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Determining The Effect Of Building Geometry On Energy Use Patterns Of Office Developments

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**DETERMINING THE EFFECT OF BUILDING GEOMETRY ON ENERGY USE
PATTERNS OF OFFICE DEVELOPMENTS**

by

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Bachelor of Architecture

Bangladesh University of Engineering and Technology, 2008

A Major Research Project

presented to Ryerson University

in partial fulfillment of the
requirements for the degree of
Master of Building Science
in the Program of
Building Science

Toronto, Ontario, Canada, 2012

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Author's declaration

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Abstract

The project investigates potentials of building geometry to minimize energy consumption in office developments. Five distinct building geometries are developed to represent mid-size office occupancies in the context of Toronto (located at southern Ontario, Canada). A square, a rectangle elongated on east-west, a rectangle elongated on north-south, an H-shape, and a cruciform are examined with varied design parameters; such as: window to wall ratio and external static solar control devices (horizontal overhangs and vertical fins). The IES VE software is applied to predict the yearly energy consumption results for 40 analysis permutations. The outcome of this research shows that, the deviation of energy use values from one shape to another is relatively small. In addition to that, window to wall ratio appears slightly overpowering on the energy use pattern of a building than its shape. Shading design is found particularly helpful in reducing cooling energy demand in offices spaces. Overall, the energy performance of five archetypes is observed to comply with individual building aspect ratios (i.e. compactness). Thus, the findings of this project are expected to provide useful guidelines to the architects to utilize building geometry as an energy saving measure when designing office buildings.

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1. Introduction

1.1. Problem statement

Energy is an important environmental parameter and energy use is directly related to climate change as well as a variety of air emissions (BOMA Canada, 2011). Optimization of energy performance is a crucial factor in any office building design. Energy consumption in the commercial and institutional building sector accounts for almost 13.8% of secondary energy use in Canada and almost 8.9% of the country's greenhouse gas (GHG) emissions (National Resources Canada, 2008). Office buildings (and civic administrative buildings) contribute significantly in Canada's commercial building sector as well as the energy consumption statistics (NRTEE & SDTC, 2008). Climate change and its consequences has become a center of a public concern worldwide and the energy consumption in the building sector is seen as the core of the problem. It necessitates undertaking strategies that stimulate a more sustainable design in line with less consumption of energy, at the conceptualization phase. Utilization of passive solar design, accurately proportioned fenestration system to maximize daylight, and controlling direct solar gain to lower the cooling demand during cooling seasons; are strategies gaining importance among architects and building scientists. The role of building geometry can become a potential means to reduce building's overall energy performance. It is unfortunate that, 'form' often receives less concern as a design element while prioritizing the accommodation of complex functions in an office space by any means. As a matter of fact, the shape of a building respective to the climate and context is the only element which will not change radically during the life cycle of a building. Selection of the formal configuration along with depth and height of rooms and the size of windows can together double the eventual energy consumption of the finished building (Gratia & De Herde, 2003). Thus decisions at the early stages of a building design would have substantial impact on the energy efficiency of the resultant building. With the application of building simulations designers can predict the energy loads, test and compare permutations of design strategy in order to optimize design (Pollock, Roderick, McEwan, & Wheatley, n.d.).

Several researches are found which have examined the effect of shapes, fenestration design, and shading strategies on the energy use of buildings. However, studies combining different design parameters are rare especially in the context of Canada. There are disputes among researchers about how to conclude about the role of geometry that modulates energy performance of office buildings. Some studies identify that the shape of a building can have significant impact on the energy costs of heating and cooling (AlAnzi, Seo, & Krarti, 2009). Others opine that building form and orientation do not largely influence the energy consumption, especially in case of mid-size or large buildings (Straube, 2012). Hence, it is required to

attempt a thorough research to examine the potentials of building geometry, along with other envelope design parameters, to minimize energy consumption in office developments in Canada.

1.2. Objective and approach of the research

The research aims at exploring:

- The influence of building geometry¹ on the energy use patterns of office buildings.
- It is intended to identify the importance of ‘shape’ compared to other building envelope factors such as fenestration² (window to wall ratio) and sun control strategies (external shading devices).

To achieve these objectives, following steps are taken in methodology of this research:

- Archetype buildings of equal floor area are developed with basic geometries to be modeled as office buildings.
- As the site climate determines the general magnitude of each energy end use; the selection of location and climate zone is an important factor. Hence, the research is conducted for Toronto representing the context and climate of southern Ontario, Canada.
- Daylight harvesting with properly designed fenestration can have great impact on the electric consumption by artificial lighting in a space. To investigate this issue, analysis of daylighting with respect to fenestration system is also carried out in this project.
- While glazing can assist with natural lights it can also lead to excessive solar gains. Therefore, the effect of external shading devices, as a sun control strategy, is incorporated to the parametric analysis.
- Simulations are conducted on archetype models using energy simulation software to find the whole building energy demand; specifically heating, cooling, and interior lighting energy.
- After analyzing the results, it is identified:
 - i) The impact of design parameters on energy demand,
 - ii) The dominance of design parameters on energy demand and,

¹Building geometry, in general, refers to the measurements related to building configuration and arrangement. In a broader sense, it includes the components of building envelope, such as; walls, roofs, floors, doors, and fenestration, which interact with the exteriors and mediate the difference between outdoor conditions and desired indoor conditions (Deru & Torcellini, 2005).

² Fenestration is coined as building components that transmit light including windows, translucent panels, clerestory windows, skylights, glazed portions of doors, and glass block walls (Deru & Torcellini, 2005). This study refers to windows only, as fenestration element.

iii) Correlation among different energy factors.

This research attempts to integrate design factors; such as: form, window to wall ratio, and sun control strategies to find out their relative importance over the whole building energy demand. From this standpoint, the findings of this work can become worthwhile as it is combining analysis of several parameters that have good prospects on basic building configuration and envelope decisions that are made early in the design process by the architects. Moreover, the simulation results of the examined archetypes provide a prediction of annual energy use at their operational phase. If building design, at its preliminary phase, is guided by its future energy performance, it will essentially help designers to contribute toward the environmental sustainability. The five archetypes explored in this project are of very basic geometries; yet, the study does not intend to pose limit on the choice of building geometry for office design. Rather, the results of this research can be reviewed to be manipulated on a variety of building configurations.

2. Literature review

A thorough literature review is carried out based on four parameters: building aspect ratios, geometry, fenestration design, and solar shading analysis. The literature review is helpful to identify key concepts which have supported the methodology of this research and provided useful comparison to the findings of this work.

2.1. Importance of ‘building aspect ratio’ on energy performance

Several literatures have employed the concept of building aspect ratios as an indicator to define the way by which a form responds to its climate. One concept is found to be widely used: forms with different geometry of the same contained volume have different surface areas. This is expressed as volume to surface ratio (V/S). The second concept is: a building with a high V/S takes more time to be affected by the exterior temperature variations than that of a lower V/S of the same structure (Behsh, 2002). Based on these concepts, the shape of a building can play a significant role since it determines the surface of the external envelope.

Gratia and De Herde (2003) have defined the volume to surface area ratio (V/S) as ‘compactness’ (C) of a form. Here the surface area of a building includes wall surfaces, roof surface, and ground surface. As heat losses are proportional to the surface area of envelope, the more compact a form, the less will be the heat loss. Buildings with non- rectangular plan (or with complicated configurations) are prone to thermal bridges and losses; as the junctions of structural components do not lie on the same plane. The authors perform simulations on five different forms (Figure 1) to identify the role of ‘compactness’ on the heating loads of buildings in the context of Belgium. Envelope design and fenestration areas remain fixed for all five forms. Their study turns out with the result that a high C (compactness) form corresponding to the least heating load requirement per year (Figure 1). The building with a V/S of 1.24 (highly compact)

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requires 20.73% less space heating energy while compared to a building with a V/S of 0.84 (the least compact form studied).

Figure 1: Impact of the building shape on heating loads; Gratia & De Herde, 2003

Ross (2009) has conducted a research to determine the influence of decisions taken at the preliminary design stage on the energy intensity of the built project. The author analyzes mid-size office buildings with a total floor area of 4662m² (with 4 stories, 1165.5m² per floor) for Toronto climate for five distinct geometries (Figure 2). The built forms are specified primarily with the ratio of 'façade area: gross floor area (GFA)' and secondly, with the ratio of 'surface area (including roof): GFA'. Three variation of façade layout (with window to wall ratio of 20%, 40%, and 60% respectively) are tested for each form. The thermal resistances of the enclosure are maintained similar in all simulations. When the annual energy intensity is compared, the square form (regardless of window to wall ratio) is resulted with the least energy requirement among others. The most energy intensive is found the H-shape regardless of its orientation. It supports that, the building with the highest 'façade to GFA' ratio consumes less energy on an annual basis and the lower the ratio, the greater the energy consumptions. It is also found factual for the 'surface area to GFA ratio'. The study concludes that, regardless the effect of fenestration amount, a building's energy performance is always determined by the proportions of its surface.

Figure 2: Different plan forms representing mid- size office buildings; Ross (2009)

AlAnzi, Seo, and Krarti (2009) have proposed a different metric to measure the ‘compactness’ of a form; relative compactness (RC) is used in their study as an indicator while assessing the impact of shape on the building energy performance. It is mathematically described as: $RC = (V/A_s)_{\text{building}} / (V/A_s)_{\text{ref}}$; where $(V/A_s)_{\text{building}}$ is the compactness of a specific shape, and $(V/A_s)_{\text{ref}}$ is the compactness of a reference building. Here V and A_s are referred, respectively, to the conditioned volume and envelope surface area exposed to the outdoor air (i.e., exposed exterior wall area but except the roof surface). The ratio is further simplified as $RC = (A_s)_{\text{ref}} / (A_s)_{\text{building}}$; since the floor area and total height of any building configuration are identical in their work, the building volume is constant in all cases. The authors have developed seven different shapes as representative of prototypical office building in Kuwait (Figure 3). All buildings are modeled as 20 stories with the same floor area of 12500m^2 (i.e. 625 m^2 per floor). Analysis is carried out with window to wall ratios to vary from 0% to 75%. The overall U-values in each analysis remain constant. After the simulations, it is observed that as the RC increases, the exterior wall area exposed to ambient conditions decreases and consequently the building energy decreases regardless of WWR. However, the trend is found to depend slightly on the building shape due most likely to variation in solar exposure for different building shapes.

Figure 3: L-type, T-shape, H-shape, cross shape, U-shape, cut shape, and rectangular shape office buildings; AlAnzi, Seo, & Krarti (2009)

Behsh (2002) has researched on the thermal response of building envelop as a function of its geometric shape in the context of Mediterranean region. His study depicts that the volume to surface area ratio (V/S) is not precise enough for providing a clear understanding of the thermal response of forms with complex shapes; such as: building with a courtyard, L shape, U shape, and a large number of other forms. He investigates three levels of relations between the forms and the surroundings:

- i) The relation between surfaces and volume (V/S)
- ii) The relation between the south oriented surfaces to the west oriented surfaces (S_{wsouth}/S_{wwest})
- iii) The relation between the roof area and walls (S_{roof}/S_{wall})

A number of different geometries are developed in his work to have similar contained volume, glazing area, and structural properties. The results of the simulation study are discussed in terms of duration of cooling period. It is observed that form with a rectangular shape (elongated on east-west axis) shows better response during the overheated days. In opposite to that, a square form demonstrates better response during the cold days. Therefore, if the compact form is chosen as a design option, the form with a low V/S placed along east-west is the most perfect for the Mediterranean climate. An important result comes out from his research: despite of having equal V/S buildings can show different thermal performance. Therefore, the author suggests the most relevant factor to analyze their thermal performance would be the ' S_{wsouth}/S_{wwest} '. Behsh (2002) also finds that the form with the least roof area of the same total space is mostly recommended as the roof is a major component of a building where it constitutes the primal source for thermal stress both under the cold and the overheated period. The author concludes that, a form with a large size of southerly oriented areas is the most optimal form, as it will receive the lowest amount of heat during summer and the highest amount during winter in the climate of Mediterranean region.

'Building form and orientation do not have as large an impact on energy consumption as sometimes thought, especially for mid-size or large buildings' (Straube, 2012). Here, the author prefers the ratio of usable floor area (F) to above grade enclosure area (E) for commercial buildings (Figure 4). With a high F/E , forms become more compact. Buildings like offices do not require volume for their function; it is the floor area which is needed to be concerned. This metric (i.e., F/E) includes the roof area but does not account for ground contact area like V/S ratio. The ground remains at a more moderate temperature difference compared to that of walls or roofs, and is not affected by solar radiation; therefore the slab and basement influence on decisions should be of less concern. The author also depicts that, for the same heat loss through the enclosure (i.e., the same overall U value or R value) on a winter night, the heating energy intensity will be higher for a low F/E and lower for high F/E ratios. However, the benefit of compactness

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of forms can be achieved technologically by improving the enclosure R value. In practice, a small increase in overall average R value is easier than modifying the building geometry.

Figure 4: F/E ratios for different building forms; Straube (2012).

The size of a building in floor area is a better indicator of energy gain/loss through the enclosure than plan shape (Straube, 2012). Ross (2009) has found that the impact of a building form on total energy consumption for a given floor size is less for larger buildings than small buildings. Pope (2012) performs a fixed area proportion analysis on office occupancy beginning from a single story up to 18 stories stacking. With increasing number of floors, the V/S increases; consequently, the energy intensity goes down significantly. Behsh (2002) observes that a form that has the less roof surface among others of the same total space area would be least energy intensive.

2.2. Impact of building geometry on lighting energy

Some geometry is found to be preferred particularly for daylight harvesting (Figure 5). Access of natural light to interior can control cooling and heating loads of a building to some extent. Therefore, choosing geometry to maximize daylighting would have significant impact over the total energy use of a building. Long and narrow footprints better serves this purpose compared to square ones (Public Works and

Figure 5: Example of building footprints with high daylight access; PWGSC (2002)

Government Services Canada [PWGSC], 2002). In addition to that, buildings can be arranged as a series of wings to get better access to daylight.

A long narrow floor plan gets benefit over a square form in relation to daylighting and natural ventilation; although the square form is regarded as the most compact of all forms. Therefore, certain trade-off occurs between a compact form that minimizes conductive heat transfer through the envelope and a form that facilitates daylighting, solar gain, and natural ventilation. Although square buildings have lower heating loads, daylighting the interior is critical and the imbalance between perimeter heating loads and interior cooling loads often necessitates a complex HVAC system. While a narrow shape may appear to compromise the thermal performance of the building, the electrical load and cooling load savings achieved by a well- designed daylighting system will more than compensate for the increased skin losses (Los Alamos National Laboratory [LANL], 2002). Many low energy commercial buildings are designed as a compact form with the short dimension of around 14 to 18 m (Straube, 2012). Such configuration helps to reduce lighting loads to a minimum, using daylight controls and daylight harvesting. Offices around a double loaded corridor can be daylit, if the building is about $2 \times 2-2.5$ (daylight zone depth) $\times 2.74-3$ (ceiling height) = 10.97-15.24m plus the corridor or core width (Straube, 2012). All these studies suggest minimizing the depth of a building on north-south to have greater exposure from south orientation for daylighting design.

2.3. Impact of fenestration design on energy demand

Low-energy and passive buildings in northern climates typically are not designed with highly glazed facades as windows are traditionally the least insulating and highest-air leakage component of the building envelope. ASHRAE (2004) recommends a 20% -40% WWR suitable for Toronto climate (or for climate zone 6). Moreover, it is recommended that, glazed area on east and west orientation should be less in proportion to that of north and south orientation (ASHRAE, 2004). Although windows provide many benefits that enhance building performance and occupant comfort through passive heating, daylight and views; most of these benefits are overshadowed by excessive window area and lack of solar protection.

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Consequently, window assemblies are often considered responsible for increased heating loads due to daily net-heat loss, glare, and increased cooling loads due to overheating.

Pope (2008) has studied the effect of window to wall ratio (from 40% up to 95%) on a MNECB'97 (Model National Energy Code for Buildings) reference building for small office archetype. The author observes that if WWR is increased, along with high performance glazing, it provides performance benefit. For instance, windows with triple pane, U (thermal transmittance) of 0.94 and SC (shading coefficient) of 0.31 found to reduce 16% energy consumption, if applied with WWR of 40%. With the same specification, if WWR is increased to 55%, still performance benefit is achievable, with a 10% reduction from MNECB (Figure 2.7). These comparisons declare that, if high quality windows are used, despite of higher fenestration area, a building can perform well.

Building geometry for energy conservation is often related to fenestration area and orientation of windows. Proper positioning of windows can influence the daylighting design as well as the artificial lighting consumptions in office spaces. Cooling loads become a matter of concern in case glazed surfaces are directed to east- west. These orientations require external solar protection resulting with reduced daylight harvesting to interior (thus induces internal gain from intensive use of artificial lights); which eventually increases the cooling demand (Gratia & De Herde, 2003). Gratia and De Herde (2003) have experimented aiming to determine which orientation is most preferable for glazing to be positioned in conjunction with external shading devices. According to their study, large glazing areas with sun control facing south are preferable compared to north oriented glazing without solar protection. The referenced work provides useful findings on impact building orientation over heating and cooling demands; however it does not account for fenestrations on all four elevations (i.e., only north and south glazing are simulated separately for some cases and only east- west windows are simulated separately in other cases).

According to Ross (2009), WWR has slightly stronger impact on the energy results compared to building shape and orientation. The author analyzes different geometries (refer to Figure 2) with window to wall ratio of 20%, 40%, and 60% respectively. The annual energy intensity ($\text{kWh/m}^2/\text{yr}$) of other shapes when compared to the square form (for similar WWR) is found to increase in the range of 1% to 6%. For instance, a square form uses $172\text{kWh/m}^2/\text{yr}$; in comparison a rectangular form uses $174\text{kWh/m}^2/\text{yr}$, an increase of 1%, and an H shape uses $182\text{kWh/m}^2/\text{yr}$, an increase of 6%. On the contrary, changing WWR from 40% to 60% (in case of a square form) causes the energy intensity to increase by 4.9% (from $164\text{kWh/m}^2/\text{yr}$ to $172\text{kWh/m}^2/\text{yr}$) which indicates the power of WWR.

2.4. Impact of shading design on energy demand

The question of sun control comes next to design for daylighting. The goal of shading design is to shade direct sun but not daylight. Researches based on fenestration and shading design often regard daylight controlled dimming systems with respect to daylight harvesting. Photo-sensors, as one of the daylight harvesting strategies, can reduce electric consumption of lights if properly positioned in accordance with fenestration design. Relevant work is done by Hammad and Abu-Hijleh (2010). They have explored the impact external louvers (both dynamic and static) on the energy consumption of an office building in of Abu Dhabi- UAE. Horizontal louvers are used for the south façade while vertical louvers are used for both the east and west facades. The potential of energy savings due to the dynamic louvers are found with lighting and cooling control. The reduction in these loads is roughly proportional to the degree of the louver's openness and its relation to solar position. The energy savings, placing dynamic louvers in east and west orientation, are lower than savings for the south façade. This is mainly due to the sun's daily path as each of the east and west facades is not exposed to direct sunlight throughout the day, unlike the south facing facades (which has a high and long duration exposure to sunlight) in the climate of UAE. Even if only dimming control is employed (no shading devices) it is found advantageous in energy reduction.

Ross (2009) has explored the effect of daylight control dimming coupled with fenestration design. She identifies that a mid- sized office in Toronto (for instance a square building with 60% WWR) may become 8.2% more energy intensive if does not use daylight dimming sensors (without dimming the energy intensity is 172 kWh/m²/yr whereas with daylight dimming sensors, it requires 159 kWh/m²/yr). The energy use profiles show that daylight sensors reduce the energy required for lights per month, fairly throughout the year. The energy for heating goes up slightly to compensate for the heat not generated internally by lights. In opposite to that, energy needed for cooling and fans drops when area lights are on daylight controls. The study provides useful data regarding the application of daylight dimming controls to be utilized in our project. However, the author concludes that there is no special synergy between plan form and daylight sensors, with respect to energy use.

It can be assumed that, exterior shading devices could lower or perhaps eliminate the need for cooling in northerly latitudes. To investigate this issue, Ross (2009) has performed another study to know the effect of sunshades in Toronto climate. She applies a standard shading design (horizontal overhang) for all windows except those facing north. The shading strategy is applied on five distinct geometries (4645 m² each and 4 stories) with a WWR of 40% (referred to Figure 2 for the geometries tested). Only the square building has been observed with an increase in energy intensity when awnings are added to the design. Cooling and fan energy are reduced, but heating energy goes up slightly greater amount. The

author explains a reason for this: additional heating is needed in January and February, perhaps because the awnings shade the south windows partially, during mid-day, at the time. The other four forms remain unaffected with inclusion of external shading. However, the referenced work does not consider daylight dimming sensors therefore, the effect of shading design on lighting consumption remains unexplored. It would be interesting to observe how the results appear in this project in case when external shading design is incorporated to various building geometries.

2.5. Importance of computer simulation on the selection of building geometry

Computer simulations are the only practical way to predict the dynamic energy performance for a large number of design solutions (LANL, 2002). A detailed load analysis through computer simulation can identify energy saving opportunities early in the design process. Based on the findings, modifications can be made on the form, orientation, or fenestration of the building (LANL, 2002). To really influence a building's design at early stages simplified versions of energy modeling are needed to be developed (Settlemyre, 2009). An analysis has been done by Settlemyre (2009) on three very different forms (Figure 6) each with 18600m² of total floor area. Energy simulation tool IES VE is used to calculate peak building loads and shape the full year energy picture. The three models are first analyzed with a 'split system with mechanical ventilation and cooling'. The rectangular form is found as the best performer in total energy consumption for the year (187 kWh/m²). The worst of the three forms is the wing shape, which is 11% higher, while the U shape is 6% higher compared to the rectangle. In the next phase, simulations are run for a VAV dual duct system. In each case the VAV dual duct was the better performer with 5.5% reduction for the rectangular form, 4.25% reduction in U shaped form, and the lowest, a 3.7% reduction in the wing form. The study of Settlemyre (2009) becomes a useful reference for this research, because it provides background to the early stage energy modeling. Moreover, the choice of mechanical systems (VAV dual duct) for this project is determined based on the findings of the referenced work.

Figure 6: Three distinct geometries explored in the work of Settlemyre (2009)

A summary table depicting the major findings of all the reviewed researches is presented below (in Table 1):

Table 1: Summery of the reviewed researches

Topic	Author	Study context	Major findings
Building aspect ratio	Gratia & De Herde (2003)	Belgium	Forms with a high V/S correspond to the least annual heating load.
	Ross (2009)	Canada	Regardless the effect of fenestration amount, a building's energy performance is always determined by the proportions of its surface.
	AlAnzi, Seo, & Krarti (2009)	Kuwait	For buildings with low WWR the total energy use is proportional to building's exterior wall area independent of its form.
	Behsh (2002)	Mediterranean region	Buildings with similar compactness can behave differently due to the difference in wall area and orientation for solar exposure.
	Straube (2012)	Canada	For the same heat loss through the enclosure, the heating energy intensity will be higher for a low F/E and lower for high F/E ratios.
Size of a building	Straube (2012)	Canada	Size of the building in floor area is a better indicator of energy gain/loss through the enclosure than plan shape.
	Ross (2009)	Canada	A square form large building uses 9.33% less energy compared to a medium square building and 29.33% less energy than a small square building.
	Pope (2012)	Canada	With increasing number of floors, the V/S increases; consequently, the energy intensity goes down significantly.
	Behsh (2002)	Mediterranean region	A form that has the less roof surface among others of the same total space area would be least energy intensive.
Building geometry and	PWGSC (2002)	Canada	A long narrow floor plan gets benefit over a square form in relation to daylighting and natural ventilation

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lighting energy	LANL (2002)	U.S.A.	While a narrow shape may appear to compromise the thermal performance of the building, the electrical load and cooling load savings achieved by a well-designed daylighting system will more than compensate for the increased skin losses.
	Straube (2012)	Canada	Commercial buildings with the short dimension of 14 to 18 m have reduced lighting loads.
WWR and energy demand	ASHRAE (2004)		A 20% -40% WWR suitable for Toronto climate.
	Pope (2008)	Canada	If high quality windows are used, despite of higher fenestration area, a building can perform well.
	Gratia & De Herde (2003)	Belgium	Large glazing areas with sun control facing south are preferable compared to north oriented glazing without solar protection.
	Ross (2009)	Canada	WWR has slightly stronger impact on the energy results compared to building shape and orientation.
Shading design and energy demand	Hammad & Abu Hijleh (2010)	U.A.E.	The potential of energy savings due to the dynamic louvers are found with lighting and cooling.
	Ross (2009)	Canada	In Toronto, exterior awnings are not useful for reducing the overall energy use in an office building.
Daylight dimming control	Hammad & Abu Hijleh (2010)	U.A.E.	Even if only dimming control is employed (no shading devices) it is found advantageous in energy reduction.
	Ross (2009)	Canada	There is no special synergy between plan form and daylight sensors, with respect to energy use.
Early stage energy modeling	Settlemyre (2009)	U.K.	To influence a building's design at early stages simplified versions of energy modeling are needed to be developed.
	McEwan, Roderick, Pollock, & Wheatly (n.d.)	U.K.	Changing the design at the early stages is most flexible and it helps to improve overall energy performance.

The studies [Gratia & De Herde (2003), Ross (2009), AlAnzi, Seo, & Krarti (2009), Behsh (2002), and Straube (2012)] discussed in this section represent different climate and regions. Nevertheless, all of them depict 'building aspect ratios' as an important indicator of a building's energy performance from individual perspective. Among them, the concept of 'compactness' defined by the floor to enclosure area ratio (F/E) (Straube, 2012) would be analyzed in this research for its relevancy to this project. 'Compactness' measured by the ratio of volume to surface area (V/S) will also be compared for different geometries to see if the plan forms do actually conform to this aspect ratio (V/S) for their energy pattern or not. The parametric analysis and methodology of the reviewed studies are found to be dissimilar if compared to one another in many cases. For instance, the finding of Behsh (2002) and AlAnzi, Seo, and Krarti (2009) state that building with similar compactness can behave differently due to the difference in wall area and orientation for solar exposure. Here the former research is conducted on low rise buildings and the latter is performed on high rise buildings. Therefore, it would be interesting to see how geometries of similar compactness but with different configurations behave in regard to energy consumption in the context of this project. Several reports are available focusing on the fenestration design to determine buildings' energy consumption pattern. Gratia and De Herde (2003) in their study suggest increasing the south glazing with solar shading in office buildings. However, their study has not accounted for fenestrations on all four elevations simultaneously. Therefore, their conclusion is not complete enough to understand the impact of fenestration over the building's heating and cooling demands. The most relevant work is found in the report of Ross (2009) which is conducted for Toronto climate. She has identified that, WWR is more dominant than plan forms in modulating energy usage of a building. However, the author has not considered the impact of daylight for varying WWR. Afterwards, she performs some supplemental simulations with addition of daylight control dimming sensors. In that case, she concludes that there is no special synergy between plan form and daylight sensors with regard to energy use. The finding of Ross (2009) thus requires further investigation to provide a comprehensive final remark. The study of Hammad and Abu- Hijleh (2010) has shown that daylight dimming sensors and external shading can reduce total energy demand in office spaces in the climate of Abu-Dhabi. However, they only made observations based on a single plan form. Ross (2009) has analyzed the impact of shading devices on several plan forms and concluded that exterior awnings are not useful to reduce overall energy use in offices in Toronto. To be noted, Ross (2009) has put horizontal overhangs on south, east, and west orientations and has not accounted for natural light; which resulted with decrease in cooling loads only with lighting demand remain unchanged.

Several queries remain unanswered if the previous works are reviewed. Such as: what would be the impact of variable fenestration ratio on different building geometries if daylight harvesting becomes a

major concern? Moreover, the importance of a building's orientation might have crucial impact on its overall energy pattern which is needed to be explored. In addition to that, it would be beneficial to find out if geometry of a building has more importance compared to other envelope parameters. From this standpoint, this research attempts to analyze several design parameters to determine their effect on energy usage of office developments.

3. Case study projects

Several office buildings are identified as case studies which have utilized building form as a measure to obtain energy efficiency. Besides geometries, concentrations are also placed upon fenestration design, building orientation, and shading strategies in these projects. The integration of strategically designed parameters eventually helped these case study projects to attain low energy goals in operation phase. Four projects (with distinct geometric configurations) are discussed in this section those have motivated in selecting certain geometries for this research.

3.1. Case study 1: Agenda 21 Demonstration Energy-Efficient Office Building

Agenda 21 Demonstration Energy-Efficient Office Building at Beijing is the first LEED Gold-rated building in China. Among other principles, this project utilizes its geometry to attain energy efficiency. The 9 story 13000m² (1444 m² each floor) has a cross shaped plan which maximizes daylight potential (Figure 7). Windows are placed strategically on the north and south facades for better solar control. To attain the cross-shape, the design team undertakes energy modeling from a very primary stage. The designers begin their experiments with a square form and explore energy savings achievable by modifying the building's geometry and orientation. Five different building footprints are analyzed with DOE-2 and the cruciform shape is found to perform most efficiently in the field of energy consumption. The energy savings due to the change in building geometry is estimated as 5-10% (Department of Energy, U.S. [DOE], 2000). Besides the geometry, the building facades have windows recessed into the walls on all four elevations. In particular, the south facing windows have combination of light shelf and exterior shading devices located two-thirds of the way up the windows. The external shades extend outward of 0.4 m to control direct solar radiation during cooling season and light shelves extend inward about 0.2m to admit daylight deep into the perimeter zones. On basis of measured data, the building is found to be 60% more energy efficient than ASHRAE 90.1- 1999 (DOE, 20000).

Figure 7: Typical floor plan of Agenda 21 Demonstration Energy-Efficient Office Building; DOE (2000)

Figure 8: Aerial view of DOE- NREL Research Support Facility;
<http://www.wausauwindow.com>

3.2. Case study 2: DOE- NREL Research Support Facility

The new Research Support Facility for the U.S. Department of Energy's (DOE) National Renewable Energy Laboratory (NREL) at Colorado is a LEED platinum building. The 20624.47 m² (total floor area) facility has an H-shaped configuration with two separate wings of 18.29 m (Figure 8). The H-shape facilitates the building with every work station having 100% of daylighting. Moreover, an east-west orientation has helped the building to increase the natural daylight entering the building. The optimal orientation of the building also benefits it in minimizing unwanted heat gains and losses. Shading strategies are applied to south facing windows as a measure to guard direct sun penetration during the summer time. On a warm sunny winter day, the artificial lighting demand is observed only 60kW; which is 62.5% less than the ASHRAE 90.1 baseline lighting power (160kW). The measured energy consumption, after one year of occupancy is monitored as 213.97 MWh/m²/year; which is 50% better than the ASHRAE 90.1- 2004 standard (Commercialwindows.org, 2012).

3.3. Case study 3: Office building of Energinet.dk

The new office building of Energinet.dk in Ballerup, Denmark is recognized as a low energy office building. The low energy use solely is a result of optimization of the design and geometry. The building

consumes only 47.4kWh/m² a year which meets the requirements for low-energy class 1 ³ according to Danish building regulations, without the use of energy producing technologies (Henning Larsen Architects, n.d.). A square plan is chosen as a highly compact form to reduce the heat loss (Figure 9). Workstations are strategically placed to the north-west and north-east to avoid overheating and blinding. Electric energy consumption is reduced with optimization of artificial lighting which consequently cut down cooling loads. To ensure a comfortable inflow of daylight, permanent sunlight protections are designed on the facades. This strategy also limits the risk of overheating in indoors. The offices only gain direct sun from the west in summer; the rooms remain in shadow for the rest of the year.

Figure 9: Typical floor plan; Henning Larsen Architects (n.d)

Figure 10: Typical floor plan of Lewis and Clark State Office Building; MDNR (n.d.)

3.4. Case study 4: Lewis and Clark State Office Building

Lewis and Clark State Office Building at Missouri, US; has received a LEED platinum rating from U.S. Green Building Council. The building is developed with a narrow footprint to maximize daylighting strategy with its axis oriented along east- west (Figure 10). The building has an aspect ratio (width to length ratio) of 5.68:1 which is decided based on comparing the results of several energy modeling schemes. Other two aspect ratios are compared, 4:1 and 1:1 respectively. However, the designers go with the 5.68:1 option based on the energy reduction potential and efficiency of the skin. A comparison chart is shown in Figure 1. The chosen aspect ratio demonstrates the ideal balance between the interior flexibility

³Two low energy classes for buildings are conventional in Denmark. The low energy class 1 and low energy class 2 correspond to total energy use, i.e. energy use for heating, ventilation, cooling and domestic hot water, as 50% and 75% of the minimum requirement respectively.

and environmental performance (Hickson, n.d.). For example, the 5.68:1 ratio allows designers to daylight 75-90 percent of all spaces within the building which also reduces the electrical costs. Each elevation of the building is designed to respond to its respective climatic condition. Precast concrete sunshades protrude from the south facade and allow low sun angles to provide supplemental heat during the winter months yet block heat gain during the intense summer months. The north facade was developed without shading devices, a design strategy that maximizes daylight and views (Missouri Department of Natural Resources [MDNR], n.d).

4. Methodology

To carry out the research five archetypes are designed based on their potential of energy reduction in functionality. Parametric analysis are done on fenestration design and obtaining a standard shading strategy to be incorporated to the archetypes. An energy simulation tool is selected which best serves the intended purpose of this research. Assumptions are made and justified based on standard guidelines and models are prepared to be input in simulation software. Finally, analysis and comparisons are made based on the simulation results. This section briefly outlines the methodology adopted in current research. More detail explanations on some of the topics are included as appendices. Figure 11 graphically shows the methodological framework of this project.

4.1. Parametric analysis

4.1.1. Building geometry

Five different geometries are chosen to be modeled as office buildings. Those are: a square, a rectangle elongated on east- west, a rectangle elongated on north- south, an H-shape, and a cruciform. For the ease of discussion the forms are identified with specific terminology, such as: SQ, RecEW, RecNS, H, and Cross respectively. After reviewing literatures and looking at successful case studies; these five forms are chosen for their distinct features to contribute to the energy performance of office developments. To the first priority, simple geometry with comparatively high compactness is chosen. A highly compact form will benefit the energy use pattern of a building with being less affected by external environment. Secondly, each five shape are expected to receive advantage of daylight harvesting because of their configurations. For instance, the RecEW, RecNS, H, and the Cross all have their wing depth between 13 to 18 m, which is considered as daylight optimizing building shapes. Moreover, the H shape and cruciform masses will be self-shaded because of their staggered configuration. Schematic plans and are 3D images of all five building are presented in Figure 12.

Figure 11: Methodological framework

Figure 12 (a): Schematic plans of archetype buildings (dimensions are in meters)

Figure 12 (b): 3D images of archetype buildings

The gross floor area ⁴(GFA) is kept constant as 6000 m² for all shapes (1200 m² per floor). To ensure that the conditioned building volume remains constant, the total height is kept the same (as 20 m) for all building configurations. The five archetypes are modeled as actual office buildings with service zones (restrooms and stairs) and with five consecutive stories. A multi- floor model would provide more accurate understanding of energy use as it contains a ground contact floor, several intermediate floors, and a roof top. Because, the heat transfer mechanism with exterior varies at different floor levels (for instance, ground floor and roof will response to the exterior differently than intermediate floor; Straube, 2012 and Behsh, 2002).

⁴ The total floor area of a building's enclosed spaces, measured from the outside face of exterior walls or from the centerline of walls of adjoining buildings, is referred to the gross building floor area (Deru and Torcellini, 2005).

Service cores are positioned in the middle of each mass to have better daylight access to the perimeter zones. Placing service core at the center of each plan provides the flexibility to put glazing on all four elevations. It also helps the geometries to become comparable to each other in terms of fenestration design. No basement and rooftop service core (for equipment) are included to the models. The archetypes are designed in such a context which does not consider neighboring built forms, site, and surroundings. As the sun's position constitutes most important parameter guiding a building's design; solar position is regarded carefully in this study and all five archetypes are designed as south facing buildings. Geometric descriptions of five archetype buildings along with external dimensions, perimeter, volume to surface ratio (V/S), floor to enclosure ratio (F/E), and surface to surface ratio (in case of south and west elevations, $S_{\text{south}}/S_{\text{west}}$) are presented in Table 2.

Table2: Geometric description of archetype buildings

Archetypes	Dimensions, m				Perimeter, m	Building aspect ratio		
	w	d	a	b		V/S	F/E	$S_{\text{south}}/S_{\text{west}}$
Square (SQ)	34.64	34.64			138.56	4.64	1.51	1
Rectangle elongated on east-west (RecEW)	69.28	17.32			173.22	4.09	1.28	4
Rectangle elongated on north-south (RecNS)	17.32	69.28			173.22	4.09	1.28	0.25
H- shape (H)	41.58	34.64	13.86	8.66	187.061	3.9	1.214	0.8
Cruciform (Cross)	51.96	41.58	17.32	13.86	187.06	3.9	1.214	1.25

4.1.2. Window to wall ratio

The window to wall ratio (WWR) corresponds to:

$$\text{WWR} = \frac{\text{Area of Exterior Openings (excluding mullions and window frames)}}{\text{Total Wall Area of Exterior Façade (width} \times \text{floor to ceiling height)}}$$
 [Otis & Reinhart, 2009]. The study of window to wall ratio is one of the major topic of parametric analysis in this research. The five archetypes are examined with WWR of 30%, 50%, 70%, and 80% to observe the impact of fenestration at a low level up to the higher level respectively. To achieve a comparable result, each façade of an archetype is designed with the same window to wall ratio. The fenestrations are designed to enhance daylight harvesting potential in each mass. To achieve more daylight benefits, the floor to ceiling heights are chosen as 3.35 m (ASHRAE, 2004). It allows achieving a window head height of 3.35 m and a useful daylit zone depth of 8.375 m (3.35mx2.5) without shading devices and 6.7 m (3.35mx2) with shading devices. Daylight penetration in a space varies linearly with window head height. With no shading device, daylit zone is usually regarded as ‘2.5x window head height’ and with shading devices the depth is ‘2x window head height’ (Otis & Reinhart, 2009). While designing models with lower WWR (for instance models with 30% WWR) glazing are placed above 0.762 m from the finished floor level. Glazing below the desk height (0-0.762 m above the floor) offers little or no benefits for daylighting in an office (ASHRAE, 2004). The elevations of SQ (as a representative of five archetypes) for varying WWR are presented in Appendix I.

4.1.3. External shading design

The function of external shading devices is to shade direct sun but not hinder daylight access. North facing windows receive predominantly diffuse solar radiation and indirect daylight, and therefore do not need overhang (LANL, 2002). South facing windows will benefit from horizontal shading devices (such as: awings, overhangs, and recessed windows). Vertical fins on east and west windows can be effective at reducing direct solar radiation and glare between 9 AM and 3 PM, particularly 2 PM to 5PM (the warmest part of the day) for the west orientation. Exterior sun control is recommended for south, east, and west façades only, in case of Toronto climate (ASHRAE, 2004). Following these guidelines, horizontal overhangs are designed to shade the south façade and vertical fins are considered for east and west orienting windows in the current project. For each facade, a critical month and time for shading is selected. For the south façade, solar altitude angles for June 21 (noon) and December 21 (noon) are most crucial. The period between June 21 and December 21 is considered as the under-heated period. A fixed overhang designed to shade a window during whole over-heated period will also shade part of the window during the under-heated period (PWGSC, 2002). For east and west façade, critical months and time are recommended as September 10 am and September 3pm (Ernest Orlando Lawrence Berkeley National Laboratory, 1997). The current project uses the similar shading strategy for both east and west

facades. The sun angles for the selected months and location are identified with the ‘sun angle tools’ by Gronbeck (2009). Before applying the solar shading devices to the archetypes, a preliminary analysis is performed using the ‘window tools’ (Gronbeck, 2009) to justify the shading design for both south and west facades. The results of the initial shading analysis are included in Appendix II. The shading design for a typical south façade and west façade are presented in Figure 13. Overhang and fin designs for varied window to wall ratio are included in Appendix III.

Figure 13(a): Typical section showing overhang design for south facade (WWR 30%)

Figure 13(b): Vertical fin design for a typical west facade (WWR 30%)

Note: Dimensions are in meters

4.1.4. Design of building enclosure

The performance of building enclosure is regarded among the major parameters which can directly affect the energy intensity of any structure. Buildings with a poor enclosure specification might nullify the helpful effects of form and solar orientation (Ross, 2009). Therefore, enclosure specifications constitute a vital part of the archetype building design in this project. To be noted, exploration of the envelope design on energy use pattern is outside of the domain of this research. Hence a standard construction set is developed and applied to every model as unmodified. The recommendations of ASHRAE (2004)

(Climate zone 6 recommendation table) are closely followed while designing all the assemblies. The Advanced Energy Design by ASHRAE (2004) is specially designed for small offices to achieve 30% energy savings over ANSI/ASHRAE/IESNA Standard 90.1-1999. Therefore, the recommendations of ASHRAE (2004) is applied in this project to build energy efficient office buildings that would use significantly less energy than those built to minimum code requirements. The construction U values of envelope components used in this project are listed in Table 3. Construction details of each assembly (including materials, conductivity, surface properties, and drawings) are presented in Appendix IV.

Table 3: Construction U values

Construction element	U- value (W/m ² K)
External wall 1 (steel framing)	0.2624
Roof	0.2407
Ground floor	0.2514
Internal ceiling or floors	0.8869
Internal partition 1 (lightweight plaster board partition)	1.6474
Internal partition 2 (concrete plastered on both side) ⁵	1.5280
Windows	2.2150

4.2. Climate analysis

According to the international definition of climate zone, Toronto is situated at zone 6 (ASHRAE, 2007), which is identified as cold humid with heating degree days between 4000 and 5000. In Toronto, buildings require energy not only for heating, but also for a significant amount of cooling, over a 4-5 month period (Ross, 2009). Toronto's climate is modified by its location on the shores of Lake Ontario. Toronto is considered as one of Canada's warmer cities; however, winters are still severe, with snows between mid-December and mid-March. Toronto summers usually have an abundance of warm or hot sunny days; whereas winters become less sunny (Living in Canada, n.d.).

An analysis on Toronto climate is performed (using the 'bioclimatic analysis' and 'climate metrics' tools in IES VE) before the energy simulations of archetype buildings. Building design in Toronto must minimize heating energy as the winter is potentially most dominant. For its mid- latitude location, solar radiation on south/ east/ and west walls is significant. In addition to that, solar radiation on roof would

⁵ 'Functional space: stairs' is modeled with concrete walls as 'internal partition 2'. All other spaces have internal partition 1 (lightweight plaster board partition).

also be significant. Prevailing wind flow in winter and summer is typically from the north and south respectively. More detail findings of climatic analysis of Toronto are included in Appendix V.

4.3. Energy simulation tool

To attain the objectives of this research, an energy analysis program is required which can produce both thermal as well as lighting energy results and is able to measure consumption of artificial lighting in affect with daylight illuminance. In general, energy analysis programs are tools to study energy performance and thermal comfort during the building life cycle. Energy analysis tools are more beneficial if they are applied earlier in the design process to determine building form and envelope design with response to the simulated energy performance of the whole building (Paradis, 2010). In this project, IES Virtual Environment (IES VE 6.4.0.9) is selected to perform a total of 40 simulations on five archetype buildings. The IES VE offers an integrated system that operates all of its building simulations from a central building model (Integrated Environmental Solutions [IES], n.d.). The software use hourly data for the exterior temperature and the solar radiation intensity. A number of well-documented research works [Hammad & Abu-Hijleh (2010); McEwan, Roderick, Pollock, & Wheatley, n.d.; and Settlemyre (2009)] are based on IES VE for full- scale experiment buildings, which has proved its reliability. Among its beneficial features, the analysis on electric lighting energy prediction with relation to available daylight level is very significant to this research. To undertake simulations on various investigated forms, distinct modules of IES VE are utilized; such as: SunCast (to analyze solar gain in conjunction with solar control devices), Radiance (analysis of daylight illuminance level), and ApacheSim (dynamic simulation to produce energy reports). A brief description of the utility of each module along with their application in this project is presented in section 4.3.1. The process work flow for energy simulation can be discussed under two titles; one is developing energy models and the second is performance analysis.

4.3.1. Developing models for energy simulations (massing and volumes)

In the first of phase of developing simulation models, 3D massing of each archetype are created using 'IES VE plug-in for Google SketchUp'. SketchUp is also used to create bounded 'rooms'⁶ to be identified by the IES VE. The mass models are then exported to IES VE analysis as 'gbxml'⁷ file. The model

⁶ Bounded rooms are geometrical surfaces that fully enclose a space or volume or thermal boundaries for the IE VE analysis.

⁷ The Green Building XML (gbxml) open scheme helps facilitate the transfer of building properties stored in 3D energy simulation models to engineering analysis tools (<http://www.gbxml.org/>).

builder (module named 'ModelIT') in IES VE is applied to draw the external shading devices to each archetype.

4.3.2. Performance analysis

In performance analysis phase, three different modules of IES VE are applied in each simulation. They are: SunCast, RadianceIES, and ApacheSim. The function of each module and their application to the current project are delineated below:

i) 'SunCast' analyzes how solar gain impacts a building. SunCast analysis is performed to account shading from both external shading devices and self- shading from each form. For instance, the H-shape mass and the cruciform mass have to be analyzed for self- shading by individual forms. To obtain accurate results from daylight controlled dimming in RadianceIES, it is necessary to perform a solar shading calculation prior to the Radiance analysis. Therefore, SunCast is also run for SQ, RecEW, and RecNS in order to facilitate the Radiance simulation. The SunCast result can be fed into the thermal calculation to determine the impact on heating and cooling energy use.

ii) 'RadianceIES' module is used for daylight illuminance level analysis in case of each mass. Photocells can be positioned in this module to record accurate daylight levels for dimming controls. If dimming profile is applied to lighting gains⁸ in Radiance and linked to ApacheSim, the energy reduction of electric lighting can be quantified.

Analysis of power consumption for artificial lighting in conjunction with varied fenestration design is one of the parametric studies to be conducted in current project. In affect with variable window to wall ratio, daylight illuminance level in workplaces would also be changed. If sensors with daylight dimming controls are applied in perimeter spaces, they would have effect on the lighting energy consumption results. For this purpose, RadianceIES is particularly useful in current research.

iii) ApacheSim performs simulations of building thermal performance based on dynamic thermal analysis. Within ApacheSim, conduction, convection and radiation heat transfer processes for each element of the building fabric are individually modeled and integrated with models of room heat gains, air exchanges and plant (Integrated Environmental Solutions [IES] Ltd, n.d.). In this project, the simulation

⁸ For spaces with daylight dimming, a dimming profile is applied to the lighting controls in the internal gains dialog. Lighting gains to the space and lighting power consumption are reduced when adequate daylight levels are achieved.

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of heating, cooling and humidity control systems are achieved in ApacheSim by means of idealized room control method with respect to the set data in thermal templates.

4.4. Simulation inputs and assumptions

To complete an energy model it is necessary to provide it with several data inputs. When performing the building analysis it is important to feed the BIM with location and weather data, construction sets, use profiles, and gain characteristics. These will be representative of how the office would be used in reality.

4.4.1. Site and weather data

The external climate is an important driving force affecting thermal conditions in a building. For the thermal and solar shading calculation in ApacheSim, location and weather data have to be input. The current project uses location and site data Toronto which is presented below:

Location: Toronto Lester B. Pearson Int, Ontario

Latitude: 43.67 N

Longitude: 79.63W

Altitude (m): 173.0

Terrain type⁹: City

Simulation weather file¹⁰: Toronto_ON_CWEC.fwt

4.4.2. Zoning

Zoning is of critical importance for developing an energy model. A model becomes over complex if specified with too many zones. On the contrary, if zones are too few, details will be lost. An energy model for office should be zoned with core functional spaces (e.g. office areas) along with auxiliary spaces like elevator shafts, toilets, stairs etc. (IES Ltd, 2010). For an early stage performance evaluation, these space types are not required to be represented exactly and individually to effectively convey the energy consumption of the building (IES Ltd, 2010). Following these guidelines, each archetype model is divided into three functional spaces; such as: open plan office, stairs, and restrooms.

⁹ The terrain type defines how the wind speed will vary with height, dependent upon the local terrain which affects the external convective losses in ApacheSim.

¹⁰ The CWEC files contain hourly weather observations representing an artificial one-year period specifically designed for building energy calculations. Data for CWEC are derived from the Canadian Energy and Engineering Data Sets of hourly weather information for Canada from the 1953-1995 period of record (Energy Efficiency and Renewable Energy, 2012).

i) Zoning based on functional spaces

In order to distinguish the three functional spaces, IES VE software requires each space as a separate bounded ‘room’. Therefore, each model is initially divided into four rooms; two office spaces, one staircase, and one restroom zone (Figure 14). This zoning method enables all the five geometries to be specified with ‘rooms’ of equal floor area for each functional space. Further each model is divided into eight rooms to facilitate placement of photo sensors (which is discussed in the following paragraph). The internal partitions between office areas are modeled as transparent (with 0% opacity); which omits the physical boundaries and helps analyzing the space as an open plan office.

Figure 14: Zoning of archetypes based on functional spaces (plan view)

i) Zoning based on photocells

To understand the consequence of window to wall ratio to vary from 30% to 80% respectively, photocells have to be put in the model (referred to section 4.3.2). Therefore, while creating ‘rooms’ for each model,

the location of photocells is crucial. RadianceIES allows placing only one sensor per room and by default it positions sensor at a weighted centroid of each room. For daylight harvesting it is recommended to apply dimming control for window to wall ratio of 25% or higher (ASHRAE, 2004). To figure out the best location for a sensor, it would be ideal to identify the daylit zone in a building. As denoted earlier (referred to section 4.1.2), the depth of daylit zone in each model is identified between 6.7 m to 8.375m from the window walls. Accordingly, each plan form is divided into perimeter spaces and interior spaces separately to facilitate the positioning of photo sensors. Drawings of each archetype with zoning based on photocells (along with the description of photo sensor placement process) are presented in Appendix VI.

Prior to create the BIMs for the archetype buildings, performance rating method (informative appendix G) by ASHRAE 90.1-2007 is reviewed as a guideline. The document provides recommendations to building simulation for performance rating method. Decisions which are taken based on these guidelines are attached in Appendix VII.

4.4.3. Scheduling and profiles

Profiles describe the time variation of thermal input parameters. Examples of their use include scheduling plant equipment, modulating casual gains and ventilation rates, and defining time-varying set-points and supply temperatures (IES Ltd). The following table (Table 4) summarizes the simulation inputs for various profiles (details can be obtained from Appendix VIII).

Table 4: Summary of scheduling and profiles

Profile	Schedule
Heating and cooling	8am-6pm no lunch
Auxiliary energy plant	
System outdoor air supply	
Variation profiles (for internal gains from people, miscellaneous, and fluorescent lighting)	
Dimming profile (for fluorescent lighting)	Modulating profile which changes from 1 (when there is not natural light) down to 0 (when 538 lux or more is available)

4.4.4. Thermal conditions

Three different thermal templates are assigned to serve the three functional spaces in model. These templates (for open plan office, restrooms, and stairs) are summarized in Table 5. The explanations of various parameters of the assigned thermal templates, along with the sources of data obtained, are described in Appendix IX.

Table 5: Summary of template inputs

Thermal template	Design temperature, °C		Equipment gain, W/m ²	Lighting gain, W/m ²	Occupancy, m ² /person	Occupants gain, W/person		System outside air supply (max. flow rate)
	Heating set point (constant)	Cooling set point (constant)				Sensible heat gain	Latent heat gain	
Open plan office	20.6	23.9	16.146	12	20	75	55	10 l/s/person
Restrooms	20.6	23.9	5.382	10	No occupancy	No occupancy		5.08 l/sm ²
Stairs	20.6	23.9	10.764	6	No occupancy	No occupancy		0.3 l/sm ²

4.4.5. Description of systems

This project uses VAV dual duct as HVAC system and auxiliary mechanical ventilation system in all functional spaces (referred to Appendix X). The auxiliary ventilation system calculates the heating, cooling and dehumidification required to process outside air to the specified supply condition. Domestic hot water (DHW) consumption is the amount of hot water supplied to the room and the consumption pattern is linked to the space occupancy profile. DHW consumption is specified as about 1.5 liter per hour per person and heating equipment is considered with the type of fuel source used for the HVAC heating system (ASHRAE, 2004). By default the DHW system will be handled by the main system serving the room in IES. Therefore, VAV dual duct is specified as the system handling the DHW in open plan office spaces ('restrooms' and 'stairs' are assigned with 'no occupancy'; therefore, DHW consumption is not assigned to these spaces).

5. Analysis of results

A total of 40 simulations are performed with five archetype office buildings for various permutations. This section will discuss and compare the findings based on the simulation results. Summary of the analysis permutations are presented in Table 6 (in the following page). Each scenario is identified with specific terminology. The first term refers to the form, the second term refers to the window to wall ratio, and the third term indicates the shading situation (i.e. either no shading or with shading). Thus a square mass if tested for 30% WWR without external shading devices, would be coined as SQ30Noshad.

5.1. Explanation of energy factors

The simulation results are obtained as total energy use profiles on annual basis. The total energy refers to energy consumptions for systems, interior lighting, and miscellaneous equipment. Description of selected result parameters are presented below:

- i) Total system energy is calculated as the sum of the energy consumptions for system components, or alternatively as the sum of system fuel consumptions. The total system energy can be broken down into the energy use of boilers (for space heating and hot water)¹¹, chillers (for space cooling), auxiliary systems, and heat rejection fan/ pumps¹².
- ii) Lights energy and equipment energy correspond to the energy consumption associated with internal gains from lighting and equipment respectively.

Among the above energy factors, importance is given to the analysis of boilers space conditioning energy (termed as heating energy), chillers energy (termed as cooling energy), and lighting energy. Boilers DHW energy and miscellaneous equipment energy are calculated based on occupancy (liter/hour/person) and internal gains (from equipment) per area (W/m^2) respectively. Therefore, energy consumptions by these two parameters do not differ from one form scenario to another. However, minor deviation is observed in the energy numbers of these two categories; which has occurred due to the marginal difference in the total area and the fenestration drawings of the archetype models. The energy usages for space heating, cooling (associated with heat rejection fan/ pumps), and lighting vary expressively in each analysis permutation.

¹¹ In this project DHW (domestic hot water) is set to be handled by the main system serving the room. Therefore, energy use of boilers is divided into: Boilers space conditioning energy and Boilers DHW energy.

¹² Auxiliary energy value indicates the power consumption of fans, pumps and controls associated with the space heating and cooling systems.

Table 6: Summary of analysis permutations

Archetype buildings	Simulation number	Simulation terminology	Window to wall ratio (WWR)				External shading devices	
			30%	50%	70%	80%	No shading	With shading
Square (SQ)	1	SQ30Noshad	√				√	
	2	SQ30Shad	√					√
	3	SQ50Noshad		√			√	
	4	SQ50Shad		√				√
	5	SQ70Noshad			√		√	
	6	SQ70Shad			√			√
	7	SQ80Noshad				√	√	
	8	SQ80Shad				√		√
Rectangle elongated on east-west (RecEW)	9	RecEW30Noshad	√				√	
	10	RecEW30Shad	√					√
	11	RecEW50Noshad		√			√	
	12	RecEW50Shad		√				√
	13	RecEW70Noshad			√		√	
	14	RecEW70Shad			√			√
	15	RecEW80Noshad				√	√	
	16	RecEW80Shad				√		√
Rectangle elongated on north-south (RecNS)	17	RecNS30Noshad	√				√	
	18	RecNS30Shad	√					√
	19	RecNS50Noshad		√			√	
	20	RecNS50Shad		√				√
	21	RecNS70Noshad			√		√	
	22	RecNS70Shad			√			√
	23	RecNS80Noshad				√	√	
	24	RecNS80Shad				√		√
H- shape (H)	25	H30Noshad	√				√	
	26	H30Shad	√					√
	27	H50Noshad		√			√	
	28	H50Shad		√				√
	29	H70Noshad			√		√	
	30	H70Shad			√			√
	31	H80Noshad				√	√	
	32	H80Shad				√		√
Cruciform (Cross)	33	Cross30Noshad	√				√	
	34	Cross30Shad	√					√
	35	Cross50Noshad		√			√	
	36	Cross50Shad		√				√
	37	Cross70Noshad			√		√	
	38	Cross70Shad			√			√
	39	Cross80Noshad				√	√	
	40	Cross80Shad				√		√

5.2. Performance analysis of individual archetypes

If a single geometry is analyzed with variables of fenestration ratio and shading scenario; each archetype is observed with a generic energy behavior. As a representative, the performance of SQ is described in this section. Graphs plotting energy pattern of the rest four archetypes are included in Appendix XI. To complement the graphs, numerical results of all simulations are also attached with it.

Eight simulations are performed on SQ. Results of simulation 1- 8 are compiled and presented in Figure 15. It is understandable that energy demands for space heating, space cooling, and interior lighting are actually changing with effect of solar shading (referred to section 5.1). It is also clear that heating energy is the major contributor (except for the static parameters) to the total energy. Lighting and cooling appear as the second and third contributors respectively. The heat rejection fan/ pumps energy changes proportionally to the cooling energy but constitutes only 3% of the energy consumption totals of an archetype (for both shading situation) and is not highlighted in the results discussion.

Figure 15: Energy use pattern (MWh/yr) of SQ for variable WWR and shading scenario

All eight simulations portray a common trend, heating energy increases with the increase in window to wall ratio regardless of external shading devices. If there is no shading, cooling energy also becomes greater as WWR is increased. On the other hand, with external shading, cooling energy becomes lower as WWR is increased. The energy use for artificial lighting becomes lower as glazing is increased from 30% to 80% continually; both for ‘no shading’ and ‘with shading’ situations. Lighting energy gets significantly

affected (for instance, 43.9% increase from SQ30Noshad to SQ30Shad) when there is external shading. The external shading, applied to this project, is found to limit the opportunity of daylight harvesting to some extent. However, it is important to note that, conversely cooling energy gets reduced in each scenario when there is shading. This finding portrays the importance of carefully designed sun control devices in office buildings that maximizes daylighting while reducing both glare and cooling loads.

It can be also inferred from the results that, electrical load for artificial lights and cooling load savings are reciprocal to each other. For instance, SQ80Noshad needs 22% more cooling than SQ30Noshad but 37.9% less lighting energy. That means, with greater fenestration, additional cooling load from solar gain is overcome by the reduced cooling from lower lighting gains. Therefore, cooling load does not increase much with high glazing level as it was expected to. To support this finding, a test simulation is run on SQ once with daylight control dimming sensors and then without sensors to see how the scenarios modulate cooling energy of that building. It is observed that on a specific day cooling energy becomes 22% more if electric lights are not on dimming control. The results are listed in Appendix XII.

5.3. Comparison of five archetypes

The five archetypes are compared in this section to identify which form is performing most efficiently in relation to annual energy use. The deviation of total energy values from one shape to another is found relatively small. The absolute values of energy results may not exactly match to any real life office building because of some abstractions in building design and simulation assumptions. Despite of this, the simulations have produced several outcomes which would shed new light on the research question ‘how building geometry can influence energy use patterns of workplaces.’ The simulation study of the five building shapes shows that the difference in energy consumption from one to another is relevant to their geometric characteristics (which are described in detail in section 5.4). Therefore, while comparing one plan form to another, building aspect ratios are also analyzed to relate with the energy usage pattern.

The total energy demands of five geometries are listed for various fenestration ratios in Table 7. Results are presented for both shading situations. The summary table helps to observe the results of 40 simulations collectively. The scenarios with the least energy numeric are placed at the bottom of the table. The buildings with high energy values are put sequentially to the top. According to the result sheet, SQ requires the lowest amount of energy per year whereas H-shape is found to be the highest energy consumed building. Total energy values in relation to window to wall ratio are listed from left to the right of the result sheet. As WWR increases gradually from 30% to 80%, energy consumption in each archetype also increases. Thereby, the scenarios with low energy are placed at the left of the table and the

scenarios with high energy are positioned to the right. It is interesting to note that, the increase of energy with respect to geometry (the vertical line of increase) is much less than the energy increase values in relation to WWR (the horizontal line of increase). Another important finding can be pointed out comparing the results of ‘no shading’ simulations to ‘with shading’s; shading devices increase total energy requirement in each permutation. This does not convey the idea of omitting shading devices because it might create other problems with glare and overheating. Rather, the situation highlights the importance of strategically designed shading devices to maximize their benefits while minimizing their negative impacts. It also highlights the difficulties of appropriately shading highly glazed facades.

Table 7: Total energy comparison of five archetypes

Archetype buildings	Total energy use, MWh/year				
	Increasing (10.9% ~ 16.3%)				
	Shading scenario	WWR 30%	WWR 50%	WWR 70%	WWR 80%
H- shape (H)	Shad	1190.6	1277.4	1337.9	1385
	No Shad	1134.8	1219.1	1288.9	1328.9
Cruciform (Cross)	Shad	1179.1	1256.8	1336.1	1380
	No Shad	1137.5	1216.8	1288.2	1330.7
Rectangle elongated on north-south (RecNS)	Shad	1197.7	1274.6	1332.6	1372.6
	No Shad	1137.8	1211.3	1282.2	1318.1
Rectangle elongated on east- west (RecEW)	Shad	1164.2	1228.6	1284.9	1324
	No Shad	1121.8	1179.9	1241.8	1274.2
Square (SQ)	Shad	1154	1214.5	1254.4	1289
	No Shad	1110.5	1162.4	1209.9	1231.4

Increasing (2.2 % ~7.5%)

Note: ‘No Shad’ and ‘Shad’ corresponds to without shading and with shading respectively.

The result sheet has a few scenarios, which do not follow the general sequence of energy results described above. The exceptions fall within the margin of error and thus can be disregarded in the next discussions of analysis of results.

5.3.1. Impact of 'shape' versus 'window to wall ratio'

From the discussion of section 5.3, it can be inferred that window to wall ratio has more impact on a building than its shape. To strengthen this finding, this part of the report will focus on the impact of 'shapes' versus WWR. The total energy results of five archetypes are presented in graph format separately for each shading scenario in Figure 16(a) and 16(b).

Figure 16(a): Total energy (MWh/yr) results of five archetypes (no shading)

Figure 16(b): Total energy (MWh/yr) results of five archetypes (with shading)

Note: The vertical axes is set minimum at 1100 MWh/yr in figure 16(a) and 16(b)

The energy rise from SQ30Noshad to H30Noshad is 2.19%; whereas, the energy demand increases about 10.89% from SQ30Noshad to SQ80Noshad [referred to Figure 16(a)]. Looking at Figure 16(b), the energy rise from SQ30Shad to H30Shad is 3.17%; whereas, the energy demand increases about 11.7% from SQ30Shad to SQ80Shad. Therefore, inclusion of shading devices also indicates that the power of WWR is larger than the power of geometry in any archetype.

Geometry or shape of a building contributes toward a small variation in annual energy consumption if only forms are considered with other parameters being equal. In support of this, archetypes are compared first with a WWR of 30% and secondly with a WWR of 80%, without the effect of external shading. The energy increase is found to be 2.2% (if measured from SQ30Noshad to H30Noshad) and 7.9% (if measured from SQ80Noshad to H80Noshad). It is evident that, with more fenestration, energy usage of different forms varies within a larger range compared to forms with less fenestration. Therefore, it would be justifiable to comment that, in case of buildings with low glazing levels 'geometry' is less indicative than for buildings with high glazing levels. Similar observation is found analyzing energy results with external shading; buildings with fewer windows would get less affected with inclusion of shading devices regardless of its geometry.

5.3.2. Discussion on individual energy factors

Until now discussion has been focused on comparing the total annual energy requirement of the 40 simulation permutations. This section will examine selected parameters of energy to identify how they modulate the total energy demand of a building. Three separate result graphs (Figure 17 through Figure 19) are generated based on energy demands of space heating, space cooling, and interior lighting respectively. To be noted, although variations in total energy use are small, variation in heating, cooling and lighting may be significant but offsets each other out in some cases. For example, as some strategies to reduce the space heating may lead to greater energy usage for artificial lighting or space cooling. On an average, SQ appears as the lowest heating energy consumer and Cross and H-shape are found to use the least energy for cooling and lighting among others.

i) Space heating energy

SQ requires the least energy for space heating in all 40 permutations. RecEW, RecNS, Cross, and H-shape show a gradual increase. Archetypes with external shading are resulted with higher heating energy than that of without shading [looking at Figure 17(a) and 17(b)]. The important thing to notice here is the relative importance of window to wall ratio compared to the shape on heating energy use. The heating energy nearly doubles for each plan type (with inclusion of shading devices) when WWR is increased from 30% to 80%. For instance, SQ30Shad (222 MWh) is resulted with 45.9% less heating consumption

in a year while compared to SQ80Shad (410 MWh). In contrary to that, a change in plan form increases the heating energy to a lesser extent. SQ30Shad (222 MWh) requires only 26.1% less heating a year; setting opposite to H30Shad (300.6 MWh). Also the shape becomes more significant in absolute terms when WWR increases.

Figure 17(a): Space heating energy (MWh/yr) results of five archetypes, for WWR of 30% - 80% (no shading)

Figure 17(b): Space heating energy (MWh/yr) results of five archetypes, for WWR of 30% - 80% (with shading)

ii) Space cooling energy

Figure 18(a): Space cooling energy (MWh/yr) results of five archetypes, for WWR of 30% - 80% (no shading)

Figure 18(b): Space cooling energy (MWh/yr) results of five archetypes, for WWR of 30% - 80% (with shading)

Space cooling energy is found to depend on interior lighting energy (referred to section 5.2). It is observed that H-shape and Cross particularly require less energy for space cooling as well as for interior lighting regardless of external shading. In opposite to that, SQ and RecNS need more energy for cooling among the others (in both shading situation). Without shading devices cooling energy increases as

fenestration increases. For instance, SQ30Noshad (76.62 MWh) requires 18.14% less cooling while than SQ80Noshad (93.6 MWh). On the contrary, when shading is included cooling energy does not show a significant variation [Figure 18(b)]. It is interesting to note that, the cooling demand seems unaffected with large WWR when there are carefully designed shading devices. Heating energy still increases a lot with high WWR even with external shading.

Difference in cooling energy due to building geometry is more evident if the results are compared to the difference for WWR. For example, SQ30Shad (71.87 MWh) will need only 2.76% more energy than SQ80Shad (69.95 MWh) but 17.6% more energy if compared to Cross30Shad (61.12 MWh). Thus plan form makes more difference than fenestration magnitude.

iii) Lighting energy

Figure 19(a): Lighting energy (MWh/yr) results of five archetypes, for WWR of 30% - 80% (no shading)

The H-shape building enjoys the benefit of daylight harvesting the most, among other archetypes if no external shading is included. On the other hand, Cross shows the least lighting energy consumption if shading is combined as a design parameter. SQ is resulted with the highest lighting energy consumer in both shading situations. Looking at Figure 19(a) and 19(b), energy demand of lighting reduces as area of window wall increases (in both shading condition). Shading devices are found to result higher electric consumption for lightings in all 20 scenarios.

Figure 19(b): Lighting energy (MWh/yr) results of five archetypes, for WWR of 30% - 80% (with shading)

Variation in plan form is observed to have similar impact on the lighting energy as the impact of fenestration (if no shading devices are combined). For example, SQ30Noshad (102.9 MWh) requires nearly 61% more electricity if compared to SQ80Noshad (63.94 MWh) and H30Noshad (63.7 MWh) respectively. Here, the variation in shape causes lighting energy variations approximately as large as the WWR. With external shading, however, the impact is less evident. As an example, SQ30Shad (148.06 MWh) uses 51.6% more energy than SQ80Shad (97.66 MWh) but only 15.78% more energy compared to H30Shad (124.69 MWh). This is how, window to wall ratio has greater impact on reducing lighting energy than to building geometry if there would be external shading in a building.

5.4. Features of archetypes that modulate energy performance

The five archetypes are found to behave according to individual geometric characteristics. The following table (Table 8) is compiled with the energy consumption (indicating the range of total energy use for different scenario in case of each archetype) in comparison with various building aspect ratios. It can be seen that, SQ has the highest volume to surface ratio, and floor to enclosure area ratio. If we go downward this table, the compactness becomes less. To be noted, RecEW and RecNS have the same V/S and F/E but different $S_{\text{south}}/S_{\text{west}}$. Similarly, H and Cross have the same compactness with slightly different $S_{\text{south}}/S_{\text{west}}$.

Looking at the correlation chart, the most compact form has the least annual energy use. According to the definition of compactness, the more compact the form, the less it gets affected by the external environment (referred to section 2.1).

Table 8: Total energy comparison of five archetypes with building aspect ratios

Archetype buildings	F/E	V/S	S _{south} /S _{west}	Total energy, MWh/yr
Square (SQ)	1.51	4.64	1	1110.5~ 1289
Rectangle elongated on east- west (RecEW)	1.28	4.09	4	1121.8~ 1324
Rectangle elongated on north-south (RecNS)	1.28	4.09	0.25	1137.8~ 1372.6
Cruciform (Cross)	1.214	3.9	1.25	1137.5~ 1380
H- shape (H)	1.214	3.9	0.8	1134.8~ 1385

Although SQ consumes more energy compared to H-shape for space cooling and interior lighting; it performs better over the latter regarding the space heating energy use. For instance, SQ30Noshad show 12.9% more energy usage for space cooling (calculated from 76.62 MWh/yr to 67.84 MWh/yr) and 61.46% more energy requirement for artificial lighting (calculated from 102.89 MWh/yr to 63.72 MWh/yr) if compared to H30Noshad. In opposite to that space heating energy is found 27.62 % less (calculated from 216.94 MWh/yr to 299.70 MWh/yr) in SQ30Noshad to H30Noshad. The heating energy comprises about 20 percentage of the total energy figure and lights contribute to only 9% (Figure 15). Therefore, despite of using more energy for space cooling and interior lighting, SQ displays less total energy demand than H-shape. In all 40 permutations, RecEW gets benefitted over SQ, having greater potential of daylight harvesting; consequently resulted with less artificial lights demand. For instance, SQ30Noshad (102.9 MWh/yr) will need 23.7% more of electric consumption for lighting than RecEW30Noshad (83.2 MWh/yr). Cooling energy demand is also found lower in RecEW than the most compact of all, 'Square' form. Despite of this, RecEW does not overcome the heating energy requirement and thus falls behind SQ in total energy demand. It can be commented that, a building's energy performance, especially the heating energy, is largely determined by its building aspect ratios and for the climate of Toronto (where energy

consumption is predominantly heating oriented), a building geometry that requires less space heating energy might perform better than others in terms of total energy consumption.

5.4.1. Forms with different orientation

RecNS is a reoriented form of RecEW, with respect to the sun's position. Both have same building aspect ratios (F/E and V/S); but RecEW has 4 times more surface oriented to south than RecNS. If results of all 8 simulations of RecNS are compared to that of RecEW; the latter shows lower total energy values per year. Positioning a building elongated on east-west improves the energy performance in summer, reducing the high solar gains from the east and west and therefore reducing cooling loads. For instance, RecEW80Noshad (91.72MWh/yr) has 15% less cooling energy compared to RecNS80Noshad (107.9 MWh/yr) (Figure 20). If external shading is considered; this reduction becomes 10.71%. In each scenario, whether with varying window to wall ratio or shading design; cooling energy of RecNS remains higher than that of RecEW.

Figure 20: Comparison of energy patterns (MWh/yr) of RecEW and RecNS for variable WWR and shading scenario; Note: No Sh and Sh refer to 'no shading' and 'with shading' respectively

Same pattern is observed for heating energy profile; RecEW requires less heating energy as well, compared to RecNW. It is interesting to note that, with external shading, the increase in lights energy is more significant in RecNS compared to RecEW. Solar control with shading devices is more critical for the east and west elevation compared to south facades. For that reason, building with a lower $S_{\text{south}}/S_{\text{west}}$ receives less benefit from natural lighting when sun control devices are incorporated. An illustration is put in Appendix XIII comparing the daylight illuminance values in these two buildings in effect with variable shading situation.

In accordance with scenarios compared in this section, it would be wise to comment that building orientation has effects on the total energy consumption along with individual energy parameters, particularly in case of a rectangular form simulated here.

5.4.2. Forms with narrow wings

The four archetypes analyzed in this study, except that of SQ, have narrow wings with dimension ranging 13.86 m to 17.32 m (referred to Table 2). As discussed in section 2.2, buildings with a narrow wing are particularly advantageous for daylight harvesting as well as reducing electric lighting loads. The concept is found to relate to the outcome of the simulations performed in this project. For instance, H-shape is found to use the least energy for artificial lighting (if there is no external shading device) among the other archetypes. It gets particularly benefitted through its own shape. H-shape has perimeter wings of 13.86 m each and the staggered configuration helps it to access more daylight to the interior. The same strategy applies to Cross; which has wing depths of 17.32 m and a unique configuration which improves daylighting in it. Most interestingly, regardless of fenestration area Cross is observed with lower electric consumption for lighting in comparison to the H-shape when there is external shading (Figure 21). It can be explained with regard the $S_{\text{south}}/S_{\text{west}}$ (referred to Table 2) of these two geometries. H has 1.25 times more surface facing west compared to Cross and Cross has 1.25 times more south oriented surface than H. As depicted in section 5.4.1, solar shading on the west is critical compared to the south windows. Therefore, Cross gets benefitted with more windows on south which increases daylight potential in it when there is external shading.

As the H-shape and Cross have less electric consumption for lighting the interior; they would require less energy for space cooling. Less amount of internal gain occurs from artificial lighting which eventually reduces the cooling demand of the space. These two geometries enjoy the benefit of self-shading from town configurations which can be described as an additional feature (this feature is described graphically in Appendix XIV). Therefore, buildings with H-shape and cruciform impose less cooling loads while taking the advantages of high daylight access to the interior spaces.

Figure 21: Comparison of energy patterns (MWh/yr) of Cross and H for variable WWR and shading scenario; Note: No Sh and Sh refer to ‘no shading’ and ‘with shading’ respectively

5.5. Performance comparison with industry standards

The average Canadian commercial or institutional buildings use approximately 400 kWh/m² annually (Carpenter, 2011). A survey of Enermodal Engineering predicts that, the actual energy use of their monitored LEED certified projects use (on an average) just over 200kWh/m²; which is 45% less than the Canadian average (Carpenter, 2011). The energy section of BOMA Canada identifies that 50% of BOMA BESt certified buildings use 279.76 kWh/m² on an annual basis; which is 30% less if compared to the national average office buildings (BOMA Canada, 2011). Energy intensity of the five archetypes (for each simulation permutation), modeled in current project, are compared to the Enermodal LEED buildings and BOMA BESt certified offices to identify their performance in the national context. First, the total energy values are converted to energy intensity result; afterwards the results are compared with industry standards mentioned above. If the archetypes are found to perform in keeping with Enermodal or BOMA BESt certified low energy buildings; it would appear as a testimonial for the five building geometry in the context of energy consumption rates.

Figure 22: Comparison of energy intensity results of 40 simulations to the industry standards

According to Figure 22, the archetypes are found to use energy between a range of 185.08 kWh/m2/yr and 230.83 kWh/m2/yr in all 40 simulation scenario. It is observed that one 100% of cases fall below the energy use values of BOMA BEST certified buildings and obviously below the national average buildings. 12 out of 40 cases are less energy intense if performance is compared to the LEED buildings. Therefore, if the archetype buildings, developed from the five basic geometries are put to actual operation, they would lead to low energy buildings particularly in the context of Toronto. To be noted, the energy use patterns of each case may not represent exact accurate numbers due to abstraction in energy models and analysis assumptions.

5.6. Summary of results

After analyzing the results, the major observations can be listed under three captions:

Impact of design parameters on energy demands

- i) Geometries are found to follow the definition of compactness: the most compact form has the least total annual energy use.
- ii) SQ building requires the lowest amount of energy per year. RecEW, RecNS, Cross, and H are found to display a gradual increase in energy consumption. However, the difference in total energy values is relatively small (ranging between 2.2% and 7.5%).
- ii) As window to wall ratio increases gradually from 30% to 80%, the total annual energy consumption results in each archetype also increases.

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- iii) Shading devices are found particularly useful to reduce cooling loads in offices even with high fenestration ratio.
- iv) H-shape and cruciform impose less cooling loads while taking the advantages of high daylight access to the interior spaces. These two forms particularly receive benefit from self- shading because of their staggered configurations.
- v) Orientation of a building with respect to solar position has effects on the total energy consumption (along with individual energy parameters) in case of a rectangular form simulated here.

Identification of dominance of design parameters on energy demands

- i) Geometry or shape of a building contributes toward a small variation in annual energy consumption if only forms are considered with other parameters being equal (within a range of 2.2% and 7.5%).
- ii) In case of buildings with low glazing levels, 'geometry' is less indicative than for buildings with high glazing levels.
- iii) Buildings with fewer windows get less affected with inclusion of shading devices regardless of its geometry.
- iv) Window to wall ratio has a slightly stronger impact on the total energy demand than building geometry
- v) Space heating is also dominated by the WWR. The heating energy nearly doubles for each plan type (with inclusion of shading devices) when WWR is increased from 30% to 80%.
- vi) Difference in cooling energy due to geometry is more evident if the results are compared to the difference for WWR. Thus for cooling, plan form makes more difference than fenestration magnitude.
- viii) WWR have greater impact on reducing lighting energy than building geometry if there is external shading in a building.

Correlation among the energy parameters

- i) The pattern of total energy found in each archetype is dominated by the heating energy demands.
- ii) Geometries with lower heating demands can easily compensate the greater cooling energy and artificial lighting requirements.
- iii) Cooling load and lighting demand are found reciprocal to each other. Cooling energy with high fenestration level does not increase greatly as there is lower internal gain from artificial lighting.

6. Conclusion and recommendations to future work

The results of parametric analysis indicate that the impact of building geometry on total energy use depends on primarily two factors: the compactness and the window to wall ratio. Orientation of buildings

performs significant role over the energy consumption patterns. Thus, geometry with high east- west oriented surfaces is less preferable in the context of Toronto. According to the findings of this work, external shading is particularly helpful in reducing cooling demand in offices spaces, although the total energy values are found to be higher. To be noted, these observations are only based on a single type (fixed external shading) of shading devices. Therefore, shading devices with different features may show different outcomes than the findings of this project. Shading devices have other importance for maintaining visual comfort and avoiding glare in the office spaces, especially with high fenestration ratio. From this project it can be concluded that a greater emphasis should be given to the integration of various design parameters rather than individual components.

As an extension of this research, different shading strategies can be compared to find out if shading devices could reduce the impact on heating demand in office spaces without limiting the daylight harvesting opportunities. In addition, the impact of varying enclosure performance (by modifying the construction U-values) could be examined. Geometries can be analyzed with respect to actual site and surroundings to see how their impact gets modified compared to our findings. Thus the featured impacts of various design parameters could be combined to have an optimal design solution.

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Appendix I: Elevations of SQ for varying WWR

The elevations of SQ for varying WWR are presented below. All four elevations (north, south, east, and west) are identical in case of a particular WWR.

WWR 30%

Window sill height: 1.219m
Window head height: 3.35m
Daylight zone depth: 6.7 m (2x head height)

WWR 50%

Window sill height: 0.762m
Window head height: 3.35m
Daylight zone depth: 6.7 m (2x head height)

WWR 70%

Window sill height: 0.53m
Window head height: 3.35m
Daylight zone depth: 6.7 m (2x head height)

WWR 80%

Window sill height: 0.135m
Window head height: 3.35m
Daylight zone depth: 6.7 m (2x head height)

Appendix II: Developing shading strategies

i) Identification of sun angles using ‘sun angle tools’ by Gronbeck (2009)

INPUTS					
longitude	79.63	West	time	12:00	PM
latitude	43.67	North	time zone	USA Eastern (GMT - 5:00)	
date	Jun	21	time basis	Clock time	
year	2011	daylight saving	Yes		
elevation	173	meters	zero azimuth	South	
calculate					
OUTPUTS					
altitude angle	63.90	declination	23.44		
azimuth angle	-45.68	equation of time	- 0.03		
clock time	12:00pm	time of sunrise	5:33am		
solar time	10:39am	time of sunset	9:06pm		
hour angle	-20.07				

INPUTS					
longitude	79.63	West	time	12:00	PM
latitude	43.67	North	time zone	USA Eastern (GMT - 5:00)	
date	Dec	21	time basis	Clock time	
year	2011	daylight saving	Yes		
elevation	173	meters	zero azimuth	South	
calculate					
OUTPUTS					
altitude angle	20.63	declination	-23.44		
azimuth angle	-18.74	equation of time	0.03		
clock time	12:00pm	time of sunrise	8:45am		
solar time	10:43am	time of sunset	5:47pm		
hour angle	-19.13				

For south façade, solar altitude angles for June 21 (noon) and December 21 (noon) are identified as 63.90° and 20.63° respectively.

INPUTS					
longitude	79.63	West	time	3:00	PM
latitude	43.67	North	time zone	USA Eastern (GMT - 5:00)	
date	Sep	21	time basis	Clock time	
year	2011	daylight saving	Yes		
elevation	173	meters	zero azimuth	South	
calculate					
OUTPUTS					
altitude angle	40.64	declination	0.62		
azimuth angle	36.89	equation of time	0.12		
clock time	3:00pm	time of sunrise	7:02am		
solar time	1:48pm	time of sunset	7:21pm		
hour angle	27.10				

For east and west façade, critical months and time are recommended as September 10 am and September 3pm. The current project uses the similar shading strategy for both east and west facades. Therefore, solar azimuth for September 21 at 3pm is determined as 36.89°.

ii) Initial shading analysis

Before applying the solar shading devices to the archetypes, a preliminary analysis is performed using the ‘window tools’ (Gronbeck, 2009) to justify the shading design for both south and west facades. The results of the initial shading analysis are presented below:

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Figure 1: Shading percentage by the overhangs for a typical south façade

the right angle). Gray cells indicate the degree of partial shading. A green cell indicates that the sun is below the horizon. A blue cell indicates that the sun is above the horizon, but behind (i.e, not shining on) the facade shaded by the louver system.

Figure 2: Shading percentage by the vertical fins for a typical west façade

In Figure 1, results may vary as the program analyses shading for a louvered system whereas the current project would apply overhang. The above chart presents the degree of shading provided by the louver system, for each hour of the day, for each month of the year for an entire year. The color of the cell indicates the degree of shading provided by the louver system at that time on the 15th day of that month. A black cell indicates total shading. A white cell indicates complete sun (which you won't see unless your slats are extremely thin and the sun is at just

Appendix III: Overhang design for varied WWR

A standard shading strategy is applied to five archetypes while simulation with shading devices (referred to section 4.1.3). However, the size of overhangs has to be adjusted for different fenestration ratio. Overhang design for south facades are presented in the following drawings for varied WWR.

Appendix IV: Construction details of building envelope (specifications and drawings)

All assemblies are designed using the available construction set in IES VE Apache construction database. Details are presented below:

i) External wall

Steel framing (150mm) at 400mm OC (R 2.3 Ins+ R-1.3 Ins)

Construction thickness 0.3520 m

Total R value 3.6602 m²K/W

U value 0.2625 W/m²K

Outside surface			Inside surface		
Emissivity	Resistance, m ² K/W	Solar absorptance	Emissivity	Resistance, m ² K/W	Solar absorptance
0.9	0.0299	0.7	0.9	0.1198	0.550

Material	Thickness, m	Conductivity, W/m-K
Norman brick	0.09	0.7270
Air space	0.025	
Continuous insulation (rigid) RSI 1.3	0.048	0.03671
Exterior sheathing board	0.013	0.16
Cavity insulation R 2.3 (insulation between studs)	0.15	0.0841
Gypsum board	0.013	0.16
Gypsum board	0.013	0.16

ii) Roof

Roofs with insulation entirely above deck (R 3.5 Ins)

Construction thickness 0.67 m

Total R value 3.9653 m²K/W

U value 0.2407 W/m²K

Outside surface			Inside surface		
Emissivity	Resistance, m ² K/W	Solar absorptance	Emissivity	Resistance, m ² K/W	Solar absorptance
0.9	0.0299	0.7	0.9	0.1074	0.550

Material	Thickness, m	Conductivity, W/m-K
Stone chippings	0.0500	0.9600
Felt fabric	0.0050	0.5000
Roof insulation R 3.5	0.1000	0.0288
Concrete lightweight	0.3000	2.3076
Cavity	0.2050	
Ceiling tiles	0.0100	0.0560

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iii) Ground floor

Steel joist floor with spray-on insulation

Construction thickness 0.79 m

Total R value 3.7665 m²K/W

U value 0.2514 W/m²K

Outside surface			Inside surface		
Emissivity	Resistance, m ² K/W	Solar absorptance	Emissivity	Resistance, m ² K/W	Solar absorptance
0.9	0.0299	0.7	0.9	0.1620	0.550

Material	Thickness, m	Conductivity, W/m-K
Soil	0.0254	1.2981
Cavity	0.3048	
Continuous insulation (R 1.4)	0.1222	0.0361
Metal deck	0.0122	160.0000
Concrete lightweight	0.3	2.3076
Carpets and pad	0.0254	0.1174

iv) Internal ceiling

Concrete slab internal ceiling

Construction 0.67 m

Total R value 0.7357 m²K/W

U value 1.0520 W/m²K

Outside surface			Inside surface		
Emissivity	Resistance, m ² K/W	Solar absorptance	Emissivity	Resistance, m ² K/W	Solar absorptance
0.9	0.1074	0.550	0.9	0.1074	0.550

Material	Thickness, m	Conductivity, W/m-K
Synthetic carpet	0.0100	0.0600
Screed	0.0500	0.4100
Cast concrete	0.3	1.1300
Cavity	0.3	
Ceiling tiles	0.0100	0.0560

v) Internal partition 1

Lightweight plasterboard partition

Construction thickness 0.0800 m

Total R value 0.3675 m²K/W

U value 1.6474 W/m²K

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Outside surface			Inside surface		
Emissivity	Resistance, m ² K/W	Solar absorptance	Emissivity	Resistance, m ² K/W	Solar absorptance
0.9	0.1198	0.550	0.9	0.1198	0.550

Material	Thickness, m	Conductivity, W/m-K
Gypsum board	0.0150	0.1600
Cavity	0.075	
Gypsum board	0.0150	0.1600

vi) Internal partition 2

300mm heavy weight concrete plastered both sides

Construction thickness 0.3430 m

Total R value 0.4149 m²K/W

U value 1.5280 W/m²K

Outside surface			Inside surface		
Emissivity	Resistance, m ² K/W	Solar absorptance	Emissivity	Resistance, m ² K/W	Solar absorptance
0.9	0.1198	0.550	0.9	0.1198	0.550

Material	Thickness, m	Conductivity, W/m-K
Gypsum board	0.0191	0.1600
HW concrete undried aggregate	0.3048	1.7300
Gypsum board	0.0191	0.1600

vii) Windows

Low E double glazing SC= 0.5

U value (glass only) 2.0606 W/m²K

Total R value 2.2150 m²K/W

Visual light transmission 0.65

Outside surface		Inside surface	
Emissivity	Resistance, m ² K/W	Emissivity	Resistance, m ² K/W
0.837	0.005	0.837	0.1198

Frame

Material	Percentage	Resistance	Absorptance	U value
Aluminum	10.00%	0.1526 m ² K/W	0.7	3.6055 W/m ² K

Glass

Material	Thickness, m	Conductivity, W/m-K
Solar 6MM	0.0060	1.0600
Cavity	0.0120	
Clear float 6MM	0.0060	1.0600

Appendix V: Analysis on Toronto climate

i) Climate index and climate metrics

The Climate Energy Index demonstrates the potential energy required in maintaining the CEI comfort zone based on climate alone excluding any consideration of building design or occupancy. The Climate Energy Index for Toronto Lester B. Pearson Int is predominantly heating based.

The monthly breakdown chart(per m³/hr) illustrates the patterns of energy use (seasons) and the energy use breakdown. This is also summarized below:

kWh/yr	Hours in use
Sensible heating	16.55
Humidification	2.25
Sensible Cooling	0.43
Dehumidification	0.16

- Winter is potentially most dominant - the design must minimize heating energy.
- Latitude is mid - solar radiation on south/east/west walls is significant. Solar radiation on roofs is significant. Summer is warm. Summer also has a large diurnal range. Summer also has cool summer nights.
- Winter is cold. Winter prevailing winds typically from the north. Summer prevailing winds typically from the south. Wind patterns: Typically westerly winds.
- Warmest month Jul
- Max annual temperature (Aug) 32.5 °C

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- Warmest six months Jul, Au, Jun, Sep, May, and Oct
- Coldest month Jan
- Min annual temperature (Jan) -19.4 °C
- Coldest six months Jan Feb Dec Mar Nov Apr
- Number of months warmer than 10.0°C mean = 5
- Annual solar resource 1312.2 kWh/m².yr
- HDD(18.0) = 4274.1
- CDD(10.0) = 1245.2
- Max. moisture content 0.019 kg/kg
- Min. moisture content 0.000 kg/kg
- Mean moisture content 0.006 kg/kg
- Mean relative humidity 73.9 %
- Wind5:
- Annual mean speed 4.2 m/s
- Annual mean direction E of N -80.0°
- Annual rainfall 834.1 mm
- Annual hourly mean global radiation(a) 149.8 W/m²
- Mean daily global radiation 3588.2 Wh/m²

ii) Bioclimatic analysis (design priorities)

- Minimize heat loss
- Compact/clustered plan (minimum surface area for minimum heat loss)
- U shaped building - protected court facing south, south facing roof
- Southern protected balconies
- Closed and low northern facades
- Heat production zoning - place heat gains to benefit north (south in S hemisphere) facing spaces.

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- High levels of insulation for envelop construction
- Employ heavyweight (high mass) construction. -
- Lightweight roof, well insulated.
- Triple glazing required
- Glazing bias - more glazing to southerly aspects (northerly in southern hemisphere), but with appropriate summer sun protection.
- Limit northerly (southerly in southern hemisphere) facades to 15% of total window area, but sufficient for good daylighting
- User control of glare, direct sun and passive ventilation openings
- Low sun occupant protection S (N in southern hemisphere), E, W

Appendix VI: Zoning based on photocells

Daylight-responsive electric lighting controls are absolutely essential to any daylighting system. No daylighting design will save any energy unless the electric lights are dimmed or turned off when there is sufficient illumination from daylight (Ander, 2011). To put photo sensors, each model is divided into 4 perimeter spaces and 4 interior spaces. However, the restrooms and the stairs do not have any exposure to exterior; therefore, dimming controls are not applied. Positioning a photo sensor is very sensitive. If it's in front of a window in one model and behind a wall in the other, the comparison will be inaccurate. Moreover, in some cases the sensor may receive direct sun on it. If each archetype is designed with a uniform band of glazing and has the sensors at the same distance from the façade; only then a comparable result could be achieved. Furthermore, to compare any two archetype buildings sensors have to be located at exactly the same position. Therefore, rooms are recreated in each model based on the photo sensor placement each model having the same number of sensors. The location of each sensor is tried to keep similar in each model. The zoning of each archetype based on photocells is presented in Figure 3.

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- Symbolizes Photo sensors

1, 2, 3...Stands for 'Rooms'

Figure 3: Plan view of rooms in accordance with the position of photo sensors (dimensions are in millimeters)

Note:

- All the sensors are placed at working plane height (0.85m) direction pointing upward
- All sensors are positioned within the daylit zone (0- 6.7 m or 8.375 m from the window walls)
- Each model has 8 rooms and 6 photo sensors
- Room 5 and 6 in each archetype, have no dimming sensors
- Room sizes are not same in each model

Appendix VI: Performance rating method, ASHRAE (2007)

Prior to create the BIMs for the archetype buildings, performance rating method (informative appendix G) by ASHRAE 90.1-2007 is reviewed as a guideline. The document provides recommendations to building simulation for performance rating method. Decisions which are taken based on these guidelines are discussed below:

i) Space use classification (space by space method)

For space use classification of a proposed building should be specified using the building type or space type lighting classification. The current project has three different functional spaces. Therefore, the ‘space by space’ method is chosen for computational simulations. Accordingly, lighting power density (LPD) values are obtained from ASHRAE/IESNA Standard 90.1-2007 for the three functional spaces for each archetype.

Table 1: LPD values using space by space method

Space type	LPD, W/m²
Open plan office	12
Restrooms	10
Stairs- active	6

ii) Thermal Blocks (HVAC zones not designed)

For the initial stage energy modeling, where the HVAC zones and systems have not yet been designed, thermal blocks shall be defined based on similar internal load densities, occupancy, lighting, thermal and space temperature schedules. Separate thermal blocks shall be assumed for interior and perimeter spaces. The current project, a single type of HVAC (VAV dual duct) system is chosen for each space. Therefore, no HVAC zone is designed in the models for simulations.

Appendix VIII: Scheduling and profiles

Schedules are capable of modeling hourly variations in occupancy, lighting power, miscellaneous equipment power, thermostat set points, and HVAC system operation. . Schedules for HVAC fans that provide outdoor air for ventilation should run continuously whenever spaces are occupied and should be cycled on and off to meet heating and cooling loads during unoccupied hour (ASHRAE, 2007). The use of control strategies can help to reduce energy.

Weekly operating hours are the number of hours per week that a building (or space within a building) is occupied by at least 75% of the tenant employees, and is therefore considered to be operational. The

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current project assumes weekly operating hours of 50; each weekday between 8am- 6pm with no lunch. The assumption is made after the 'ASHRAE 8am- 6pm no lunch' profile available in IES VE database.

i) Occupancy profile

The current project uses a modulating profile based on the weekly operating hours. Modulating profiles are used to modulate inputs such as internal gains, ventilation rates, and to schedule plant. They take the form of a time series of values in the range 0 – 1. A Modulating profile specifies a time-varying value, and is used to modulate an input parameter or as a control switch. If the profile is used as a control switch, values greater than 0.5 are interpreted as 'on' and other values as 'off' (IES Ltd). The occupancy profile used for all functional spaces (8am-6pm no lunch) is presented in figure 4. Heating, cooling profile, auxiliary energy plant, and system outside air supply also follow the same profile. Accordingly, internal gains from people, miscellaneous, and fluorescent lighting are calculated based on the occupancy hours.

Figure 4: Occupancy profile (1 when the variable lies between 8 and 24 otherwise 0)

The explanations of different profile used in this project are mentioned below (referred to table 4.3 in section 4.4.3 of this report):

- **Heating Profile**

Heating profile is the percentage profile group that defines the operation of the heating system. For heating to operate, the percentage profile must exceed 50% (IES Ltd).

- **Cooling profile**

Cooling profile is the percentage profile group that defines the operation of the cooling system. For cooling to operate, the percentage profile must exceed 50% (IES Ltd).

- **Plant profile (auxiliary energy)**

Plant profile is a modulating profile specifying the times when auxiliary energy will be incurred.

- **Variation profile**

Variation profile is a control to set the modulating profile group reference that describes the variation of the heat gain throughout the year (IES Ltd). Variation profiles for each type of internal gain is selected same as the occupancy profile of the office development.

- **Dimming profile**

A dimming profile is set for the fluorescent light which makes lights to be fully on when there is no light (0 lux) and gradually reduce to 0% when the luminance level 538 lux is achieved (Figure 5).

The target lighting in open offices is 323 lux for ambient lighting with a total of at least 538 lux provided on the desktop by a combination of the ambient and supplemental task lighting (ASHRAE, 2004).

Therefore, the illuminance level on the working plane is set as 538 lux. The working surface height is considered as 0.85m (as default setting by IES VE). A proportional dimming profile is set as ramp* function. This function modulates the artificial light contribution as a function of the natural light illuminance on the work plane level. The value of the profile changes from 1 when there is no natural light, i.e. the full 538 lux is to be provided by artificial light, down to zero when there is 538 lux or more of natural light available, i.e. no artificial light is used.

*(e1, 0, 1, 538, 0) or

ramp (e1, [min daylight to begin dimming], [fraction of gain at max lighting level], [work-plane illuminance target $\times$ (1 - minimum electric lighting fc or lux level at the work plane)], [fraction of gain at minimum lighting level])

Figure 5(a): Graph showing the proportional dimming profile

Figure 5 (b): Location of photo sensor in Y axis

This dimming profile will modulate the lighting energy consumption and thermal gain as a fraction of the lighting power density indicated for a space after any modulation of lighting power and gain provided by the lighting schedule profile and any diversity factor that has been included in the lighting gain properties.

Appendix IX: Description of the thermal templates

- **Heating and cooling set point**

Heating set point is the set point for heating control. This value must be less than or equal to the simulation cooling set point at all times. In this project heating and cooling set point are kept constant as 20.6 °C and 23.9 °C respectively. Heating and cooling set point are obtained from the default values used in the thermal templates.

- **Internal gains**

Internal gains are considered from people, fluorescent lighting, and equipment. At first, occupancy density for the office space is determined according to the default values listed in ANSI/ASHRAE Standard 62.1- 2007 as 20person/m². No occupancy is chosen for ‘restrooms’ and ‘stairs’.

- i) Heat gain from people**

For 24 °C room dry bulb temperature, an adult male will produce 75 W sensible heat and 55W latent heat performing moderately active office works (ASHRAE, 2009). Following this guideline, sensible heat gain and latent heat gain are set as 75W/person and 55W/person respectively.

- ii) Heat gain from equipment**

In a medium to heavy load density office* the recommended load factor for equipment is 16.1 W/m². Here equipment refers to computers, monitors, laser printer, and fax machines (ASHRAE, 2009). Therefore, equipment gains are set as 16.1 W/m² for open plan offices in current project. Internal gains from equipment in case of ‘restrooms’ and ‘stairs’ are obtained from the default values set by the IES VE database.

* Assumes 9.3 m²/ workstation (11workstations per 100m²) with computer and monitor at each plus printer and fax.

- iii) Heat gain from fluorescent lighting**

Maximum sensible heat gains from the interior lights are determined according to the lighting power density for each functional space (referred to table 1 in appendix 4G) as 12W/m², 10 W/m², and 6 W/m² for office spaces, restrooms, and stairs respectively.

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- **System outside air supply**

It is the maximum flow rate of air supplied to the room from the system (not including any room air recirculated through the room units) which is operated with variation profile of '8am-6pm no lunch'.

According to the ANSI/ASHRAE Standard 62.1- 2007, for an office space with an occupancy density of 20person/m², combined outdoor air rate has to be 8.5 l/s-person. The current project uses the default air supply value (10 l/s-person) for the open plan offices set by the IES VE database. The supply air rates in case of 'restrooms' and 'stairs' are set as the default value specified in the thermal templates of IES VE.

Appendix X: Selection of systems

For nonresidential and 4- 5 stories building (2300 m² to 14,000 m²) the recommended HVAC system by ASHRAE (2007) is:

Packaged VAV with Reheat

Fan coil: VAV

Cooling type: Direct expansion

Heating type: Hot-water fossil fuel boiler

Settlemyre (2008) has analyzed three different building forms once with 'split system with mechanical ventilation and cooling' and afterwards with 'VAV dual duct'. In each case the 'VAV dual duct' system was the better performer.

Based on the above references, the current project uses VAV dual duct as the HVAC system and auxiliary mechanical ventilation system in all functional spaces. The auxiliary ventilation system will calculate the heating, cooling and dehumidification required to process outside air to the specified supply condition.

For DHW system, VAV dual duct is specified in case of open office spaces. According to ASHRAE (2004), the service water heating equipment considers the type of fuel source used for the HVAC heating system.

Appendix XI: Energy use patterns of the archetypes (graphical representations and numerical results)

Energy use pattern (MWh/yr) of RecEW for variable WWR and shading scenario

Energy use pattern (MWh/yr) of RecNS for variable WWR and shading scenario

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Energy use pattern (MWh/yr) of H for variable WWR and shading scenario

Energy use pattern (MWh/yr) of Cross for variable WWR and shading scenario

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Energy I Permutation	SQ30Noshad	SQ30Shad	SQ50Noshad	SQ50Shad	SQ70Noshad	SQ70Shad	SQ80Noshad	SQ80Shad
Equipment	314.5	314.5	314.5	314.5	314.5	314.5	314.5	314.5
Aux+DHW	190.8	190.8	190.8	190.8	190.8	190.8	190.8	190.8
Boiler DHW	177.1	177.1	177.1	177.1	177.1	177.1	177.1	177.1
Heat rejection fan/ pumps	31.6	29.6	34.3	29.6	37.0	28.6	38.6	28.9
Space heating	216.9	222.0	279.2	296.9	333.2	374.0	352.8	410.2
Interior lighting	102.9	148.1	83.3	133.7	67.5	100.1	63.9	97.7
Space cooling	76.6	71.9	83.2	71.8	89.7	69.3	93.6	69.9
Total	1110.5	1154.0	1162.4	1214.5	1209.9	1254.4	1231.4	1289.0
Archetype: SQ								

Energy use pattern (MWh/yr) of SQ for variable WWR and shading scenario; showing results of simulation 1-8

EnergyI Permutaion	RecEW30Noshad	RecEW30Shad	RecEW50Noshad	RecEW50Shad	RecEW70Noshad	RecEW70Shad	RecEW80Noshad	RecEW80Shad
Equipment	311.1	311.1	311.1	311.1	311.1	311.1	311.1	311.1
Aux+DHW	189.0	189.0	189.0	189.0	189.0	189.0	189.0	189.0
Boiler DHW	175.1	175.1	175.1	175.1	175.1	175.1	175.1	175.1
Heat rejection fan/ pumps	29.5	26.9	32.2	26.3	35.7	26.0	37.8	26.6
Space heating	262.5	275.4	336.0	368.5	397.4	455.0	422.9	493.2
Lighting	83.2	121.7	58.6	94.7	46.8	65.6	46.6	64.7
Space cooling	71.5	65.1	78.0	63.8	86.7	63.1	91.7	64.4
Total	1121.8	1164.2	1179.9	1228.6	1241.8	1284.9	1274.2	1324.0
Archetype: RecEW								

Energy use pattern (MWh/yr) of RecEW for variable WWR and shading scenario; showing results of simulation 9-16

EnergyI Permutaiton	RecNS30Noshad	RecNS30Shad	RecNS50Noshad	RecNS50Shad	RecNS70Noshad	RecNS70Shad	RecNS80Noshad	RecNS80Shad
Equipment	311.1	311.1	311.1	311.1	311.1	311.1	311.1	311.1
Aux+DHW	189.0	189.0	189.0	189.0	189.0	189.0	189.0	189.0
Boiler DHW	175.1	175.1	175.1	175.1	175.1	175.1	175.1	175.1
Heat rejection fan/ pumps	32.2	29.4	36.9	29.5	41.9	29.0	44.5	29.6
Space heating	272.8	275.1	350.8	375.1	417.0	478.8	444.2	517.9
Lighting	79.5	146.6	58.8	123.4	46.5	79.5	46.3	78.2
Space cooling	78.1	71.3	89.6	71.5	101.6	70.2	108.0	71.7
Total	1137.8	1197.7	1211.3	1274.6	1282.1	1332.6	1318.1	1372.6
Archetype: RecNS								

Energy use pattern (MWh/yr) of RecNS for variable WWR and shading scenario; showing results of simulation 17-24

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EnergyI Permutation	H30Noshad	H30Shad	H50Noshad	H50Shad	H70Noshad	H70Shad	H80Noshad	H80Shad
Equipment	311.2	311.2	311.2	311.2	311.2	311.2	311.2	311.2
Aux+DHW	189.1	189.1	189.1	189.1	189.1	189.1	189.1	189.1
Boiler DHW	175.2	175.2	175.2	175.2	175.2	175.2	175.2	175.2
Heat rejection fan/ pumps	28.0	26.2	31.8	26.2	34.9	25.0	36.6	25.4
Space heating	299.7	300.6	383.9	404.6	452.0	507.9	486.6	554.9
Interior lighting	63.7	124.7	50.7	107.6	41.7	68.8	41.3	67.5
Space cooling	67.9	63.6	77.2	63.5	84.7	60.6	88.8	61.6
Total	1134.8	1190.6	1219.1	1277.4	1288.9	1337.9	1328.9	1385.0
Archetype: H								

Energy use pattern (MWh/yr) of H for variable WWR and shading scenario; showing results of simulation 25-32

EnergyI Permutation	Cross30Noshad	Cross30Shad	Cross50Noshad	Cross50Shad	Cross70Noshad	Cross70Shad	Cross80Noshad	Cross80Shad
Equipment	311.0	311.0	311.0	311.0	311.0	311.0	311.0	311.0
Aux+DHW	188.9	188.9	188.9	188.9	188.9	188.9	188.9	188.9
Boiler DHW	175.1	175.1	175.1	175.1	175.1	175.1	175.1	175.1
Heat rejection fan/ pumps	28.3	25.2	31.6	24.7	34.6	24.9	38.0	26.5
Space heating	294.7	309.0	379.9	416.0	448.1	511.3	479.6	551.0
Interior lighting	71.3	108.7	53.7	81.8	46.4	64.4	46.0	63.2
Space cooling	68.1	61.1	76.6	59.2	84.0	60.4	92.1	64.2
Total	1137.5	1179.1	1216.8	1256.8	1288.2	1336.1	1330.7	1379.9
Archetype: Cross								

Energy use pattern (MWh/yr) of Cross for variable WWR and shading scenario; showing results of simulation 33-40

Appendix XII: Correlation between cooling and lighting energy in SQ

Figure 6: Correlation between space cooling and lighting energy in SQ30Noshad (Jul 15)

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A test simulation is run on SQ (with WWR of 80% and without shading devices) once with daylight control dimming sensors and then without sensors to see how the scenarios modulate cooling energy of that building. It is observed that on a specific day cooling energy (average) and lighting energy (average) are found as 90kW and 20kW respectively when the lights are on dimming control. On the contrary, when daylight dimming sensors are not applied, cooling energy (average) and lighting energy (average) are found as 110kW and 70kW respectively. Cooling energy increases by 22% if electric lights are not on dimming control.

Appendix XIII: Comparison of daylight illuminance in RecEW and RecNS

Daylight illuminance in RecNS30Noshad [Figure 7(a)] is compared to that of RecNS30Shad [Figure 7(b)]. For a west facing room on Jan 26, the results are found as 160000 lux and 24000 lux respectively.

Figure 7(a): Daylight illuminance in RecNS30Noshad (in a west facing room on Jan 26)

Figure 7(b): Daylight illuminance in RecNS30Shad (in a west facing room on Jan 26)

Similar comparison is performed on a RecEW. In case of a west facing room on a particular day, RecEW30Noshad [Figure 8(a)] has an illuminance level of 28000 lux whereas, RecEW30Shad [Figure 8(b)] has 26000 lux.

Figure 8(a): Daylight illuminance in RecEW30Noshad (in a west facing room on Sep 21)

Figure 8(b): Daylight illuminance in RecEW30Shad (in a west facing room on Sep 21)

From the above comparison, it is clearly understandable that, RecNS gets more affected with external shading devices if compared to RecEW for the same fenestration ratio.

Appendix XIV: Comparison of daylight illuminance in H and Cross

For a west facing room on the same day, daylight illuminance is found as 36000 lux in H50Noshad [Figure 9(a)] and 34000 lux in H50Shad [Figure 9(b)].

Figure 9(a): Daylight illuminance in H50Noshad (in a west facing room on Aug 17)

Figure 9(b): Daylight illuminance in H50Shad (in a west facing room on Aug 17)

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Figure 10(a): Daylight illuminance in Cross50Noshad

Figure 10(b): Daylight illuminance in Cross50Shad

On the other hand, illuminance values are found as 23500 lux and 22000 lux in Cross50Noshad [Figure 10(a)] and Cross50Shad [Figure 10(b)] for a south oriented room in a specific day.

Comparing the results of H and Cross it can be commented that, Cross gets less affected with inclusion of shading devices than the H-shape.

Self- shading analysis in H and Cross

H and Cross buildings receive advantages from their own configurations. The staggered shape provides self- shading to these two geometries. A solar shading analysis is done to see the effect of self-shading in various critical time of the day.

Determining the effect of building geometry on energy use pattern of office developments

Sep 3pm- critical for west facade

Sep 10 am- critical for east facade

Sep 12 pm- critical for south facade

Sep 3pm- critical for west facade

Sep 10 am- critical for east facade

Sep 12 pm- critical for south facade