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A Comprehensive Study on Electrochromic Glazing Versus Conventional Shading Device In the Context of Energy Efficiency

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A Comprehensive Study on Electrochromic Glazing Versus Conventional Shading Device In the Context of Energy Efficiency

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Abstract

A Comprehensive Study on Electrochromic Glazing Versus Conventional Shading Device In the Context of Energy Efficiency

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This study is focused on a comparative simulation-based energy performance assessment of conventional shading devices and electrochromic glazing (EC) in an office building in hot climate. Seven fixed exterior shading devices and four EC glazing alternatives have been modeled in EnergyPlus and the energy saving potential of them has been compared in South, East and West orientation. The results indicate that different levels of energy saving (in heating, cooling and electrical lighting) can be reached using each alternative scenario, which also varies by orientation. EC glazing can provide either considerable saving or waste in different orientations which is highly dependent on the control strategy. The comprehensive analysis provided in this thesis helps designers choose among the alternatives with an understanding of energy efficiency according to their criteria of concern.

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CHAPTER 1: INTRODUCTION

Annual energy consumption of buildings in US is approximately 14.4 quads (15.2 EJ) which is 73% of national electricity consumption (U.S. D. of E. EIA, 2015.). Lighting, heating, ventilation, and air-conditioning (HVAC) are the main parts of this energy consumption. All the aforementioned energy consumption methods are affected to some extent by the thermal and optical properties of the windows which is more obvious in hot climates (Fasi & Budaiwi,2015).

For years, shading devices have been employed in hot climates in order to provide occupant's visual and thermal comfort and minimize mechanical cooling loads. The main benefits of efficient shading devices include savings in cooling load besides controlling the intensity and distribution of the daylight entering the space. For the sake of occupants' satisfaction and comfort, shading devices can reduce the glare and the view of the bright sky by shielding the uncomfortable direct sun.

The technology for switchable windows is emerging, which creates an obvious opportunity to save energy in buildings. The solar factor and the transmission of radiation in the solar spectrum of these glazing are some of the properties that changes in response to the environmental conditions or an electric current. The highly glazed buildings might benefit from these windows in terms of drastic reduction in cooling load, heating load, and electric lighting. Among all these switchable window, Electrochromic glazing (from now on, called EC in this study) have made a great advancement compared to static glazing and several manufacturers are providing novel EC windows in US market constantly (de Frost, 2017).

1.1 SIGNIFICANCE

Windows as a building component require the larger maintenance and are the least energy efficient part of the fenestration. As a result of this fact, the energy performance of a building relies on the window to a great extent (Baetens et al. 2010). However, windows are an inseparable component of a building as they are the main way through which natural light can get into the buildings. Additionally, several researches have proven that natural light is essential for the biological health, and so is the exterior view. Thus, the trade-off between the energy performance of the buildings and window's nature of providing natural light and external view requires should be efficiently planned through the design of fenestration in buildings.

In cooling-dominant climates, solar radiation represents one of the most significant source of potential summer heat gains. The external shading can provide the windows with preferably low solar heat gain when there is a need for cooling. However, such a solution might have disadvantages such as sensitive mechanical parts, blocking outside view as well as outside aesthetics and mounting problems. (Jonsson & Roos,2010).

A recent solution for controlling the solar radiation is Electrochromic (EC) glazing. It optimizes daylight, outdoor views, and comfort with controlling the penetration of the sunlight while it prevents glare, fading, and overheating. Energy consumption could be reduced significantly by using EC glazing to let sunlight in on cool days and block it on hot days. Dynamic glass preserves views of the outdoors with eliminating the shades that block the view (the reason we have windows and skylights in the first place). There are several drawbacks for the EC glazing as well, such as higher upfront and also maintenance costs, relatively difficult installation, long transition times to name a few.

1.2 Description Of Problem Areas

There are many studies investigating the benefits of the solar control techniques. Hoeeverr, designers mainly face the issue how to define the best window shading strategy and alternative foe a specific application. There are rules of thumb that the architectures and designers follow in order choosing the shading strategy which provides them with both energy efficiency and aesthetic needs of a building. Higher initial cost, higher energy consumption, discomfort glare, and poor levels of illumination within a building are some of the common drawbacks of this common practices. Exterior fixed shading devices and EC glazing systems are two methods that control radiated heat transfer rates. But these two solar shading techniques do not perform/affect similarly for all orientations, and are nor even essential for some situations. Such cases can be mentioned including, but not limited to, the ones below:

- From the economical point of view, adding external shading or EC glazing might not be the choice for energy efficiency in some design cases. Climate conditions and building's use are two important factors in the success of shading device design (Hee et al., 2015).
- Additionally, in some circumstances, the site, needs of the local climate conditions, deign idea, or any other factor may result in some other criteria (such as view) to be more important than energy efficiency while choosing between shading techniques or even various conventional shading devices. In such situations, an understanding of comparative energy efficiency between all the alternative strategies would be invaluable to the architect and designer.
- According to how an alternative (shading device/EC) performs, the resulted heating, cooling, and electric lighting energy of a building may vary in different orientations. In circumstances with availability of an alternative energy resources (like solar

heating), the designer may decide to pick a shading strategy based on his energy concerns such as cooling, heating, electric lighting energy.

All of these decision making could be met or significantly improved with proper shading strategies that depend upon quantitative evaluation.

Two major forms of solar control techniques are investigated in this study which are the fixed exterior conventional shading devices and the EC glazing. The impact of these strategies on the energy performance of buildings is analyzed in this thesis. The results and findings in this study can help architects and designers to identify the most effective shading technique to control solar gains for hot climate (such as in Austin, TX) according to their concern in design.

1.3 Research Question

This study seeks to answer the main research question stated below:

<u>"Comparing EC Glazing to Conventional Shading Devices, how does each technique affect the energy consumption of an office building in Austin?"</u>

Subsequent Question:

- Is EC or one type of shading device more energy efficient in all orientations?
- How does EC compare to Conventional shading devices in terms of energy savings in East, West and South?
- How does the control strategy change the EC energy savings?

1.4 Outline of the Work

Chapter 2 provides a literature review on both EC glazing and shading devices. This chapter comprehensively reviews the previous studies conducted on energy performance of these two shading techniques.

Chapter 3 is dedicated to the methodology including the methodology approach, research method and simulation framework. All the input data along with assumptions of the simulation can be found in this chapter.

The results from the simulation is discussed for each orientation in chapter 4. This provides three cases of orientation with all the performance of all alternatives.

Chapter 5 discusses the findings for all the alternatives in all orientations together, and provides the main research findings. Subsequently, the overall conclusion of the study, and then the recommendations for future works is provided in this chapter. This chapter is followed by the list of references and Appendix A.

CHAPTER 2: REVIEW OF LITERATURE

In this section, an overview for the related work in the literature is provided. First, I go over the background for the windows in general. Next, two main groups of glazing namely static and dynamic glazing are discussed. I provided a more detailed background over the Electrochromic glazing since it includes a major part of this work. In the next section, a comprehensive overview of the related work on shading devices are provided.

1.1 WINDOW IN ARCHITECTURE

The word "Window" drives from the Icelandic word "Vindauga" which literally means "windeye" as Webster dictionary states. The time period between Millennia and Renaissance, glass panes were not used in windows but very rare occasions. Later the wealthiest inhabitants of Florence, Venice, Genoa started to gradually use the panes at the end of XIII century although rarely in Roman Thermae and in a few rich Roman houses glass panes were used. Around early XIX century majority of the people started using the glazed windows very slowly and only very poor people were not able to acquire them. (Butera,2005).

With glass panes, windows ceased to be 'wind eyes' and it became possible to have natural light and warm air at the same time. The existence of glazed windows provided the opportunity to enhance the thermal comfort indoor as it made it possible to have stoves. This technological innovation has provided human the opportunity to have natural light in a uniformly warm environment.

In addition, trapping solar radiation in the room was another capability of the glass. With no heating source, indoor thermal comfort was improved during winter sunny days. Within the 2nd half of XIX century new heating technology commenced first in business homes by critical heating structures with radiators and hot air structures. The revolution induced through glass panes turn out to be then whole where we become capable of create a synthetic micro-surrounding our home, our workplace, and so forth., in which we should experience daylight hours and a comfortable temperature even inside the coldest wintry weather day.

Windows are now considered as an indispensable part of a building through which occupants take advantage of daylight whenever possible. It is essential for the healthy well-being and productivity of the building inhabitants. There's a surely clear preference for daylight from interviewed workplace employees (Galasiu & Veitch, 2006a; Heerwagen, 1986). Several studies verify that access to daylight hours and view are vital for humans well-being and fitness (Paredes, 2016; Rassia & Pardalos, 2012 ;Wågø et al., 2016), and there may be clear proof that daylight alter circadian cycles (Dubois & Blomsterberg, 2016; Charles, 2013; Smolensky & Lamberg, 2000). Furthermore, many respondents believed that daylight and view are pacifying pressure and showed a clean choice for places with windows to work, due to the possibility of getting an outdoor view. The presence of windows lets in occupants to get the sense of the time of the day and the weather, can restrict eye sfatigue by supplying horizon to attention on, and restrict the sensation of claustrophobia (Wågø et al., 2016).

Moreover, the use of natural daytime light can also save tremendous amount of electricity and greenhouse fuel emissions, as artificial lighting can make a contribution to between 20% and 60% of a building's general power consumption (Galasiu & Veitch, 2006a; 2006b).

2.2 GLAZING TYPES

One of the crucial tasks in designing window is the selection of window glazing type. Previously, researchers had performed the literature review in window glazing to provide the review of various types of glazing. For instant, Arasteh (Arasteh,1995) performed a literature assessment on the advances in window era within the year of 1973–1993. In his studies, he noted the ability of power saving from windows and mainly focused on the improvement of glazing, which was similarly investigated in (Baetens et al., 2010; Jelle et al., 2012; Hee et al., 2015). In their studies, Hee et al. tried to reveal the influences of window glazing on the energy and daylighting performances of constructions using the result of the previous researches with classifying the glazing types into two categories of static and dynamic windows.

2.2.1 Static Glazing

Static glazing refers to glazing that possesses single fixed optical and thermal properties (Hee et al., 2015). The thermal performance of a glazing mainly depends on U-value and solar heat gain coefficient (SHGC), while it is the visible transmittance (Tvis) that runts its visual performance. Figure 1 illustrates SHGC and U-value. Higher Tvis will result in more solar heat penetration into a building space (Colaco,2008).

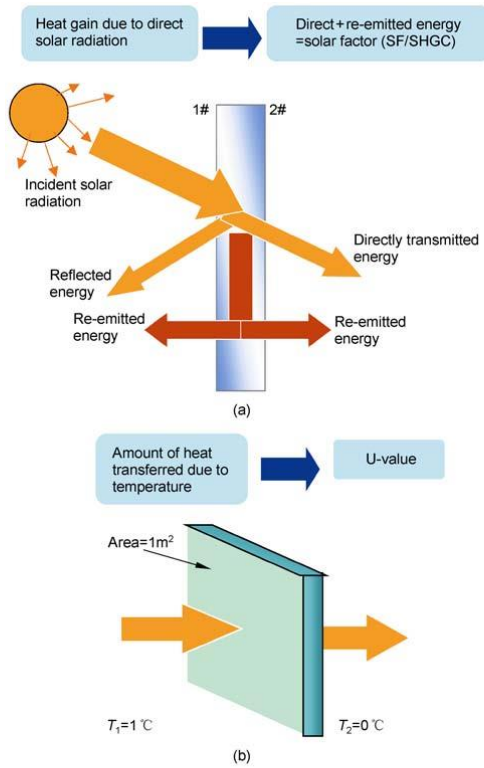

Figure 1. SHGC and U-value(Colaco,2008).

Various studies have investigated the effect of static glazing properties on thermal energy performance of buildings. Hassouneh et al. (2010) investigated the influence of glazing types and orientation on energy balance of apartments in Amman, Jordan. This research intended to discover the suitable glazing and its area for four main orientations from eight choices of glazing. Sadrzadehrafiei et al., (2011), has investigated the effect of certain glazing (such as single clear, Low-E, and double Low-E) on cooling load. Jaber and Ajib (2011) explored the optimum window type and size for both heating and cooling demands in three different climate zones: Amman, Aqaba and Berlin. Thermal performance of double-glazed and triple-glazed windows was the focus for Shakouri et al. (2011). Sadrzadehrafiei et al. (2012) also conducted an examination on triple-glazing and its benefits towards cooling energy in tropical climates such as Malaysia.

Effect of static glazing properties on daylighting level has also been investigated in a number of studies. The daylight penetration heavily depends on the Tvis of the static glazing. In Malaysia's office interior, the daylight availability by varying different type of window glasses was studied by Ibrahim and Zain-Ahmed (2007), i.e., clear glass, tinted green glass, and reflective glass with three different visible transmittance (Tvis) values. To obtain the best levels of natural light, various types of glazing were analyzed by Taylor et al. (2009). Syed Husin and Hanur (2012) examined the ability distributing daylight into space in a number of window types that are typically used in Malaysia. For instance, the casement windows and louver windows were investigated by the authors in this work.

Some other studies have also looked into the effect of static glazing on total energy performances of building. Johnson et al. (1984) investigated the influence of glazing systems on component loads and annual energy use in prototypical office buildings. The authors analyzed the sensitivity of total energy use to orientation, window area, glazing properties (U-value, shading coefficient, visible transmittance), window management strategy, installed lighting power, and lighting control strategy using simulation analysis. All three cases (opaque wall, non-daylit building, and daylit building) were examined and compared. Stegou-Sagia et al. (2007) inspected the effect of static glazing on the energy breakdown for office buildings in Greece. Hassouneh et al., (2010) stated that the best type of window from an energy standpoint is the one that saves energy and money, reduces heat loss, and is also low cost. Jaber and Ajib (2011) did a series of thermal optimization of glazing at Amman, Aqaba and Berlin. Lee et al., (2013) studied various window systems in order to find the optimized window for five distinctive Asian climates (Manila, Taipei, Shanghai, Seoul and Sapporo). Lee et al., (2013) also presented an optimization of window systems for the building's annual heating, cooling and lighting energy consumption in the Asian region. Alrubaih (2014) investigated the effect of four different static glazing types, such as the single clear, double clear, double low-e clear, and double reflect clear on energy savings and daylighting quality of sawtooth top-lighting system under the principle orientations.

2.2.2. Dynamic (Smart) Glazing

Dynamic window properties may be controlled actively or modified passively because of environmental conditions. These type of windows are a promising class of advanced building technologies which can make contributions to reducing electricity use in buildings, particularly if they are capable and quick and responsive switching (Loonen et al., 2013; Favoino et al., 2015; Hee et al., 2015; DeForest, et al., 2017).

Prominent dynamic window technologies include Electrochromic (EC) glazing, Thermochromic glazing, and Photovoltachromic glazing. EC glazing optical properties undergo reversible changes under an applied voltage. For thermochromic glazing, optical properties undergo reversible changes under changes in temperature; and, photovoltachromic glazing incorporate solar energy collection to self-power switching of optical properties (De Forest et al., 2017).

One of the smart non-electrically activated glazing is Thermotropic glazing. Instead of electricity, heat activates this type of glazing. Altering the radical property as a result of exceeding a threshold temperature triggers the scattering or absorption of light. These glazing perform better in the near infrared region, and are capable of providing diffuse daylight. Some of the side effects of the change in physical phases are the loss of certain visual parts of the spectrum and diminishing the window's view in the process.

For Photovoltachromic glazing transparent glass is made with fabricated solar cells that turns the glass into solar cells via glazing. The potential of this alternative uses of window seems expansive and promising to the building industry. Higher Tvis will reduce the sun radiation for solar cells to produce electricity so that comparing to other glazing the available Tvis for PV glazing may be lower. Therefore, optimizing daylighting and electricity generation features are one of the challenges for solar cells window (Hee et al.,2015).

Electrochromic glazing is the most popular among all dynamic glazing, and its performance was widely investigated by researchers. This glazing is discussed in detail in the next section.

2.3. A LITERATURE REVIEW ON ELECTROCHROMIC (EC) GLAZING

As mentioned in the previous sections Electrochromic (EC) glazing are one of the most popular method for energy saving strategies. In this section, a general overview of EC glazing will be discussed. Next, different types of EC glazing along with the related work in this context are defined and studied, followed by list of the advantages of the EC glazing.

2.3.1. Background

Electrochromism could be seen as a device characteristic rather than the property of the material. In so doing, once an external potential is applied, the optical properties of a device would change reversibly, which is associated with ion insertion and extraction processes. The optical properties of electroactive layers (electrochromics) change by switching between their oxidized and reduced form (Beatens et al., 2010).

1990s could be considered as the start of the investigate on EC glazing. Prior researches centered on the EC innovation and the examination of EC glass properties.

Afterward studies moved to creating EC applications in several fields, such as in design, vehicle industry, etc. Due to the significance of the energy-saving potential of EC windows for the building industry, a number of studies have been conducted on energy savings of EC windows in completely different climate conditions. Beginning in 2000, the integration of EC windows with other shading frameworks caught the consideration of researchers and analysts (Ardakan, 2015).

Electrochromic glazing is made of five layers (Figure 2) of coating on glass. When electricity is applied, lithium ions and associated electrons transfer from the counter electrode (CE) to the electrochromic electrode (EC) which results in darkening of EC glazing. EC glazing returns to the clear mode by reversing the voltage, and the ions and associated electrons return to their original layer. Less than five volts in needed to switch the glazing (Sbar et al., 2012).

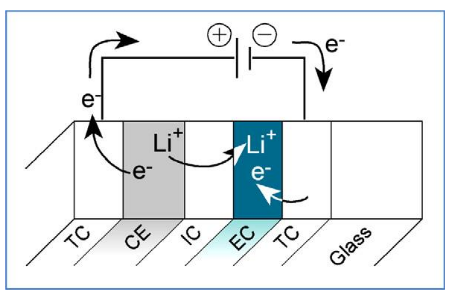

Figure 2. SAGE thin film EC stack on glass (Sbar et al., 2012)

An interior light sensor is used to provide an input to control EC to maintain a comfortable level of daylight in the space. An upper and lower acceptable lighting range configures the range of light entering. When the upper illuminance set-point is crossed for a configurable amount of time, the glass will tint to the next available level. When the lower illuminance set-point is crossed, the glass will clear to the previous level (Figure 3,4).

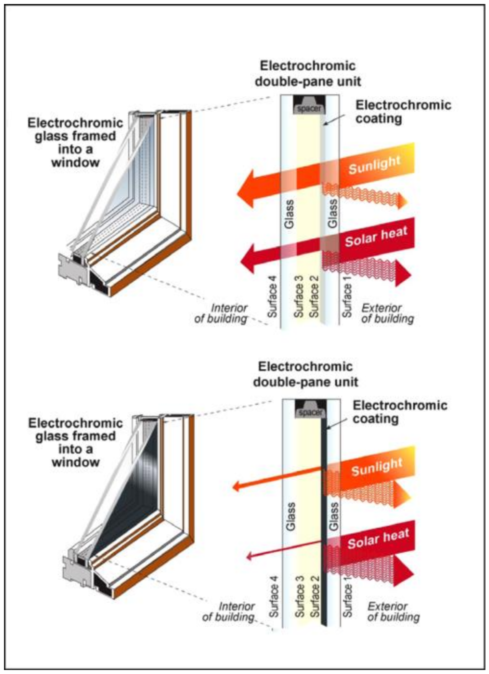

Figure 3. EC in clear and tinted states (Sbar et al.,2012)

EC glazing of various types have been in development for decades. The focus of these studies is related to their underlying material properties, as well as their suitability for deployment in building window applications. A large portion of the new EC technology emergence is related to the recent advances in material science which also exhibit dramatically different dynamic optical properties and switching ranges (Cannavale et al., 2015).

Figure 4. Switching sequence of an electrochromic laminated glass (Baetens et al., 2010)

2.3.2. Types of Electrochromic Glazing

2.3.2.1. Conventional electrochromic glazing

For decades Electrochromic glazing based on tungsten oxide films have been in development and are currently available as commercial products from a number of window and glass manufacturers (Hee et al.,2015). Conventional Electrochromic (CEC) glazing demonstrate broadband switching, which means their transmission of near-infrared (NIR) and visible light are reduced in unison when switching states (Mortimer et al.,2013)

Although prototypes of reflective devices have been exhibited, current commercially available coatings reduce transmission by absorption. This functionality gives CEC glazing the potential to be highly effective at blocking solar heat and mitigating glare. Typically, some portion of near-infrared heat is blocked by the CEC in both states. The visually perceptible darkening is provided when transitioning to a ‘‘dark” state and the transmission of visible light and NIR get slowed down by CEC. Several papers reviewing the current state of advanced window technologies, including CEC and other dynamic glazing have also been published recently (Granqvist, 2013; Hee et al.,2015). Research on tungsten oxide based EC glazing is ongoing, and their manufacturing cost, durability, and other properties continue to improve incrementally (De Forest, et al.,2017).

2.3.2.2. NIR-switching electrochromic glazing

In the past several years a transparent electrochromic film is created which modulates NIR transmission without changing visible light transmission (Garcia et al.,2011; Wang, et al.2016). In a variety of building applications and climates, the transparent NIR-switching electrochromic (NEC) glazing benefits this feature which provides an aesthetic advantage over conventional electrochromic glazing. A plasmonic electrochromic effect that dynamically modulates the localized surface plasmon resonance of doped semiconducting nanocrystals is the foundation of the recent NEC glazing [40]. Moreover, as a part of new innovations, the cost of manufacturing NEC glazing have been potentially lowered by several methods, including spray or slot die coating of a nanocrystal based ink added to an annealing process to fix the film to the substrate (Runnerstrom, 2014). On the other hand, the conventional dynamic coatings have high cost, which currently manufactured using more expensive and complicated vacuum based sputter coating processes. There several lower cost methods and techniques that are revealed based on recent studies on CEC glazing which are not currently used for commercially available products.

2.3.2.3. Dual-band electrochromic glazing

Developing a composite that embodies the properties and switching ranges of both CEC and NEC glazing has been the subject of recent studies. The first demonstrated so-called ‘‘dual-band” electrochromic (DBEC) relies on a synergistic interaction between niobium oxide (NbOx) and indium tin oxide (ITO) nanocrystals glass (Korgel,2013;

Llordes et al.,2013). These materials exhibit different regions of the spectrum and demonstrate electrochromic properties. As result of these properties, this combination introduces an ITO-NbOx composite glazing to independently modulate transmission in both the NIR (ITO) and visible (NbOx) regions. An under development composition uses tungsten oxide (WO3-x) nanocrystals instead of ITO in combination again with NbOx glass that introduces a DBEC material with improved modulation range (Kim et al.,2015). As with the NEC, a less costly process can be adopted where glass can be coated using the nanocrystal that requires less energy intensive application and annealing process (Korgel,2013), meaning the manufacturing cost of the coated glazing may be lower relative to sputtered glazing.

Acceptance of the EC technology by the end user have been studied over the last two decades for instance, Sottile (2002, 2005), Tenner and Zonneveldt (2002), Clear (2006), Clear et al. (2006), Zinzi (2006), Rottmann et al. (2007), Piccolo and Simone (2009) and Granqvist et al. (2010). In general users like this technology as part of building with EC glasses. The main reason behind it that it reduces glare, reflections and discomfort near the windows. The studies mentioned above include a field study and reports the observation based on the inquiries from the users in the building (Tavares at al., 2016).

2.3.3. Advantages of Electrochromic Glazing: Energy Saving

The reason that EC glazing is the most popular in this particular field is that they have some advantages over the other dynamic glazing. According to Lampert (1993), the advantages of EC glazing are listed below:

(i) Power only involved when switching of EC.

(ii) Switching is available with only small voltage.

(iii) EC have durable memory (12–48 h).

(iv) They are specular in all states.

(v) EC is capable of large area fabrication.

However, an extensive amount of research has been conducted to date on the benefits of EC. The main aspects of such advantages are discussed in the following.

A number of studies were conducted to quantify the energy savings of EC windows over other glazing and shading systems.

Lawrence Berkeley National Laboratory (LBNL) conducted numerous studies on DOE-2 commercial building energy applying simulation in the mid-1990s, e.g. (Sullivan et al.,1994;1997). The conclusion of these investigations confirms that significant annual total energy savings can be obtained compared to spectrally selective low-emittance (low-e) windows in moderate to hot climates if large-area EC windows are controlled to maintain the interior illuminance setpoint level and are combined with daylighting controls (Lee & Tavil, 2007).

Karlsson (2001) controlled EC windows and used incident vertical solar radiation limits (50–300 W/m2) in combination with occupancy-controlled lighting and ventilation systems and a heat recovery mode regulated by interior temperatures to quantify heating and cooling annual energy savings for EC windows. In the northern Stockholm climate this method of control yielded small savings and slightly greater savings in the warmer climates of Denver and Miami given the moderate window-to-wall ratio (WWR=0.30).

Gugliermetti and Bisegna (2003) conducted a parametric investigate to recognize ideal occurrence solar radiation limits that would abdicate the slightest add up to essential energy. A second set of simulations was conducted to address inconvenience glare due to daylight sky luminance at that point compared to these ideal savings. Total essential energy utilize was expanded by a significant margin (19%) on the north façade and a little margin (4–10%) on the east, south, and west exteriors and with the visual comfort procedure compared to the finest occurrence solar radiation techniques. These results were given for a direct measured window (WWR=0.33) in an ordinary office for three climates in Italy. The electric lights were darkened in reaction to sunshine with photoelectric controls. The EC was undone (which tragically increments cooling) once the space was unoccupied,

Based on a DOE-2.1 simulation study reported by Lee et al. (2004), comparing to Low-E windows with daylighting controls without shading, the energy consumption could be reduced up to 10-20% by utilizing EC windows in commercial buildings in most climates. Peak demand for the same conditions could be reduced by 20-30%. In the year of 2030, an approximate of 91.5-97.3 x 1012 Btu is projected to be saved by the emerging electrochromic windows with daylighting controls and this is compared to spectrally selective Low-E windows with manually controlled interior shades and with no daylighting controls. This is in the case of condition that EC window reaches a 40% market penetration level in that year.

Lee et al. conducted a 20-month field study in which they focused on the energy performance of south-facing large-area electrochromic windows with a broad switching range in a private office setting. Several setting for EC windows were used in this study where the windows divided into different zones or were equipped with Venetian blinds. Comparing to utilizing fully lowered Venetian blind as the reference case, the scenario of equipping two-zone EC window provided average daily lighting energy savings of 10% and cooling load reduced by 3%. Compared to a reference case with or without daylighting controls, peak demand reductions in lighting energy use were 0% or 72-100%, respectively. Lighting energy savings would be 44% in case of assuming that the reference case to have no daylighting controls. On clear sunny days, considering a critical demand-response mode, peak demand reductions based on window cooling load, were 19-26% maximum. Lighting energy use was found to be very sensitive to how glare and sun were controlled (Lee et al., 2005).

In another study, a private office is assumed with switchable electrochromic windows and manually operated Venetian blinds with 43 subjects working in the office. Based on the analysis of subject responses and physical data, use of the electrochromic windows lowered the impact of glare comparing to a fixed transmittance (60%) condition. Electric lighting usage has been slightly more than the instance with fixed window transmittance although the subjects used the Venetian blinds less often and preferred the variable transmittance condition. (Clear et al., 2006)

The performance of EC windows in prototypical energy models representing a single-family home in Atlanta was simulated with BEopt software. In a 2006 IECC-compliant home the models predicted that the EC windows could produce whole-house electricity demand savings of 13.5% and whole-house source energy savings of 9.1%. During the cooling season the windows were assumed to operate automatically meaning that they tint in response to incident solar compared to a Low-E window with the same daylighting control system. In this scenario, the electrochromic window showed lighting energy use savings of 48–67% when controlled for visual comfort and annual peak cooling load reductions of 19–26% (Lee et al., 2006a). In this study, large-area electrochromic windows were evaluated as prototypes throughout a 2.5-year field test under outdoor solar and sky conditions. It also analyzed data from simulations and laboratory tests.

The Lawrence Berkeley National Laboratory (LBNL) conducted another study in which multi-zone EC window configurations as well as various control strategies were studied (Lee et al. ,2006b). The authors investigated the effect of integrating overhangs with EC with the direct sun getting away from the EC windows by utilizing overhangs. According to this study, the authors stated that the average annual daylight glare index (DGI) would be drastically reduced by using EC windows with overhangs and result in significant annual energy use savings if the window area is large in both hot and cold climates. Total primary annual energy use was increased by 2–5% for moderate-area windows in either climate but decreased by 5% in Houston and 10% in Chicago for large-area windows as examples of hot and cold climates. In either climate, Peak electric demand can be reduced by 14–16% for large-area windows and by 7–8% for moderate-area windows. Energy and peak demand can be significantly reduced, in case the reference case does not have exterior shading or state-of-the-art static glass.

The reliability of commercially available windows has been proven to be viable, with their tested properties falling within our expectations based on the literature review by Baetens et al. (2010). Compared to well-turned daylighting control via blinds lighting energy is reduced by almost 26% in these windows, and around 20% of the peak cooling loads in warmer climates, such as California (USA). Further investigations are necessary for confirmation in this context for cooler climates as these studies are not definitive for that scenario.

Jonsson and con Roos evaluated utilized several control mechanisms to measure the heating and cooling needs of the building using computer simulations. They concluded that it is beneficial to use an occupancy-based control system. Also the best way to combine the panes in the switchable window differed depending on the balance temperature of the building and on the climate. They also suggested different window combinations for different orientations. Based on the result of this study, it is essential to use a careful selection of glazing combinations and a thoroughly worked out control strategy for energy efficiency. (Jonsson & Roos,2010)

In making the comparison between the EC and static glazing, the focus of Belzer's study (Belzer,2010) prepared for the U.S. Department of Energy was on the energy savings associated with the dynamic nature of the EC glazing. Three different variants of EC glazing (characterized with varying SHGC) in their "clear" states were examined using Energy Plus in an exploratory analysis. These different configurations were compared to the static glazing that meets ASHRAE Standard 90.1-2004 energy standard conducted for five different locations in the U.S. The result of this study demonstrate that electrochromic glazing achieves a modest level of source energy savings. On the basis of these simulations, depending on the amount (square footage or meters) of window area and building location, the total source-level savings in small and medium office buildings range between 2 to 7%. The potential savings are almost the same in both northern and southern locations and the reason behind it is that EC glazing can be used to both reduce heating and cooling loads.

In another study the results show that EC windows could save energy up to 45%, compared to single pane static glazing, based on the simulation of another software named e-Quest. An eight-story commercial office building was the subject of this study and was modeled in three U.S. climate zones, covering a range of environmental exposure conditions from hot and dry (Arizona) to very cold (Minnesota). When EC glass was deployed, energy savings greater than 20% were calculated for the same building configuration as ASHRAE 90.1 2007 code-compliant glazing (Sbar et al., 2012).

Aste et al. (2012), conducted a simulation-based study and modeled a virtual test cell representing a portion of an office building in order to evaluate the energy balance. Also the authors investigated the economic convenience related to the use, as solar control devices, of a switchable EC glazing system and of an automated external venetian blind system. It demonstrated that better overall energy performance can be achieved using external solar control systems rather than a glazing system without external shading devices. In particular, the EC is shown as the most efficient one among the compared configurations from the primary energy consumption. However, this study mentions that because of the high purchasing cost of EC it is not an affordable choice.

Integrating EC glazing with solar cells in order to generate electricity required for EC control is the focus of several other studies. Energy harvesting electrochromic (EH-ECW) windows allowed the windows to admit heat and light relative to interior comfort requirements. These glazing is also converting the of incident solar radiation into electric current while in a darkened state. In buildings where the unwanted solar heat gains can be converted to electricity rather than rejected to the surrounding site, this property is very useful. Energy harvesting (EH) is another innovative feature that is available for the organic electrochromic windows (ECW). This is valid not only for the self-power of window controls and switching, but also for providing on-site power generation for other building functions (Meek & Bruot, 2013).

Aldawoud (2013) analyzed solar gains in space zones at the East, South and West facades with simulation and compared the results of the conventional shading systems (overhangs and vertical fins) with EC glasses in hot and dry climates. The sizing of overhangs and fins turned out to be very important based on this study to ensure the proper function especially in case of combining the overhangs and fins. Also, these research confirms that in all windows orientations facing east, south, or west, the electrochromic glazing offers high potential for significant reduction in annual peak cooling load from controlling solar heat gains in hot climates.

EC control strategy could also affect the energy performance of EC windows. The results of simulations performed in Tavares et al. (Tavares at al.,2011, 2014,2016) demonstrates that the incident solar radiation is the best physical variable to control the

EC glasses state. It was also concluded the west façade yields the best performance for the Mediterranean climate when the EC is used. No significant advantages in using EC windows was obtained for the south façade based on this investigation.

In another study, Tavares et al. also used simulations to research the energy savings resulting from the application of EC windows, considering the comparison of several windows solutions and orientations on of EC glazing in Mediterranean climates (Tavares at al., 2016). The EC technology is an effective option in cooling dominated buildings, yet the impact of EC windows is highly dependent on facade orientation. The result of this study demonstrates no significant advantage of using EC windows for the South facade while EC was a valid option in the cases of the East and West facades.

Dussault and Gosselin investigated on a representative office building zone with an EC glazed facade using TRNSYS and Radiance/Daysim as their simulation tool. This study includes a large number of different combinations of design parameters (such as location, facade orientation, window control, window-to-wall ratio, internal gains, thermal mass and envelope air tightness) and was conducted for 10 different cities in Canada and in the U.S. The greatest total energy savings considering EC windows were found to be in warmer climates with higher solar radiation exposures. The cooling peak load is the most affected parameter in the presence of an EC window which could be considered as an alternative solution to thermal mass from the perspective of peak reductions. The analysis demonstrate that the choice of the specific window control strategy has a larger impact on the visual comfort while this parameter is having a limited impact on the energy savings and peak load reductions (Dussault & Gosselin,2017).

Three dynamic EC window glazing -including a novel glazing capable of independently modulating its optical properties in both the visible and near-infrared spectrums- was studied by De Frost et al. (2017). Annual energy performance of the dual-band electrochromic (DBEC) glazing in three building types and 16 U.S. climate regions was simulated in EnergyPlus. Analysis shows that the DBEC glazing are capable of outperforming alternatives in a diverse set of locations and building types, which includes both heating and cooling-dominated regions.

2.4. A LITERATURE REVIEW ON SHADING DEVICES

Shading devices are the traditional strategy to save energy in buildings. In this section, a background about the relative work on shading devices is provided. Energy performance of the shading devices is then discussed and overviewed based on the literature work on this field.

2.4.1. Background

Shading devices are defined in the “Building Energy Conservation Design Standards” as follows: “They are devices installed for the purpose of reducing solar heat coming into the room and they are divided into external shading devices, internal ones, and the ones between window glasses according to the installation positions. They can be divided into fixed ones and movable ones according to whether they can be moved or not” (Kim et al., 2017).

Several methods exist for controlling the thermal, lighting properties, and performance of a facade. The traditional way of altering the amount and distribution of incident solar radiation is done by using solar shading devices. In this context, this method could be easily considered as a low-tech alternative which might nevertheless be an effective alternative. Controlling or blocking the solar radiation that is coming inside the building using any of the aforementioned methods is referred to as common shading which purposed to provide a pleasant indoor environment. During the winter the heat gained through the daylight that comes through the windows reduces the heating load although the cooling loads in can be drastically increased through solar radiation in summer. Using shading controls would help reducing the energy consumption and create a comfortable indoor environment while complementing the weak points of windows in summer (Grynning et al., 2017).

Although fixed shading devices offer significant protection from heat gain, they should be adjustable as possible to adapt to different outdoor conditions. It should be also considered that they also have a major effect on the appearance of a building and sometimes they block part of the view to outdoors.

2.4.2. Advantages of Shading Devices: Energy Saving

Various studies were previously conducted on shading devices. In this section, I provide an overview of the energy performance relative work.

TRANSYS was utilized as the simulation engine by Datta (2001) to study the energy consumption of buildings. Datta conducted a comprehensive analysis on appropriate shading device models in order to study the effects of thermal performance of fixed horizontal shading devices.

As part of a decision management study by obtaining the Balance Point Temperature Eom et al. (2005) simulated and recognize that there are periods when shading devices are not as necessary while during some other periods they are not required. Based on this study the shading devices are designed on the basis of the periods separated in such a manner. They proposed a specification for optimal shading devices within the size range of shading devices based on the solar altitude, and a quantitative basis for the projection length was proposed using annual heating and cooling loads

As a part of another study, Tzempelikos and Athienitis (2007) investigated the control of shading devices for the cooling and lighting of buildings. A guideline was provided on the design of the window glass ratio and the performance of shading devices. The properties that they considered in their guidelines are shading control, and how to select the glass ratio of the facade.

Using IES 5.5.1, Kim et al. (2008) measured the sunshine amount on the living room floor surface and analyzed annual cooling and heating loads. They also evaluated the impact of a new type of movable horizontal shading device on the indoor thermal environment and solar access performance.

The effect of a louvered sunshade system was analyzed by Palmero-Marrero and Oliveira (2010). For different orientations of the building and situations, the performance of shading devices was evaluated, and they analyzed the effects of the louvered sunshade system which vary depending on diverse factors.

Using the e-Quest program, Kim et al. (2010) evaluated the shading coefficient applied to the energy saving building envelope technology of office buildings. Based on the different types of horizontal shading devices and different orientations, they evaluated the loads. They also analyzed the envelope elements according to the orientations.

Al-Tamimi and Fadzil (2011) focused on finding a way to reduce the energy consumption of a tropical high rise residential building through research on the possibility of applying shading devices. Main part of this study is about the indoor temperature control effect for high-rise residential buildings in the hot and humid climate of Malaysia. With the use of simulations, they analyzed optimal external shading devices that can reduce incoming heat and consequently optimize energy consumption.

In a similar study, Kim et al. (2012) conducted an energy simulation using a computer model created for residential buildings in Korea. The authors utilized a practical approach in order to introduce optimal external shading devices by conducting comparative research of thermal performances of the external shading devices of residential buildings.

Considering the physical properties of the envelope components, they quantitatively evaluated the various facades (Kim and Yoon 2012). With respect to the combination of windows and fixed external shading devices, the property of the envelope components can be selected in the envelope design and annual loads could be calculated through simulation, and analyzed the design suitability.

A parameter design methodology was developed by Choi et al. (2014) which combines heat and the design pyramid by performing a thermal analysis and investigating a parameter design methodology. They also conducted research upon a parametric louver design system for optimization of the shape of the louver.

Song et al. (2014) used a building energy analysis program to conducted an analysis of full solar irradiation of the vertical glass surface. This study depends on the length of the horizontal shading device according to the orientations concerning the perimeter boundary in office buildings in Seoul.

Horizontal shading devices or Venetian blinds were also the focus of a study by Kim et al. (Kim et al.,2015) where the cooling and heating energy consumption of office buildings in Korea were analyzed to find the suitable shading devices according to regions and orientations.

Lee et al. (2015) carried out the research on climate index development using the local weather data in order to make it possible to confirm the validity of shading devices which can be judged by the user with the understanding of the characteristics of the local climate in the early design stage. In order to confirm the effect of an efficient design of shading devices Kim et al. evaluated cooling load decreases by assessing the reduction of cooling loads in the office buildings with a large cooling load. This study aimed to confirm that shading devices are installed for the purpose of improving the visual comfort of indoor building occupants by blocking excessive sunlight and allowing adequate daylight to come through windows.

Singh et al. (2015) analyzed the effect of extended values of shade transmittance on energy and visual performances of the office building. The city subject of this study is Shillong as representative of cold climates in India. A number of glazing and internal roller shade combinations were simulated and the results for south, west, north, and east facing offices with varying window sizes, properties of glazing, and shading devices were investigated.

Kim (Kim, 2015) conducted a study for deriving improvement methods of solar radiation control standards of windows and shading devices on the basis of the analysis of South Korea and other countries' related standards by analyzing the current status of energy saving design standards of buildings of major countries. An investigation of complementary elements for the national standards and necessary amendments of them was conducted by Kim et al. as well. They also provided a comparative analysis of them with the national standards.

Karlsen et al. (Karlsen et al.,2016) developed a solar shading control strategy for Venetian blinds applied on office buildings in cold climates in order to achieve acceptable energy use and indoor environmental performance.

A multi objective evolutionary design approach was introduced by Khoroshiltseva et al. (2016) to optimize (m-EDO) shading devices which are part of the renovation kits of an existing residential building in Madrid.

CHAPTER 3: METHODOLOGY

In this section, the research method for this thesis is explained. The simulation techniques and tool are described in detail and the assumptions on environment setup such as building, climate, and orientations is discussed. Moreover, the alternative scenarios that are investigated and analyzed in this study are explained in detail.

3.1. RESEARCH METHODOLOGY

This study makes its assumptions by applying positivist methodological approach. According to Groat and Wang:" In the context of architectural research, the positivist tradition is the most influential mode of research in the technical domains of the field, such as energy conservation practices or structures. These are topics of research in which there is an assumed consensus that the physical properties of materials or the processes of mechanical systems can be objectively measured or, at the very least, that such measurements can practically be assumed to reflect reality" (Groat and Wang 2013).

Within the general framework of simulation research, the independent variables are the glazing system parameters and configurations, climate and building. Dependent variables are the heating, cooling load and electric lighting energy.

In order to assess the effect of the external solar shading devices and EC glazing system on the energy performance of buildings, a model for a typical office building is generated using a simulation software. DOE's EnergyPlus building energy simulation software was the principal analytical tool employed in this work.

3.2. Simulation Framework

In this section, EnergyPlus as the main simulation engine of this study is explained. This framework in mainly inspired by the body of simulation-based work of literature. A table including the all input or simulation logics and frameworks of a series of studies (Lee et al.,2004; Belzer,2010; Johnsson & Roos,2010; Aste et al.,2012; Sbar et al.,2012; Aldawoud,2013; Ardakan,2015; Tavares et al.,2016; DeForest 2017) was generated which really helped the author define the simulation software and framework. A snapshot of this table can be seen in Figure 5.

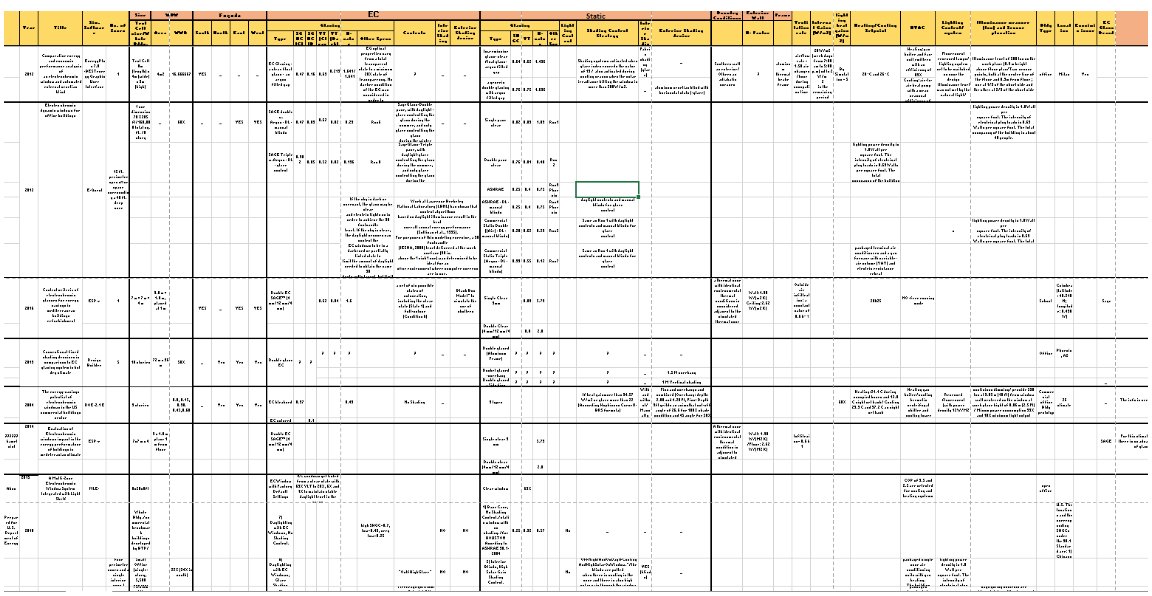

Figure 5. Table of literature review on EC/Shading Device simulation-based works

3.2.1. Simulation tool

Building energy simulations are performed in EnergyPlus 8.8. EnergyPlus is available for public usage as simulation tool for modeling thermal and electrical loads. This simulation engine is also capable of performing annual energy analysis of whole buildings or building zones at hourly time increments. Building geometry, envelope characteristics, mechanical system characteristics, lighting system characteristics and occupancy and HVAC set point schedules are defining EnergyPlus models. While being developed over the past 20 years, EnergyPlus has been one popular source for simulating and analyzing building energy (Mortimer,2013). The reliability of EnergyPlus has been extensively tested and validated, and additional details of methods and results of these validations are available on the USDOE website (URL1,2016).

At the beginning, the building geometry was modeled in OpenStudio 2.4, which later indicated some unreasonable discrepancies in the thermal loads resulted from EnergyPlus (due to some boundary issues). Thus, an Ecotect model of the same geometry was provided which could modify and validate the previous OpenStudio one and alleviate the discrepancies.

3.2.2. Building Description, Location, and Orientation

The analysis cell is considered as a portion of an office building, whose specifications is derived from the medium-office commercial benchmark buildings developed by BTP (Department of Energy's Building Technologies Program). The medium office has just over 50,000 square feet, with three floors, and a window-wall ratio of 33%. The dimensions (9*6*4m) of the analysis cell can be seen in figure 6.

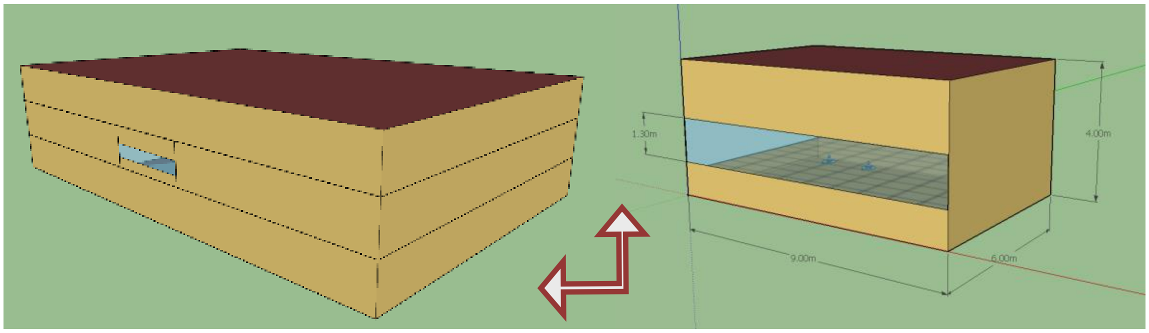

Figure 6. Building and analysis cell

The simulated building is located in Austin, Texas. In order to comply with BTP benchmark buildings, the thermal characteristics of the opaque envelope (walls, roof, and foundation) reflect the ASHRAE requirements applied to the prototype building of Houston.

According to the study by Tavares et al. (2016), for different types of facades, the energy required for heating and cooling varies regardless of the type of glass used which makes the orientation a factor of great importance in solar gains. As this study compares the total energy performance of EC and conventional shading devices, three sets of simulations were conducted in which the analysis cell faces either the South, West, or East.

3.2.3. Simulation Assumptions

Several main assumptions were made in order to limit the numerous variables in the project and focus on the major objective of it:

- Minimum insulation levels, internal loads, schedules, and opaque envelope materials were all established according to the mentioned commercial prototype building. The only difference was the glazing parameters. This info can be seen in Appendix A.

- Daylight controls and electronic dimming were included in all alternatives. At a point 3 meters from the exterior and 0.8 meters from the floor (i.e. desk height), two daylighting controls are set to maintain an illuminance of 500 lux. continuous dimming control is used which reduce the lighting output level to 5% of its maximum value, with an associated minimum percentage of input power of 20%.
- The glazing parameters of the static windows are identical to those of EC in its clear state. It is due to the fact that this study focuses on the energy savings associated with the dynamic nature of the EC glazing; so the thermal performance (U-factor) of the glazing is considered a constant with the aim of limiting the variables of the study.
- Unlike the commercial prototype building, Ideal Air Loads has been utilized in this study. It is a practical component built in EnergyPlus that represents an ideal HVAC system (DOE,2016). That allows for achieving preliminary results without neither specifying some operating parameters nor specifying certain HVAC system (Alghoul, 2017). As this study aims at the comparison of various cases (and not the estimation of energy consumption), Ideal air loads template was applied into all building zones with the same set point (in order to reduce the effect of adjacent zone on thermal behavior of the analysis cell).
- In EnergyPlus, the capability to switch between clear (high transmittance) and dark (low transmittance) states defines the EC glazing. The default situation is assumed the clear state. The choice of control strategy then determines the extent to which the window is darkened. The EC glazing parameters are associated with that of SAGE GLASS. EnergyPlus can only simulate two states, the parameters of each has been shown in Table 1.

Table 1. Optical and thermal properties of static and EC glazing

	U-Factor [W/m2-K]	SHGC Clear	SHGC Dark	Visible Transmittance Clear	Visible Transmittance Dark
Static Glazing	1.64	0.44		0.62	
EC Glazing	1.64	0.44	0.08	0.62	0.01

3.2.4. Alternative Analysis Scenarios

The strategy in the simulation study was to explore the relative savings associated with a number of options including either window conventional shading devices (seven types) or EC glazing (with four control strategies).

The baseline for the calculation is the first alternative. There are then seven alternatives with different conventional shading devices, the parameters of which are mainly taken from the study by Fajkus (Fajkus, 2011). These alternatives are actually the baseline to which shading devices are added, so they all have static glazing. The four EC alternatives share the same glazing parameters, yet are different in control strategy. The emphasis of the previous simulation and experimental studies has confirmed the importance of control strategy on the overall performance of EC windows. A previously proven viable method for modeling dynamic window technologies is using the EMS functionality of EnergyPlus to implement the control schemes (Favoino et.al.,2015;2016).

All the alternatives have been tested in all three orientation cases; that is the South, West, and East. Figure 7 provides an illustration of all the alternatives.

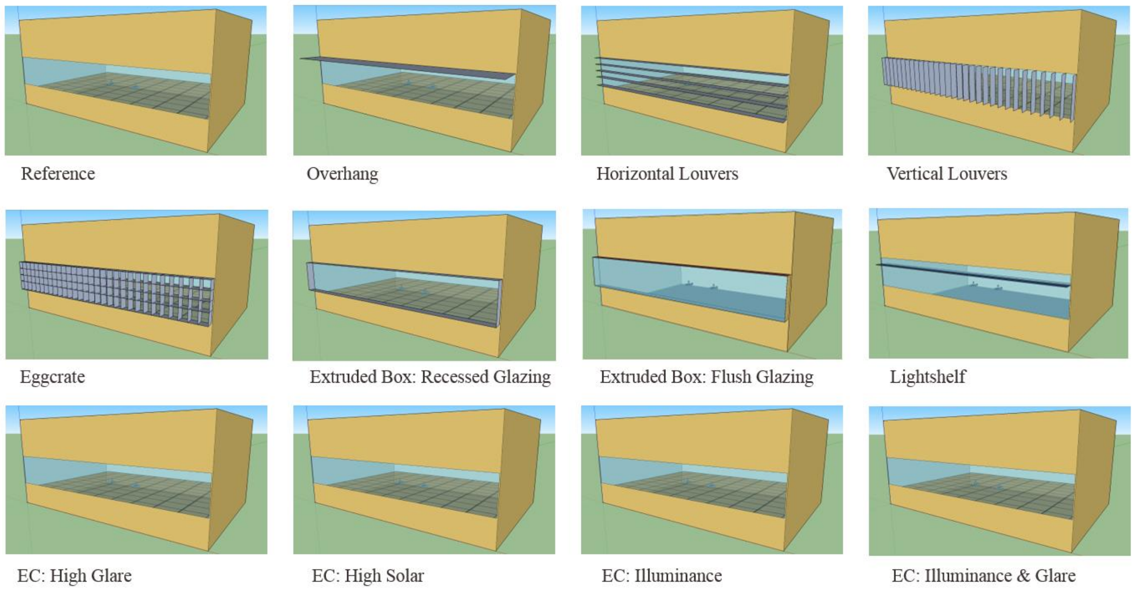

Figure 7.Simulation alternatives

1. Reference: It consists of simple double-glazed fixed type window with no interior or exterior shading devices. As mentioned, the baseline (static) window was assumed to incorporate the same properties as the EC window in its clear state.
2. Overhang: This alternative has the static window with an overhang with the depth of 1m.
3. Horizontal Louvers: This alternative has the static window with external horizontal louvers consisting of blinds perpendicular to the surface. They have a depth and a distance between each blind of 30 cm and span over the entire width of the window.
4. Vertical Louvers: In this alternative, the static window is provided with external vertical blinds. Each blind has a depth and a distance of 30 cm between and covers the entire height of the window wall.

5. Eggcrate: This alternative has an external eggcrate over the static window, which is a combination of the horizontal and vertical blinds. The square-type eggcrate consists of openings with of 30 in width, height, and depth
6. Extruded Box- Recessed Glazing: In this simulation alternative, the static window is shaded by an external box which is actually a combination of two horizontal (at the top and bottom of the window) and two vertical blind (at the edges). In such configuration, the window is recessed in the box.
7. Extruded Box- Flush Glazing: This alternative is mainly the previous one, but the window is flush with the box surface. This configuration may not be considered a real shading device, yet the extruded box makes the difference between this alternative and the Reference one.
8. Lightshelf: This alternative has the static window with an added light shelf at the top of the window, at a 30 distance from the above. The external and inner depth of the lightshelf is also 30cm.
9. EC- High Glare: In this and all subsequent alternatives, the window is replaced by an EC glazing one. In this alternative though, the control strategy for the EC is set to change to dark state only when there is excessive glare (glare as measured by what EnergyPlus defines as "Discomfort Glare Index"). In the language of EnergyPlus, the strategy is termed: "OnIfHighGlare". When the glare index exceeds a value of 20 it simulates that the dark state is deployed
10. EC- High Solar: In this alternative, the EC transits to its dark state when there is a high solar gain through the window (> 100 W/sq. meter). In terms of the EnergyPlus, the shading control type is "OnIfHighSolarOnWindow".
11. EC- Illuminance: The EC glazing in this alternative is controlled to vary the amount of daylight in the space to meet a specified level of illumination (500 Lux). As

described in the EnergyPlus documentation, "… the transmittance of the glazing is adjusted to just meet the daylight illuminance setpoint at the first daylighting reference point". In terms of the EnergyPlus, the shading control type is "MeetDaylightIlluminanceSetpoint."

12. EC- Illuminance & Glare: In the last simulation EC alternative, the glare control option is combined with the control to just meet the illuminance requirements of the zone.

CHAPTER 4: RESULTS

This section of this thesis includes the results of the simulation for three orientations of the modeled building. All 12 shading control strategies that were introduced in the section 3.2.4 are analyzed from the perspective of heating and cooling load as well as lighting energy demand. The total Energy Use Intensity (EUI) for all scenarios in all cases are also compared and analyzed.

4.1. SOUTH-FACING WINDOWS

This section compares the energy consumption of all the alternatives in which the window of the analysis cell is facing south. First, the thermal load is analyzed, and then followed by the electric lighting energy investigation. Furthermore, the total EUI of all the alternatives is presented and compared.

4.1.1. Cooling and Heating Load

Figure 8 indicates the relative percentage of energy saving (compared to Reference alternative) in cooling [J] resulted by all the alternatives in South-facing case. As depicted in Figure 8, Lightshelf and Extruded Box-Flush Glazing increase the cooling load by 9 and 3% respectively, while all the other alternatives reduce it within a range of 16-33%. Among all alternative, the Extruded Box-Recessed Glazing is the least effective one, with a considerable difference in relative percentage of saving energy. The energy saving values (%) can be seen in Table 2.

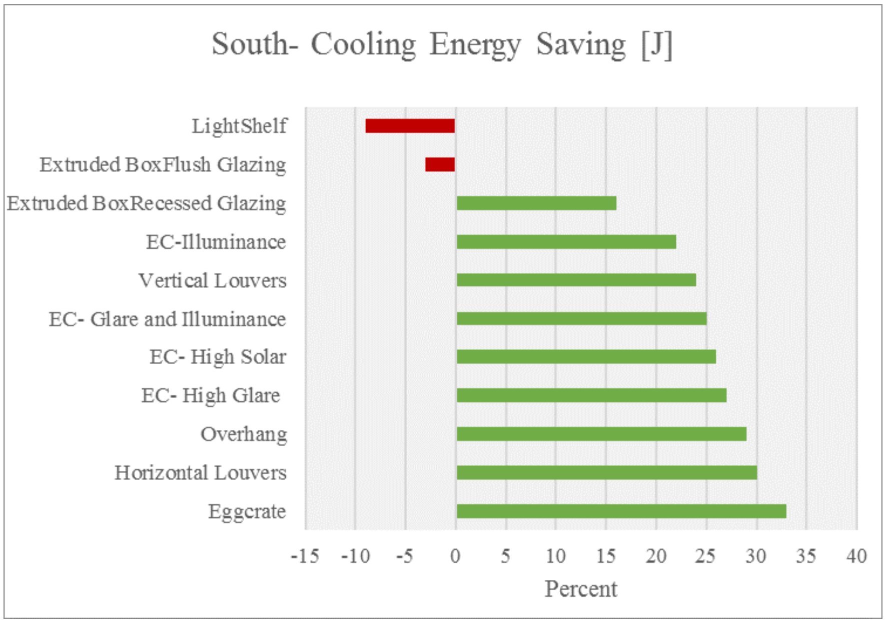

Figure 8. South- Cooling- Relative percentage of energy saving

Table 2. South- Cooling- Relative percentage of energy saving

Lightshelf	Extruded Box Flush Glazing	Extruded Box Recessed Glazing	EC-Illuminance	Vertical Louvers	EC- Glare & Illuminance	EC- High Solar	EC- High Glare	Overhang	Horizontal Louvers	Eggcrate
-9	-3	16	22	24	25	26	27	29	30	33

As explained in Figure 8, all the EC alternative have improved cooling situation, from 22% to 27%. EC-High Glare yields the highest energy saving between them.

Regarding the effect of alternatives on heating load in case of South-facing window, only the Lightshelf reduces the heating load, the percentage value of which is really negligible. All other alternatives increase the heating load within a range of 3 to 79%, the Extruded Box Flush Glazing and Eggcrate being the lowest and highest respectively (Figure 4.2, Table 4.2). This seems to be rational as the result of blocking the solar radiation.

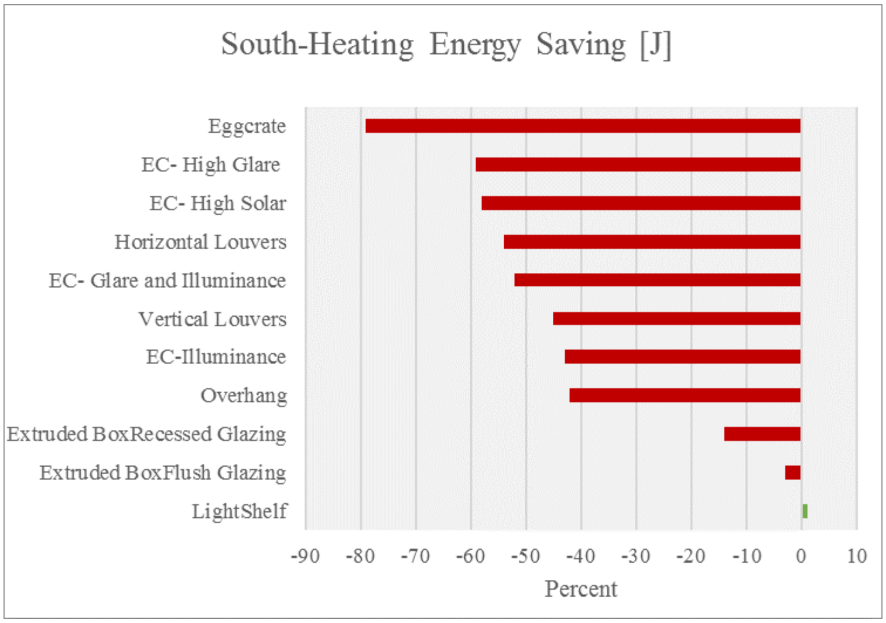

Figure 9. South- Heating- Relative percentage of energy saving

Table 3. South- Heating- Relative percentage of energy saving

Eggcrate	EC-High Glare	EC- High Solar	Horizontal Louvers	EC- Glare & Illuminance	Vertical Louvers	EC- Illuminance	Overhang	Extruded Box Recessed Glazing	Extruded Box Flush Glazing	Lightshelf
-79	-59	-58	-54	-52	-45	-43	-42	-14	-3	1

As indicated in the table, the application of all EC alternatives has considerably elevated the heating load. The EC-Illuminance, EC- Glare and Illuminance, EC- High Solar, and EC- High Glare show an increase of 43, 52, 58, and 59% respectively.

4.1.1. Electric Lighting Energy

The relative percentage of energy saving by each alternative in electrical lighting (with respect to the Reference) can be seen in Figure 10 and Table 4.

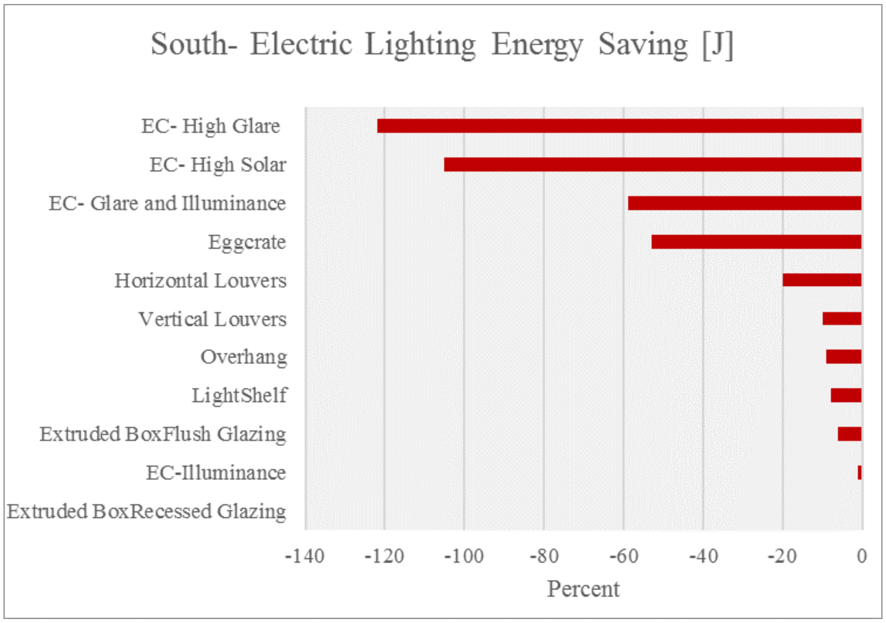

Figure 10. South- Electric lighting- Relative percentage of energy saving

Table 4. South- Electric lighting- Relative percentage of energy saving

EC- High Glare	EC- High Solar	EC- Glare & Illuminance	Eggcrate	Horizontal Louvers	Vertical Louvers	Overhang	Lightshelf	Extruded Box Flush Glazing	EC- Illuminance	Extruded Box Recessed Glazing
-122	-105	-59	-53	-20	-10	-9	-8	-6	-1	0

Except for the Extruded Box-Recessed Glazing that has no effect, all the cases reduce the transmitted solar radiation into the space and increase the electric lighting energy consumption. This increase is really negligible in EC-Illuminance, but gets pretty significant as it reaches 59, 105, and 122% of increase in EC- Glare and Illuminance, EC-High Solar, and EC- High Glare. These three EC alternatives highly increase the lighting energy. These EC alternatives seem to be the worst alternatives among all, in lighting energy saving.

4.1.1. Total Energy Consumption

In this study, the total energy consumption of any alternative is considered as the sum of heating, cooling, and electric lighting, which varies by the application of each shading device or EC glazing. Figure 11 and Table 5 show the total EUI [MJ/m2] in each alternative (the energy intensity, i.e. per square meter) in South-facing case. The proportion of each energy category is indicated in this figure too.

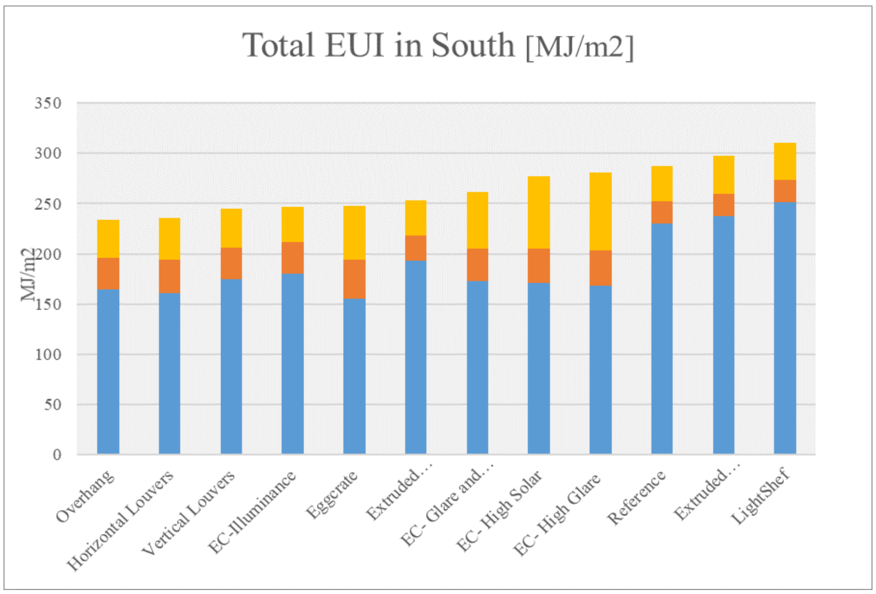

Figure 11. South- Total EUI

Figure 11 illustrated how the various shares of heating, cooling and electrical lighting energy in each alternative can affect its total EUI compared to other ones. Each energy section accounts for a different portion (%) of the Total EUI in each alternative.

Table 5. South- Total EUI

	Electric Lighting EUI [MJ/m2]	Heating EUI [MJ/m2]	Cooling EUI [MJ/m2]	Total EUI [MJ/m2]
Overhang	38	31	165	234
Horizontal Louvers	42	33	161	236
Vertical Louvers	38	32	175	245
EC-Illuminance	35	31	180	247
Eggcrate	54	39	155	248
Extruded Box-Recessed Glazing	35	25	193	253
EC- Glare and Illuminance	56	33	173	261
EC- High Solar	72	34	171	277
EC- High Glare	78	34	169	281
Reference	35	22	230	287
Extruded Box-Flush Glazing	37	22	238	297
Lightshelf	38	21	252	311

Table 6 shows the average and standard deviation of heating, cooling, and electrical lighting energy portion (%) in all alternatives for South-facing case. For example, the mean value of electric lighting portion for all alternatives is 17.6% of the total EUI (as with the Standard Deviation of 5.5). However, each alternative has a different electric lighting portion (as a percentage of total EUI).

Table 6. South- Mean percentage of heating, cooling and lighting portion of total EUI

	Lights Electric EUI (%)	Heating EUI (%)	Cooling EUI (%)
Mean	17.6	11.5	70.9
Standard Deviation	5.5	2.8	7.3

In case of South, all the alternatives are more energy efficient than the Reference, except for Extruded Box-Flush Glazing and Lightshelf. As stated in table 5, the Overhang has the least amount of total energy need (234 MJ/m2), followed by Horizontal Louvers (236 MJ/m2). Although the cooling EUI is lower in the latter, this is the Lighting EUI which results in a higher value of the total. The same trend could be seen in Eggcrate: it has the lowest cooling load, yet the high value of Lighting EUI (54 MJ/m2) and heating EUI (39 MJ/m2) has made it as the fifth efficient alternative among others. On the other hand, Lightshelf is the highest in total EUI due to its high cooling portion in spite of its relatively low lighting energy. Figure 4.5 shows the portion of each energy sector in these three alternatives as an example.

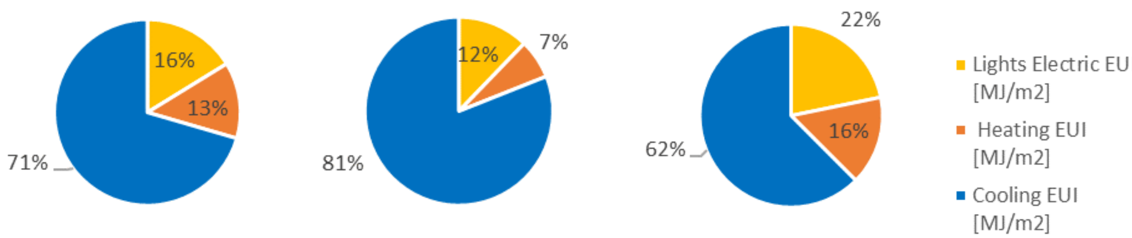

Figure 12. Portion of heating, cooling and lighting in Total EU (South-Overhang, South-LightShef, and South-Eggcrate)

Considering and comparing the EC alternatives, it is obvious that EC-Illuminance is the fourth most efficient strategy among all alternatives. However, the other EC alternatives can be rated as 7th, 8th and 9th in EC- Glare and Illuminance, EC- High Solar, and EC- High Glare. All EC alternatives perform better than the Reference in this case.

4.2. West-Facing Windows

A similar analysis with the same model alternatives is conducted while the window of the analysis cell is facing West. First the heating and cooling load are analyzed, and then followed by the electric lighting energy analysis. Furthermore, the total EUI of all the alternatives is presented and compared.

4.2.1. Cooling and Heating Load

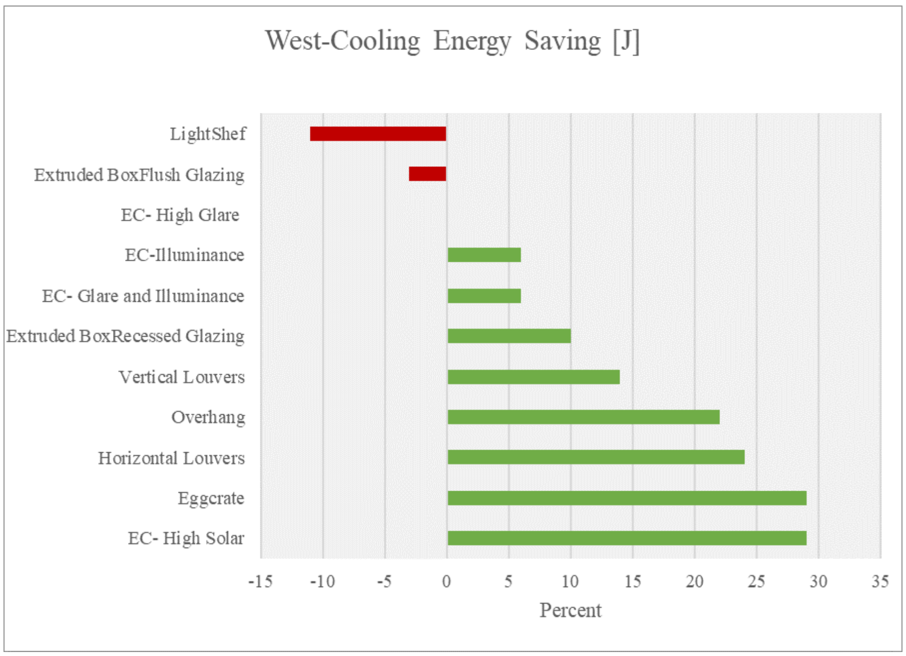

Figure 13. West- Cooling- Relative percentage of energy saving

The relative percentage of saving energy in cooling can be seen in Figure 13 for all the West-facing alternatives. Like the South orientation, Lightshelf and Extruded Box-Flush Glazing increase the cooling energy by 11 and 3% respectively. While the EC-High Glare does not affect the cooling load in the West-facing window, other alternatives decrease the cooling load within a range of 6-29%, with EC-High Solar and Eggcrate being the most effective ones (29%), and then Horizontal Louvers (Table 7).

Table 7. West- Cooling- Relative percentage of energy saving

Lightshelf	Extruded Box Flush Glazing	EC- High Glare	EC- Glare & Illuminance	EC- Illuminance	Extruded Box Recessed Glazing	Vertical Louvers	Overhang	Horizontal Louvers	EC- High Solar	Eggcrate
-11	-3	0	6	6	10	14	22	24	29	29

Regarding the efficiency of EC in cooling load reduction of the West case, some fluctuations can be seen. EC- High Glare has no effect on cooling load, while the EC- Illuminance and EC- Glare and Illuminance show a 6% energy saving. On the other hand, the EC- High Solar results in 29% of reduction in cooling load and has the greatest potential to save cooling energy among all alternatives.

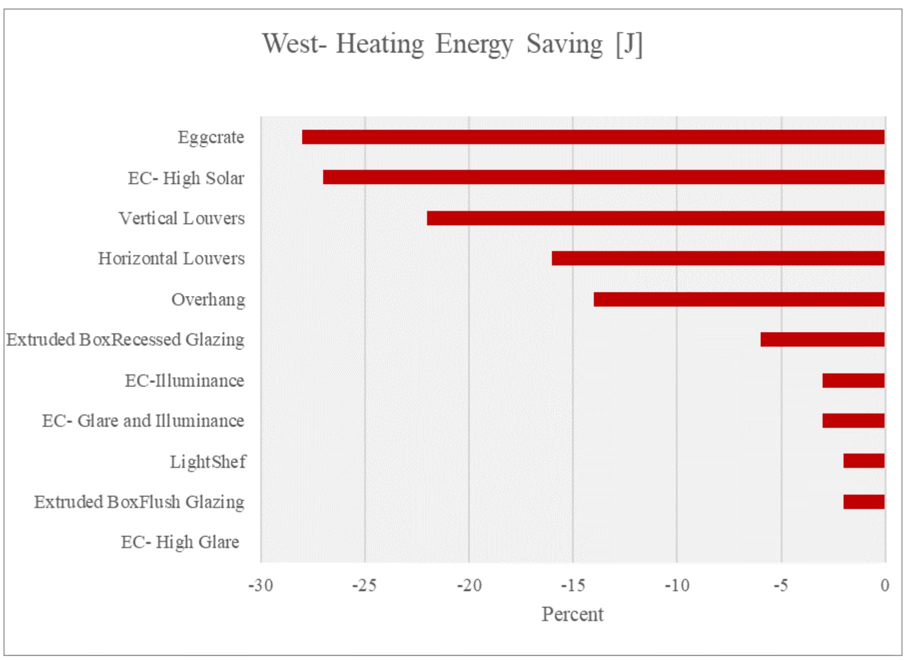

Figure 14. West- Heating- Relative percentage of energy saving

Applying all shading devices and EC glazing in West-facing window increases the heating load (Figure 14), which seems to be justifiable as the result of blocking the solar radiation. However, the EC-High Glare shows no difference compared to the Reference. The two cases Eggcrate and EC-High Solar are the worst in terms of cooling load (with 28 and 27% of increase), while Extruded Box-Flush Glazing and Lightshelf increase the heating load only for 2% (Table 8).

Table 8. West- Heating- Relative percentage of energy saving

Eggcrate	EC- High Solar	Vertical Louvers	Horizontal Louvers	Overhang	Extruded Box Recessed Glazing	EC- Glare & Illuminance	EC- Illuminance	Extruded Box Flush Glazing	Lightshef	EC- High Glare
-28	-27	-22	-16	-14	-6	-3	-3	-2	-2	0

Application of all EC alternatives has elevated the heating load. However, the EC-High Solar indicates much further uplift effect (i.e. 27%) compared to the other EC alternatives (that is from no effect to only 3%).

4.2.2. Electric Lighting Energy

The relative percentage of saving energy in electrical lighting can be seen in Figure 15. Except for the Lightshelf, all the cases have no effect or reduce the transmitted solar radiation into the space and increase the light electric energy consumption. EC-High Solar and Eggcrate are the worst (with 44 and 35% of increase in energy consumption compared to the Reference), while all other EC cases show no effect at all. This could be as a result of daylighting controls in the space which adjusts the EC performance according the minim 500 lux of illuminance in the space and lets the solar radiation into the space. However, this has not improved the lighting energy situation (Table 9).

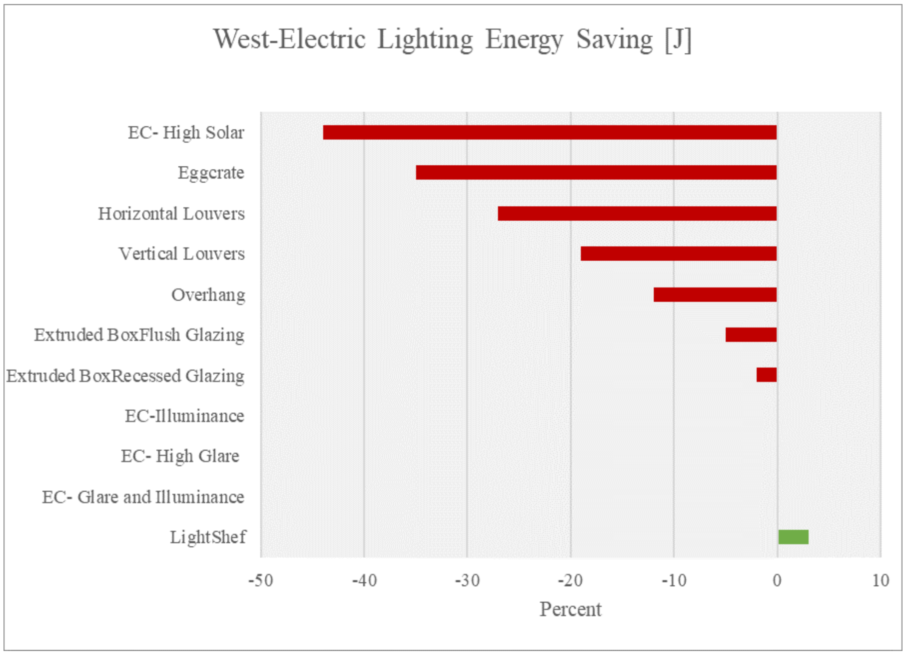

Figure 15. West- Electric lighting- Relative percentage of energy saving

Table 9. West- Electric lighting- Relative percentage of energy saving

EC- High Solar	Eggcrate	Horizontal Louvers	Vertical Louvers	Overhang	Extruded Box Flush Glazing	Extruded Box Recessed Glazing	EC- Glare and Illuminance	EC- High Glare	EC- Illuminance	LightShef
-44	-35	-27	-19	-12	-5	-2	0	0	0	3

4.2.3. Total Energy Consumption

Figure 16 and Table 10 demonstrate the total EUI in West orientation for all the alternatives.

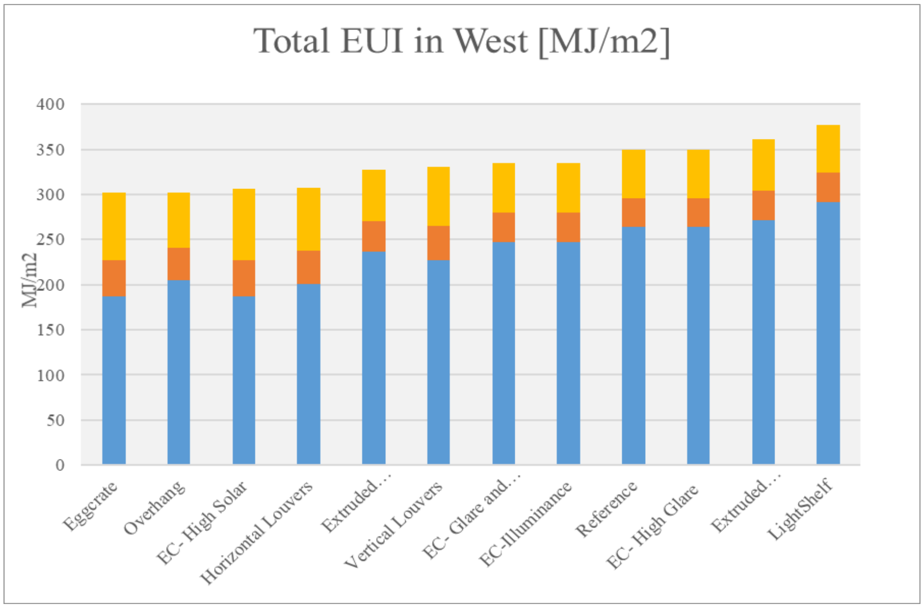

Figure 16. West- Total EUI

Table 10. West- Total EUI

	Electric Lighting EUI [MJ/m2]	Heating EUI [MJ/m2]	Cooling EUI [MJ/m2]	Total EUI [MJ/m2]
Eggcrate	74	40	187	302
Overhang	61	36	205	302
EC- High Solar	79	41	187	306
Horizontal Louvers	70	37	200	307
Extruded Box-Recessed Glazing	56	34	237	327
Vertical Louvers	65	39	227	331
EC- Glare and Illuminance	55	32	247	334
EC-Illuminance	55	32	247	334
Reference	55	32	264	350
EC- High Glare	55	32	264	350
Extruded Box-Flush Glazing	58	32	272	362
Lightshelf	53	32	292	377

Table 11 shows the average and standard deviation of heating, cooling, and electrical lighting energy percentage in all alternatives of West-facing case. As it can be seen, lighting energy is responsible for a greater portion of total energy consumption as an average in all alternative, while the mean value of heating and cooling percentage portion has slightly decreased compared to the South.

Table 11. West - Mean percentage of heating, cooling and lighting portion of total EUI

Lights Electric EUI [MJ/m2]	Heating EUI [MJ/m2]	Cooling EUI [MJ/m2]
18.8	10.6	70.6
4	1.7	5.5

In this case, three alternatives perform worse than the Reference: EC- High Glare (350 MJ/m2), Extruded Box-Flush Glazing (362 MJ/m2), and Lightshelf (377MJ/m2). The Eggcrate and Overhang are the most efficient alternatives (302 MJ/m2), although Eggcrate has a relatively high lighting energy consumption. A comparison between the alternatives of the highest and lowest efficiencies reveals the dominant value of cooling load in Lightshelf further compensates for its relatively lower lighting energy, resulting the current trend. Figure 4.10 shows the portion of each energy sector in these three alternatives.

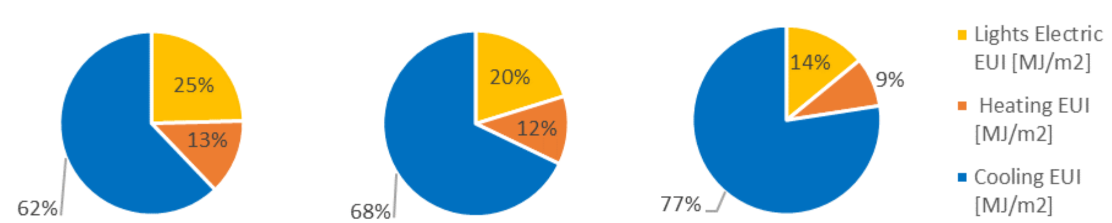

Figure 17. Portion of heating, cooling and lighting in Total EU (West-Overhang, West-LightShef, and West-Eggcrate)

Considering and comparing the EC alternatives, it can be seen that EC-High Solar is the third most efficient one among all alternatives. EC- Glare and Illuminance and EC-Illuminance are the 7th and 8th, still performing better than the Reference. On the other hand, EC- High Glare is less efficient compared to the Reference.

4.3. EAST-FACING WINDOWS

Finally, the last case of the orientation is the one with the window of the analysis cell facing East. The heating and cooling load is first analyzed, and then followed by the electric lighting energy. Furthermore, the total EUI of all the alternatives is presented and compared.

4.3.1. Cooling and Heating Load

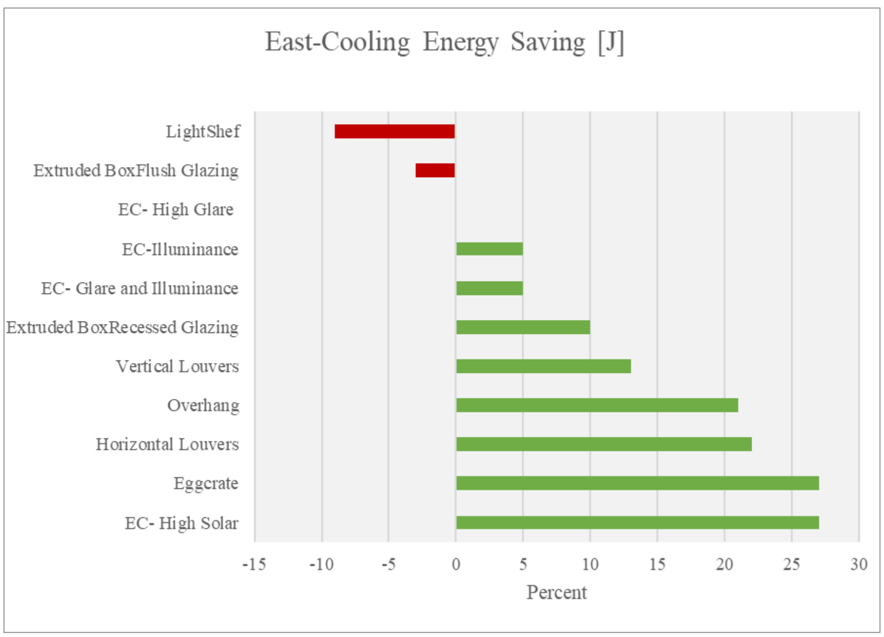

Figure 18. East- Cooling- Relative percentage of energy saving

The relative percentage of saving energy in cooling can be seen in Figure 18. Like the both South and West orientations, Lightshelf and Extruded Box-Flush Glazing increase the cooling energy (by 9 and 3% respectively). However, while the EC-High Glare does not affect the cooling load in the East-facing windows, other alternatives decrease the cooling load within a range of 5-27%, with EC-High Solar and Eggcrate being the most effective ones (27%), and then Horizontal Louvers (Table 12).

Table 12 East- Cooling- Relative percentage of energy saving

Lightshelf	Extruded Box Flush Glazing	EC- High Glare	EC- Glare & Illuminance	EC- Illuminance	Extruded Box Recessed Glazing	Vertical Louvers	Overhang	Horizontal Louvers	EC- High Solar	Eggcrate
-9	-3	0	5	5	10	13	21	22	27	27

As described, EC alternatives perform distinctively in this case. While the EC-High Solar provides the highest efficiency among all alternatives, the other three EC alternatives either have no effect or slightly increase the cooling load.

Figure 19 shows the energy saving percentage in heating load resulted by all the alternatives (with respect to the Reference) of the East-facing case. The EC-High Glare does not affect the heating, while all other alternatives increase the heating load within a range of 2 to 26%. EC- Illuminance, EC-Glare & Illuminance, Lightshelf, and Extruded Box-Flush Glazing are the lowest saving. Eggcrate and EC-High Solar are the most efficient ones with 26 and 25% of reduction in heating load (Table 13). The truly effective EC alternative is the EC-High Solar

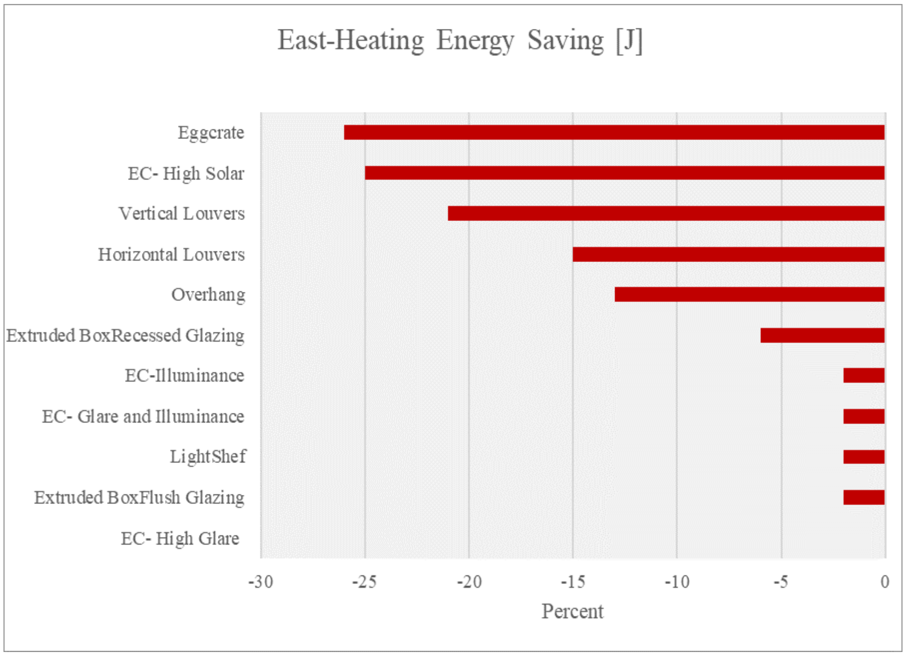

Figure 19. East- Heating- Relative percentage of energy saving

Table 13. East- Heating- Relative percentage of energy saving

Eggcrate	EC- High Solar	Vertical Louvers	Horizontal Louvers	Overhang	Extruded Box Recessed Glazing	Extruded Box Flush Glazing	Lightshelf	EC- Glare and Illuminance	EC- Illuminance	EC- High Glare
-26	-25	-21	-15	-13	-6	-2	-2	-2	-2	0

4.3.2. Electric Lighting Energy

The saved amount of lighting energy by each alternative (with respect to the Reference) in East-facing case can be seen in Figure 20 and Table 14. In this case, the Lightshelf is the only alternative which saves the electric lighting for 3%. Other strategies have no effect or they increase the lighting energy. The highest waste compared to the Reference is the EC- High Solar which increases the lighting by 40%. Other EC alternatives show no effect on lighting energy.

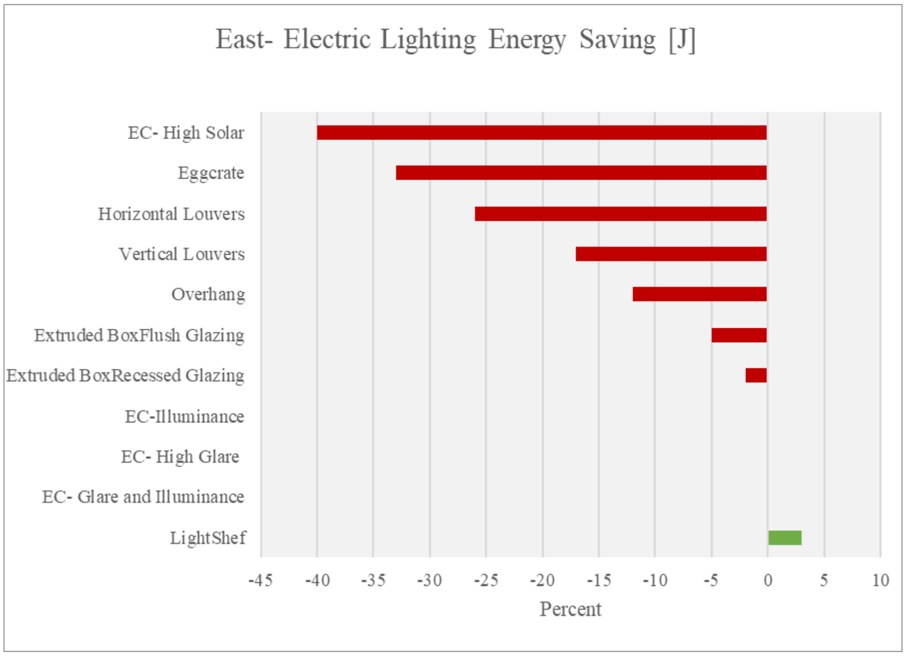

Figure 20. East- Electric lighting- Relative percentage of energy saving

Table 14. East- Electric lighting- Relative percentage of energy saving

EC- High Solar	Eggcrate	Horizontal Louvers	Vertical Louvers	Overhang	Extruded Box Flush Glazing	Extruded Box Recessed Glazing	EC- Glare and Illuminance	EC- High Glare	EC- Illuminance	Lightshelf
-40	-33	-26	-17	-12	-5	-2	0	0	0	3

4.3.3. Total Energy Consumption

Figure 21 and Table 15 demonstrate the total EUI in East-facing case for all the alternatives.

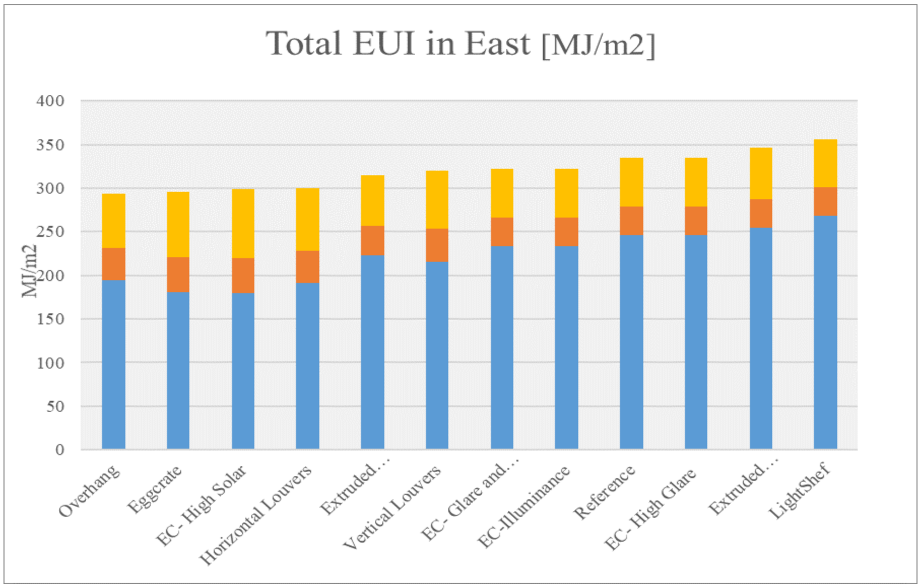

Figure 21. East- Total EUI

Table 15. East- Total EUI

	Electric Lighting EUI [MJ/m2]	Heating EUI [MJ/m2]	Cooling EUI [MJ/m2]	Total EUI [MJ/m2]
Overhang	63	36	195	294
Eggcrate	75	40	181	296
EC- High Solar	79	40	180	299
Horizontal Louvers	71	37	192	300
Extruded Box Recessed Glazing	58	34	223	314
Vertical Louvers	66	39	215	320
EC- Glare and Illuminance	56	33	233	322
EC-Illuminance	56	33	233	322
Reference	56	32	246	335
EC- High Glare	56	32	246	335
Extruded Box Flush Glazing	59	33	254	346
Lightshelf	55	33	268	356

Table 16 shows the mean value and standard deviation of heating, cooling and electrical lighting energy portion (%) for all alternatives of East-facing case. As it can be seen, both lighting and heating energy are responsible for greater portions of total energy consumption, while the mean value cooling percentage portion has slightly decreased, compared to both the South and West.

Table 16. East- Mean percentage of heating, cooling and lighting portion of total EUI

	Electric Lighting EUI [MJ/m2]	Heating EUI [MJ/m2]	Cooling EUI [MJ/m2]
Mean	19.7	11.2	69
Standard Deviation	3.6	1.5	5.2

In this case, like the West, three alternatives perform worse than the Reference: EC- High Glare (335 MJ/m2), Extruded Box-Flush Glazing (346 MJ/m2), and Lightshelf (356 MJ/m2). The Overhang and Eggcrate are the most efficient alternatives (294 and 296 MJ/m2 respectively), although Eggcrate has a higher lighting energy consumption. A comparison between the alternatives of the highest and lowest efficiencies reveals the dominant value of cooling load in Lightshelf further compensates for its relatively lower lighting energy. Figure 4.15 shows the proportion of each energy sector in these three alternatives.

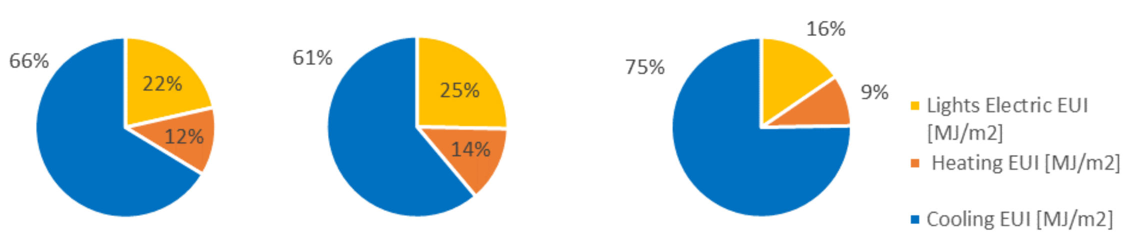

Figure 22. Portion of heating, cooling and lighting in Total EU (East-Overhang, East - LightShef, and East-Eggcrate)

Considering and comparing the EC alternatives, it is clear that EC-High Solar is the third most efficient strategy among all alternatives. EC- Glare and Illuminance and EC-Illuminance are the 7th and 8th, still performing better than the Reference. On the other hand, EC- High Glare is less efficient compared to the Reference.

4.4 Hourly Comparison Analysis

In this section, the hourly comparison for all alternatives is provided in two days, June 18 and Dec 18, as the representative for presumably hot and cold days of the year.

4.4.1 Hourly Comparison of Cooling Load: June 18

The heating load for the Summer days in Austin, TX is mostly 0 as expected for a hot climate. Therefore, only the diagrams for the cooling rate is available for the date of June 18 which can be seen in Figures 23-25.

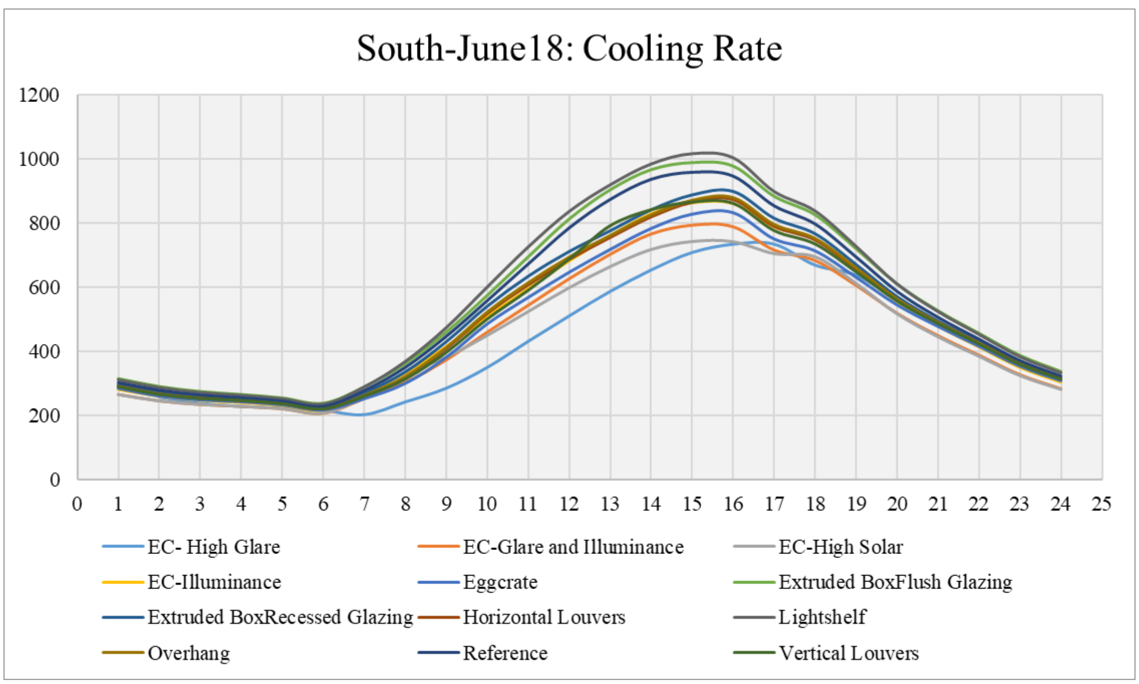

Figure 23. South-Hourly cooling load on June 18

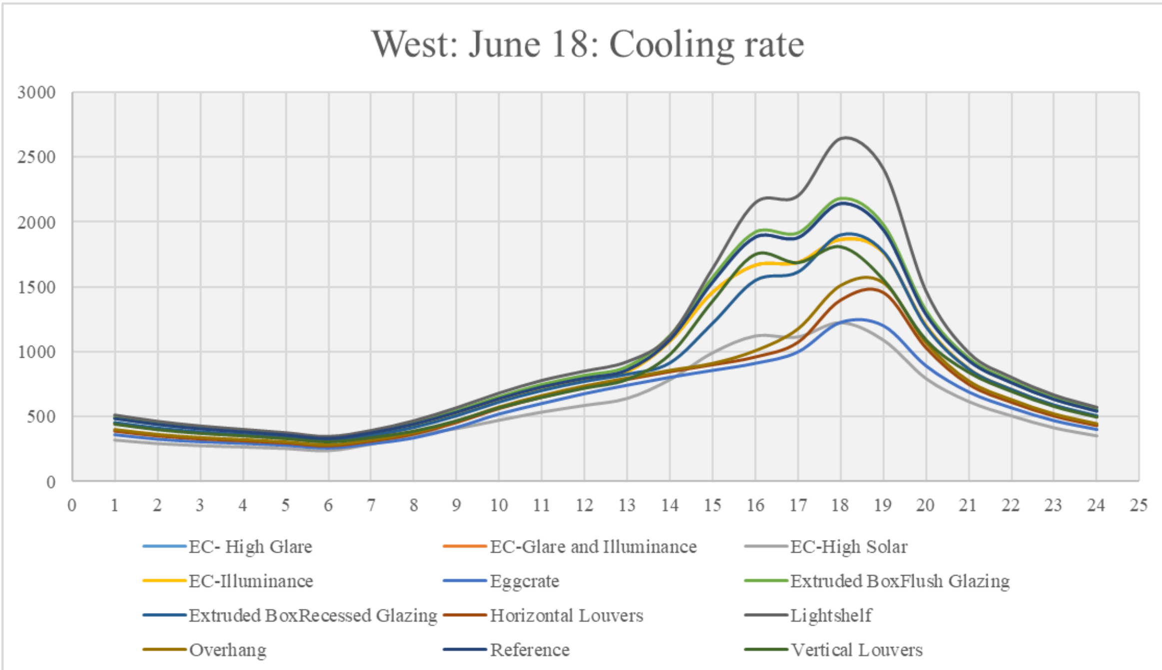

Figure 24. West-Hourly cooling load on June 18

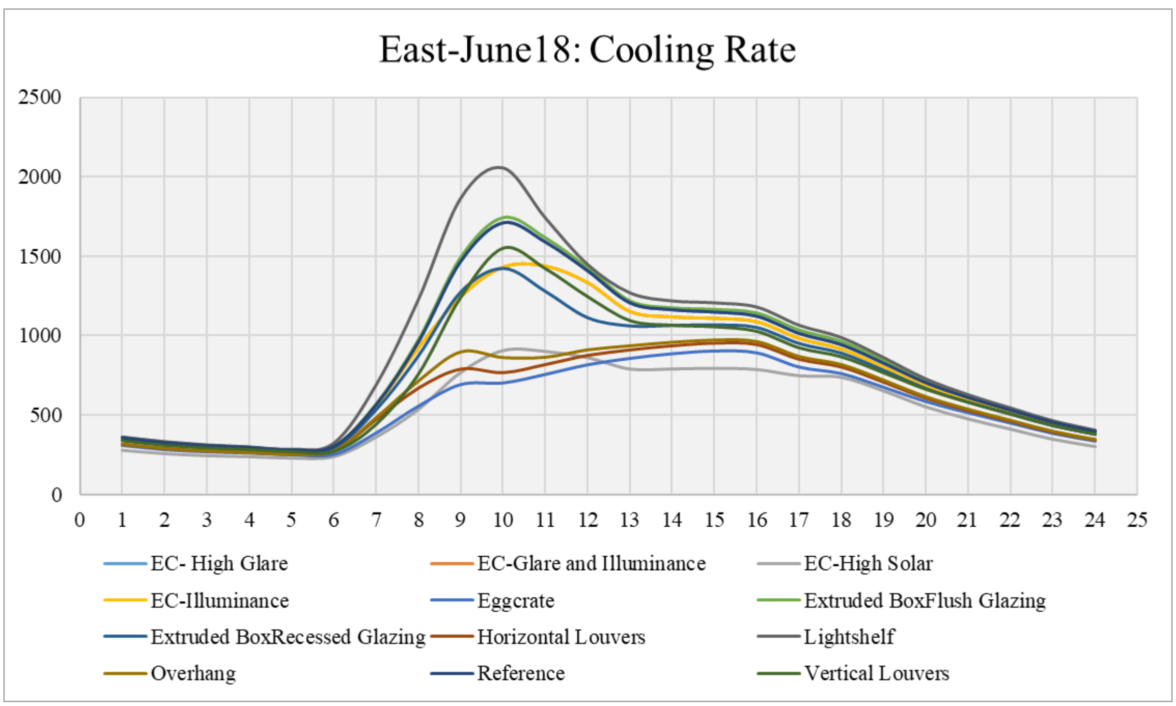

Figure 25. East-Hourly cooling load on June 18

Figure 26 shows the comparison of all scenarios for all the orientation in a 3 dimensional graph. This diagram demonstrates the overall energy consumption on June 18 is higher in West-facing units and it is the lowest in South facing units.

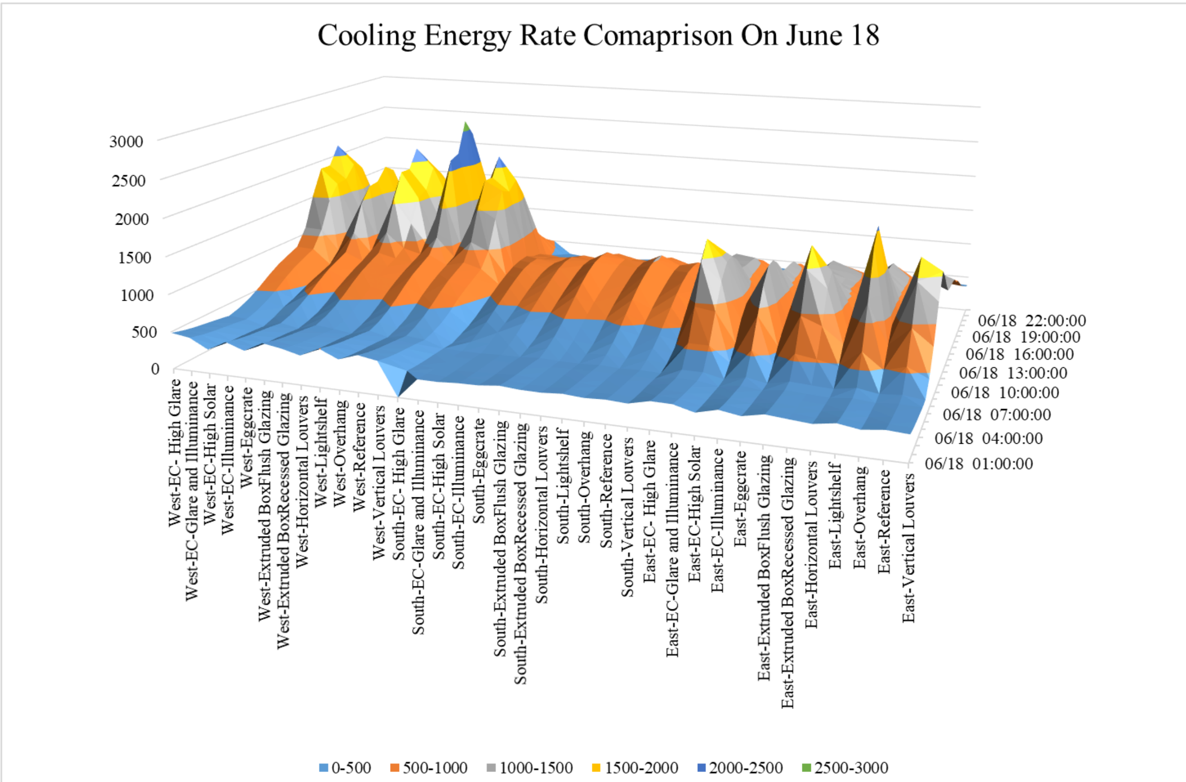

Figure 26. Cooling energy rate for all alternatives on June 18

4.4.1 Hourly Comparison of Heating Load: Dec 18

Figures 27 to 29 are representing the heating rate on Dec 18 for the South, West, and East cases.

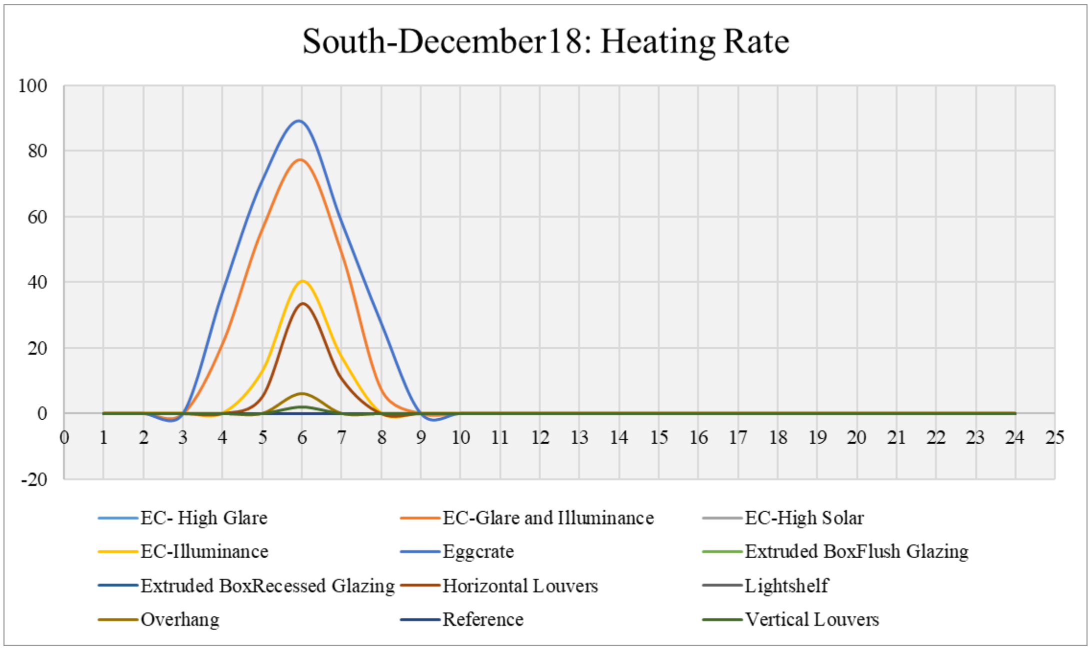

Figure 27. South-Hourly heating load on Dec 18

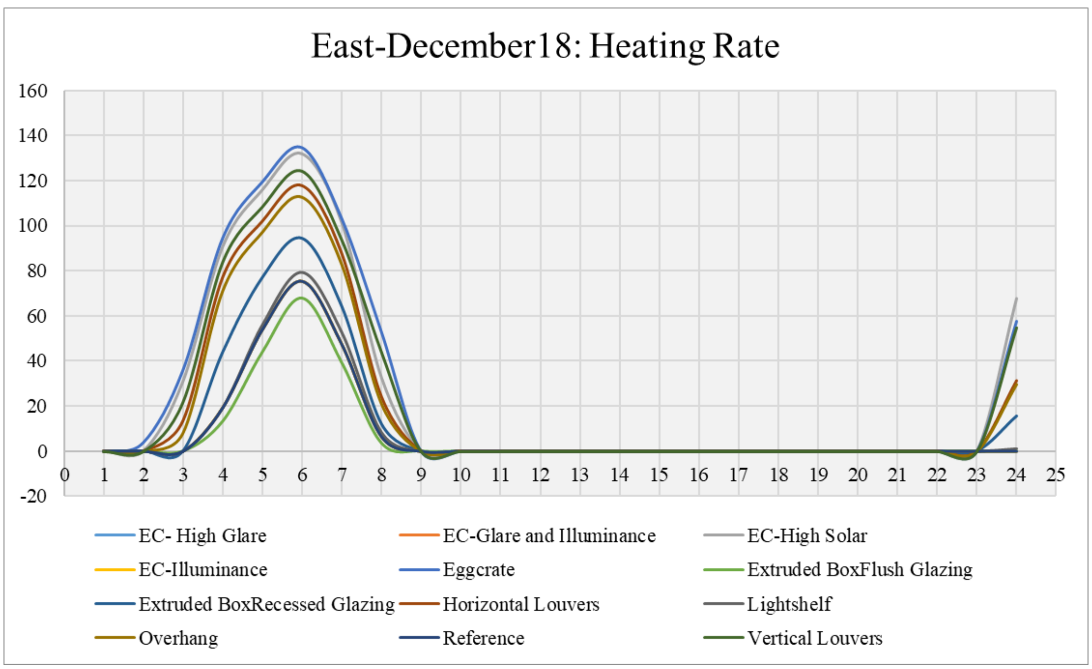

Figure 28. East-Hourly heating load on Dec 18

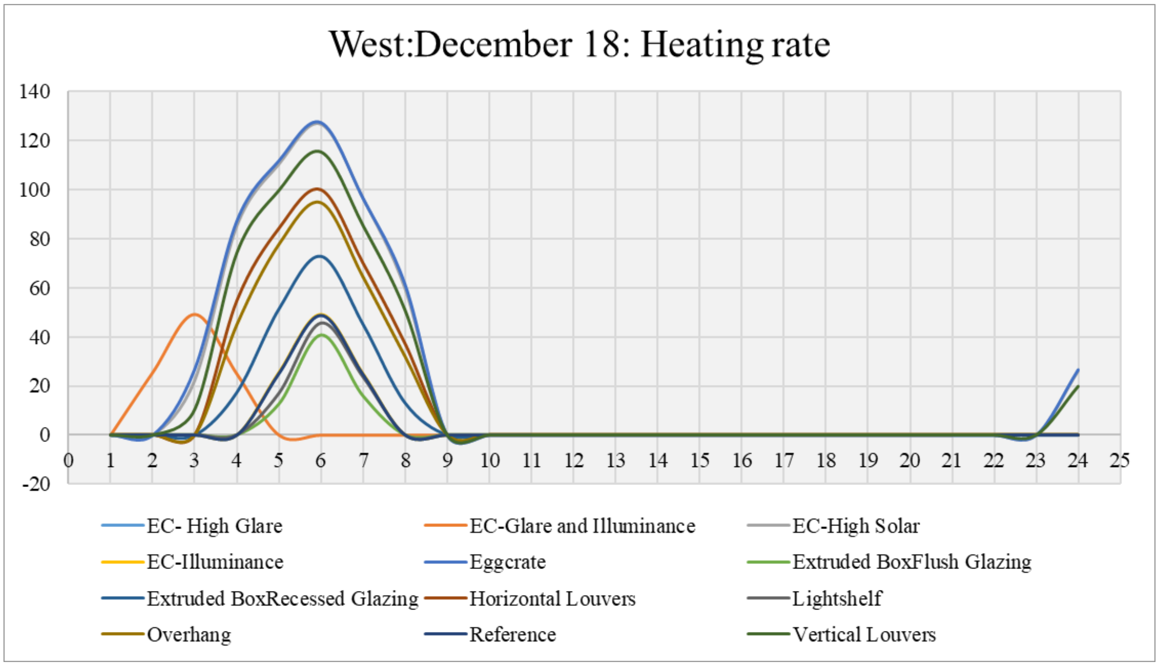

Figure 29. West-Hourly heating load on Dec 18

Based on the comparison of the heating rate, it is shown that East, West, and south are having the having highest and lowest heating rate respectively.

Cooling is available only for West and South orientations, and East orientation does not have any cooling load during the day of Dec 18 since there is no direct sun light for the east orientation.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

In this section, the comparison of energy consumption of the all alternative scenarios as well as different orientations are analyzed. Next, a comprehensive discussion on how to select the right approach and the trade-offs based on the orientation and the preferences are provided. Finally, recommendations for possible extensions and future work is provided.

5.1. ENERGY SAVING IN ALL ALTERNATIVES ALL ORIENTATION CASES

In this section, all the alternatives in all three orientation cases are presented and compared with each other. Figure 30 indicates the energy saving results for all alternatives compared to the Reference. It is shown that in Austin, as far as cooling is considered (and it is a dominant issue), Lightshelf and Extruded Box-Flush Glazing are not suitable alternatives, no matter in which orientation they are installed. Eggcrate has the greatest potential to save cooling energy results in South, while in the West and East EC-High Solar deliver the highest reduction in cooling load. Horizontal Louvers and Overhang are the next best alternatives for the South, especially the later one when view is a concern. This figure has the potential to provide an architect with the most energy efficient alternative for each orientation as far as solely cooling is an issue in decision-making.

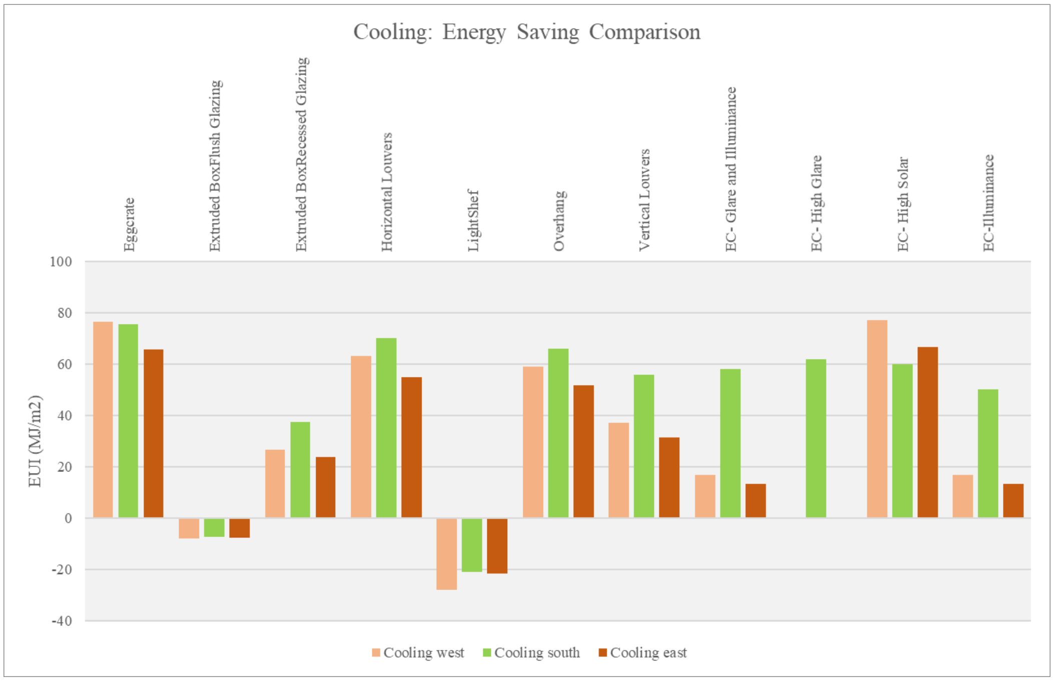

Figure 30. Cooling energy saving comparison, all alternatives all orientations

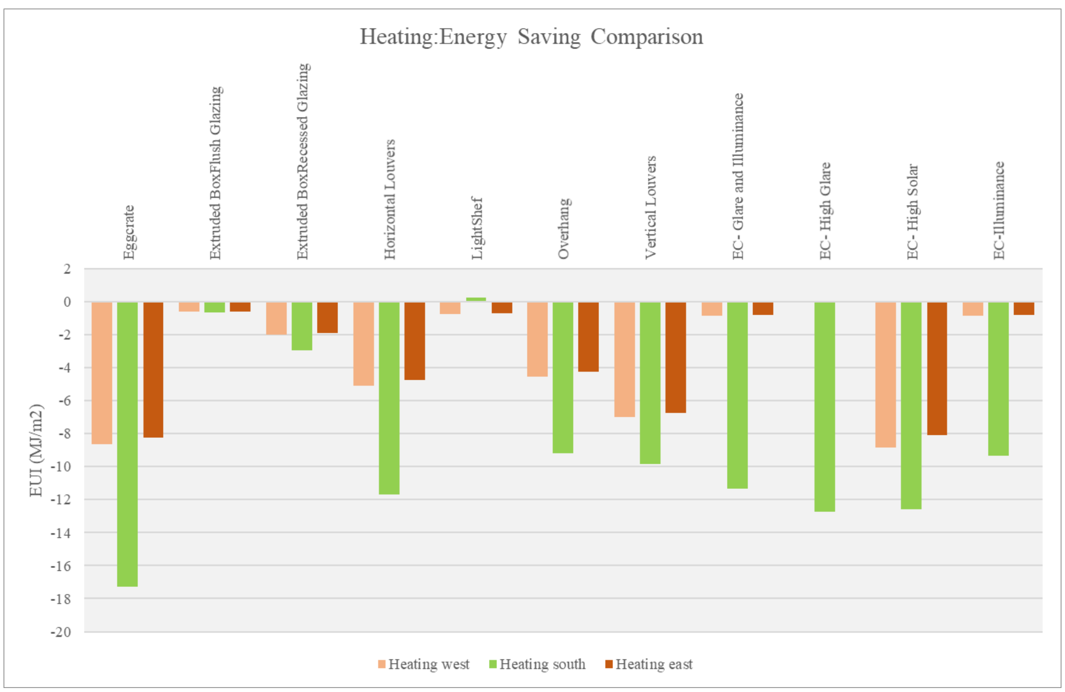

Figure 31. Heating energy saving comparison, all alternatives all orientations

Figure 31 shows the similar result for heating load. Unlikely to be an issue in Austin, heating load yet can be reduced by some alternative more than others. Therefore, no more analysis is provided in this part. However, the results can be useful in case this is a concern of design for any probable reason.

When lighting energy is a concern (Figure 32), EC-High Solar is not an option, regardless of the orientation. The EC-High Glare even performs worst in the South. EC-Illuminance seems to deliver the highest energy efficiency in all three orientations, with a negligible increase in lighting energy.

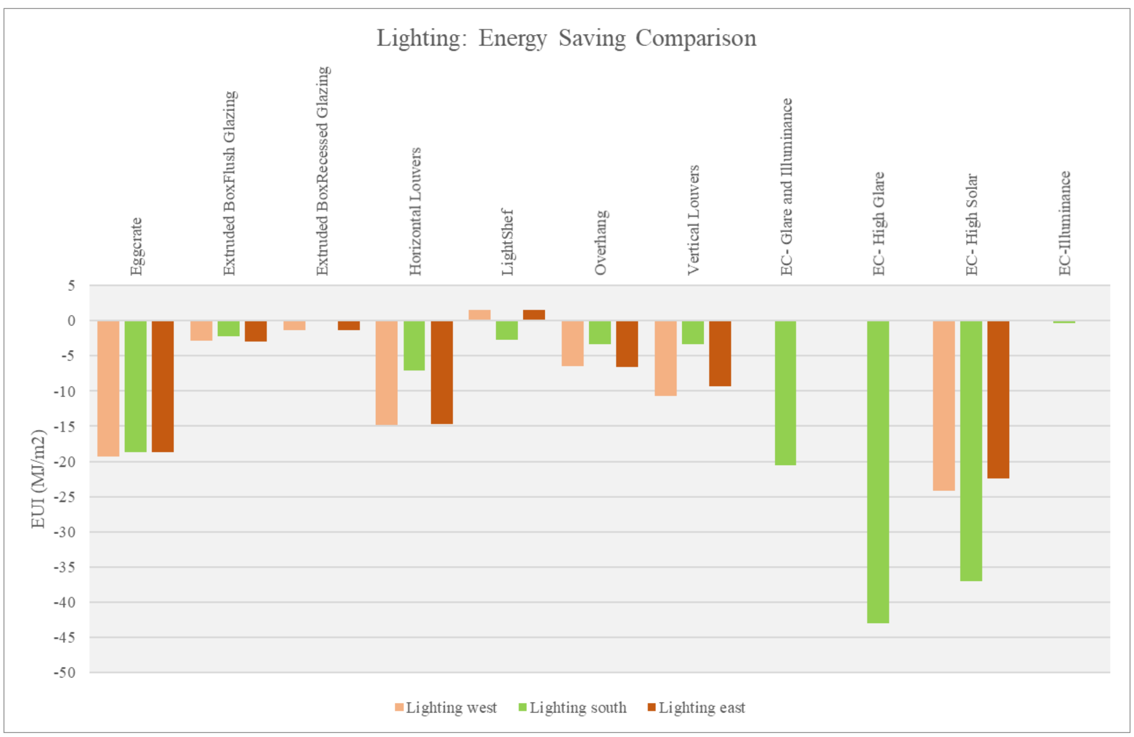

Figure 32. Electrical lighting energy saving comparison, all alternatives all orientations

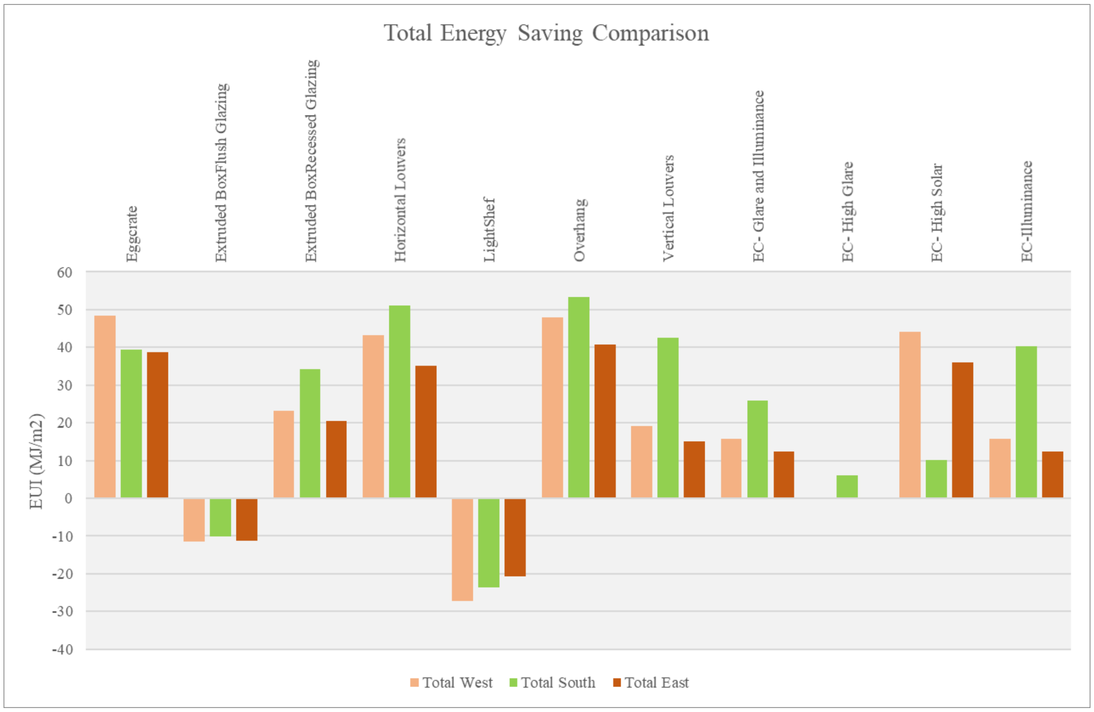

Figure 33.Total energy saving comparison , all alternatives all orientations

The overall energy saving result by all the alternatives in all orientations is depicted in Figure 33.

Lightshelf performs as the worst alternative among all analyzed strategies in Austin. However, if it is going to be installed in a building, it would give a better energy consumption performance first in East, then South, and finally West orientation.

After Lightshelf, the Extruded Box-Flush Glazing is the second worst alternative in all three orientations (with not much of a difference), and increases the total energy consumption in Austin.

Overhang is the most energy efficient alternative in both the South and East orientation, with about 2 (MJ/m2) difference in EUI compared to their second best (i.e.

Horizontal Louvers and Eggcrate in south and east respectively). Overhang is the second most energy efficient alternative in West, just after the Eggcrate with less than 0.5 MJ/m2 difference in EUI. Therefore, especially as Eggcrate considerably blocks the view, the Overhang can be counted as the best alternative in West too.

An interesting point is the performance of horizontal and vertical louvers in all orientations. Horizontal Louvers are more energy efficient than Vertical ones (with 8.5 MJ/m2 EUI difference) in South, which is not a surprise. These strategies also perform better in both West (with 24 MJ/m2 EUI difference) and East (with 24 MJ/m2 EUI difference). This is totally again the rule of thumb assumption that Vertical louvers are the best alternative for East and West in terms of energy efficiency.

In order to evaluate the performance of EC alternatives compared to all other alternatives, a diagram indicating relative percentage difference of EUI in each category would be useful, which is illustrated in Figure 34 and Table 17.

As shown in Table17, depending on the control strategy, the EC alternatives can achieve relative percentage reduction of EUI in each orientation as follows:

- In the West, they can reduce the EUI from 0 to 12.6%, while other alternatives fall in a range of -7.8 to 13.8%, while the mean value of reduction is 5.7%. This means that EC-High Solar is considered a really efficient in the West, while others cannot even reach the average energy saving value though.
- In the South, they can reduce the EUI from 2.1 to 14%, while other alternatives fall in a range of -8.2 to 18.5%, and the mean value of reduction is 8.5%. EC-Illuminance and EC-Glare & Illuminance perform better than the average in this orientation.
- In the East, they can reduce the EUI from 0 to 10.7 %, while other alternatives fall in a range of -6.2 to 12.2%, and the mean value of reduction is 4.9%. EC-High Solar perform far better than average in this orientation.

Table 17. Relative energy saving for EC alternatives

	EC-Glare & Illuminance	EC-High Glare	EC-High Solar	EC-Illuminance	Minimum Value (All Alternatives)	Maximum Value (All Alternatives)	Mean Value (All Alternatives)
Total EUI Savings West	4.5%	0.0%	12.6%	4.5%	-7.8%	13.8%	5.7%
Total EUI Savings South	9.0%	2.1%	3.5%	14.0%	-8.2%	18.5%	8.5%
Total EUI Savings East	3.7%	0.0%	10.7%	3.7%	-6.2%	12.2%	4.9%

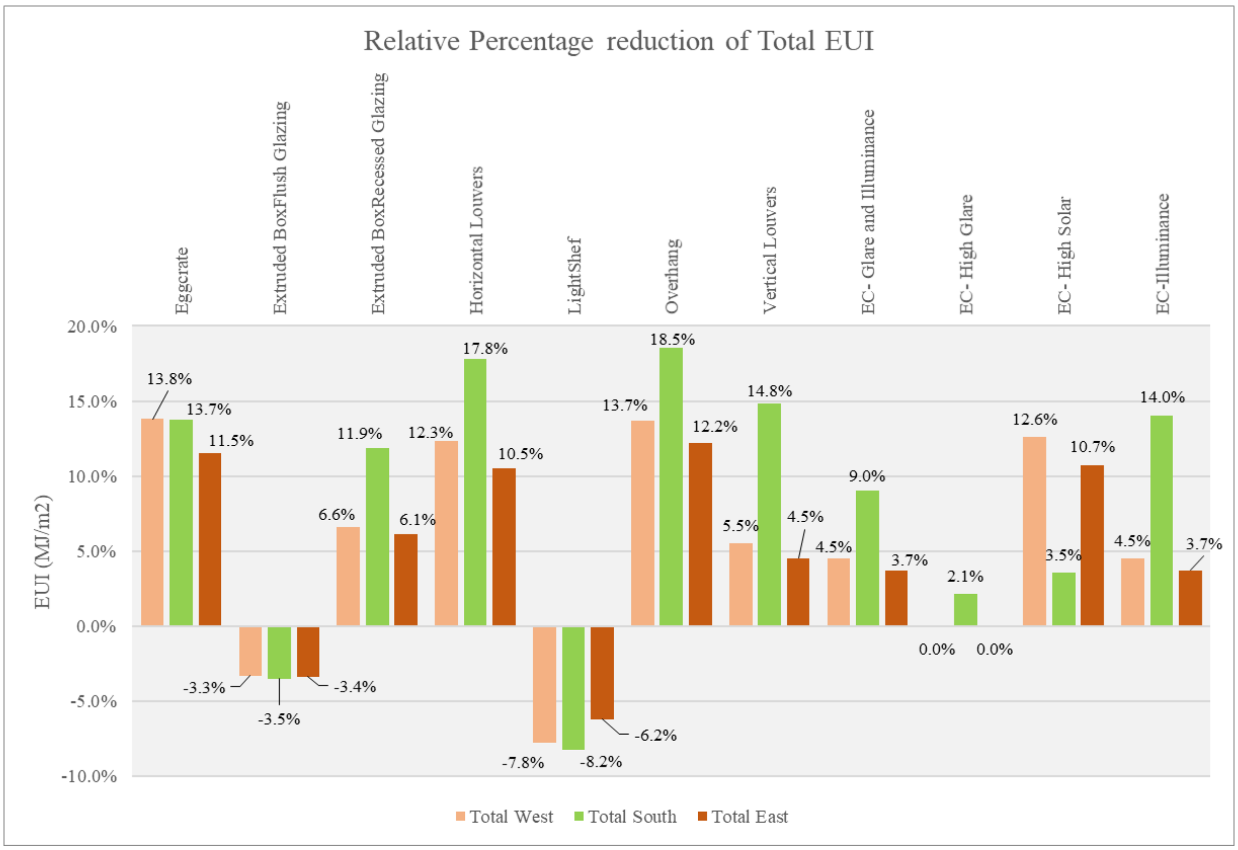

Figure 34. Relative reduction of total EUI by percentage

According to the results in Figure 34, we can decide which alternative strategy is a better choice for each orientation. Table 18 shows orientation priority for conventional shading device alternatives and EC alternatives. It is demonstrated that almost all the alternatives follow the pattern of efficiency South-West-East. Among conventional shading devices, two strategies, Lightshelf and Extruded Box Flush, with negative effect show a different pattern. EC-High Solar also shows a distinctively different pattern, performing the best and worst in the West and South.

Table 18. Orientation priority according to energy efficiency

Conventional Shading Device Alternatives			
	1st in Energy Efficiency	2nd in Energy Efficiency	3d in Energy Efficiency
Eggcrate	West	South	East
Extruded Box: Flush Glazing	-(West)	-(East)	-(South)
Extruded Box: Recessed Glazing	South	West	East
Horizontal Louvers	South	West	East
Lightshelf	-(East)	-(West)	-(South)
Overhang	South	West	East
Vertical Louvers	South	West	East
EC Alternatives			
EC- Glare and Illuminance	South	West	East
EC- High Glare	South	0	
EC- High Solar	West	East	South
EC-Illuminance	South	West	East

An overall summary of all the above-mentioned conclusions and also the results from chapter 3 can be seen in the summary map in Figure 35. This map shows how efficient each alternative in each orientation performs compared to other alternatives either in the same orientation or in others. The total EUI (MJ/m2) is shown on the vertical axis.

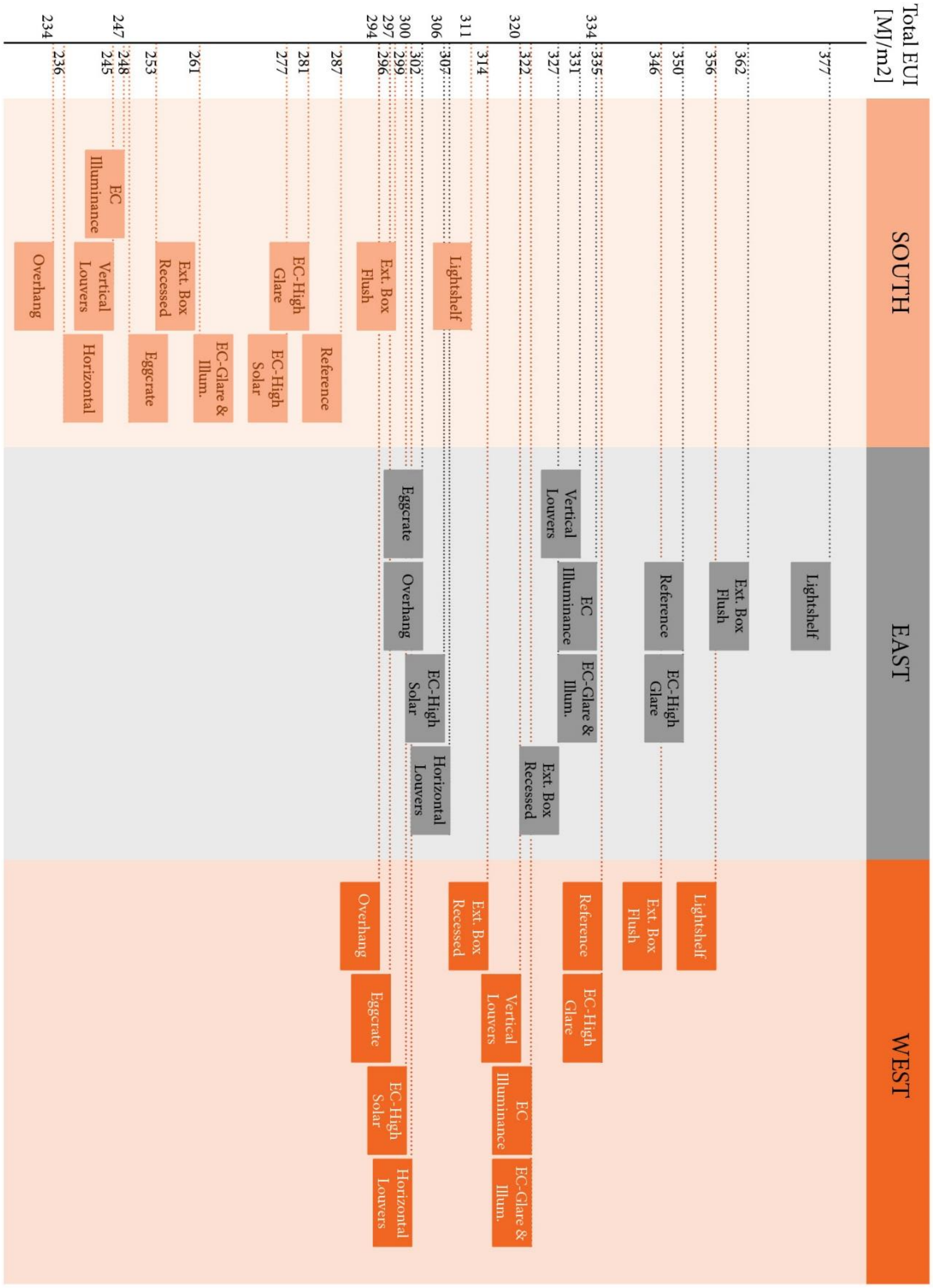

Figure 35. Summary map

5.2. The effect of Control Strategy on Energy Saving

As it was shown in different energy sectors (heating, cooling, and lighting) and also total energy need for each orientation case, the control strategy of an EC is a decisive factor for its energy efficiency (which is in line with previous studies mentioned in the literature review).

Tables 5, 10, and 15 show how the control strategy can make the EC provide a positive/negative or even no effect on energy efficiency in each orientation. This can even define how an EC alternative performs in each energy sector. Table 17 indicates the role of EC control strategy in energy efficiency as well.

5.3. Recommendations for Future Works

According to the research method and limitation of this study, there are some recommendations that might be useful for future work as well with the same research question and objectives.

First of all, this study considered the more common shapes and easily applicable size of each shading device. Optimum-sized shading devices would provide us with a more accurate comparison results which are closer to the real world. Moreover, other types of shading devices (including interior and In-between too) can be added to this comparison.

Also, the similar simulation framework can be employed with a HVAC system which was out the scope of this work. This would also provide an estimation about the energy consumption value in each case.

Moreover, EnergyPlus only provides two states of the EC glazing. More stages between the clear and dark state can be added employing the MLE+ or E-Quest.

Finally, this study only investigated the energy efficiency of shading device and EC. More investigation is required to evaluate each alternative in interior lighting quality and glare as well as the view.

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Appendix

```
!-   ===========  ALL OBJECTS IN CLASS: MATERIAL ===========

Material,
    F13 Built-up roofing,    !- Name
    Rough,                   !- Roughness
    0.0095,                  !- Thickness {m}
    0.16,                    !- Conductivity {W/m-K}
    1120,                    !- Density {kg/m3}
    1460,                    !- Specific Heat {J/kg-K}
    0.75,                    !- Thermal Absorptance
    0.45;                    !- Solar Absorptance

Material,
    F07 25mm stucco,         !- Name
    Smooth,                  !- Roughness
    0.0254,                  !- Thickness {m}
    0.72,                    !- Conductivity {W/m-K}
    1856,                    !- Density {kg/m3}
    840,                     !- Specific Heat {J/kg-K}
    0.9,                     !- Thermal Absorptance
    0.7,                     !- Solar Absorptance
    0.7;                     !- Visible Absorptance

Material,
    G01 16mm gypsum board,   !- Name
    MediumSmooth,            !- Roughness
    0.0159,                  !- Thickness {m}
    0.16,                    !- Conductivity {W/m-K}
    800,                     !- Density {kg/m3}
    1090;                    !- Specific Heat {J/kg-K}

Material,
    100mm Normalweight concrete floor,  !- Name
    MediumRough,             !- Roughness
    0.1016,                  !- Thickness {m}
    2.31,                    !- Conductivity {W/m-K}
    2322,                    !- Density {kg/m3}
    832;                     !- Specific Heat {J/kg-K}

Material,
    1/2IN Gypsum,            !- Name
    Smooth,                  !- Roughness
    0.0127,                  !- Thickness {m}
    0.16,                    !- Conductivity {W/m-K}
    784.9,                   !- Density {kg/m3}
    830.000000000001,        !- Specific Heat {J/kg-K}
    0.9,                     !- Thermal Absorptance
    0.4,                     !- Solar Absorptance
    0.4;                     !- Visible Absorptance

Material,
    1IN Stucco,              !- Name
    Smooth,                  !- Roughness
```

```
    0.0253,                  !- Thickness {m}
    0.691799999999999,       !- Conductivity {W/m-K}
    1858,                    !- Density {kg/m3}
    836.999999999999,        !- Specific Heat {J/kg-K}
    0.9,                     !- Thermal Absorptance
    0.92,                    !- Solar Absorptance
    0.92;                    !- Visible Absorptance

Material,
    8IN Concrete HW,         !- Name
    MediumRough,             !- Roughness
    0.2033,                  !- Thickness {m}
    1.72959999999999,        !- Conductivity {W/m-K}
    2242.99999999999,        !- Density {kg/m3}
    836.999999999999,        !- Specific Heat {J/kg-K}
    0.9,                     !- Thermal Absorptance
    0.65,                    !- Solar Absorptance
    0.65;                    !- Visible Absorptance

Material,
    8IN CONCRETE HW RefBldg, !- Name
    Rough,                   !- Roughness
    0.2032,                  !- Thickness {m}
    1.311,                   !- Conductivity {W/m-K}
    2240,                    !- Density {kg/m3}
    836.800000000001,        !- Specific Heat {J/kg-K}
    0.9,                     !- Thermal Absorptance
    0.7,                     !- Solar Absorptance
    0.7;                     !- Visible Absorptance

Material,
    F08 Metal surface,       !- Name
    Smooth,                  !- Roughness
    0.0008,                  !- Thickness {m}
    45.2800000000001,        !- Conductivity {W/m-K}
    7823.99999999999,        !- Density {kg/m3}
    500,                     !- Specific Heat {J/kg-K}
    0.9,                     !- Thermal Absorptance
    0.7,                     !- Solar Absorptance
    0.7;                     !- Visible Absorptance

Material,
    F16 Acoustic tile,       !- Name
    MediumSmooth,            !- Roughness
    0.0191,                  !- Thickness {m}
    0.06,                    !- Conductivity {W/m-K}
    368,                     !- Density {kg/m3}
    590.000000000002,        !- Specific Heat {J/kg-K}
    0.9,                     !- Thermal Absorptance
    0.3,                     !- Solar Absorptance
    0.3;                     !- Visible Absorptance

Material,
    G01a 19mm gypsum board,  !- Name
    MediumSmooth,            !- Roughness
    0.019,                   !- Thickness {m}
    0.16,                    !- Conductivity {W/m-K}
    800,                     !- Density {kg/m3}
```

```
    1090,                    !- Specific Heat {J/kg-K}
    0.9,                     !- Thermal Absorptance
    0.4,                     !- Solar Absorptance
    0.4;                     !- Visible Absorptance

Material,
    G05 25mm wood,           !- Name
    MediumSmooth,            !- Roughness
    0.0254,                  !- Thickness {m}
    0.15,                    !- Conductivity {W/m-K}
    608,                     !- Density {kg/m3}
    1630,                    !- Specific Heat {J/kg-K}
    0.9,                     !- Thermal Absorptance
    0.5,                     !- Solar Absorptance
    0.5;                     !- Visible Absorptance

Material,
    I01 25mm insulation board,  !- Name
    MediumRough,             !- Roughness
    0.0254,                  !- Thickness {m}
    0.03,                    !- Conductivity {W/m-K}
    43,                      !- Density {kg/m3}
    1210,                    !- Specific Heat {J/kg-K}
    0.9,                     !- Thermal Absorptance
    0.6,                     !- Solar Absorptance
    0.6;                     !- Visible Absorptance

Material,
    IEAD Roof Insulation R-19.72 IP,  !- Name
    MediumRough,             !- Roughness
    0.170137206506431,       !- Thickness {m}
    0.049,                   !- Conductivity {W/m-K}
    265,                     !- Density {kg/m3}
    836.800000000001,        !- Specific Heat {J/kg-K}
    0.9,                     !- Thermal Absorptance
    0.7,                     !- Solar Absorptance
    0.7;                     !- Visible Absorptance

Material,
    M11 100mm lightweight concrete,  !- Name
    MediumRough,             !- Roughness
    0.1016,                  !- Thickness {m}
    0.53,                    !- Conductivity {W/m-K}
    1280,                    !- Density {kg/m3}
    840.000000000002,        !- Specific Heat {J/kg-K}
    0.9,                     !- Thermal Absorptance
    0.5,                     !- Solar Absorptance
    0.5;                     !- Visible Absorptance

Material,
    Mass Wall Insulation R-4.23 IP,  !- Name
    MediumRough,             !- Roughness
    0.0365371685816,         !- Thickness {m}
    0.049,                   !- Conductivity {W/m-K}
    265,                     !- Density {kg/m3}
    836.800000000001,        !- Specific Heat {J/kg-K}
    0.9,                     !- Thermal Absorptance
    0.7,                     !- Solar Absorptance
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   0.7;                     !- Visible Absorptance

Material,
   MAT-CC05 4 HW CONCRETE,  !- Name
   Rough,                   !- Roughness
   0.1016,                  !- Thickness {m}
   1.311,                   !- Conductivity {W/m-K}
   2240,                    !- Density {kg/m3}
   836.800000000001,        !- Specific Heat {J/kg-K}
   0.9,                     !- Thermal Absorptance
   0.85,                    !- Solar Absorptance
   0.85;                    !- Visible Absorptance

Material,
   Metal Decking,           !- Name
   MediumSmooth,            !- Roughness
   0.0015,                  !- Thickness {m}
   45.006,                  !- Conductivity {W/m-K}
   7680,                    !- Density {kg/m3}
   418.4,                   !- Specific Heat {J/kg-K}
   0.9,                     !- Thermal Absorptance
   0.6,                     !- Solar Absorptance
   0.6;                     !- Visible Absorptance

Material,
   Metal Roofing,           !- Name
   MediumSmooth,            !- Roughness
   0.0015,                  !- Thickness {m}
   45.006,                  !- Conductivity {W/m-K}
   7680,                    !- Density {kg/m3}
   418.4,                   !- Specific Heat {J/kg-K}
   0.9,                     !- Thermal Absorptance
   0.6,                     !- Solar Absorptance
   0.6;                     !- Visible Absorptance

Material,
   Roof Insulation [18],    !- Name
   MediumRough,             !- Roughness
   0.1693,                  !- Thickness {m}
   0.049,                   !- Conductivity {W/m-K}
   265,                     !- Density {kg/m3}
   836.800000000001,        !- Specific Heat {J/kg-K}
   0.9,                     !- Thermal Absorptance
   0.7,                     !- Solar Absorptance
   0.7;                     !- Visible Absorptance

Material,
   Roof Insulation [21],    !- Name
   MediumRough,             !- Roughness
   0.2105,                  !- Thickness {m}
   0.049,                   !- Conductivity {W/m-K}
   265,                     !- Density {kg/m3}
   836.800000000001,        !- Specific Heat {J/kg-K}
   0.9,                     !- Thermal Absorptance
   0.7,                     !- Solar Absorptance
   0.7;                     !- Visible Absorptance

Material,
```

```
    Roof Insulation [25],    !- Name
    MediumRough,             !- Roughness
    0.263,                   !- Thickness {m}
    0.049,                   !- Conductivity {W/m-K}
    265,                     !- Density {kg/m3}
    836.800000000001,        !- Specific Heat {J/kg-K}
    0.9,                     !- Thermal Absorptance
    0.7,                     !- Solar Absorptance
    0.7;                     !- Visible Absorptance

Material,
    Roof Insulation [26],    !- Name
    MediumRough,             !- Roughness
    0.2941,                  !- Thickness {m}
    0.049,                   !- Conductivity {W/m-K}
    265,                     !- Density {kg/m3}
    836.800000000001,        !- Specific Heat {J/kg-K}
    0.9,                     !- Thermal Absorptance
    0.7,                     !- Solar Absorptance
    0.7;                     !- Visible Absorptance

Material,
    Roof Membrane,           !- Name
    VeryRough,               !- Roughness
    0.0095,                  !- Thickness {m}
    0.16,                    !- Conductivity {W/m-K}
    1121.29,                 !- Density {kg/m3}
    1460,                    !- Specific Heat {J/kg-K}
    0.9,                     !- Thermal Absorptance
    0.7,                     !- Solar Absorptance
    0.7;                     !- Visible Absorptance

Material,
    Wall Insulation [31],    !- Name
    MediumRough,             !- Roughness
    0.0337000000000001,      !- Thickness {m}
    0.0432,                  !- Conductivity {W/m-K}
    91,                      !- Density {kg/m3}
    836.999999999999,        !- Specific Heat {J/kg-K}
    0.9,                     !- Thermal Absorptance
    0.5,                     !- Solar Absorptance
    0.5;                     !- Visible Absorptance

Material,
    Wall Insulation [35],    !- Name
    MediumRough,             !- Roughness
    0.0452,                  !- Thickness {m}
    0.0432,                  !- Conductivity {W/m-K}
    91,                      !- Density {kg/m3}
    836.999999999999,        !- Specific Heat {J/kg-K}
    0.9,                     !- Thermal Absorptance
    0.5,                     !- Solar Absorptance
    0.5;                     !- Visible Absorptance

Material,
    Wall Insulation [36],    !- Name
    MediumRough,             !- Roughness
    0.0565999999999999,      !- Thickness {m}
```

```
  0.0432,                 !- Conductivity {W/m-K}
  91,                     !- Density {kg/m3}
  836.999999999999,       !- Specific Heat {J/kg-K}
  0.9,                    !- Thermal Absorptance
  0.5,                    !- Solar Absorptance
  0.5;                    !- Visible Absorptance

Material,
  Wall Insulation [37],   !- Name
  MediumRough,            !- Roughness
  0.0680999999999999,     !- Thickness {m}
  0.0432,                 !- Conductivity {W/m-K}
  91,                     !- Density {kg/m3}
  836.999999999999,       !- Specific Heat {J/kg-K}
  0.9,                    !- Thermal Absorptance
  0.5,                    !- Solar Absorptance
  0.5;                    !- Visible Absorptance

Material,
  Wall Insulation [40],   !- Name
  MediumRough,            !- Roughness
  0.0793999999999999,     !- Thickness {m}
  0.0432,                 !- Conductivity {W/m-K}
  91,                     !- Density {kg/m3}
  836.999999999999,       !- Specific Heat {J/kg-K}
  0.9,                    !- Thermal Absorptance
  0.5,                    !- Solar Absorptance
  0.5;                    !- Visible Absorptance

Material,
  Wall Insulation [42],   !- Name
  MediumRough,            !- Roughness
  0.0913999999999999,     !- Thickness {m}
  0.0432,                 !- Conductivity {W/m-K}
  91,                     !- Density {kg/m3}
  836.999999999999,       !- Specific Heat {J/kg-K}
  0.9,                    !- Thermal Absorptance
  0.5,                    !- Solar Absorptance
  0.5;                    !- Visible Absorptance

Material,
  Wall Insulation [44],   !- Name
  MediumRough,            !- Roughness
  0.1104,                 !- Thickness {m}
  0.0432,                 !- Conductivity {W/m-K}
  91,                     !- Density {kg/m3}
  836.999999999999,       !- Specific Heat {J/kg-K}
  0.9,                    !- Thermal Absorptance
  0.5,                    !- Solar Absorptance
  0.5;                    !- Visible Absorptance

Material,
  Air Wall Material,      !- Name
  MediumSmooth,           !- Roughness
  0.01,                   !- Thickness {m}
  0.6,                    !- Conductivity {W/m-K}
  800,                    !- Density {kg/m3}
  1000,                   !- Specific Heat {J/kg-K}
```

```
    0.95,                    !- Thermal Absorptance
    0.7,                     !- Solar Absorptance
    0.7;                     !- Visible Absorptance

Material,
    PLASTERBOARD-1,          !- Name
    MediumSmooth,            !- Roughness
    0.01200,                 !- Thickness {m}
    0.16000,                 !- Conductivity {W/m-K}
    950.000,                 !- Density {kg/m3}
    840.00,                  !- Specific Heat {J/kg-K}
    0.900000,                !- Thermal Absorptance
    0.600000,                !- Solar Absorptance
    0.600000;                !- Visible Absorptance

Material,
    FIBERGLASS QUILT-1,      !- Name
    Rough,                   !- Roughness
    0.066,                   !- Thickness {m}
    0.040,                   !- Conductivity {W/m-K}
    12.000,                  !- Density {kg/m3}
    840.00,                  !- Specific Heat {J/kg-K}
    0.900000,                !- Thermal Absorptance
    0.600000,                !- Solar Absorptance
    0.600000;                !- Visible Absorptance

Material,
    WOOD SIDING-1,           !- Name
    Rough,                   !- Roughness
    0.00900,                 !- Thickness {m}
    0.14000,                 !- Conductivity {W/m-K}
    530.000,                 !- Density {kg/m3}
    900.00,                  !- Specific Heat {J/kg-K}
    0.900000,                !- Thermal Absorptance
    0.600000,                !- Solar Absorptance
    0.600000;                !- Visible Absorptance

Material,
    PLASTERBOARD-2,          !- Name
    Rough,                   !- Roughness
    0.01000,                 !- Thickness {m}
    0.16000,                 !- Conductivity {W/m-K}
    950.000,                 !- Density {kg/m3}
    840.00,                  !- Specific Heat {J/kg-K}
    0.900000,                !- Thermal Absorptance
    0.600000,                !- Solar Absorptance
    0.600000;                !- Visible Absorptance

Material,
    FIBERGLASS QUILT-2,      !- Name
    Rough,                   !- Roughness
    0.1118,                  !- Thickness {m}
    0.040,                   !- Conductivity {W/m-K}
    12.000,                  !- Density {kg/m3}
    840.00,                  !- Specific Heat {J/kg-K}
    0.900000,                !- Thermal Absorptance
    0.600000,                !- Solar Absorptance
    0.600000;                !- Visible Absorptance
```

```
Material,
    ROOF DECK,               !- Name
    Rough,                   !- Roughness
    0.01900,                 !- Thickness {m}
    0.14000,                 !- Conductivity {W/m-K}
    530.000,                 !- Density {kg/m3}
    900.00,                  !- Specific Heat {J/kg-K}
    0.900000,                !- Thermal Absorptance
    0.600000,                !- Solar Absorptance
    0.600000;                !- Visible Absorptance

Material,
    HF-C5,                   !- Name
    MediumRough,             !- Roughness
    0.1015000,               !- Thickness {m}
    1.729600,                !- Conductivity {W/m-K}
    2243.000,                !- Density {kg/m3}
    837.0000,                !- Specific Heat {J/kg-K}
    0.9000000,               !- Thermal Absorptance
    0.6500000,               !- Solar Absorptance
    0.6500000;               !- Visible Absorptance


!-   ===========  ALL OBJECTS IN CLASS: MATERIAL:NOMASS ===========

Material:NoMass,
    Nonres_Roof_Insulation,  !- Name
    MediumSmooth,            !- Roughness
    4.31888738734588,        !- Thermal Resistance {m2-K/W}
    0.9,                     !- Thermal Absorptance
    0.7,                     !- Solar Absorptance
    0.7;                     !- Visible Absorptance

Material:NoMass,
    Nonres_Exterior_Wall_Insulation,  !- Name
    MediumSmooth,            !- Roughness
    1.71282848878858,        !- Thermal Resistance {m2-K/W}
    0.9,                     !- Thermal Absorptance
    0.7,                     !- Solar Absorptance
    0.7;                     !- Visible Absorptance

Material:NoMass,
    Nonres_Floor_Insulation, !- Name
    MediumSmooth,            !- Roughness
    0.0299387330245182,      !- Thermal Resistance {m2-K/W}
    0.9,                     !- Thermal Absorptance
    0.7,                     !- Solar Absorptance
    0.7;                     !- Visible Absorptance

Material:NoMass,
    CP02 CARPET PAD,         !- Name
    Smooth,                  !- Roughness
    0.1,                     !- Thermal Resistance {m2-K/W}
    0.9,                     !- Thermal Absorptance
    0.8,                     !- Solar Absorptance
    0.8;                     !- Visible Absorptance
```

```
!-   ===========  ALL OBJECTS IN CLASS: MATERIAL:AIRGAP ===========

Material:AirGap,
    F04 Wall air space resistance,  !- Name
    0.15;                    !- Thermal Resistance {m2-K/W}

Material:AirGap,
    F05 Ceiling air space resistance,  !- Name
    0.18;                    !- Thermal Resistance {m2-K/W}

!-   ===========  ALL OBJECTS IN CLASS: WINDOWMATERIAL:GLAZING ===========

WindowMaterial:Glazing,
    Clear 3mm,               !- Name
    SpectralAverage,         !- Optical Data Type
    ,                        !- Window Glass Spectral Data Set Name
    0.00299999999999999,     !- Thickness {m}
    0.837,                   !- Solar Transmittance at Normal Incidence
    0.075,                   !- Front Side Solar Reflectance at Normal Incidence
    0,                       !- Back Side Solar Reflectance at Normal Incidence
    0.898,                   !- Visible Transmittance at Normal Incidence
    0.081,                   !- Front Side Visible Reflectance at Normal Incidence
    0,                       !- Back Side Visible Reflectance at Normal Incidence
    0,                       !- Infrared Transmittance at Normal Incidence
    0.84,                    !- Front Side Infrared Hemispherical Emissivity
    0.84,                    !- Back Side Infrared Hemispherical Emissivity
    0.9,                     !- Conductivity {W/m-K}
    1,                       !- Dirt Correction Factor for Solar and Visible Transmittance
    No;                      !- Solar Diffusing

WindowMaterial:Glazing,
    Glass_4603_LayerAvg,     !- Name
    SpectralAverage,         !- Optical Data Type
    ,                        !- Window Glass Spectral Data Set Name
    0.005750,                !- Thickness {m}
    0.443963,                !- Solar Transmittance at Normal Incidence
    1.340067e-001,           !- Front Side Solar Reflectance at Normal Incidence
    1.964032e-001,           !- Back Side Solar Reflectance at Normal Incidence
    0.695925,                !- Visible Transmittance at Normal Incidence
    0.119460,                !- Front Side Visible Reflectance at Normal Incidence
    0.133308,                !- Back Side Visible Reflectance at Normal Incidence
    0.000000,                !- Infrared Transmittance at Normal Incidence
    0.840000,                !- Front Side Infrared Hemispherical Emissivity
    0.158889,                !- Back Side Infrared Hemispherical Emissivity
    1.000000;                !- Conductivity {W/m-K}

WindowMaterial:Glazing,
    Glass_103F_LayerAvg,     !- Name
    SpectralAverage,         !- Optical Data Type
    ,                        !- Window Glass Spectral Data Set Name
    0.005715,                !- Thickness {m}
    0.770675,                !- Solar Transmittance at Normal Incidence
    7.023712e-002,           !- Front Side Solar Reflectance at Normal Incidence
    6.997562e-002,           !- Back Side Solar Reflectance at Normal Incidence
    0.883647,                !- Visible Transmittance at Normal Incidence
    0.080395,                !- Front Side Visible Reflectance at Normal Incidence
    0.080395,                !- Back Side Visible Reflectance at Normal Incidence
    0.000000,                !- Infrared Transmittance at Normal Incidence
```

```
    0.840000,               !- Front Side Infrared Hemispherical Emissivity
    0.840000,               !- Back Side Infrared Hemispherical Emissivity
    1.000000;               !- Conductivity {W/m-K}

WindowMaterial:Glazing,
    CLEAR 6MM,              !- Name
    SpectralAverage,        !- Optical Data Type
    ,                       !- Window Glass Spectral Data Set Name
    0.006,                  !- Thickness {m}
    0.775,                  !- Solar Transmittance at Normal Incidence
    0.071,                  !- Front Side Solar Reflectance at Normal Incidence
    0.071,                  !- Back Side Solar Reflectance at Normal Incidence
    0.881,                  !- Visible Transmittance at Normal Incidence
    0.080,                  !- Front Side Visible Reflectance at Normal Incidence
    0.080,                  !- Back Side Visible Reflectance at Normal Incidence
    0.0,                    !- Infrared Transmittance at Normal Incidence
    0.84,                   !- Front Side Infrared Hemispherical Emissivity
    0.84,                   !- Back Side Infrared Hemispherical Emissivity
    0.9;                    !- Conductivity {W/m-K}

WindowMaterial:Glazing,
    Glass_4601_LayerAvg,    !- Name
    SpectralAverage,        !- Optical Data Type
    ,                       !- Window Glass Spectral Data Set Name
    0.005750,               !- Thickness {m}
    0.005685,               !- Solar Transmittance at Normal Incidence
    1.208047e-001,          !- Front Side Solar Reflectance at Normal Incidence
    1.940365e-001,          !- Back Side Solar Reflectance at Normal Incidence
    0.012413,               !- Visible Transmittance at Normal Incidence
    0.098355,               !- Front Side Visible Reflectance at Normal Incidence
    0.113942,               !- Back Side Visible Reflectance at Normal Incidence
    0.000000,               !- Infrared Transmittance at Normal Incidence
    0.840000,               !- Front Side Infrared Hemispherical Emissivity
    0.159635,               !- Back Side Infrared Hemispherical Emissivity
    1.000000;               !- Conductivity {W/m-K}

!-   ===========  ALL OBJECTS IN CLASS: WINDOWMATERIAL:GASMIXTURE ===========

WindowMaterial:GasMixture,
    Gap_9_W_0_0127,         !- Name
    0.0127,                 !- Thickness {m}
    2,                      !- Number of Gases in Mixture
    Air,                    !- Gas 1 Type
    0.10,                   !- Gas 1 Fraction
    Argon,                  !- Gas 2 Type
    0.90;                   !- Gas 2 Fraction

!-   ===========  ALL OBJECTS IN CLASS: CONSTRUCTION ===========

Construction,
    nonres_roof,            !- Name
    F13 Built-up roofing,   !- Outside Layer
    Nonres_Roof_Insulation, !- Layer 2
    F08 Metal surface;      !- Layer 3
Construction,
    nonres_ext_wall,        !- Name
    F07 25mm stucco,        !- Outside Layer
    G01 16mm gypsum board,  !- Layer 2
```

```
    Nonres_Exterior_Wall_Insulation,  !- Layer 3
    G01 16mm gypsum board;   !- Layer 4

Construction,
    nonres_floor,            !- Name
    Nonres_Floor_Insulation, !- Outside Layer
    100mm Normalweight concrete floor,  !- Layer 2
    CP02 CARPET PAD;         !- Layer 3

Construction,
    Conventional same as EC, !- Name
    Glass_4603_LayerAvg,     !- Outside Layer
    Gap_9_W_0_0127,          !- Layer 2
    Glass_103F_LayerAvg;     !- Layer 3

Construction,
    int_slab_floor,          !- Name
    100mm Normalweight concrete floor,  !- Outside Layer
    CP02 CARPET PAD;         !- Layer 2

Construction,
    int_slab_ceiling,        !- Name
    CP02 CARPET PAD,         !- Outside Layer
    100mm Normalweight concrete floor;  !- Layer 2

Construction,
    EC-Dark,                 !- Name
    Glass_4601_LayerAvg,     !- Outside Layer
    Gap_9_W_0_0127,          !- Layer 2
    Glass_103F_LayerAvg;     !- Layer 3

!-   ===========  ALL OBJECTS IN CLASS: WINDOWPROPERTY:SHADINGCONTROL ===========

WindowProperty:ShadingControl,
    EC,                      !- Name
    SwitchableGlazing,       !- Shading Type
    EC-Dark,                 !- Construction with Shading Name
    MeetDaylightIlluminanceSetpoint,  !- Shading Control Type
    ,                        !- Schedule Name
    500,                     !- Setpoint {W/m2, W or deg C}
    No,                      !- Shading Control Is Scheduled
    No,                      !- Glare Control Is Active
    ,                        !- Shading Device Material Name
    FixedSlatAngle,          !- Type of Slat Angle Control for Blinds
    ;                        !- Slat Angle Schedule Name


!-   ===========  ALL OBJECTS IN CLASS: PEOPLE ===========

People,
    People Bala,             !- Name
    Main_Zone,               !- Zone or ZoneList Name
    BLDG_OCC_SCH,            !- Number of People Schedule Name
    Area/Person,             !- Number of People Calculation Method
    ,                        !- Number of People
    ,                        !- People per Zone Floor Area {person/m2}
    18.5787942465724,        !- Zone Floor Area per Person {m2/person}
    0.3000,                  !- Fraction Radiant
```

```
    AUTOCALCULATE,          !- Sensible Heat Fraction
    ACTIVITY_SCH,           !- Activity Level Schedule Name
    ,                       !- Carbon Dioxide Generation Rate {m3/s-W}
    No,                     !- Enable ASHRAE 55 Comfort Warnings
    ZoneAveraged,           !- Mean Radiant Temperature Calculation Type
    ,                       !- Surface Name/Angle Factor List Name
    WORK_EFF_SCH,           !- Work Efficiency Schedule Name
    ClothingInsulationSchedule,  !- Clothing Insulation Calculation Method
    ,                       !- Clothing Insulation Calculation Method Schedule Name
    CLOTHING_SCH,           !- Clothing Insulation Schedule Name
    AIR_VELO_SCH,           !- Air Velocity Schedule Name
    FANGER;                 !- Thermal Comfort Model 1 Type

!-   ===========  ALL OBJECTS IN CLASS: LIGHTS ===========

Lights,
    Main Lights,            !- Name
    Main_Zone,              !- Zone or ZoneList Name
    BLDG_LIGHT_SCH,         !- Schedule Name
    Watts/Area,             !- Design Level Calculation Method
    ,                       !- Lighting Level {W}
    8.826406542,            !- Watts per Zone Floor Area {W/m2}
    ,                       !- Watts per Person {W/person}
    0.0000,                 !- Return Air Fraction
    0.7000,                 !- Fraction Radiant
    0.2000,                 !- Fraction Visible
    1.0000,                 !- Fraction Replaceable
    General Lights,         !- End-Use Subcategory
    No;                     !- Return Air Fraction Calculated from Plenum Temperature
!-   ===========  ALL OBJECTS IN CLASS: ELECTRICEQUIPMENT ===========

ElectricEquipment,
    Main  Equipment,        !- Name
    Main_Zone,              !- Zone or ZoneList Name
    BLDG_EQUIP_SCH,         !- Schedule Name
    Watts/Area,             !- Design Level Calculation Method
    ,                       !- Design Level {W}
    7.5,                    !- Watts per Zone Floor Area {W/m2}
    ,                       !- Watts per Person {W/person}
    ,                       !- Fraction Latent
    ,                       !- Fraction Radiant
    ;                       !- Fraction Lost

!-   ===========  ALL OBJECTS IN CLASS: DAYLIGHTING:CONTROLS ===========

Daylighting:Controls,
    New Sensor,             !- Name
    Main_Zone,              !- Zone Name
    ,                       !- Daylighting Method
    ,                       !- Availability Schedule Name
    Continuous,             !- Lighting Control Type
    ,                       !- Minimum Input Power Fraction for Continuous or ContinuousOff Dimming Control
    ,                       !- Minimum Light Output Fraction for Continuous or ContinuousOff Dimming Control
    ,                       !- Number of Stepped Control Steps
    ,                       !- Probability Lighting will be Reset When Needed in Manual Stepped Control
    Daylighting Control 1,   !- Glare Calculation Daylighting Reference Point Name
    180,                    !- Glare Calculation Azimuth Angle of View Direction Clockwise from Zone y-Axis {deg}
    20,                     !- Maximum Allowable Discomfort Glare Index
```

```
    ,                        !- DElight Gridding Resolution {m2}
    Daylighting Control 1,   !- Daylighting Reference Point 1 Name
    0.5,                     !- Fraction of Zone Controlled by Reference Point 1
    500,                     !- Illuminance Setpoint at Reference Point 1 {lux}
    Daylighting Control 2,   !- Daylighting Reference Point 2 Name
    0.5,                     !- Fraction of Zone Controlled by Reference Point 2
    500;                     !- Illuminance Setpoint at Reference Point 2 {lux}

!-   ===========  ALL OBJECTS IN CLASS: DAYLIGHTING:REFERENCEPOINT ===========

Daylighting:ReferencePoint,
    Daylighting Control 1,   !- Name
    Main_Zone,               !- Zone Name
    23.5,                    !- X-Coordinate of Reference Point {m}
    3,                       !- Y-Coordinate of Reference Point {m}
    4.8;                     !- Z-Coordinate of Reference Point {m}

Daylighting:ReferencePoint,
    Daylighting Control 2,   !- Name
    Main_Zone,               !- Zone Name
    26.5,                    !- X-Coordinate of Reference Point {m}
    3,                       !- Y-Coordinate of Reference Point {m}
    4.8;                     !- Z-Coordinate of Reference Point {m}

!-   ===========  ALL OBJECTS IN CLASS: ZONEINFILTRATION:DESIGNFLOWRATE ===========

ZoneInfiltration:DesignFlowRate,
    Below_Zone_INFILT,       !- Name
    Below_Zone,              !- Zone or ZoneList Name
    Below_Zone_OPERATION,    !- Schedule Name
    ,                        !- Design Flow Rate Calculation Method
    0.015,                   !- Design Flow Rate {m3/s}
    ,                        !- Flow per Zone Floor Area {m3/s-m2}
    ,                        !- Flow per Exterior Surface Area {m3/s-m2}
    0.50000,                 !- Air Changes per Hour {1/hr}
    0.66667,                 !- Constant Term Coefficient
    0.00000,                 !- Temperature Term Coefficient
    0.33333,                 !- Velocity Term Coefficient
    0.00000;                 !- Velocity Squared Term Coefficient

ZoneInfiltration:DesignFlowRate,
    Middle_Zone_INFILT,      !- Name
    Middle_Zone,             !- Zone or ZoneList Name
    Middle_Zone_OPERATION,   !- Schedule Name
    ,                        !- Design Flow Rate Calculation Method
    0.015,                   !- Design Flow Rate {m3/s}
    ,                        !- Flow per Zone Floor Area {m3/s-m2}
    ,                        !- Flow per Exterior Surface Area {m3/s-m2}
    0.50000,                 !- Air Changes per Hour {1/hr}
    0.66667,                 !- Constant Term Coefficient
    0.00000,                 !- Temperature Term Coefficient
    0.33333,                 !- Velocity Term Coefficient
    0.00000;                 !- Velocity Squared Term Coefficient

ZoneInfiltration:DesignFlowRate,
    Main_Zone_INFILT,        !- Name
    Main_Zone,               !- Zone or ZoneList Name
    Main_Zone_OPERATION,     !- Schedule Name
```

```
    ,                    !- Design Flow Rate Calculation Method
    0.015,                  !- Design Flow Rate {m3/s}
    ,                    !- Flow per Zone Floor Area {m3/s-m2}
    ,                    !- Flow per Exterior Surface Area {m3/s-m2}
    0.50000,                !- Air Changes per Hour {1/hr}
    0.66667,                !- Constant Term Coefficient
    0.00000,                !- Temperature Term Coefficient
    0.33333,                !- Velocity Term Coefficient
    0.00000;                !- Velocity Squared Term Coefficient

ZoneInfiltration:DesignFlowRate,
    Upper_Zone_INFILT,      !- Name
    Upper_Zone,             !- Zone or ZoneList Name
    Upper_Zone_OPERATION,   !- Schedule Name
    ,                    !- Design Flow Rate Calculation Method
    0.015,                  !- Design Flow Rate {m3/s}
    ,                    !- Flow per Zone Floor Area {m3/s-m2}
    ,                    !- Flow per Exterior Surface Area {m3/s-m2}
    0.50000,                !- Air Changes per Hour {1/hr}
    0.66667,                !- Constant Term Coefficient
    0.00000,                !- Temperature Term Coefficient
    0.33333,                !- Velocity Term Coefficient
    0.00000;                !- Velocity Squared Term Coefficient

!-   ===========  ALL OBJECTS IN CLASS: HVACTEMPLATE:THERMOSTAT ===========

HVACTemplate:Thermostat,
    thermostat,             !- Name
    ,                    !- Heating Setpoint Schedule Name
    20,                     !- Constant Heating Setpoint {C}
    ,                    !- Cooling Setpoint Schedule Name
    24;                     !- Constant Cooling Setpoint {C}

!-   ===========  ALL OBJECTS IN CLASS: HVACTEMPLATE:ZONE:IDEALLOADSAIRSYSTEM
===========

HVACTemplate:Zone:IdealLoadsAirSystem,
    Main_Zone,              !- Zone Name
    thermostat,             !- Template Thermostat Name
    ,                    !- System Availability Schedule Name
    50,                     !- Maximum Heating Supply Air Temperature {C}
    13,                     !- Minimum Cooling Supply Air Temperature {C}
    0.0156,                 !- Maximum Heating Supply Air Humidity Ratio {kgWater/kgDryAir}
    0.0077,                 !- Minimum Cooling Supply Air Humidity Ratio {kgWater/kgDryAir}
    NoLimit,                !- Heating Limit
    ,                    !- Maximum Heating Air Flow Rate {m3/s}
    ,                    !- Maximum Sensible Heating Capacity {W}
    NoLimit,                !- Cooling Limit
    ,                    !- Maximum Cooling Air Flow Rate {m3/s}
    ,                    !- Maximum Total Cooling Capacity {W}
    ,                    !- Heating Availability Schedule Name
    ,                    !- Cooling Availability Schedule Name
    ConstantSensibleHeatRatio,  !- Dehumidification Control Type
    0.7,                    !- Cooling Sensible Heat Ratio {dimensionless}
    60,                     !- Dehumidification Setpoint {percent}
    None,                   !- Humidification Control Type
    30,                     !- Humidification Setpoint {percent}
    None,                   !- Outdoor Air Method
```

```
    0.00944,                 !- Outdoor Air Flow Rate per Person {m3/s}
    ,                        !- Outdoor Air Flow Rate per Zone Floor Area {m3/s-m2}
    ,                        !- Outdoor Air Flow Rate per Zone {m3/s}
    ,                        !- Design Specification Outdoor Air Object Name
    None,                    !- Demand Controlled Ventilation Type
    NoEconomizer,            !- Outdoor Air Economizer Type
    None,                    !- Heat Recovery Type
    0.7,                     !- Sensible Heat Recovery Effectiveness {dimensionless}
    0.65;                    !- Latent Heat Recovery Effectiveness {dimensionless}

HVACTemplate:Zone:IdealLoadsAirSystem,
    Middle_Zone,             !- Zone Name
    thermostat,              !- Template Thermostat Name
    ,                        !- System Availability Schedule Name
    50,                      !- Maximum Heating Supply Air Temperature {C}
    13,                      !- Minimum Cooling Supply Air Temperature {C}
    0.0156,                  !- Maximum Heating Supply Air Humidity Ratio {kgWater/kgDryAir}
    0.0077,                  !- Minimum Cooling Supply Air Humidity Ratio {kgWater/kgDryAir}
    NoLimit,                 !- Heating Limit
    ,                        !- Maximum Heating Air Flow Rate {m3/s}
    ,                        !- Maximum Sensible Heating Capacity {W}
    NoLimit,                 !- Cooling Limit
    ,                        !- Maximum Cooling Air Flow Rate {m3/s}
    ,                        !- Maximum Total Cooling Capacity {W}
    ,                        !- Heating Availability Schedule Name
    ,                        !- Cooling Availability Schedule Name
    ConstantSensibleHeatRatio,  !- Dehumidification Control Type
    0.7,                     !- Cooling Sensible Heat Ratio {dimensionless}
    60,                      !- Dehumidification Setpoint {percent}
    None,                    !- Humidification Control Type
    30,                      !- Humidification Setpoint {percent}
    None,                    !- Outdoor Air Method
    0.00944,                 !- Outdoor Air Flow Rate per Person {m3/s}
    ,                        !- Outdoor Air Flow Rate per Zone Floor Area {m3/s-m2}
    ,                        !- Outdoor Air Flow Rate per Zone {m3/s}
    ,                        !- Design Specification Outdoor Air Object Name
    None,                    !- Demand Controlled Ventilation Type
    NoEconomizer,            !- Outdoor Air Economizer Type
    None,                    !- Heat Recovery Type
    0.7,                     !- Sensible Heat Recovery Effectiveness {dimensionless}
    0.65;                    !- Latent Heat Recovery Effectiveness {dimensionless}

HVACTemplate:Zone:IdealLoadsAirSystem,
    Below_Zone,              !- Zone Name
    thermostat,              !- Template Thermostat Name
    ,                        !- System Availability Schedule Name
    50,                      !- Maximum Heating Supply Air Temperature {C}
    13,                      !- Minimum Cooling Supply Air Temperature {C}
    0.0156,                  !- Maximum Heating Supply Air Humidity Ratio {kgWater/kgDryAir}
    0.0077,                  !- Minimum Cooling Supply Air Humidity Ratio {kgWater/kgDryAir}
    NoLimit,                 !- Heating Limit
    ,                        !- Maximum Heating Air Flow Rate {m3/s}
    ,                        !- Maximum Sensible Heating Capacity {W}
    NoLimit,                 !- Cooling Limit
    ,                        !- Maximum Cooling Air Flow Rate {m3/s}
    ,                        !- Maximum Total Cooling Capacity {W}
    ,                        !- Heating Availability Schedule Name
    ,                        !- Cooling Availability Schedule Name
```

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    ConstantSensibleHeatRatio,  !- Dehumidification Control Type
    0.7,                     !- Cooling Sensible Heat Ratio {dimensionless}
    60,                      !- Dehumidification Setpoint {percent}
    None,                    !- Humidification Control Type
    30,                      !- Humidification Setpoint {percent}
    None,                    !- Outdoor Air Method
    0.00944,                 !- Outdoor Air Flow Rate per Person {m3/s}
    ,                        !- Outdoor Air Flow Rate per Zone Floor Area {m3/s-m2}
    ,                        !- Outdoor Air Flow Rate per Zone {m3/s}
    ,                        !- Design Specification Outdoor Air Object Name
    None,                    !- Demand Controlled Ventilation Type
    NoEconomizer,            !- Outdoor Air Economizer Type
    None,                    !- Heat Recovery Type
    0.7,                     !- Sensible Heat Recovery Effectiveness {dimensionless}
    0.65;                    !- Latent Heat Recovery Effectiveness {dimensionless}

HVACTemplate:Zone:IdealLoadsAirSystem,
    Upper_Zone,              !- Zone Name
    thermostat,              !- Template Thermostat Name
    ,                        !- System Availability Schedule Name
    50,                      !- Maximum Heating Supply Air Temperature {C}
    13,                      !- Minimum Cooling Supply Air Temperature {C}
    0.0156,                  !- Maximum Heating Supply Air Humidity Ratio {kgWater/kgDryAir}
    0.0077,                  !- Minimum Cooling Supply Air Humidity Ratio {kgWater/kgDryAir}
    NoLimit,                 !- Heating Limit
    ,                        !- Maximum Heating Air Flow Rate {m3/s}
    ,                        !- Maximum Sensible Heating Capacity {W}
    NoLimit,                 !- Cooling Limit
    ,                        !- Maximum Cooling Air Flow Rate {m3/s}
    ,                        !- Maximum Total Cooling Capacity {W}
    ,                        !- Heating Availability Schedule Name
    ,                        !- Cooling Availability Schedule Name
    ConstantSensibleHeatRatio,  !- Dehumidification Control Type
    0.7,                     !- Cooling Sensible Heat Ratio {dimensionless}
    60,                      !- Dehumidification Setpoint {percent}
    None,                    !- Humidification Control Type
    30,                      !- Humidification Setpoint {percent}
    None,                    !- Outdoor Air Method
    0.00944,                 !- Outdoor Air Flow Rate per Person {m3/s}
    ,                        !- Outdoor Air Flow Rate per Zone Floor Area {m3/s-m2}
    ,                        !- Outdoor Air Flow Rate per Zone {m3/s}
    ,                        !- Design Specification Outdoor Air Object Name
    None,                    !- Demand Controlled Ventilation Type
    NoEconomizer,            !- Outdoor Air Economizer Type
    None,                    !- Heat Recovery Type
    0.7,                     !- Sensible Heat Recovery Effectiveness {dimensionless}
    0.65;                    !- Latent Heat Recovery Effectiveness {dimensionless}
```