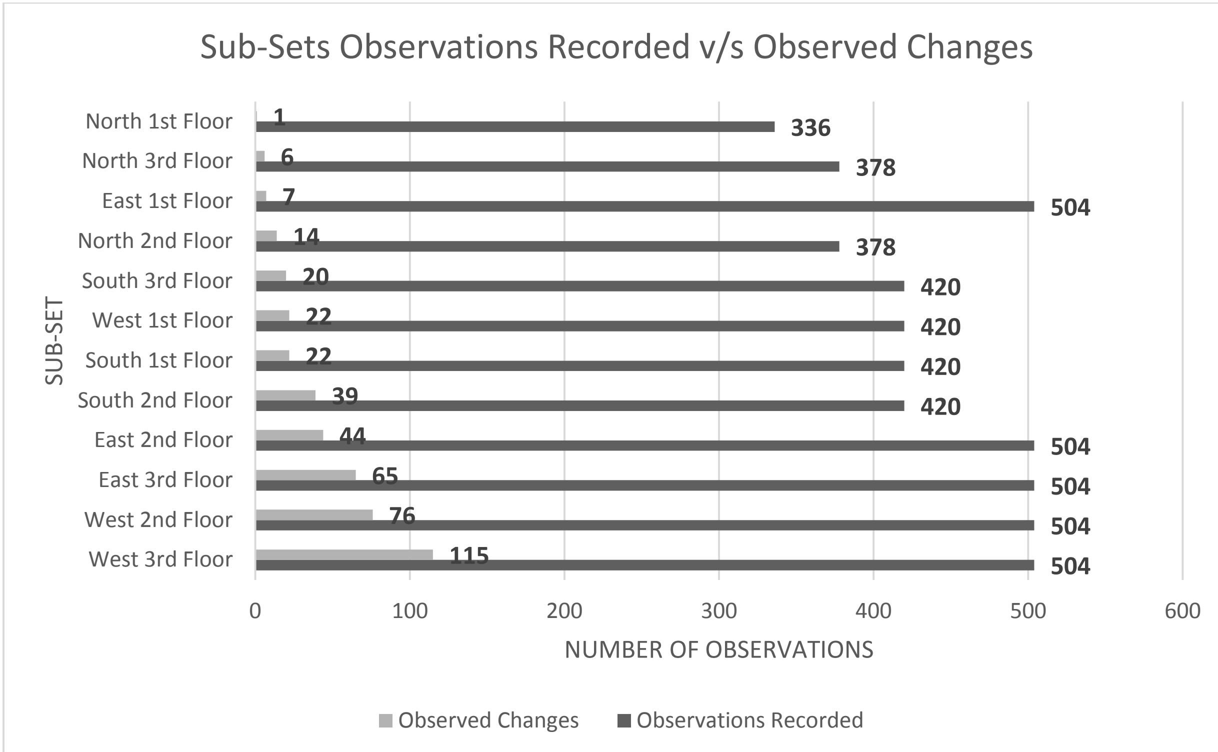


Figure 4.5. Sub-Sets Observations Recorded v/s Observed Changes

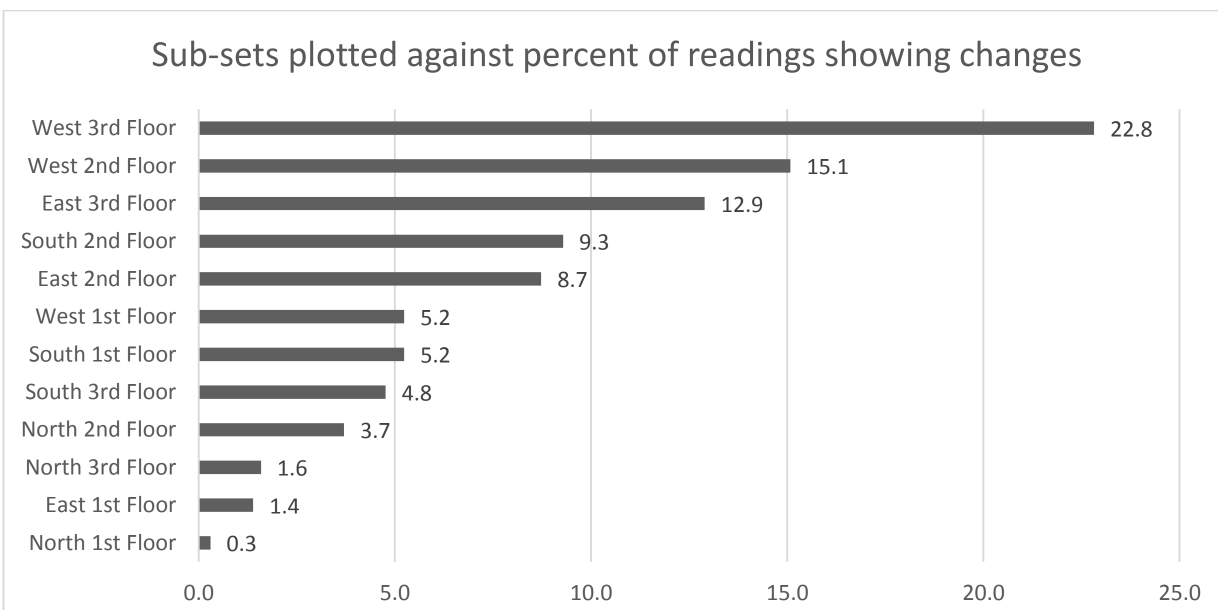


Figure 4.6. Sub-sets Plotted Against Percent of Readings Showing Changes

Table 4.3 and Figure 4.6 shows how windows on the western and eastern façade of the building under consideration show much higher window blind changes during the week. It also shows how window on the 3rd and 2nd floor show more changes than the first floor.

Even though the data shows significant differences in the window blind usage for all the different sub-sets, percent of windows that show changes on each sub-set cannot be used to represent the window blind usage of the whole building. For instance, windows on the 2nd floor of the western façade show 22.8% changes over the week. This means that 77.2% windows do not show any change in the window blind position throughout the week. Windows on other sub-sets show even less usage of window blinds. Occupants are typically very inactive at changing shading positions and rarely make a shade movement to mitigate thermal discomfort (O'Brien, Kapsis, & Athienitis, 2013).

4.5 Individual Window Blind Usage

The use of sub sets allowed the author to understand window blind usage pattern for changing parameters, but to study window blind usage of individual windows, the author has segregated the windows into categories based on changes made per week. To further understand window blind usage patterns of the building under consideration the author has broken down the total 126 windows under consideration into 5 groups. Unlike the subsets mentioned in the previous section, these groups have been formed based on the number of changes that were observed per window during the week, when the data was recorded.

The first group, GROUP A has the highest percentage of windows in it. GROUP A contains all the windows that did not show any change, 56 of the total 126 windows under consideration fall in this group. Of these 56 windows, 24 windows are on the northern façade, 16 on the southern façade, 8 on the eastern façade and 8 on the western façade. Also, 21 of these windows were on the second floor, 17 on the first floor and 18 on the main floor.

Table 4.4. Summary of Group A

GROUP A (No Changes)			
Façade	Frequency	Level	Frequency
West	8	3rd Floor	21
East	8	2nd Floor	17
South	16	First Floor	18
North	24		
Total	56	Total	56

GROUP B contains all the windows that showed 1 to 5 changes during the week, 41 of the total 126 windows under consideration fall in this group. Of these 41 windows, 8 windows are on the northern façade, 12 on the southern façade, 12 on the eastern façade and 9 on the western façade. Also, 18 of these windows were on the second floor, 17 on the first floor and 6 on the main floor.

Table 4.5. Summary of Group B

GROUP B (1-5 changes)			
Façade	Frequency	Level	Frequency
West	9	3rd Floor	18
East	12	2nd Floor	17
South	12	1st Floor	6
North	8		
Total	41	Total	41

GROUP C contains all the windows that show 6 to 10 changes during the week, 17 of the total 126 windows under consideration fall in this group. Of these 17 windows, this group has no windows from the northern façade, 4 from the southern façade, 5 from the eastern façade and 8 from the western façade. Also, 7 of these windows were on the second floor, 5 on the first floor and 5 on the main floor.

Table 4.6. Summary of Group C

GROUP C (6-10 Changes)			
Façade	Frequency	Level	Frequency
West	8	3rd Floor	7
East	5	2nd Floor	5
South	4	1st Floor	5
North	0		
Total	17	Total	17

GROUP D contains all the windows that show 11 to 15 changes during the week, just 6 of the total 126 windows under consideration fall in this group. Of these 6 windows, this group has no windows from the northern and southern façade, 2 from the eastern façade and 4 from the western façade. Also, 2 of these windows were on the second floor, 4 on the first floor and none on the main floor.

Table 4.7. Summary of Group D

GROUP D (11-15 Changes)			
Façade	Frequency	Level	Frequency
West	4	3rd Floor	2
East	2	2nd Floor	4
South	0	1st Floor	0
North	0		
Total	6	Total	6

GROUP E contains all the windows that show 16 to 20 changes during the week, just 6 of the total 126 windows under consideration fall in this group. Of these 6 windows, this group has no windows from the northern façade, one from the southern façade, 1 from the eastern façade and 4 from the western façade. Also, 2 of these windows were on the second floor, 4 on the first floor and none on the main floor.

Table 4.8. Summary of Group E

GROUP D (11-15 Changes)			
Façade	Frequency	Level	Frequency
West	4	3rd Floor	2
East	2	2nd Floor	4
South	0	1st Floor	0
North	0		
Total	6	Total	6

Overall looking at individual window blind usage of windows, it can be said that a significant percent of windows does not show any change what so ever. Over 76 percent of the windows show less than 6 changes during the week, that is less than one change per day.

4.6 Statistical Analysis

One of the primary objectives of this study was to identify if there is any correlation between any parameters that the study mentions earlier, and window blind usage pattern by the occupants of the building under consideration.

The author tried linear regression model and Chi Square test to find any relation between change in occlusion values, and changing environmental factors. The author also used the Spearman Test to find any correlation between changing conditions and window blind occlusion. These tests did not find any relation between the changes in occlusion and changes in various variables like outdoor temperatures, lighting intensity, direct sunlight, etc. because 76 percent of the windows in the data set did not show even one change in occlusion per day.

The author used the statistical consultation service, from Purdue University to understand why the tests were not able to prove any statistically significant correlation between the variables and window blind usage. The statistical consultants after examination of the data reported that since most of the observations did not show any change in occlusion level, a linear or multiple regression model will fail to identify a relation between occlusion and related variables. Also, consultants from the statistics department recommended Spearman Correlation Test as it did not require any linear relationship between the data sets to test correlation.

4.7 Spearman Correlation Test

To perform this test, the author selected only those windows that showed some change during the week. To accomplish this the occlusion values of all the windows on one façade was averaged to get one value. This process was repeated to get 42 averaged occlusion values for each of the 42 readings throughout the week. This process was also repeated for all of the 4 facades of the building.

Correlation between Occlusion level and Temperature

Spearman correlation (West Face)

```
                      WAverage_Occlusion WAverage_Temperature
WAverage_Occlusion                  1.00                -0.03
WAverage_Temperature               -0.03                 1.00

n= 175


P
                      WAverage_Occlusion WAverage_Temperature
WAverage_Occlusion                       0.6567
```

Spearman correlation (East Face)

```
                      EAverage_Occlusion EAverage_Temperature
EAverage_Occlusion                     1                    0
EAverage_Temperature                   0                    1

n= 140


P
                      EAverage_Occlusion EAverage_Temperature
EAverage_Occlusion                       0.9813
EAverage_Temperature 0.9813
```

Spearman correlation (South Face)

```
                      SAverage_Occlusion SAverage_Temperature
SAverage_Occlusion                  1.00                 0.05
SAverage_Temperature                0.05                 1.00

n= 119


P
                      SAverage_Occlusion SAverage_Temperature
SAverage_Occlusion                       0.6069
SAverage_Temperature 0.6069
```

Spearman correlation (North Face)

```
                     Average_Occlusion Average_Temperature
Average_Occlusion                 1.00                0.13
Average_Temperature               0.13                1.00

n= 56


P
                     Average_Occlusion Average_Temperature
Average_Occlusion                      0.3374
Average_Temperature 0.3374
```

Figure 4.7. Spearman Correlation Results for Average Occlusion and Temperature

Correlation between Occlusion level and Light reading

Spearman correlation (West Face)

```
                      WAverage_Occlusion WAverage_Light_Reading
WAverage_Occlusion                   1.0                    0.1
WAverage_Light_Reading               0.1                    1.0

n= 175


P
                      WAverage_Occlusion WAverage_Light_Reading
WAverage_Occlusion                       0.2047
WAverage_Light_Reading 0.2047
```

Spearman correlation (East Face)

```
                      EAverage_Occlusion EAverage_Light_Reading
EAverage_Occlusion                   1.0                   -0.1
EAverage_Light_Reading              -0.1                    1.0

n= 140


P
                      EAverage_Occlusion EAverage_Light_Reading
EAverage_Occlusion                       0.2554
EAverage_Light_Reading 0.2554
```

Spearman correlation (South Face)

```
                      SAverage_Occlusion SAverage_Light_Reading
SAverage_Occlusion                  1.00                   0.01
SAverage_Light_Reading              0.01                   1.00

n= 119


P
                      SAverage_Occlusion SAverage_Light_Reading
SAverage_Occlusion                       0.8791
SAverage_Light_Reading 0.8791
```

Spearman correlation (North Face)

```
                      Average_Occlusion Average_Light_Reading
Average_Occlusion                  1.00                  0.12
Average_Light_Reading              0.12                  1.00

n= 56


P
                      Average_Occlusion Average_Light_Reading
Average_Occlusion                       0.385
Average_Light_Reading 0.385
```

Figure 4.8. Spearman Correlation Results for Average Occlusion and Lighting Level

Once the average occlusion value was generated per façade, their correlation with temperature changes and changes in lighting levels were tested using the Spearman Correlation Test. The test results for occlusion and temperature are presented in Figure 4.7

The test results show a very small correlation between change in occlusion and temperature on the northern western and southern façade of the building. The eastern façade shows no correlation between occlusion and temperature. The *P* value of these tests represents that these correlations are not statistically significant.

The Spearman tests failed to find any correlation because the frequency of change of window blinds were very low. An explanation for this is, when with every different set of reading, the values of temperature and light intensity changed, the relative value for window blind occlusion did not show any change. Previous research in regions with an arid climate, with high luminance contrasts and great thermal amplitude between winter and summer have shown a low correlation between glare indices and the subjective perception of glare (Yamin, Pattini, & Rodriguez, 2014). Overall the above correlation tests, performed on each of the building facades, failed to recognize any statistically significant correlation between average occlusion values, and outdoor temperatures or lighting intensity.

4.8 The Survey Results

The survey questionnaire was handed out to all the occupant of the building under consideration. A total of 62 survey questionnaires were distributed by the author. A total of 19 residents responded to the survey for a 30.6% response rate. These 19 respondents represent 38 windows which is almost 30 percent of the windows under consideration.

The primary purpose of conducting the survey was to identify the subjective reasons for window blind position changes. One of the questions asked the occupants of the building to reveal their self-reported temperature preference. Table 4.9 shows the response from the occupants on temperature preference. This response shows that 74 percent of all the occupants prefer temperatures between 66 °F and 75°F.

Table 4.9. Self-Reported Temperature Preference

Temperature Preference	Frequency
56 °F - 60 °F	0
61 °F - 65 °F	0
66 °F - 70 °F	8
71 °F - 75 °F	6
None of the above	5

The survey results revealed that 15 of the 19 respondents prefer preferred Natural Light over Artificial Light and just 4 of the 19 preferred Artificial Lighting over Natural Lighting. The survey also asked the participants to report their brightness preference, Figure 4.9 presents the distribution of self-reported preferences.

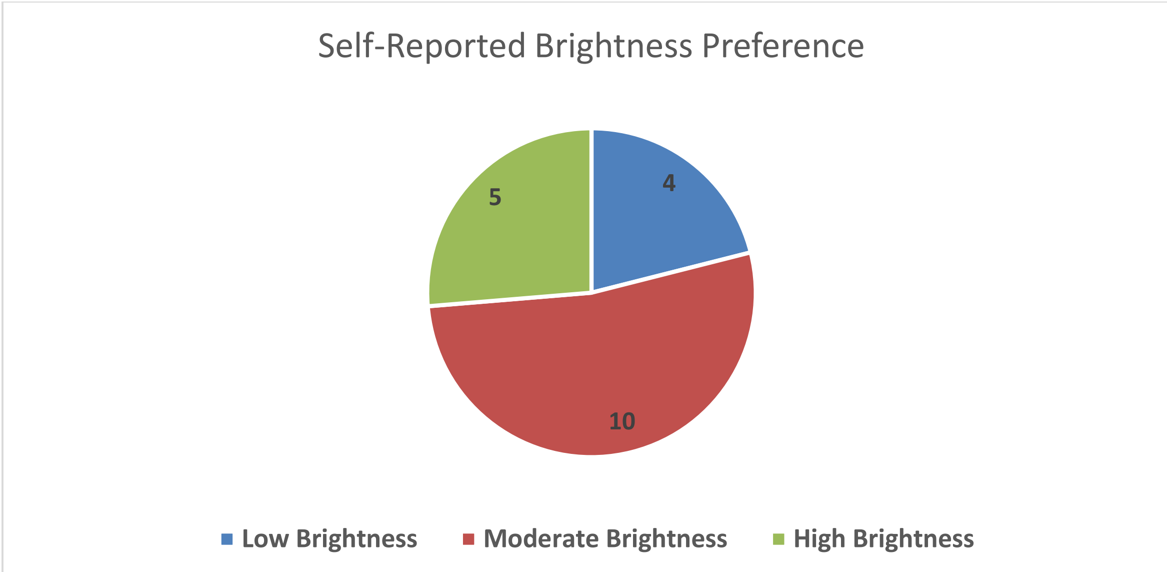


Figure 4.9. Self-Reported Brightness Preference

Seventy-five percent of first floor survey respondents reported privacy as a concern and a reason behind them keeping their window blinds closed all the time. Some other prominent reasons mentioned by survey respondents, that changed their window blind usage were quality of view, distracting light at night, plants and pet animals. Details on this is presented in the discussion section of chapter 5.

4.9 The Energy Model

The author modeled the building under consideration in E-Quest to simulate the energy consumption under the current window blind usage pattern. This predicted energy consumption was compared to the predicted energy consumption under optimum window blind usage.

Under present condition, the occupants of the building keep the window blinds 20 percent closed between 8AM to 5PM and 90 percent closed every other time. For the optimum condition the author divided the year into 3 seasons and the windows were simulated to be completely open between 8AM to 5PM and completely closed every time else during heating season(12/21-3/20). During the summer season the building was modeled to have all windows closed all the time (6/21 – 9/20). Also, 50 percent open between 8AM and 5PM and completely closed every other time during fall and spring season. Figure 4.10. Figure 4.11 presents a screen shot of the model created for the building under consideration. Figure 4.12 and 4.13 are the energy simulation results generated by E-Quest for the two conditions described above.

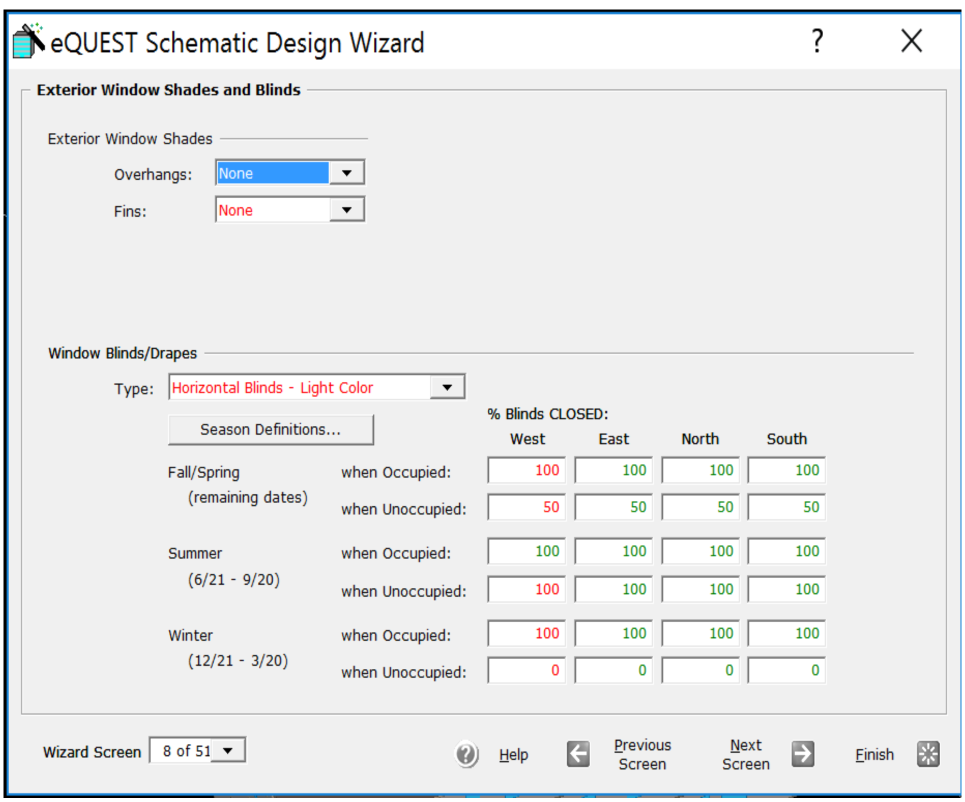


Figure 4.10. Optimum Window Blind Usage

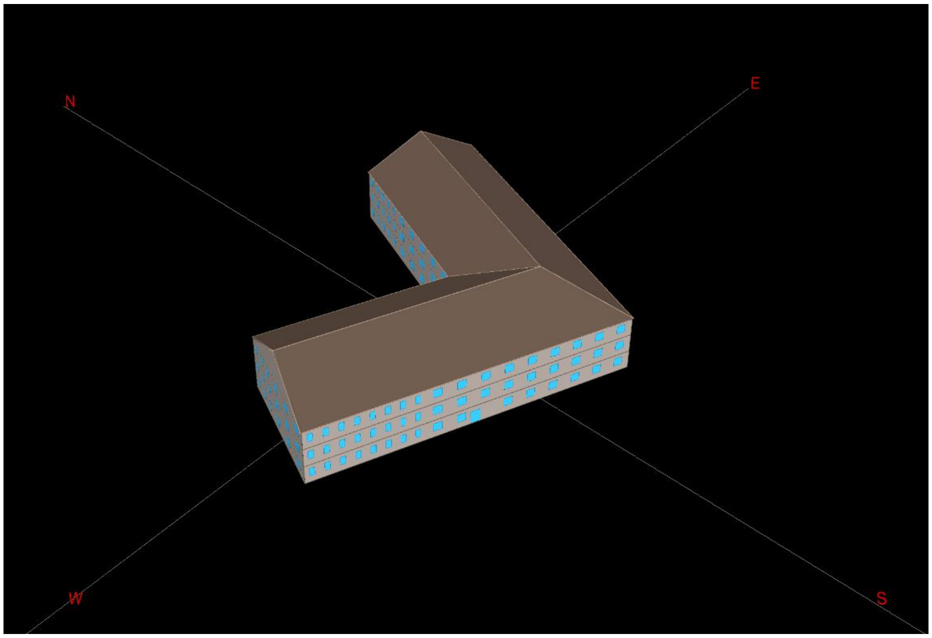
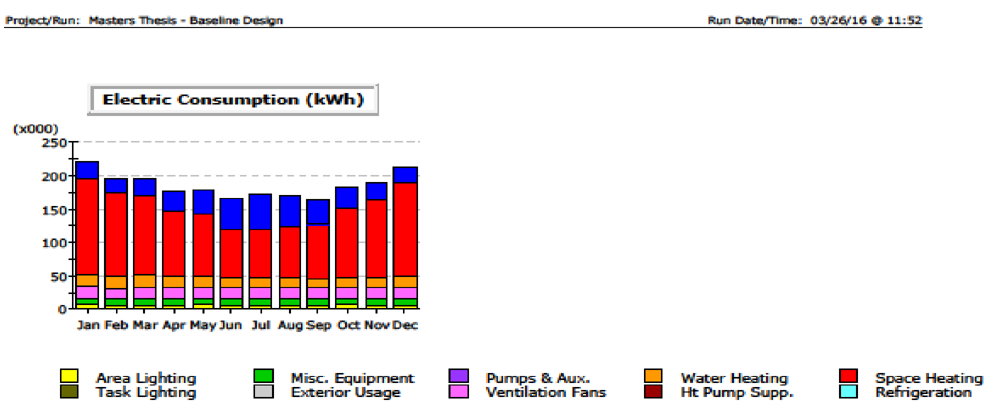


Figure 4.11. 3-D view of the E-Quest Model

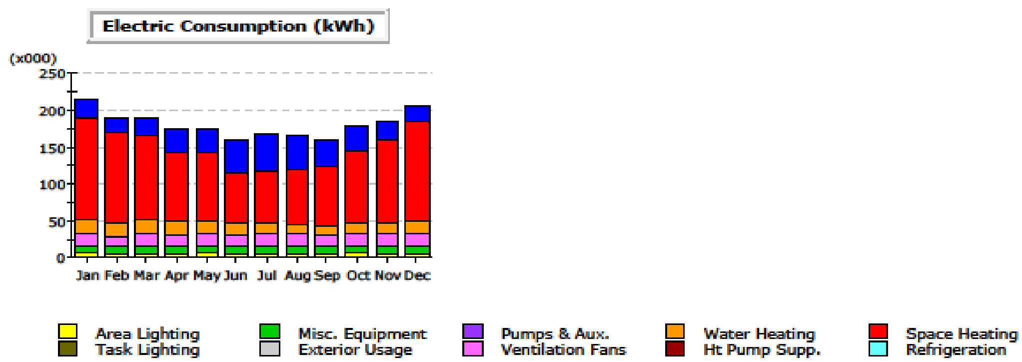


Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	24.2	21.2	26.4	29.5	35.5	46.8	52.1	47.2	38.2	33.3	26.2	23.6	404.3
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	143.7	126.7	116.6	97.0	93.7	71.7	73.0	76.9	82.6	103.4	117.0	138.2	1,240.4
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	19.2	18.7	21.3	20.0	18.1	16.1	14.7	13.7	13.2	14.3	15.4	17.9	202.6
Vent. Fans	17.1	15.1	16.4	15.9	16.9	15.9	16.7	16.5	16.1	16.9	16.2	16.7	196.4
Pumps & Aux.	0.0	0.0	0.0	0.0	0.0	-	-	-	0.0	0.0	0.0	0.0	0.1
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	9.1	8.2	9.1	8.8	9.1	8.8	9.1	9.1	8.8	9.1	8.8	9.1	107.2
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	6.6	5.8	6.3	6.1	6.5	6.1	6.5	6.4	6.2	6.5	6.3	6.5	76.0
Total	220.0	195.8	196.0	177.4	179.9	165.5	172.1	169.8	165.0	183.5	190.0	212.0	2,227.0

Figure 4.12. Simulation Results Under Present Window Blind Usage

Project/Run: Optimum Usage - Baseline Design Run Date/Time: 03/26/16 @ 13:29



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	23.4	20.5	25.5	28.4	34.3	45.3	50.4	45.7	37.0	32.2	25.3	22.8	390.6
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	139.3	122.6	112.8	94.1	91.0	69.4	71.1	74.8	80.1	100.0	113.4	134.3	1,203.1
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	19.2	18.7	21.3	20.0	18.1	16.1	14.7	13.7	13.2	14.3	15.4	17.9	202.6
Vent. Fans	16.5	14.6	15.8	15.3	16.3	15.3	16.1	16.0	15.5	16.3	15.7	16.1	189.5
Pumps & Aux.	0.0	0.0	0.0	0.0	0.0	-	-	-	0.0	0.0	0.0	0.0	0.1
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	9.1	8.2	9.1	8.8	9.1	8.8	9.1	9.1	8.8	9.1	8.8	9.1	107.2
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	6.6	5.8	6.3	6.1	6.5	6.1	6.5	6.4	6.2	6.5	6.3	6.5	76.0
Total	214.2	190.5	190.8	172.9	175.4	161.2	167.9	165.7	160.7	178.5	185.0	206.7	2,169.2

Figure 4.13. Simulation Results under Optimum Usage

The shading device control model are a representation of possible energy savings. Often these models are difficult to implement as they are based on high-order models that require detailed and accurate as-built construction information in order to be effective (Sˇiroky´ et al., 2011). Overall, for a full year of energy consumption the author noted that there could be a savings of 58,000 KWh, which would be a saving of 2.6 percent by optimum usage of window blinds.

CHAPTER 5. DISCUSSION CONCLUSION AND RESULTS

This chapter discusses the conclusion that were drawn from the results obtained in the previous chapter. Also, recommendations for other similar studies and future work to build upon this study is discussed in the chapter.

There were three areas that this study primarily focused on

- Understanding the window blind usage pattern of occupants of a multi-family residential building in Lafayette Indiana.
- To calculate the correlation between outdoor temperatures, outdoor lighting intensities and occlusion values of window blinds.
- To model the building under consideration in an energy modeling software, and compute energy savings under present usage of window blinds and suggested optimum usage of window blinds as discussed in chapter 4.

Throughout the course of data collection and pilot study, the author identified some interesting trends in the window blind usage patterns of occupants of the building under consideration. The author was also able to answer some questions that were not a part of the research initially, but are still important in window blind usage pattern research. These points have been mentioned in the discussion section.

5.1 Discussion

- During the pilot study it was noted that most of the windows on the first floor of the building under consideration do not show any change in their position. It was noted that almost all the windows had 100 percent occlusion from window blinds during the pilot survey. After completion of final data collection, comparing the survey results with window blind usage patterns reveals that privacy concern is the major reason behind this behavior. It was noted that the window blinds on North, East and West facades of the building have walk-ways along the windows and show the highest value of occlusion. Also, seventy-five percent of the survey respondents living on the main floor of these facades mentioned privacy as a primary concern for having the window blinds closed all year round. To add to this hypothesis, the Southern façade of the building showed significantly higher window blind changes and lesser percentage of window blind occlusion. The southern façade of the building under consideration does not have a walkway along these window openings, as other facades of the building, hence reducing privacy issues. Unfortunately, the author did not receive any survey responses from occupants of first floor of the southern façade hence no subjective opinions from occupants is available.
- Prior to final data collection the author conducted several pilot tests to study

occupant behavior and window blind usage patterns. It was observed by the author, that during Christmas time all the windows that displayed a Christmas tree, also displayed a decrease in occlusion from window blinds, throughout the holiday season.

- Several windows on various different facades of the building under consideration, had the window-sill lined with decorative plants. The author observed that even though these windows did not show a statistically significantly different window blind usage pattern, these window openings were almost never completely covered by the window blinds. On certain occasions when these windows were covered completely, they were again reopened to match previous positions of being partially or completely open.
- Windows on the 2nd floor and 1st floor of the western façade of the building under consideration showed the maximum percentage change in occlusion values when compared to other facades. Explanation for this behavior is that the western façade of the building does not have any privacy issues. On the other hand, this facade, has a good view of the woods, and no direct sunlight in the morning, which is a perfect scenario for occupants to open window blinds in the morning. However, when this façade starts getting direct sunlight in the evening hours, the occupants encountered glare causing them to close the window blinds. Even though the survey results do not conclusively reveal the reasons behind the increased window blind changes, the substantially higher occlusion change rate of these windows can be a subject of study for further

research.

- Modeling the building and simulating its energy consumption predicted that the total energy savings from recommended usage of window blinds will save around 58,000KWh of energy during an entire year. The present market cost of a programmable automatic motor for an existing window blind is around $98 per window. Installation of one such piece was estimated to require 20 minutes per window, if electric outlets are available in close proximity. The total estimated cost of installation and equipment for automatic window blinds for the building under consideration would be $13,600 considering labor cost for installation as $30 per hour. The resulting annual energy savings from 12 cents per KWh sums up to $6,960 every year. According to this calculation, the simple payback period of this retrofit comes to around 2 years.

5.2 Conclusions From Analysis of Data

The study did reveals that more than 50 percent of all the windows under observation showed no change in occlusion values and over 70 percent showed less than one change per day in the window blind position. This study was aimed at collecting data on correlation between the environmental factors like temperature and lighting on the occupant’s usage of window blinds. After completion of data collection and analysis, the author did not find any statistically significant correlation, as a huge percent of windows just did not show any change in occlusion values even when the environmental factors changed significantly.

The simulation results predicted energy savings, from suggested usage of window blinds when compared to the usage pattern observed. The author also estimated the cost of retrofitting all the window blinds in the building by installing programmable motor control for the blinds. Since the building is owned and leased by an apartment management, the investment for the project should typically involve the management company. Since, the occupants are responsible for their energy bills, the savings from this project will go to the occupants, which does not make it a profitable business case for the management.

Overall, this study analyzed and presented window blind usage patterns of a multi-story, multi-family apartment building in Lafayette, IN.

5.3 Recommendations for Future Study

- The act of making changes to the position of window blinds in a residential setting is a subjective decision. Some occupants prefer frequently adjusting blind position to fit their needs, while others make few or no changes to the position of window blinds. Quantitative data on blind usage pattern is not sufficient for understanding occupant behavior or identifying the reasons that stimulate the occupants to make changes to window blinds. Qualitative data collected by surveying every occupant in the of the building, and their inputs on stimuli, factors that make them change the window blind position will produce better results, in identifying trends and correlation.
- Informing the occupants about possible energy savings, and monitoring the

change in real time energy consumption can be a significant next step in this area as this study can lead to conclusive results.

- This study recorded the window blind usage pattern during the peak of heating season. A similar study conducted in other seasons will reveal important data that can be used to improve the modelling assumption and the results of the energy simulations can be made more accurate.
- The literature review conducted for this study helped the author to recognize that not many prior studies on window blind usage have been conducted on residential buildings, the framework used for this research and the data generated during the study can be used to conduct more studies that build on previous research.

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