DETERMINING THE EFFECT OF BUILDING GEOMETRY ON ENERGY USE PATTERNS OF OFFICE BUILDINGS IN TORONTO

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ABSTRACT

The project investigated the potential of building geometry to minimize energy consumption in office buildings. Five distinct geometries were modeled as mid-size office occupancies in the context of Toronto, Ontario, and examined with varied design parameters: window to wall ratio (WWR) and external static shading devices. IES VE software was used to predict the annual energy consumption of the five archetypes for 40 permutations. The outcome of this research showed that the variation of the total energy use from one shape to another was relatively small. WWR appeared to have a stronger impact on the energy pattern of a building than its shape. Overall, the energy performance of the archetypes were observed to conform to their individual building aspect ratios. The findings are thus expected to provide useful guidelines for architects on utilizing building geometry as an energy saving measure in the design of office buildings.

KEYWORDS

building geometry, window to wall ratio, shading devices, energy consumption, simulation, IES VE

1. INTRODUCTION

Optimization of energy performance is a crucial factor in the design of office buildings. The role of building geometry can become a potential means to reduce a building's overall energy consumption. The shape of a building, respective to the climate and context, is usually the only element that does not change radically during the life cycle of a building. Selection of the formal configuration, along with the depth and height of rooms, and the size of windows can together double the eventual energy consumption of the finished building (Gratia and De Herde 2003). Thus, decisions made in the early design stages of a project that affect building geometry,¹ orientation, and glazing levels can have a significant impact on its lifetime energy performance. Effective guidance may help designers to contribute toward sustainable solutions.

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Various studies have examined the effect of shapes, fenestration,² and shading strategies on the energy use of buildings. However, studies identifying the combined impact of these design parameters are rarely found, especially in the context of Canada. There are disagreements among researchers regarding the importance of geometry on the energy performance of office buildings. Some studies claim that the shape of a building can have significant impact on the energy use and the costs of heating and cooling (AlAnzi, Seo, and Krarti 2009). Other studies claim that building form and orientation do not largely influence the energy consumption, especially in the case of mid-size or large buildings (Straube 2012). Hence, a detailed research is required to examine the potential of building geometry in combination with other envelope factors to minimize the energy consumption of office buildings in Canada.

Several researchers have employed the concept of building aspect ratio³ to define the way a form responds to its climate (Behsh 2002; Gratia and De Herde 2003; Ross 2009; AlAnzi, Seo, and Krarti 2009; and Straube 2012). Despite their contextual differences, these reports depicted that the compactness⁴ of a building can play a significant role in energy performance, since it determines the surface of the external envelope. According to the findings of Behsh (2002), plus AlAnzi, Seo, and Krarti (2009)—even with similar compactness (Volume/ Surface)—buildings can behave differently due to the difference in wall area and orientation to solar exposure. Compactness generally correlates with reductions in heating energy but leads to increases in lighting energy demands.

Building geometry for energy conservation is often related to fenestration area and orientation of windows. Gratia and De Herde (2003) suggested increasing the south glazing with solar shading in office buildings to reduce the cooling loads and the artificial lighting demands. However, their study did not account for windows on all four elevations of the building simultaneously when performing simulations. Ross (2009) in her study conducted for Toronto identified that the window to wall ratio (WWR)⁵ is more dominant than plan forms in modulating the energy usage of a building. She considered the influence of daylight (for varying WWR) with addition of daylight control dimming sensors and concluded that there is no special synergy between the plan forms and the daylight sensors with regard to energy use. The findings of Ross thus require further investigation.

Ross (2009) also analyzed the impact of shading devices on several plan forms and concluded that exterior awnings are not useful to reduce the overall energy use of office buildings. It is important to note that she put horizontal overhangs on all four orientations and considered only the impact of shading on cooling loads with lighting demands remaining unchanged. Hammad and Abu-Hijleh (2010) showed that daylight dimming sensors and external shading can reduce the total energy demand in office spaces in Abu- Dhabi, UAE. However, their observations were made based on a single geometry.

The above review of previous works leaves several unanswered questions. For instance, "What would be the impact of variable fenestration ratios on different building geometries when lighting is also considered?" This is becoming more important because insulation levels and glazing technologies are reducing heating loads. The orientation of a building may have crucial impact on its overall energy pattern, which also needs to be explored. Moreover, it would be beneficial to examine if the geometry of a building has more importance compared to the other design parameters when the heating, cooling, and lighting energy use are considered.

2. OBJECTIVE AND APPROACH

This research explored the importance of building shape compared to the other building envelope factors, such as WWR and external shading devices on the whole building energy demands of office buildings.

Five different geometries (archetypes) were modeled as mid-size office occupancies in Toronto, representing the context and climate of southern Ontario in Canada. The research considered the energy use for space heating, space cooling, and artificial lighting, which are all affected by the location and local climate conditions. Daylight harvesting with properly designed fenestration can have a significant impact on the electricity consumption of artificial lighting in a space. The analysis of daylighting with respect to various WWR was carried out to investigate this issue. While glazing can assist with natural light, it may also lead to excessive solar gains that can lead to overheating. Therefore, the effect of external shading devices, as a sun control strategy, was incorporated into the parametric analysis. Energy simulation software was used to predict the whole building energy demand of the archetypes. After analyzing the results, the impacts of design parameters on the energy demands were identified. The correlations among the various energy factors were also investigated.

The value of this research is to inform building designers about the relative importance of basic building configurations and envelope decisions that are made early in the design process.

3. METHODOLOGY

3.1. Parametric analysis

Five different geometries were explored in this project: a square, a rectangle elongated on eastwest, a rectangle elongated on north-south, an H-shape, and a cruciform. For the ease of discussion, the forms are termed as: Sq, RecEW, RecNS, H, and Cross, respectively. These simple geometries with varying compactness were chosen after studying a variety of low-energy office buildings. A compact form benefits a building by being less affected by the external environment but has more opportunity to benefit from free solar energy (Behsh 2002; Gratia and De Herde 2003; Ross 2009; AlAnzi, Seo, and Krarti 2009; and Straube 2012). The five archetypes had varying potentials for daylight harvesting because of their configurations. For instance, archetypes RecEW, RecNS, H, and Cross had their wing depth between 13 m to 18 m, which provided the potential for daylight optimizing (PWGSC 2002; Ander 2011; and Straube 2012).

All the models were designed with a gross floor area⁶ (GFA) (GFA) of 6,000 m² (1,200 m² per floor). The total height was kept the same—5 stories and 20 m—so that the conditioned building volumes remain constant for all the buildings. A multi-floor model provides a more accurate understanding of the energy use as it contains a ground contact floor, several intermediate floors, and a rooftop. No basement and rooftop service area were included in the models. The study context did not consider a particular site and so ignored the impact of neighboring built-forms and surroundings. However, the solar position was taken into account, and the archetypes were designed as south facing buildings. The geometric descriptions of the archetypes are presented in Table 1.

The archetypes were examined with WWR of 30%, 50%, 70%, and 80%, respectively to observe the impact of increasing fenestration. Each façade was designed with the same WWR. The floor to ceiling height was chosen as 3.35 m (ASHRAE 2004).

Archetype	Sq		RecEV	N	RecNS	RecNS			Cross	
				1 *W*		-l*-w		tat br		w
Dimensions ,	1	w	1	W	1	W	1	w	1	w
							42	35	52	42
	35	35	70	17	17	70	a	b	a	b
							14	9	17	14

TABLE 1. Geometric descriptions of the archetypes.

FIGURE 1. (a) Typical section showing overhang design for south façade (WWR 30%). (b) Vertical fin design for a typical west façade (WWR 30%); Note: Dimensions are shown in meters.



Horizontal overhangs were designed to shade the south façade and vertical shading fins were considered for the east and west oriented windows. A critical month and time for the shading was selected for each façade (LBNL 1997 and PWGSC 2002). The shading designs for a typical south façade and west façade are presented in Figure 1(a) and Figure 1(b), respectively.

The performance of building enclosure is one of the major parameters that directly affect the energy intensity of any structures. Buildings with poor enclosure specifications might

Component	Material	Thickness, m	Total R-value, m ² K/W	U-value, W/m ² K
External wall	Steel framing (150 mm) at 400 mm centers (R-2.3 lns + R-1.3 lns)	0.4	3.7	0.3
Roof	Insulation entirely above deck (R-3.5 Ins)	0.7	4	0.2
Ground floor	Steel joist floor with spray-on insulation (R-1.4 continuous)	0.8	3.8	0.3
Internal ceiling or floors	Concrete slab internal ceiling	0.7	0.7	0.9
Internal partition 1	Lightweight plasterboard partition	0.08	0.4	1.7
Internal partition 2	300 mm heavy weight concrete plastered both sides	0.3	0.4	1.5
Windows	Low E double glazing, SHGC (solar heat gain coefficient) ¹⁰ = 0.44	0.02 (glass)	0.4	2.2

TABLE 2. Descriptions of envelope components.

Note: The stairways were modeled with Internal partition 2 (concrete walls). All the other spaces had Internal partition 1 (lightweight plaster board partition).

nullify the helpful effects of form and solar orientation (Ross 2009). Therefore, building enclosure constituted a vital part of the archetypes design in this project, although the exploration of envelope properties on the energy use patterns was not included. A standard construction was developed according to the recommendations of Advanced Energy Design Guide for Small Office Buildings (ASHRAE 2004). Climate zone 6 (suitable for Toronto) recommendations were used for the thermal performance of the envelope components and applied to every model. ASHRAE's 2004 guide is specially designed to achieve 30% energy savings over ANSI/ASHRAE/IESNA Standard 90.1-1999. Therefore, the archetypes were expected to use less energy than the offices built to the code requirements. The descriptions of each assembly including materials, construction thickness, R-value,⁷ and U-value⁸ are listed in Table 2. The archetypes were designed with steel-framed external walls and concrete slabs. Their roofs were built with lightweight concrete. Low-emissivity double glazing was chosen for the windows with a visual light transmittance⁹ of 0.65.

3.2. Climate analysis

The external climate is an important driving force affecting the thermal conditions of a building. According to the international definition of climate zone, Toronto is located in zone 6 (ASHRAE 2007). The zone is identified as cold-humid with heating degree days between 4000 and 5000. In the simulations, site and weather data were set as Toronto, Ontario, based on the CWEC file¹¹ with latitude of 43.7 N, longitude, 79.6 W, and an altitude of 173 m.

Building designs in Toronto aim to minimize the heating energy demands first, because heating is usually dominant among the other energy usages. Toronto's mid-latitude location enables buildings to receive significant solar radiation on the south, east, and west walls. In addition, the solar radiation on the roofs are also significant. Prevailing wind flow in winter and summer are typically from the north-west and south-west, respectively. In general, compact or clustered plans (with minimum surface areas) are recommended for minimum heat loss, while southern glazing can be optimized but with appropriate summer sun protections.

3.3. Energy simulation tool

Energy analysis programs are tools to study the energy performance and the thermal comfort during a building's life cycle. Energy analysis tools are more beneficial when 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). To attain the objectives of this research, an energy analysis program was required, which can produce both thermal as well as lighting energy results and is also able to measure the consumption of the artificial lighting depending on daylight illuminace. IES Virtual Environment (IES VE 6.4.0.9) was selected to perform the energy simulations on the office archetypes. This program offers an integrated system that operates all of its building simulations from a central building model (Integrated Environmental Solutions Ltd. [IES Ltd.], n.d.). The software uses hourly data for the exterior temperature and the solar radiation intensity.

Initially, the three-dimensional mass of each archetype was created using IES VE plug-in for Google SketchUp. In the performance analysis phase, three different modules of IES VE were applied to each analysis permutation: SunCast (to analyze the solar gain in conjunction with the shading devices), Radiance (for the analysis of daylight illuminance level), and ApacheSim (for the dynamic simulation to produce the energy reports).

The function of each module and their applications in this project are delineated in the following:

- i) SunCast analyzes how solar gain impacts a building. SunCast analysis was performed to account for the shading from the external shading devices and the selfshading from each form. For instance, the H and Cross archetypes were analyzed for their self-shading potentials. It is necessary to perform a solar shading calculation prior to Radiance analysis to obtain accurate results from the daylight controlled dimming sensors in RadianceIES. Therefore, SunCast was also run for the Sq, RecEW, and RecNS archetypes in order to facilitate Radiance simulation. SunCast results were then fed into the thermal calculation to determine the impact on the heating and cooling energy use.
- RadianceIES was applied for the daylight illuminace¹² level analysis. Photocells were positioned in this module to record accurate daylight levels for the dimming controls. If a dimming profile is applied to the lighting gains in RadianceIES and linked to ApacheSim, the energy reduction of the electric lighting can be quantified.

The analysis of power consumption for the artificial lighting in conjunction with varied fenestration designs was among the parametric studies conducted in this project since the daylight illuminace level in workplaces also changes with varied WWR. If sensors with daylight dimming controls are applied in the perimeter spaces, they can have effects on the lighting energy consumption results. For this purpose, RadianceIES was particularly useful in this research.

iii) ApacheSim performs simulations of building thermal performance based on dynamic thermal analysis. ApacheSim is a dynamic thermal simulation program based on first-principles mathematical modeling of the heat transfer processes occurring within and around a building. In 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 (IES Ltd, n.d.).

3.4. Simulation inputs

To complete an energy model it is necessary to provide it with several data inputs, such as location and weather data, envelope construction sets, use profiles, and heat gain characteristics. These inputs represent how the office would function in reality.

Zoning

Each model was divided into three functional spaces: open plan office, stairs, and restrooms (Figure 2). Photocells were put in the models to measure the effect of variable WWR on the daylight illuminace level in workplaces. Each open office plan model was divided into eight areas to facilitate the placement of the photo sensors. However, the internal partitions between these office areas were modeled with 0% opacity, which omitted the physical boundaries and helped analyzing the whole space as an open plan office.

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, n.d.). The daily schedule for the office buildings was assumed as 8am–6pm for 5 days a week with 50 hours of weekly operation. The interior lighting system was controlled with a modulating profile, which changed from 1 (when there was no natural light), down to 0 (when 538 lux or more was available).

Thermal templates

Three different thermal templates were assigned to serve the three functional spaces in the models. The templates—for the open plan office, restrooms, and stairs—are summarized in Table 3 followed by a brief discussion. Casual gains from the occupancy, fluorescent lighting, and equipment were set to each functional space.









Room 3= Restrooms

N

Room 4= Stairs

Design ter °	nperature, C				Occupai W/pe	Occupants gain, W/person	
Heating set point constant)	Cooling set point (constant)	Equipment gain, W/m²	Lighting gain, W/m²	Occupancy, m²/person	Sensible heat gain	Latent heat gain	air supply (max. flow rate)
21	24	16	12	20	75	55	10 l/s/ person
21	24	5	10	No occupancy	No occupancy		5 l/sm ²
21	24	11	6	No occupancy	No occupancy		0.3 l/sm ²
				occupancy			

TABLE 3. Summary of template inputs.

• Heating and cooling set points

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 the heating and cooling set points were kept constant as 21 °C and 24 °C, respectively. The set points were obtained from the default values in IES thermal templates.

• Internal gains

Thermal template Open plan office Restrooms

Stairs

Internal gains were considered from the people, fluorescent lighting, and equipment based on an occupant density of 20 m²/person (ASHRAE 62.1-2007). No occupancy was chosen for the restrooms and the stairs.

- i) Heat gain from people: For 24 °C dry bulb temperature, an adult male will produce 75 W sensible heat and 55 W latent heat performing moderately active office work (ASHRAE 2009). Following this guideline, the sensible heat gain and the latent heat gain were set as 75 W/person and 55 W/person, respectively.
- ii) Heat gain from equipment: In a medium to heavy load density office,¹³ the recommended load factor for equipment is 16 W/m2. Here equipment refers to computers, monitors, laser printers, and fax machines (ASHRAE 2009). Accordingly, equipment gains were set as 16 W/m² for the open plan offices. Internal gains from the equipment in the case of restrooms and stairs were obtained from the default values set by the IES VE database.
- iii) Heat gain from fluorescent lighting: The maximum sensible heat gains from the interior lights were determined according to the lighting power density for each functional space: 12 W/m², 10 W/m², and 6 W/m² for the office spaces, the restrooms, and the stairs, respectively (ASHRAE 2007).
- 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 a variation profile of '8am–6pm with no lunch'. The combined air rate has to be 8.5 l/s-person for an office space with an occupant density of 20 m2/person (ASHRAE 62.1-2007). This project used an air supply of 10 l/s-person, which is the default value in the IES VE database for the open plan offices. The supply air rates in the case of restrooms and stairs were set as the default value specified in the thermal templates of IES VE.

Systems

For an initial stage energy modeling, separate HVAC zones were not created in the models. A single type of system, VAV dual duct, was assumed as HVAC system and the auxiliary mechanical ventilation system in all the functional spaces. An auxiliary ventilation system calculates the heating, cooling, and dehumidification required to process outside air to the specified supply condition.

Domestic hot water (DHW) consumption was not a focus of this study. However, IES VE calculates the amount of hot water supplied to bathrooms and sinks based on the space occupancy profile.

4. ANALYSIS OF RESULTS

A total of 40 simulations were performed on the five office archetypes for various permulations. A summary of the analysis permutations for the Sq archetype is presented in Table 4 as an example. Each permutation is identified with a specific terminology: the first term refers to form, the second term refers to WWR, and the third term indicates the shading situation (i.e. no shading or shading).

The simulation results were obtained as the total energy use on an annual basis. The total energy refers to the energy consumptions of the systems, interior lighting, and miscellaneous equipment. The total system energy can be broken down into the energy use of boilers (for space heating and hot water),¹⁴ chillers (for space cooling), auxiliary systems, and heat rejection fan or pumps.¹⁵ The interior lighting energy and the equipment energy correspond to the energy consumption associated with the artificial lighting and the equipment, respectively.

Among the energy factors, importance was given to the analysis of the boiler space conditioning energy (termed as space heating energy), the chiller energy (termed as space cooling energy), and the lighting energy (termed as interior lighting energy). DHW energy and the miscellaneous equipment energy were calculated based on the occupancy (liter/hour/person) and the internal gains (from equipment) per area (W/m²), respectively. Therefore, the energy consumed by these two parameters did not differ from one archetype to another.

4.1. Performance analysis of individual archetypes

Each archetype was observed with a generic behavior when analyzed with varied WWR and shading scenarios. As an example, performance of the Sq archetype is described in this section. First of all, Figure 3 indicates that the static parameters including DHW and Equipment

Archetype	Simulation number	Simulation terminology	Windo	ow to wa	WWR)	External devices	External shading devices	
			30%	50%	70%	80%	No shading	With shading
Sq	1	Sq30Noshad					\checkmark	
	2	Sq30Shad						
	3	Sq50Noshad					\checkmark	
	4	Sq50Shad						
	5	Sq70Noshad					\checkmark	
	6	Sq70Shad						
	7	Sq80Noshad				$$	\checkmark	
	8	Sq80Shad						

TABLE 4. Summa	ry of the	analysis	permutations	of arc	hetype	Sq
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FIGURE 3. Energy use pattern (MWh/yr) of archetype Sq for variable WWR and shading scenarios.

represented over 50% of the energy use and should not be ignored in any low-energy office design. Furthermore, of the energy uses affected by the building shape and form, the space heating was the most significant, followed by the interior lighting and the space cooling. The heat rejection fan or pumps energy changed proportionally to the cooling energy but constituted only 3% of the energy consumption totals of an archetype; therefore, it is not highlighted in this discussion.

All eight simulations portrayed some common trends:

- (i) The heating energy increased with the increase in WWR regardless of the external shading.
- (ii) Without the shading devices, the cooling energy also increased as WWR was increased.
- (iii) The energy use of lighting decreased as the glazing was increased from 30% to 80%.
- (iv) The lighting energy significantly increased when there was external shading (for instance, a 44% increase from simulation Sq30Noshad to Sq30Shad). This suggests that in this project the shading design is found to limit the daylight harvesting to some extent. This may be due to the detailed design of the shading devices.
- (v) Conversely, the cooling energy decreased in each scenario when there was shading. This finding portrays the importance of carefully designed solar shading in office buildings that maximizes daylighting while reducing both glare and cooling loads.

The modeling also suggested that the electrical loads for lighting and cooling are reciprocal to each other. For instance, simulation Sq80Noshad needed 22% more cooling than Sq30Noshad but 38% less lighting energy. That means with the greater fenestration, additional cooling load from solar gain was partly offset by the reduced cooling from the lower lighting gains. Therefore, the cooling load did not increase as much with a high glazing level as it was expected to.

4.2. Comparison of five archetypes

In this section all five archetypes are compared to one another to identify which form is performing more efficiently in relation to the annual energy use. The deviation of the total energy values from one shape to another was found to be relatively small. The total energy demands of the five geometries are listed for various fenestration ratios in Table 5. The results for both shading situations are also listed. The most efficient combination of shape and WWR are placed at the bottom left of the table, while the least sufficient combination at the top right. Table 5 indicates that the Sq archetype required the lowest amount of energy per year, whereas the H-shape was found to be the highest energy consuming archetype. As WWR increased gradually from 30% to 80%, the energy consumption in each archetype also increased, which is presented in the table from the left to right direction. 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). The analysis also suggests that shading devices can increase the total energy requirements, because they add to the lighting load throughout the year. This does not mean that shading devices should be omitted, because this will create other problems with glare and overheating. Rather, the situation highlights the importance of effectively designed shading devices to maximize their benefits while minimizing their negative impacts. It also highlights the difficulties of appropriately shading a highly glazed facade.

The total energy results of the archetypes are presented graphically in Figure 4. This again highlights that when the other factors were equal, the geometry or shape of a building contributed a much smaller variation in the annual energy consumption compared to WWR. It is also evident that with more fenestration, the energy use of different forms varied within a larger range compared to the forms with less fenestration. For instance, the energy increase was found to be 2% from the best to worst shape with 30% WWR (simulation Sq30Noshad

Archetype	Total energy use, MWh/yr								
	Increasing (11%–16%)								
	Shading scenario	WWR 30%	WWR 50%	WWR 70%	WWR 80%				
H	Shad	1191	1277	1338	1385				
	Noshad	1135	1219	1290	1329				
Cross	Shad	1179	1257	1336	1380				
	Noshad	1138	1217	1288	1331				
RecNS	Shad	1198	1275	1333	1373				
	Noshad	1138	1211	1282	1318				
RecEW	Shad	1164	1229	1285	1324				
	Noshad	1122	1180	1242	1274				
Sq	Shad	1154	1215	1254	1289				
	Noshad	1111	1162	1210	1231				

TABLE 5. Total energy comparison of the five archetypes.





to H30Noshad) and 8% when the WWR was 80% (simulation Sq80Noshad to H80Noshad). Therefore, it would be justifiable to comment that in the case of buildings with low glazing levels, geometry is less significant than for the buildings with high glazing levels. A similar observation was found after analyzing the energy results with the external shading: the buildings with the fewer windows were affected less by the inclusion of shading devices, regardless of their geometry.

4.2.1. Discussion on individual energy factors

Although the variations in the total energy were observed to be smaller, the variations in heating, cooling, and lighting energy were significant but offset each other in some cases. For example, some strategies to reduce the space heating may lead to the greater energy usage for the artificial lighting or the space cooling.

Space heating energy. Space heating is directly linked to the compactness of a building. Thus, the Sq archetype required the least energy for space heating in all the analysis permutations. Archetypes RecEW, RecNS, Cross, and H showed a gradual increase as their compactness were lower. Archetypes with the external shading resulted in higher heating energy than those without shading (refer to Figure 5). The relative importance of WWR compared to the shape on the heating energy is worthwhile to notice here. The consumption for space heating nearly doubled for each plan type (with inclusion of the shading devices) when WWR was increased from 30% to 80%. For instance, simulation Sq30Shad (222 MWh/yr) had 46% less annual heating energy consumption compared to Sq80Shad (410 MWh/yr). Conversely, a change in plan form had a much smaller impact on the heating energy. Simulation Sq30Shad (222 MWh/yr) required only 26% less heating a year compared to H30Shad (300 MWh/yr). Also the shape became more significant in absolute terms when WWR increased.



FIGURE 5. Space heating energy (MWh/yr) results of the five archetypes for variable WWR and shading scenario.





Figure 6 presents the space heating energy demands per month for the five archetypes with a WWR of 50%. All the occurrences, without shading devices and with shading devices, portrayed a common trend: the heating demands remained higher from November to March with the highest in January. The summer months, especially June through August, did not require heating.



FIGURE 7. Space cooling energy (MWh/yr) results of the five archetypes, for variable WWR and shading scenario.

Space cooling energy. The space cooling energy was found to depend on the solar radiation admitted to the space and the interior lighting demand due to unwanted heat gain from the lights (Figure 7). When WWR increased, so does the cooling, in the scenarios with no shading. This happens because the unwanted solar gain¹⁶ is admitted during the cooling season, and this overcomes the lower heat losses from the reduced lighting loads. For instance, simulation Sq30Noshad (77 MWh/yr) required 18% less cooling than Sq80Noshad (94 MWh/yr). It was observed that the H and Cross archetypes particularly required less energy for the space cooling as well as for the interior lighting regardless of the external shading. These shapes are more effective for daylighting and so reduce the heat loss occurring from the artificial lighting. Conversely, the Sq and RecNS archetypes needed more energy for cooling among the others (in both shading situations).

Shape and orientation also have some significance to the cooling load. For example, the RecNS archetype had long east and west facing elevations and so had high cooling loads due to the difficulty with shading the low-angle morning and particularly the afternoon sun. As expected, this became more pronounced as WWR increased since there was more glass for the solar radiation to enter. Thus, simulation RecNS80Noshad required 108 MWh/yr of cooling energy while H80Noshad required 89 MWh/yr (a difference of 32%). Figure 7 suggests that shading can significantly help to overcome this.

When the shading was in place, the space cooling energy demands in the archetypes were generally lowered (if results are compared to the scenarios with no shading) and varied a little with WWR. As an example, the solar gain was reduced by almost 40% in the Sq archetype with the shading devices. Utilization of appropriate shading devices can control heat gain from solar radiation within buildings, even with the higher glazing percentages. For instance, simulation Sq80Noshad (384 MWh/yr) received 144% more solar gain compared to Sq30Noshad (158 MWh/yr), while Sq80Shad (240 MWhh/yr) received only 62% more solar gain than Sq30Shad (90 MWh/yr).



FIGURE 8. Space cooling energy (MWh/month) results of the five archetypes with 50% WWR and variable shading scenario.

The monthly space cooling energy demands of the archetypes with a WWR of 50% are presented in Figure 8. In both shading scenarios, each form portrayed lower or almost no space cooling requirement from November to March. The months of July and August required cooling the most, which exactly reversed the space heating energy results.

Lighting energy. Conversely to the space heating, the less compact archetypes with the shallow plans required less lighting energy. Thus archetypes, such as H and Cross were found to have the greater benefits of daylight. With the shading devices the Cross archetype showed the least lighting energy consumption. Archetype Sq had the highest lighting energy demand in both shading situations. The shading devices designed in this project were aimed to control the solar radiation, not the desired admission of natural light into the office spaces. However, these shading devices were found to reduce some daylight entering the spaces; consequently, resulting in higher electricity consumption for the lighting in all the scenarios. This outcome indicates the importance of careful selection of sun control devices.

Figure 9 indicates that the variations in plan form and WWR both have a significant impact on the lighting energy. The energy demands for lighting reduced as the area of window wall increased (in both shading conditions).

Lighting energy demands depend on the available daylight illuminance and are directly proportional to the available momentary solar radiation. The monthly results of the lighting energy and the solar gain in the five archetypes are presented in Figure 10 (for the scenarios without the shading devices). During the cooling months when the solar gain was higher, the lighting loads from the artificial lights became lower. A similar consequence was observed in the models with the shading devices. However, the sun control devices increased the lighting energy demands in all the cases, if the results of the two shading scenarios are compared.





FIGURE 10. Lighting energy (MWh/month) and Solar gain (MWh/month) results of the five archetypes for 50% WWR and without shading devices.



4.2.2. Features of archetypes that modulate energy performance

Building aspect ratio. As stated earlier, various researchers have used "compactness", measured as volume to surface ratio (V/S) or floor area to enclosure area ratio (F/E), as an indicator of energy performance. Table 6 presents the five archetypes with their F/E, V/S, and the ranges of their total annual energy uses. Archetypes at the top have the highest compactness and reducing down the table. To note that the RecEW and RecNS archetypes have the same V/S and F/E, but their total energy results are not similar. The notion of compactness does not consider a building's orientation. To overcome this limitation, Behsh (2002) proposed a ratio of the south oriented surfaces to the west oriented surfaces (S_{south}/S_{west}) as a relevant factor to analyze the thermal performance. This factor is also presented in Table 6 for the archetypes. The results indicate that the most compact form Sq, as defined by both V/S and F/E, has the least total annual energy use. This is due to the dominance of the heating energy use. The ratios of S_{south}/S_{west} do not seem to correlate well with the total annual energy usages of the archetypes in this study.

Despite using more energy for the space cooling and the artificial lighting, archetype Sq displayed less total energy demand than the other archetypes. Conversely, the RecEW archetype used less artificial lighting and cooling energy compared to Sq, but this did not overcome the additional heating energy requirement, and so had a higher total energy demand than Sq. It can be commented that a building's energy performance, especially the heating energy, is largely determined by its building aspect ratio. And for the climate of Toronto, where the energy consumption is predominantly heating oriented, geometry that requires less energy for the space heating tends to perform better than others in terms of the total energy usage.

Forms with different orientation. The orientation of a building affects its total energy consumption due to the differing exposure to solar radiation. Archetypes RecEW and RecNS both had similar configurations but different orientations with respect to the solar position.

Archetype	F/E	V/S	S _{south} /S _{west}	Total energy, MWh/y	
Sq	1.5	4.6	1	1111–1289	
RecEW	1.3	4.1	4	1122–1324	easing
RecNS	1.3		0.3	1138–1373	nergy incr
Cross	1.2	3.9	1.3	1138–1380	Total e
H III	1.2	3.9	0.8	1135–1385	

TABLE 6. Total energy comparison of the five archetypes with building aspect ratios.

The RecEW archetype had four times more surface oriented to the south than RecNS (refer to Table 1). If the results of all eight simulations of archetype RecNS are compared to that of RecEW, the latter will show lower total energy values per year. Positioning a building elongated on east-west improves energy performance in the summer, reducing the high solar gains from the east and from the west, and therefore, reducing the cooling loads. For instance, simulation RecEW80Noshad (92M Wh/yr) had 15% less cooling energy compared to RecNS80Noshad (108 MWh/yr) (refer to Figure 7). If the external shading is considered, this reduction becomes 11%. In each scenario, whether with varying WWR or shading situation, the cooling energy of archetype RecNS remained higher than RecEW.

The same pattern is observed for the heating energy profile: the RecEW archetype required less heating energy compared to RecNW due to the higher solar gain. It is interesting to note that with the external shading, the increase in the lighting energy was more significant in archetype RecNS compared to RecEW. Solar control with shading devices is more critical for east and west facing elevations compared to the south facades. For that reason, buildings with lower S_{south}/S_{west} ratios receive less benefit from natural lighting when sun control devices are incorporated.

Forms with narrow wings. Buildings with narrow wings are particularly advantageous for daylight harvesting as well as reducing electric lighting loads (LANL 2002 and Straube 2012). This concept is supported by the outcome of the simulations performed in this project. For instance, the H archetype was found to use the least energy for the artificial lighting (without the external shading devices) among the other archetypes. Archetype H had perimeter wings of 14 m deep, and its staggered configuration helped to access more daylight to the interior. A similar strategy applies to the Cross archetype, although it had wings of greater depth (17 m). Moreover, the unique configuration of archetype Cross improved daylighting in it. With good daylighting, less internal gain occurred from the artificial lighting, which eventually reduced the cooling demand in that space. Accordingly, H and Cross required less energy for the space cooling (refer to Figure 7). These two geometries also enjoyed the benefit of self-shading. Therefore, the buildings with H-shape and cruciform shape imposed less cooling loads while taking advantages of high daylight access to the interior spaces. Nevertheless, their lower V/S and F/E ratios mean that space heating loads were higher than the more compact archetypes.

4.3. Summary of results

After analyzing the results, the major observations can be listed under two headings:

i. Impact of the design parameters on energy demands

- (a) Geometries were found to follow the definition of compactness: the most compact form has the least total annual energy use.
- (b) Archetype Sq required the lowest amount of energy per year. The RecEW, RecNS, Cross, and H archetypes were found to display a gradual increase in the energy consumption. However, the difference in the total energy values was relatively small (ranging between 2% and 8%).
- (c) As WWR increased gradually from 30% to 80%, the total annual energy consumption in each archetype also increased. This effect was more significant than the building shape.

- (d) The shading devices were found important for reducing the cooling loads in the offices (particularly with the high fenestration ratio); but could increase the lighting loads, which also impact cooling.
- (e) The H and Cross shapes imposed less cooling loads, while taking the advantages of high daylight access to the interior spaces. These two forms particularly received benefit from self-shading because of their staggered configurations.
- (f) The orientation of a building with respect to the solar position affected the total energy consumption (along with the individual energy parameters) as shown in the rectangular form simulated here.

ii. Identification of dominance of design parameters on energy demands

- (a) When the other parameters remained equal, geometry or building shape had only a small impact on the annual energy consumption (within a range of 2% to 8%).
- (b) WWR (within a range of 11% to 16%) had a greater impact on the total energy demand than building geometry, within a range of 2% to 8%.
- (c) In the case of buildings with low glazing levels, geometry was less significant compared to the buildings with high glazing levels.
- (d) The buildings with the fewer windows were less affected by the inclusion of the shading devices regardless of their geometries.
- (e) The space heating energy was dominated by WWR. For each plan type, the heating energy nearly doubled when WWR increased from 30% to 80% with the shading devices.
- (f) The space cooling energy was found to depend on the solar radiation admitted to the space and the interior lighting demand. Thus glazing, shape, and shading are all important.
- (g) The lighting energy was affected by WWR more than the building geometry, if there was external shading. However, interior lighting also has a complex relationship with cooling loads: increased daylighting can lead to solar overheating, while increased electric lighting leads to additional cooling in the summer months.

5. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

The research showed that for the climate of Toronto the heating load for offices, designed according to ASHRAE's Advanced Energy Design Guide for Small Office Buildings, were more significant than the cooling and the lighting. Since the heating was still the largest load, geometries with the lower heating demands compensated the greater cooling energy and artificial lighting requirements. The cooling loads and the lighting demands were found reciprocal to each other.

This research highlights the importance of appropriate fenestration and shading design in low-energy office buildings. Building shape is significant but tends to be dominated by these other factors. The orientation of a building also performs a significant role in energy consumption, particularly for long, thin shapes. Thus, geometry with high east-west oriented surfaces is less preferable in the context of Toronto. According to the findings of this research, external shading is important for controlling solar gain but can reduce natural daylighting and lead to more electrical lighting energy, which negates some of the cooling benefits. To note that these conclusions are made only examining a single kind of shading, and they highlight the importance of careful design of shading systems.

Future research should consider if shading devices can reduce cooling demands in office spaces but minimize the impact on natural lighting. The effect of varying enclosure performances (by modifying the U-values) could also be examined. Geometries with respect to the actual site and surroundings could be examined to see how their impacts are modified compared to the findings of this project.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to IES Technical Support team for their support throughout this research.

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NOTES

- 1. Building geometry refers to the measurements related to building configuration and arrangement (Deru and Torcellini 2005).
- 2. Fenestration is coined as building components that transmit light including windows, skylights, glazed doors, and so forth (Deru and Torcellini 2005). In this research, fenestration stands for windows.
- 3. The aspect ratio is defined as the reported building length divided by the building width (EERE, n.d.).
- 4. Compactness of a form can be defined by its volume to surface area ratio (V/S) (Gratia and De Herde 2003). Straube (2012) preferred the ratio of usable floor area to above grade enclosure area (F/E) to indicate the compactness in case of commercial buildings.
- The window to wall ratio (WWR) corresponds to: WWR = Area of exterior openings (excluding mullions and window frames)/Total wall area of exterior façade (width × floor to ceiling height) (Otis and Reinhart 2009).
- 6. The total floor area of a building's enclosed space, measured from the outside face of exterior walls, is referred to the gross building floor area (Deru and Torcellini 2005).
- 7. R-value refers to the thermal resistance of the total assembly.
- 8. U-value refers to the overall co-efficient of heat transmission.
- 9. The amount of light transmitted in the visible range through the glazing products.
- 10. Solar heat gain coefficient refers to the ability to control solar heat gain through the glazing.
- 11. CWEC files contain hourly weather observations representing an artificial one-year period, specifically designed for building energy calculations (EERE, n.d.).
- 12. Daylight can be measured in a number of different ways. Daylight illluminance refers to the amount of luminous flux (quantity of light emitted by a source) that falls on a surface. Illuminance is measured in lux (lumens per meter square).
- 13. A medium to heavy load density office assumes 9.3 m^2 / workstation (11 workstations per 100 m^2) with computer and monitor at each, plus printer and fax.
- 14. Domestic hot water (DHW) was set to be handled by the main system serving the room. Therefore, energy use of boilers was divided into Boilers space conditioning energy and Boilers DHW energy.
- 15. Auxiliary energy value indicates the power consumption of fans, pumps, and controls associated with the space heating and cooling systems.
- 16. Solar gain refers to the solar radiation absorbed on the internal surfaces of the room, plus solar radiation absorbed in glazing and transferred to the room by conduction.