A Parametric Study on the Impact of Geometric Building Shapes on Energy Consumption

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Abstract

This paper examines the impact of building orientation, number of storeys, aspect ratio, and building geometrical shapes (Courtyard, Rectangular, T-shape, U-shape, and L-shape) on total annual energy demand of National Energy Code of Canada for Buildings (NECB) 2017 (National Research Council of Canada 2017) compliant reference archetypes. The study was conducted using OpenStudio and Parametric Analysis Tool (PAT) to simulate seven archetypes (mid-rise multi-unit residential, retail strip mall, medium office, full service restaurant, primary school, warehouse, and small hotel) located in Victoria, BC, Canada.

Results showed that for most of the archetypes, excluding small hotel and multi-unit residential, rectangular shaped buildings were the most energy efficient; whereas the L-shaped buildings had lower energy use for other two archetypes. Furthermore, it was found that changing the number of storeys for the medium office and retail strip mall from two to three (while keeping all other parameters fixed) resulted an increased in annual total energy consumption by 54 and 60%, respectively; this is attributed to the modelling rules in the NECB. This is significant because in practise, it permits the design of less efficient buildings by simply adding a storey for a fixed floor area. Lastly, a detailed study for primary schools and small hotels was conducted across the six climate zones in Canada. An optimized set of parameters and articulation of these parameters is presented. This study will benefit relevant architects and stakeholders in the early design stages across Canada and future work will expand the study to other locations and archetypes.

Introduction

With the rising demand for sustainable buildings, numerous research has focused on reducing building energy usage. Globally, buildings generate almost 40% of annual greenhouse emissions (Global Status Report, 2017; World Green building Council, 2019). Accordingly, reducing buildings demand energy play a crucial role, and can contribute significantly to the reduction of world's energy consumption. Buildings can have sophisticated designs with interrelated combinations of various parameters. This has created a great interest in identifying the parameters that mostly affect the reduction of energy consumption of buildings. One of these parameters is the impact of occupant behaviour on energy consumption. This has been investigated in several research papers that aimed to assess the role of household members on energy savings, and the results showed that improving occupant behaviours can lead to considerable energy savings (Brounen et al, 2012; Longhi, 2015; Jinlong, 2009). Other research studies have focused on the impact of building envelope on energy consumption (Guohui et al, 2016; Noura et al, 2017; Junsheng and Jing, 2015; Jinghua et al 2011; Jongwook 2019; Guohui 2015), and the influence of various materials on energy demand in buildings (Yüksek 2015; Yang and Tang 2017; Ruuska and Häkkinen 2014). Despite the fact that geometrical shape is one of parameters that has a lifetime impact on buildings' energy consumption, it has not acquired the same attention as the other building envelope parameters. The application of optimum design geometrical shape at the initial building design would significantly reduce building energy demands and its associated energy costs (Pathirana et al, 2019).

Various attempts have been made to identify the influence of building shape, window to wall ratio (WWR), and orientation on total energy demand of buildings. Zhang et al. (2019) analysed the impact of building shape, WWR, orientation, and room depth on energy demand and thermal comfort in school buildings in cold climates. According to the study, results indicate that H-shape buildings have shown best performance in energy savings when thermal comfort was considered. Montenegro et al (2012) have discussed the role of building shape on energy consumption in schools for both hot and cold climates. The results showed that linear typologies achieved the best performances under both climates. Pathirana et al (2019) have explored the effect of building shape, zones, orientation and WWR on energy demand and thermal performance in houses in tropical climate. They found that that building shape does not have a significant impact on both thermal comfort and lighting energy. Further, the study discussed optimal staircase positions in square, rectangle and L-shaped buildings. Tibermacine and Zemmourib (2017) discussed the role of building typology on energy demand in multi-unit residential buildings for hot climates. The results indicated that orientation, height, building envelope in addition to compactness have an impact on energy consumption. Furthermore, the paper showed that the rectangular configuration performed better than courtyard, U-shape, and L-shape buildings. Mokrzecka (2018) investigated the role of eight various building shapes and orientation on heating demand in forty student residences. The results showed that square shaped buildings consume less heating energy compared to rectangular, L-shape, U-shape and C-shape buildings. Catalina et al (2011) in a study in France discovered that more compact shapes have the potential to reduce heating demand by 6-10 %. AlAnzi et al (2009) studied the influence of rectangular, L-shape, U-shape, and H-shape buildings on energy consumption of office buildings in Kuwait. They found that energy demand depends on relative compactness, WWR and solar heat gain coefficient in all building shapes. Tuhus-Dubrow and Krarti (2010) have studied the impact of rectangle, L-shape, T-shape, cross-shape, U-shape, H-shape, and trapezoid shapes for residential building. They've found that rectangle and trapezoid shaped buildings have outperformed the five other building shapes. Aksoy and Inalli (2006) discussed the influence of building shape and orientation on heating demand for a cold climate in Turkey. They identified that square shape buildings performed the best. A recent study was performed by Hatem et al (2020) in Egypt, where the impact of 10 different geometrical shapes, orientations, WWRs and window shading types were tested. The study found that T-shape, U-shape, and L-shape were the highest energy consumers in offices, also the results illustrated that using one facade without shading with 15% to 20% WWR outperforms multiple facades with 10% WWR.

Thus, prior research focused mainly on the effect of some building shapes on compactness, WWR and thermal comfort. The key objective of this paper was to study the effect of combinations of several design parameters including geometry shapes, number of floors, aspect ratio and orientation on energy demand in cold climate regions across Canada following the building energy calculation methodology in the NECB 2017.

Methodology

A platform called OpenStudio was used to generate, apply energy conservation measures (ECMs), simulate different buildings and collate results for this study. OpenStudio measures (i.e. ECMs) can be written using Ruby scripts, or simply by using (or editing) existing measures from the Building Component Library (BCL) that is available online. OpenStudio also provides the Parametric Analysis Tool (PAT) which facilitates studying the influence of combining several measures and processing the simulation results.

For this paper, a Ruby script was developed to create different archetypes using various geometrical shapes (courtyard, H-shape, L-shape, rectangular, and U-shape). The measure creates the specified form of the building and applies a specified space usage (office, school etc), the rules of NECB 2017 are then applied to the model. This measure was used in PAT to evaluate the effect of those five geometrical shapes on energy demand for seven different archetypes (multi-unit residential buildings, retail strip mall, medium office, full service restaurant, primary school, warehouse, and small hotel).

The selected building shapes and archetypes were simulated for a single location to identify patterns across the archetypes. Secondly two archetypes were selected for simulation in multiple climate zones to identify patterns related to climate variation.

For all simulations in this paper, total annual energy use intensity (TEUI) was calculated to compare the performance of the five geometrical shapes (courtyard, H-shape, L-shape, rectangular, and U-shape). All buildings considered in this study had a constant area set to 15,000 m^2 to simplify comparisons.

Single climate location simulation

First, 1575 simulations were performed using PAT for Victoria (225 simulations per each of the selected seven archetypes). Additionally, for each archetype, a parametric simulation consisting of combinations of number of floors (one to three), building orientations (0^o, 45^o, 90^o, 180^o and 270^o) and aspect ratio (0, 0.5, and 0.75) were all tested.

Multiple climate location simulations

The second analysis focused in detail on only two building types: primary schools and small hotels. To limit the number of simulations only three different orientations were explored 0°, 45°, and 90°. The same aspect ratios (0, 0.5, and 0.75) and also the same number of storeys (one to three) were assessed.

The analysis was extended to different locations representing the 6 different climate zones used in the NECB. Accordingly, six cities representing the six climate zones (Victoria, Windsor, Montreal, Edmonton, Fort McMurray, and Yellowknife) were selected. For primary schools and small hotels, 1620 simulations were performed.

Results and Discussion

Figure 1 illustrates overall annual energy demand intensity for the shapes, number of stories, orientations, and aspect ratios of different archetypes in Victoria, BC. It can be seen in Figure 1 that rectangular shaped buildings have the lowest TEUI for most of the archetypes. However, rectangular shape buildings lead to highest TEUI in small hotel and high rise buildings. Moreover, it can be seen that varying the number of floors has large impact on TEUI in retail strip mall and medium office buildings. The TEUI increases by 54% and 60% in medium office and retail strip mall respectively by increasing the number of floors into three floors. The crucial factor behind the energy increase is the NECB modelling requirements. According to table 8.4.4.7 of the NECB 2017, offices and retail strip malls with more

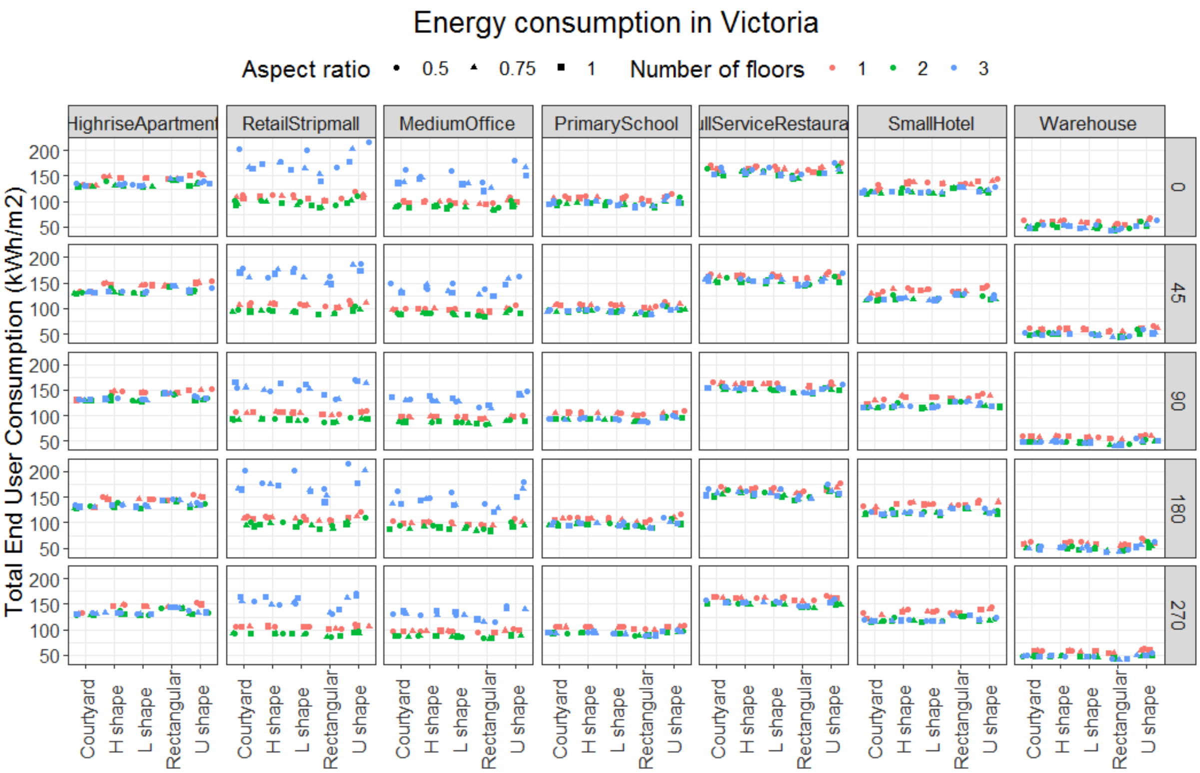

Figure 1: Energy Consumption in Victoria (right hand y-axis represents orientation).

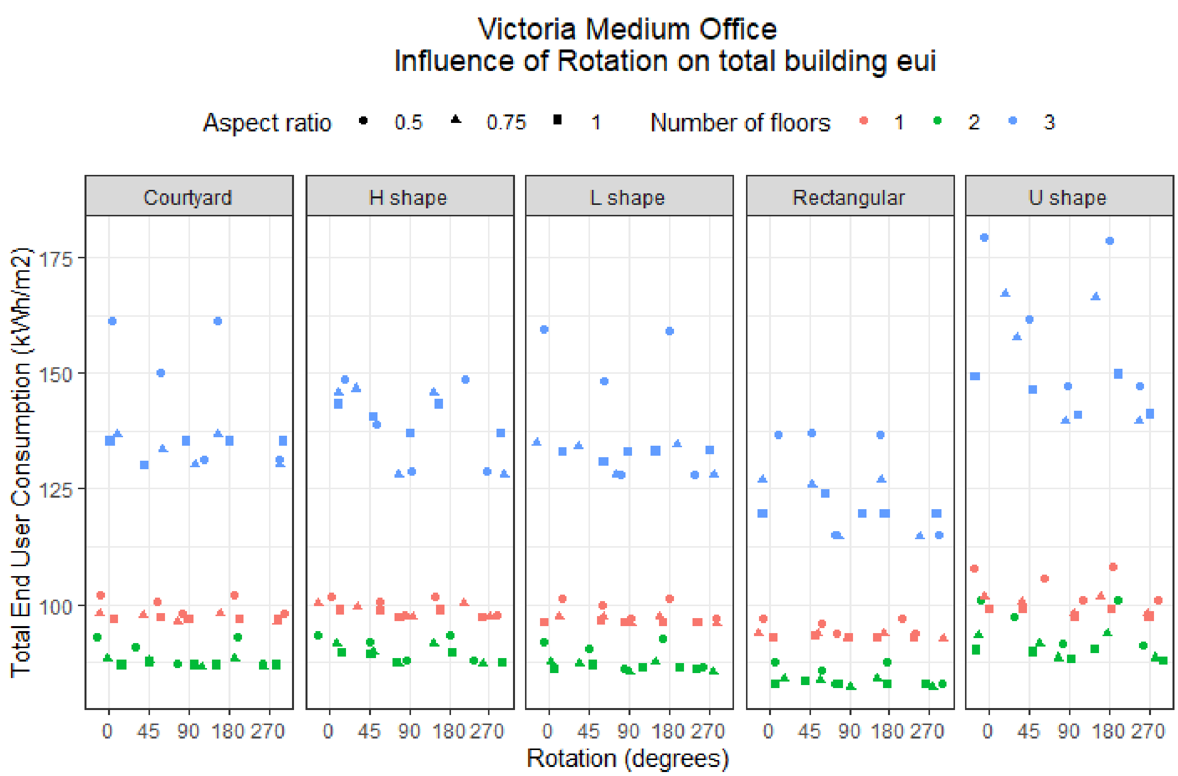

Figure 2: Influence of Orientation on Energy Demand.

Table 1: Optimal combinations of Shapes, Number of Floors, and Orientations in Victoria

Archetype	Shape	# Flrs	Aspect Ratio	Rotation	AVG EUI (kWh/ m²)
Retail Strip Mall	*Recta-ngular*	*2*	*0.75*	*90º*	*86*
Retail Strip Mall	U-Shape	3	0.5	180º	216
Medium Office	*Recta-ngular*	*2*	*0.75*	*90º*	*82*
Medium Office	U-Shape	3	0.5	0º	180
Full Service Restaurant	*Recta-ngular*	*2*	*0.75*	*270º*	*142*
Full Service Restaurant	U-Shape	1	0.5	180º	176
Primary School	*Recta-ngular*	*3*	*0.75*	*270º*	*87*
Primary School	U-Shape	1	0.5	180º	116
Warehouse	*Recta-ngular*	*3*	*0.75*	*90º*	*41*
Warehouse	U-Shape	1	0.5	180º	69
Small Hotel	*L-Shape*	*2*	*1*	*180º*	*114*
Small Hotel	U-Shape	1	0.5	180º	145
MURB	*L-Shape*	*2*	*1*	*180º*	*127*
MURB	U-Shape	1	0.5	0º	154

than two storeys must use HVAC System 6 (variable volume reheat) instead of HVAC System 3 (constant volume system), which is shown here to cause a considerable increase in energy consumption due to the a fixed supply air temperature requiring constant reheat.

Furthermore, it can be seen from Figure 1 that varying the orientation of buildings has minimal effect on energy consumption. Figure 2 explored the effect of orientation in more detail, where it presents a medium office as an example of an archetype in Victoria, BC. It was rotated by 0°, 45°, 90°, 180°, and 270°. It was found that for the five geometrical shapes, the energy demand is almost the same for the office building rotated by 0° and 180°, also exhibited same energy for 90° and 270°. These conclusions match the results obtained by Zhang et al (2017) where they have emphasized that same energy demand can be observed for schools in China when rotated by 0° and 180°, also 90° and 270° using rectangular and H-shape schools.

In order to summarize the simulation results for Victoria, Table 1 provides the influence of different combinations of building shapes, number of floors, aspect ratios and different orientations on the seven different archetypes chosen in Victoria. The results in Table 1 indicate the design parameters that achieved the minimum energy consumptions (blue italicized text), and also design parameters that lead to maximum energy consumptions (regular text). It is worth noting the fact that varying the combinations of geometrical shape and other design factors can have a crucial influence on energy consumption. Hence, as an example, energy consumption of 216 kWh/m^2 is achieved in retail strip mall by using U shape building with 3 floors, however by using a rectangular shaped building with 2 floors instead, energy consumption dropped by 60% to 86 kWh/m^2. Accordingly carefully selecting the building form can influence energy demands significantly. Moreover, it can be noted from Table 1, that rectangular shape buildings generally have the best performance, whereas U-shape buildings always have the worst performance.

Primary Schools

It can be seen in Figure 3 that energy consumption in one storey primary schools is significantly higher than two and three storey primary schools. Energy savings of an average of 7.5% and up to 17.4% can be achieved by using two or three storeys in primary schools instead of one storey. These conclusions correlates with the results of Garcia et al (2014), where their study emphasized that buildings with taller shapes outperform lower shapes in cold climates due to greater heat losses through the envelop and lower solar gains in lower shapes. The percentage of savings in energy consumption across the 6 cities by switching from one to 2 and 3 storey buildings can be seen more clearly in Figure 4.

The effect of aspect ratio on energy consumption in primary schools can be seen in Figure 5. The results show that by increasing the aspect ratio from 0.5 to 0.75 and 1, energy savings of an average of 2.5% and up to 12.7% can be achieved respectively (i.e. the more square the building the lower the energy consumption).

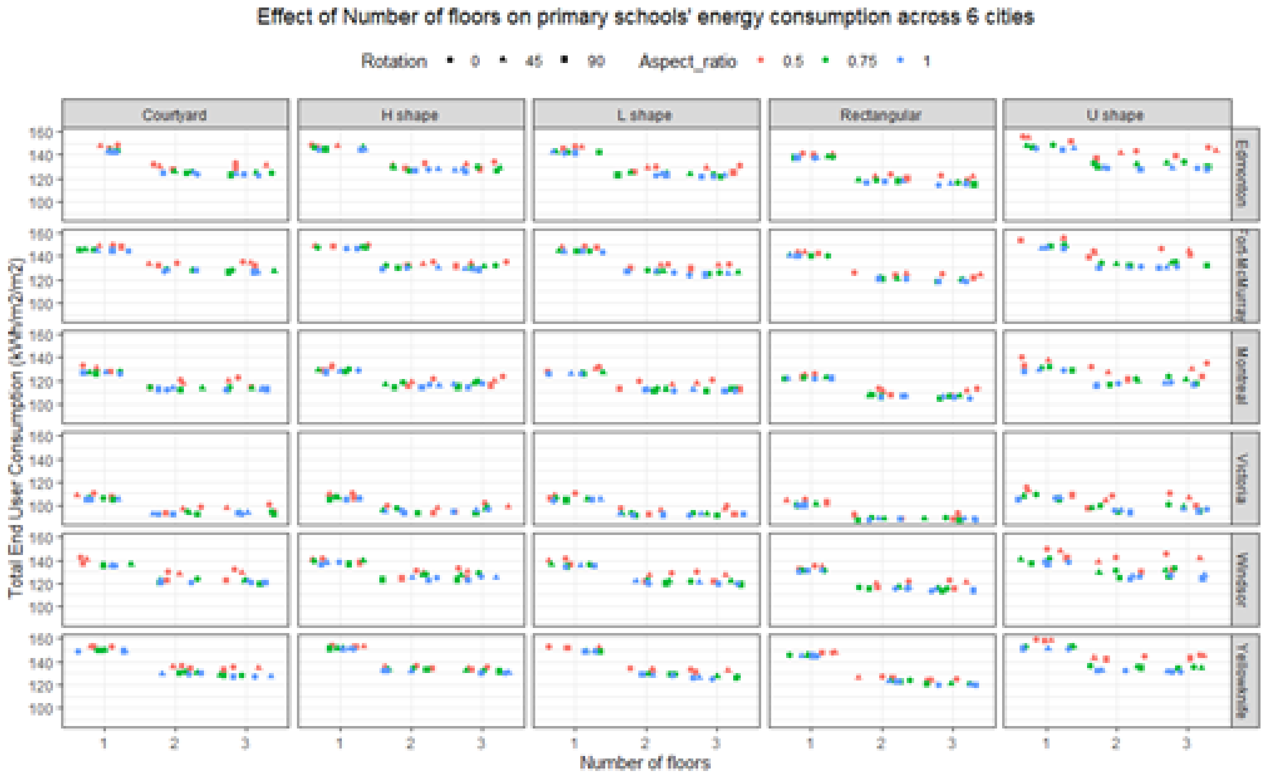

Figure 3: Effect of Number of Storeys in Primary School

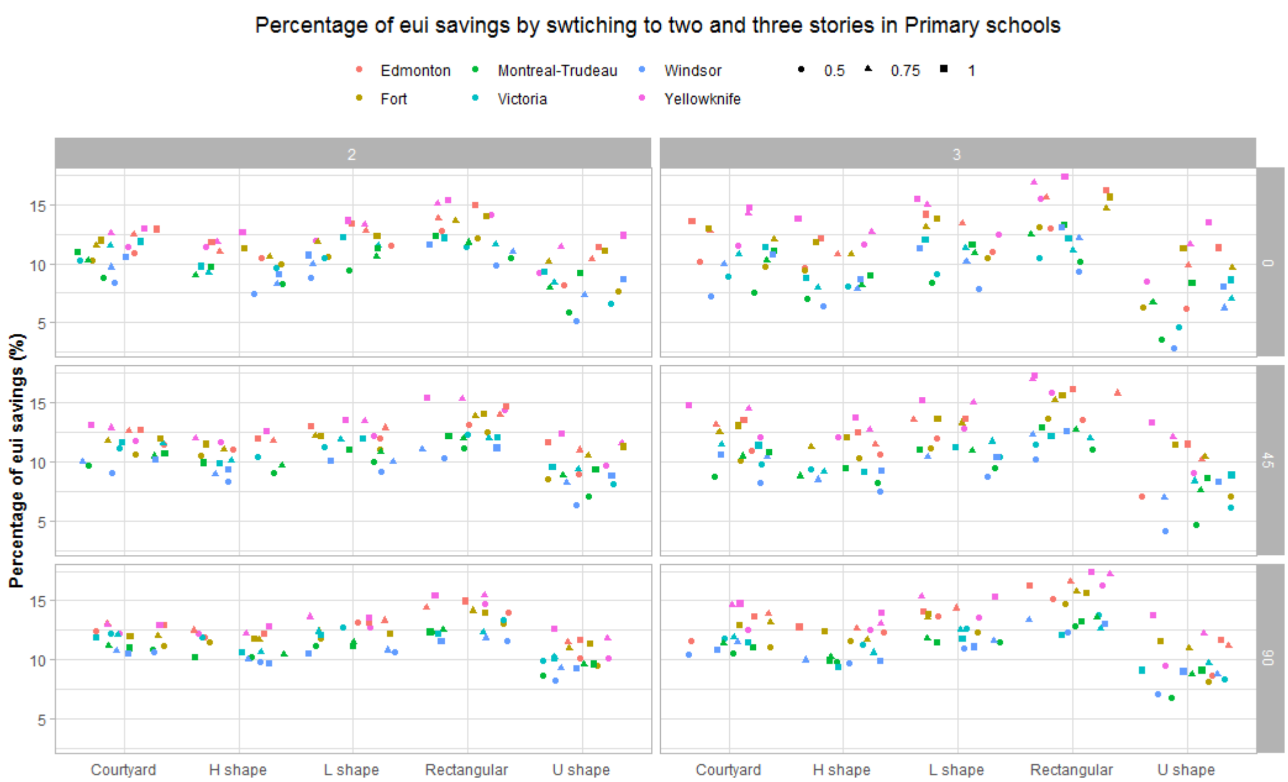

Figure 4: Effect of Number of Storeys on Energy Savings in Primary School.

combinations of three floors, rotation of 90º, and an aspect ratio of 0.75 (the square aspect ratio of 1 is the best performing in climate zone 8).

Table 2 : Optimum Design Parameters for Primary School

Shape	City (and climate zone)	# Flrs	Aspect Ratio	Rotation	EUI (kWh /m^2)
Rect.	Victoria (cz 4)	3	0.75	90º	87
Rect.	Windsor (cz 5)	3	0.75	90º	113
Rect.	Montreal (cz 6)	3	0.75	90º	105
Rect.	Edmonton (cz 7A)	3	0.75	90º	115
Rect.	Fort McMurray (cz 7B)	3	0.75	90º	118
Rect.	Yellowknife (cz 8)	3	1	90º	120

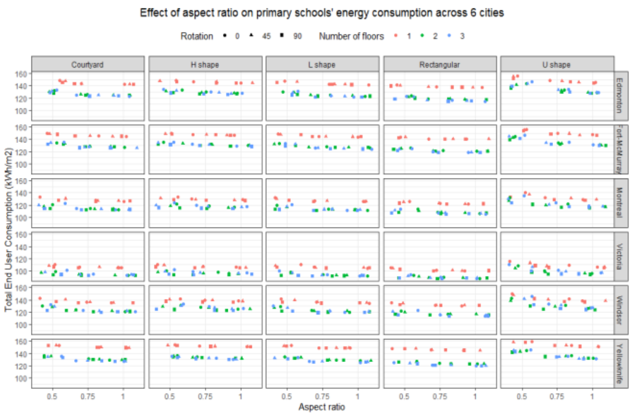

Figure 5: Effect of Aspect ratio.

Figure 6 illustrates the effect of rotation on energy savings in primary schools. Despite the fact that the effect of rotation on energy consumption is minimal for most of the geometrical shapes with an average energy savings of 1%, the savings are considerably higher for the U shape primary schools with a maximum of 10%. For example a U-Shape primary school in Victoria with 3 floors, and aspect ratio of 0.5, consumes 110 kWh/m^2 with a rotation of 0 degrees, however when same building is rotated 45 degrees, its energy dropped to 106 kWh/m^2 that yields around 4% savings, and when the building is rotated by 90 degrees from the north axis, the energy dropped again to 99 kWh/m^2 that represents around 10% of energy savings. This would indicate that the primary school archetype EUI was impacted by solar gains. The results match Lapisa's study (2018), where it was emphasized that buildings rotated by 90 degrees in Jakarta have achieved around 6% energy savings.

Figure 6: Effect of rotation.

Design parameters that led to minimal energy consumption in primary schools across the six climate zones are represented Table 2. The table illustrates that rectangular shaped schools outperformed the other geometrical shapes in energy savings. Based on the results for primary schools presented in Table 2, it can be observed that for climate zones 4 through 7B, energy savings can be achieved by

Small hotels

This section focuses on small hotels and analyses the effect of various combinations of design parameters on its energy demand. Another 810 Simulations were conducted to assess the influence of number of storeys, aspect ratio, geometry shapes and rotation across the six climate zones.

Figure 7 demonstrates the effect of the number of storeys on energy savings in small hotels. Based on the simulation results, energy consumption in one storey small hotels is significantly higher than two and three storeys hotels, in line with the results of primary schools. Variations in energy demand savings across the six cities by switching to two and three storey buildings has an average of 7.8% and up to 18.6% energy savings.

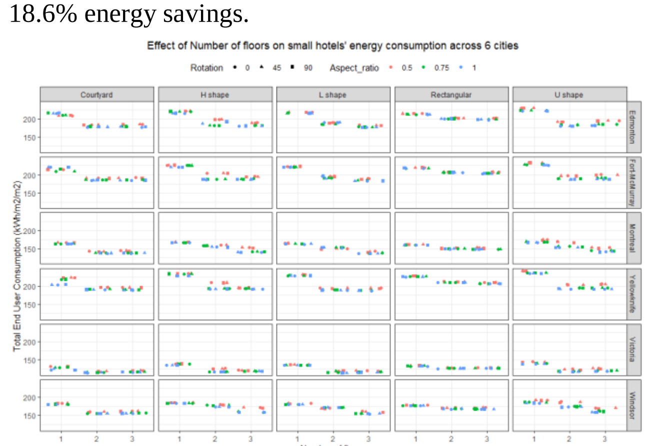

Figure 7: Effect of number of floors on small hotels.

The effect of aspect ratio on energy savings in small hotels is illustrated in Figure 8. Energy savings of an average of 1.9% and up to 9% can be achieved by increasing the aspect ratio from 0.5 to 0.75 and 1. The percentage of savings vary according to the building shape, maximum savings are in U-shape, H-shape, and courtyard buildings with maximum savings of 9%, 8.8% and 8.7% respectively. Savings of 4.9% and 3% are achieved when using L-shape and rectangular shaped buildings respectively.

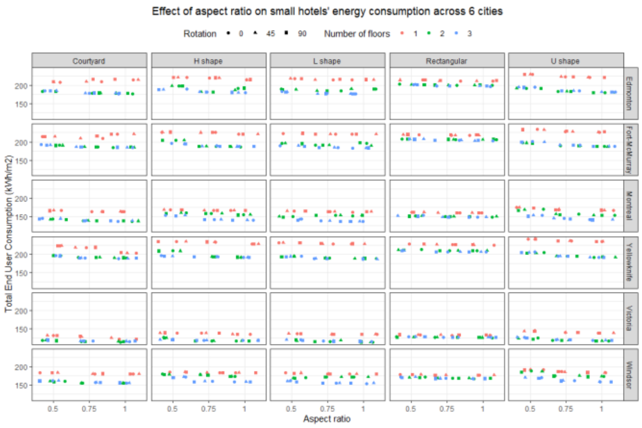

Figure 8: Effect of Aspect Ratio on Small Hotel.

Influence of rotation on energy savings in small hotels is minimal with an average energy savings of 0.2%, and up to a maximum of 3.3%. These savings are illustrated in Figure 9.

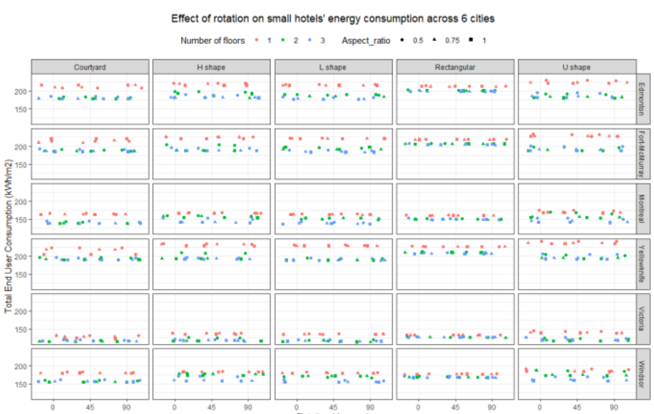

Figure 9: Effect of rotation in small hotels

Optimum building shape, number of storeys, aspect-ratio, and rotation in small hotels are shown in Table 3. The table illustrates that L-shaped small hotels outperform the other geometrical shapes in energy savings.

Table 3 : Optimum Design Parameters for Small Hotel

Shape	**City**	**# Flrs**	**Aspect Ratio**	**Rotation**	**EUI (kWh/m^2)**
L-Shaped	Victoria	3	1	90°	114
L-Shaped	Windsor	3	1	90°	155
L-Shaped	Montreal	3	1	90°	136
L-Shaped	Edmonton	3	1	90°	176
L-Shaped	Fort McMurray	3	1	90°	182
L-Shaped	Yellowknife	3	1	90°	187

Conclusions

The study emphasized the role of various geometry design parameters across the six climate zones of Canada by conducting 3195 simulations. Our preliminary study evaluated the influence of five geometrical shapes (courtyard, H-shape, L-shape, rectangular, and U-shape) on energy demand for seven different archetypes (retail strip mall, medium office, full service restaurant, primary school, warehouse, multi-unit residential buildings and small hotel) in Victoria. Various combinations of design parameters were investigated in our simulations, including varying the number of floors (one to three), varying the building orientations (0, 45^0, 90^0, 180^0 and 270^0), in addition to varying the aspect ratio (0, 0.5 and 0.75). The results revealed that three storeys in medium office and retail strip mall can lead to a significant increase in the energy demand (compared to the same buildings with fewer floors), this is partly due to the rulesets in NECB. Moreover, rectangular buildings outperformed the other geometrical shapes for retail strip mall, medium office, full service restaurant, primary school, and warehouse, except for small hotel and multi-unit residential buildings, where L-shaped buildings were performing the best in energy savings. Moreover, U-shaped buildings performed the worst for all building archetypes that were tested in this paper. Additionally, more detailed simulations were performed on primary schools and small hotels across the six climate zones. The analysis showed that one storey primary schools and small hotels are performing the worst and both consumed maximum energy when compared to two and three storey buildings. Furthermore, the results reflected that L shaped small hotel buildings are performing the best in energy savings, whereas rectangular shaped buildings perform the best in primary schools. For future work, more design parameters, building shapes and types can be further investigated.

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