Quantifying the impact of passive design on high rise buildings

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ABSTRACT: Buildings account for over 40% of all U.S. energy use (DOE 2012). This has an impact on national energy security, the economy, and the global environment. Provisions for local, state, and national building energy standards/codes exist to promote energy efficiency, making such codes a central part of the green building movement. These efforts are augmented by the architecture, engineering, and construction (AEC) industry through passive design strategies, advanced construction techniques, and the application of renewable energy technologies. This paper analyzes the sensitivity of operational energy use to variations in footprint aspect ratio and building orientation, both of which are critical design strategies for passive heating and cooling. Four identical high-rise office buildings are simulated in each of the four major climate zones (cool, temperate, arid, and tropical). All buildings are 200 meters in height, 50 stories that are 4.0 m floor-to-floor height, with a total conditioned floor area of 135,000 square meters. Preliminary energy analysis is performed using Autodesk *Ecotect Analysis* 2011, and the results are validated using the Department of Energy's *eQuest* version 3.65 building simulation software. The buildings were modeled to comply with the International Energy Conservation Code 2009. The results suggest that design strategies to maximize passive thermal conditioning and daylighting do little to reduce the load profiles of high-rise office buildings built to current energy codes.

KEYWORDS: Site Layout Planning, Orientation, Passive Solar Design, High Rise Buildings, Sustainable

INTRODUCTION

Global warming and climate change are major challenges facing the nation and the world. More than two thirds of the electricity energy and one third of the total energy in the US are used to heat, cool, and operate buildings (DOE 2012). The combustion of fossil fuels to supply energy to commercial buildings resulted in the emission of 1,075 million metric tons of carbon dioxide (CO_2) in 2008. This represented roughly 17% of all U.S. CO_2 emissions in that year (EPA/OAP 2009). A reduction in building energy consumption may help to mitigate these critical issues.

Building energy codes are intended to promote energy efficiency (DOE 2012). The reduction in energy use may translate to a financial savings that can be achieved through the development of new technologies (for the building's envelope, mechanical, and lighting systems) that save energy and reduce CO_2 emissions (Crawley, Pless et al. 2009; Hoque 2010) . The benefit to the building owner is lower monthly utility expanses, and smaller less expensive HVAC equipment (Harvey 2009). An alternative approach is the use of passive systems that employ renewable energy sources. Passive systems avoid the need for heating or cooling through better design, construction, and operation. They utilize solar or wind energy to heat, cool, or light buildings. While passive systems are relatively uncommon for large commercial buildings, hybrid mixed mode approaches may be effective in reducing the overall energy loads of conventional office buildings (Brager, Ring et al. 2000). High rise office buildings, which are the focus of this study, are well known to be "internally load dominated" buildings, which means that the operational loads (heating, ventilation, cooling, lighting, and space equipment) within these building types drive their energy profiles (Al-Homoud 1997). A building's size, use, vintage, and geographic region are among the key determinants that influence its energy use. Almost all US office buildings are conditioned with mechanical heating, ventilating, and air-conditioning (HVAC) systems and overall energy use is dominated by electric lighting loads (Pérez-Lombard, Ortiz et al. 2008). In fact, mechanical cooling and lighting energy use account for approximately 35% of commercial building electrical consumption in the United States (Figure 1), which has drawn attention to the concept of integrating passive heating, ventilation and natural daylighting in conventional office buildings (Li and Lam 2001).

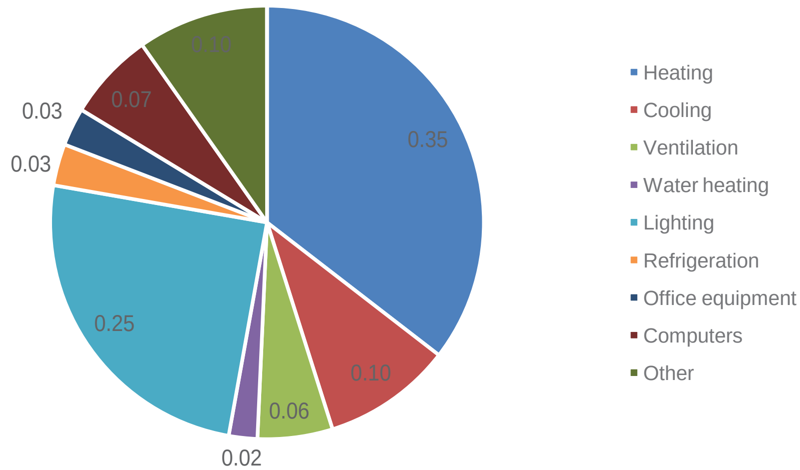


Figure 1: End Use Energy Consumption of Office Buildings in the US. Source: (EIA 2008)

Recent developments in high performance building are beginning to transform the way commercial office buildings are conceived and designed. For instance, the first Passive House Standard certified office building in the world has been constructed in Vienna, Austria. The Raiffeisenhaus Wein.2, or RHW.2 office tower, completed in December 2012, is 73 meters high and contains 18,600 square meters of office space (Meyer 2013). The design meets PHS in three critical ways: the thermal efficiency of a super-insulated double facade, the use of daylight to reduce electrical lighting requirements, and the advanced mechanical systems. Heating is primarily passive using solar gain, equipment loads, and occupants, supplemented by a geothermal heat pump. Cooling, which is only 8% of the energy loads, is a mixed mode system, using a combination of natural ventilation and mechanical cooling from the heat pump.

In the present study, we analyze the sensitivity of energy demand to two parameters of passive design related to building layout and site orientation. The key parameters we investigate are building footprint aspect ratio and the building orientation and are considered important factors in passive design (Yeang 1999; Yeang 2002). Four conventional (glazed curtain wall) high-rise office buildings with four different aspect ratios are simulated in four major Koppen climate zones: cool, temperate, arid, and tropical (Rubel and Kottek 2010). Energy demand is calculated for each model with respect to two opposing orientations. The four high-rise buildings are modeled to meet International Energy Conservation Code 2009 requirements, which references several ASHRAE standards, including Standard 90.1 for commercial building construction (IECC 2009).

Previous studies have shown potential for building site layout planning to play a positive role in influencing energy demand. For example, in *The Green Skyscraper* (1999), Kenneth Yeang suggests that in different climate zones the shape of the building footprint and the building orientation should be modified based on the climate zone in which the building is to be constructed. In the following sections we describe the analytical method and the primary variables that will be measured against energy use in the four modeled buildings. We then summarize the results for each of the thirty-two scenarios and present our conclusions.

2.0 STUDY AREA

Four models of high-rise office buildings are considered in this study to evaluate the sensitivity of energy demands to variations in: (1) footprint aspect ratio (1:1, 1:2, 1:3, and 1:4) (Figure 2), and (2) building orientation (NS and EW) (Figure 3). Since our goal is to isolate the influence of building site layout planning on energy demand, all other buildings descriptors such as the square footage, number of stories, building height, and occupancy for the four buildings are held constant across all four buildings. The four buildings are 200 meters in height, 50 stories that are 4.0 m floor-to-floor height, with a total conditioned floor area of 135,000 square meters. We also treated the thermostat range, internal design conditions, occupancy, infiltration rate, and hours of operation as fixed control variables (Table 1). Personal factors such as activity (metabolic rate) and clothing (insulation of clothing) are treated as constant for all building occupants.

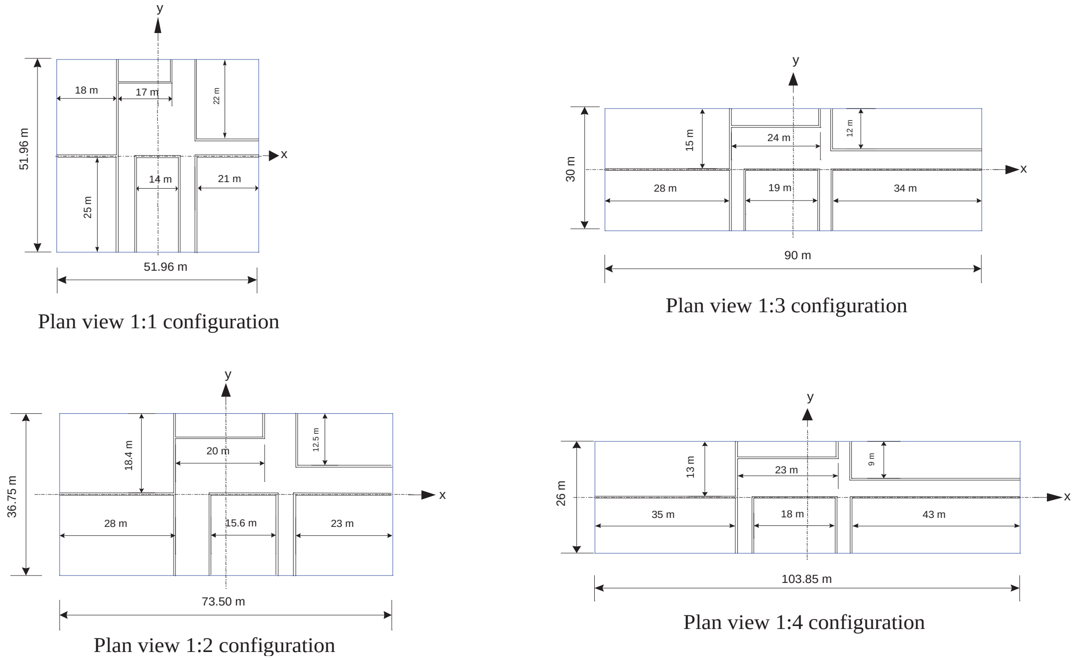


Figure 2: Footprint aspect ratios for modeled buildings in plan view.

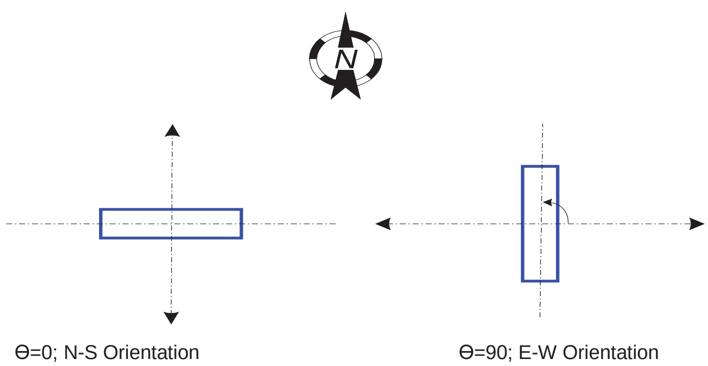


Figure 3: Building orientations considered in this study.

Table 1: Thermal analysis conditions.

Parameters		**Values**
Active system		Full air conditioning
Thermostat range		18 – 26 ^{o}C
Occupancy	People	12 m^2/person
	Activity	70 W/person
Internal design conditions	clothing	1 CLO/person
	Relative humidity	60%
	Air speed	0.5 m/s
	lighting level	300 lux
Infiltration	Air change rate	0.5 /hr
Internal heat gain		10 W/m^2
Hours of operation		Schedule (8:00 – 18:00)

The primary material for the envelope is a glazed curtain wall, which is comprised of two layers of standard glass with 10% metal framing. The floors are assembled layers of 10mm ceramic tiles, 5mm screed, 100 mm normal concrete, insulation (to meet the R-value specified for the climate according IECC 2009), 50 mm air gap, and 10 mm plaster. To simplify the thermal analysis, we have ignored the effect of adjacent buildings, in essence assuming that the buildings are erected on flat open ground and are aligned with the cardinal directions.

The four buildings are simulated in each of the four major climate zones (cool, temperate, arid, and tropical) and we selected specific US cities to represent each climate zone: Boston, Massachusetts for the cool zone, Sacramento, California for the temperate zone, Las Vegas, Nevada for the arid zone, and Honolulu, Hawaii for the tropical zone. Building envelope materials are selected for all four models to meet the requirements of thermal properties of IECC 2009, corresponding to each climate zone (Table 2).

Table 2: Building envelope properties

	Envelope Properties			
Climate / Element	Cool	Temperate	Arid	Tropical
Curtain Wall (Glazing wall with 10% metal framing)	U=2.5	U=3.4		U=5.4
	SHGC=0.4	SHGC=0.25		
Roof	R=3.7			R=2.7

U-factor (W/m^2K); R-value (m^2K/W)
SHGC Solar Heat Gain Coefficient

3.0 ANALYTICAL APPROACH

Autodesk's Ecotect energy simulation package was used for the preliminary thermal analysis. Ecotect 2011 is a comprehensive concept-to-detail sustainable building design program; it is a popular program used by architects, as its modeling procedure is simple, easy to manipulate, and it consumes a reasonably short run time for large models. For this study, the building geometry was prepared in Autodesk Revit 2010 and then imported as surfaces and rooms to Ecotect 2011. In Ecotect, thermal properties are assigned to the envelope. The basic material of an element (floor, roof, glazing wall, etc.) is assigned first, the thermal properties of element and the insulation is then applied according to specifications of IECC code. The next step is to assign a weather file that corresponds to the climatic zones selected for this study and to provide occupancy and scheduled usage data. Ecotect calculates the overall heat gain/loss, and based on Flat Comfort Bands Method (FCBM), the heating & cooling loads are calculated. FCBM sets upper and lower limits for comfort temperatures (Mourshed 2006). If the internal zone temperature is either above or below the temperature limits for the prescribed comfort zone, then thermal environmental conditions are unacceptable to a majority of the occupants within that space. Factors that determine thermal environmental conditions are temperature, thermal radiation, humidity, air speed, and personal factors such as activity and clothing. Environmental factors are influenced by: 1) Radiant flow through transparent surfaces; 2) Internal (sensible and latent) heat gain from lights, people, and equipment; 3) Conductive heat flow through opaque (envelope) elements; 4) Radiant flow through opaque (envelope) elements; 5) Ventilation and infiltration heat flow through cracks and openings; 6) Inter-zonal heat flow between adjacent zones. Conductive and radiant flows through opaque elements are treated together under the “Fabric” category in Ecotect.

Following the Ecotect analysis, we modeled the same buildings using the Department of Energy's (DOE) eQuest version 3.65 building simulation tool. eQuest analysis is supported by the DOE-2 simulation engine that uses a description of the building geometry, construction materials, schedule, environmental systems (lighting, HVAC, etc.), along with weather data, to perform an hourly simulation of the building. It has been validated by the Dept. of Energy (Neymark, Judkoff et al. 2002). eQuest is a user-friendly interactive Windows implementation of the DOE-2 program with added wizards and graphic displays to create a model and view simulation results. Because eQuest is prone to translation errors when porting a building model from another drawing program, we prepared the building geometry and assigned IECC envelope thermal properties and control schedules directly in eQuest using the Building wizard. Like Ecotect, locational and weather data was input according to each of the four climate zones selected for the study. eQuest produces summary as well as hourly report data based on contributions from walls, windows, people, plug loads, and

ventilation air. End use energy consumption for lighting, general space equipment, heating, cooling, ventilation, and pumps are tabulated (DOE-2 2009).
Our results for both Ecotect and eQuest runs were compatible thus validating our preliminary results. The following sections provide detailed explanations and the results of our analysis. The numbers provided are drawn from the Ecotect simulation runs.

4.0 THERMAL ANALYSIS

The thermal analysis involves examining each of the four models (1:1, 1:2, 1:3, and 1:4) in each of the four climatic zones (cool, temperate, arid, and tropical). For each climate zone, four models are tested under equivalent interior thermal and schedule conditions. That is, the only differences among the four runs in the same climate zone are the building width to length ratio (aspect ratio) for one orientation at a time. In this study there are two main stages of the thermal analysis. The first stage is to find the sensitivity of the energy demand (heating and cooling loads) to the change of the surface area ratio (SAR), which relates to floor plan aspect ratio:

$$SAR = \frac{(floor\ perimeter \times floor\ height)}{floor\ plan\ area}$$

This analysis consists of thirty-two different simulation runs (matrix of four models and four climate zones), where cooling and heating loads are calculated for each model in two orientations (N-S and E-W). The results corresponding to N-S orientation are provided in Table 3, and the difference in the total energy use intensity between the two orientations is not significant, as shown in Figure 4.

Table 3: Energy demand verses SAR (N-S orientation)

Width to length ratio - increase in SAR												
Type / Climate	1:1			1:2			1:3			1:4		
	Heating	Cooling	EUI	Heating	Cooling	EUI	Heating	Cooling	EUI	Heating	Cooling	EUI
	kwh/m^2			kwh/m^2			kwh/m2			kwh/m2		
Cool	49.8	9.4	59.2	51.9	9	60.9	53.6	8.7	62.3	55.9	8.4	64.3
Temperate	7.9	30.7	38.55	8.4	30.7	39.1	8.9	30.8	39.8	9.7	31	40.6
Arid	5.8	57	62.8	6.1	57.9	64.0	6.5	59	65.5	7	60.4	67.4
Tropical	0.0	62.5	62.5	0.0	62.75	62.75	0.0	63.4	63.4	0.0	64.1	64.1

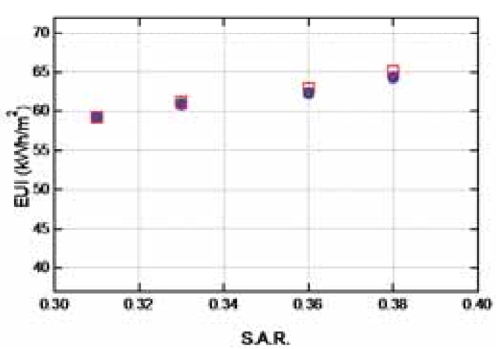


Figure 4A: Cool climate

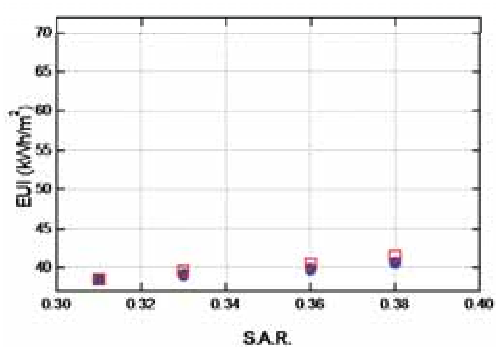


Figure 4B: Temperate climate

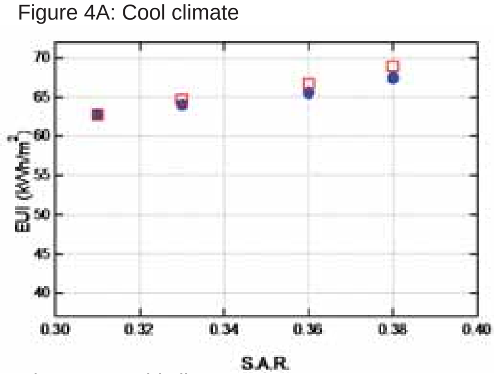


Figure 4C: Arid climate

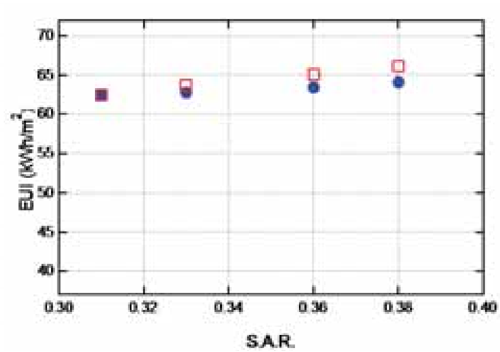


Figure 4D: Tropical climate

Figure 4: Sensitivity of EUI to the change in surface area ratio and orientation

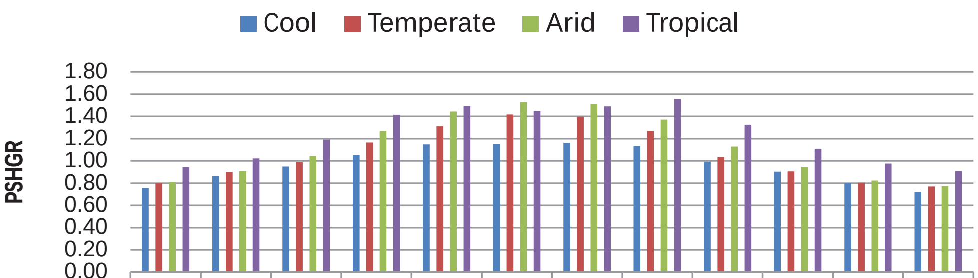
Using the model of 1:4 aspect ratio as an example, the monthly and yearly energy demand ratios (EDR) are shown in Table 4.

$$EDR = \frac{energy\ demand\ of\ East - West\ orientation}{energy\ demand\ of\ North - South\ orientation}$$

Table 4: Energy demand ratio (model of 1:4 aspect ratio).

Months	**Energy demand ratio (EDR)**			
	Cool	**Template**	**Arid**	**Tropical**
Jan	1.01	1.01	1.03	0.96
Feb	1.01	1.02	0.97	0.99
Mar	1.01	0.99	0.99	1.05
Apr	0.99	1.02	1.04	1.07
May	0.97	1.04	1.05	1.06
Jun	0.99	1.04	1.03	1.05
Jul	**1.011**	**1.034**	**1.026**	**1.055**
Aug	1.02	1.02	1.02	1.05
Sep	1.00	0.99	1.01	1.03
Oct	1.01	0.98	0.99	1.01
Nov	1.02	1.00	0.99	0.99
Dec	1.02	1.02	1.03	0.97
yearly	**1.01**	**1.02**	**1.02**	**1.03**

In Figure 5, the passive solar heat gain ratio (PSHGR) of the 1:4 aspect ratio model is displayed.



	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Cool	0.76	0.86	0.95	1.05	1.15	1.15	1.16	1.13	0.99	0.90	0.80	0.72
Temperate	0.80	0.90	0.99	1.17	1.31	1.42	1.40	1.27	1.04	0.90	0.80	0.77
Arid	0.81	0.91	1.04	1.27	1.44	1.53	1.51	1.37	1.13	0.95	0.82	0.77
Tropical	0.94	1.02	1.19	1.42	1.49	1.45	1.49	1.56	1.33	1.11	0.98	0.91

Months

Figure 5: Monthly passive solar heat gain ratio.

In Table 5, the total heat gain and heat gain ratio (HGR) of the month of July are further tabulated by individual contributions of direct loads, internal loads, envelope and ventilation loads. We did this to analyze the impact of each of these heat sources, and also to determine how changes in building orientation affect passive solar heat.

Table 5: Breakdown heat gain (Wh) in July.

Climate	**Cool**					**Temperate**				
orientation	θ=0		θ=90		July HGR	θ=0		θ=90		July HGR
Direct	1.1E+08	17%	1.3E+08	20%	**1.16**	1.1E+08	8%	1.5E+08	11%	**1.40**
Internal	5.1E+08	78%	5.1E+08	75%	1.00	5.1E+08	40%	5.1E+08	38%	1.00
Fabric	2.1E+07	3%	2.3E+07	3%	1.11	2.8E+08	22%	2.9E+08	22%	1.02
Ventilation	1.3E+07	2%	1.3E+07	2%	1.00	3.8E+08	30%	3.8E+08	29%	1.00
Total	6.573E+08		6.783E+08		**1.032**	1.277E+09		1.325E+09		**1.038**
Climate	**Arid**					**Tropical**				
orientation	θ=0		θ=90		July HGR	θ=0		θ=90		July HGR
Direct	1.1E+08	5%	1.6E+08	8%	**1.51**	9.9E+07	10%	1.5E+08	14%	**1.49**
Internal	5.1E+08	25%	5.1E+08	24%	1.00	5.1E+08	50%	5.1E+08	47%	1.00
Fabric	6.1E+08	30%	6.2E+08	29%	1.01	2.2E+08	21%	2.3E+08	21%	1.05
Ventilation	8.3E+08	40%	8.3E+08	39%	1.00	2.0E+08	19%	2.0E+08	18%	1.00
Total	2.068E+09		2.129E+09		**1.03**	1.029E+09		1.087E+09		**1.057**

In this first stage of the thermal analysis, our purpose was to find out the sensitivity of energy demand to the variation of SAR. These results are presented in Table 3 where heating and cooling loads are provided for each aspect ratio corresponding with the four climate zones. In the Cool, Temperate, and Arid climate zones, the energy demand is increasing by an average percent increment of 1.7-2.7 % while the total is increasing 5.1-7.9% with respect to increase in SAR. This increasing energy demand may be considered slightly significant, where increasing the surface area by 20% leads to demand increased by 5.1-7.9% depending on the climate zone. However, in the tropical climate the energy demand is insensitive to variations of SAR, where the average increment percent is 0.4% and the total increase is 0.84%.

Figure 4 illustrates the differences in the energy demand which results from two building orientations (N-S & E-W) in each climate zone. The horizontal axis represents the SAR corresponding to the four building aspect ratios (1:1, 1:2, 1:3, and 1:4), while the vertical axis represents EUI. The differences in the EUI (demand/m^2) are not significant, and the largest difference (of 3.1%) in energy demand for the opposing orientations occurs in the Tropical zone.

In Figure 5, we focused on the month of July, and find that direct heat gain (passive solar gain) resulting from a building oriented E-W is much higher than in the case of a building oriented N-S. This in itself might be not unexpected, yet upon closer examination, we note that the demand in this month and overall yearly cooling loads are nearly identical for both orientations as shown in Table 4. In order to know why, the heat gain broken down to its respective components and presented in Table 5. A significant difference in July's heat gain ratio (July HGR) is due to direct heat gain, which naturally varies depending on the climate zone. However, because the amount of heat gain through this source represents only 5- 20% of the total heat gain, consistent for both orientations, the effect of direct solar radiation does not significantly impact total heat gain. The total heat gains shown in Table 5 for the month of July, are slightly higher than the corresponding demand as shown Table 4. The reason is because even with some heat gain, the interior temperature is still within the comfort range and there is no need for cooling.

4.1. Demand sensitivity -- glazing walls built to code

The second stage of the thermal analysis is to find out why there are small differences in the energy demand, even though the buildings were faced to maximum passive solar heat gain in case of E-W orientation. This indicates that the reason maybe because the usage of high quality envelope. For this analysis, we modeled the glazing walls with regular glazing, which has less optimal thermal properties (U=6.0 W/m^2.K & SHGC=0.94). The analysis is performed to evaluate energy demand for both orientations. Accordingly, the results showed that buildings oriented E-W demand 12% more energy whether it oriented N-S, and also the passive solar heat gain in July is significantly increased.

In other words, we investigate the difference between built to energy code envelopes and regular glazed envelopes on passive solar heat gain. The outcomes demonstrated that due to code requirements, direct heat gain is reduced by 20-30% in the N-S and E-W orientations (Table 6 for arid climate). This also helps to explain why there is that small effect result from the variation of building orientation on monthly and yearly energy demand.

Table 6: Breakdown heat gain (Wh) in July in Arid climate – regular glass envelope.

	Heat gain (Wh)				**July HGR**
	Ɵ=0		**Ɵ=90**		
Direct	7.4E+08	24%	1.2E+09	34%	1.62
Internal	5.1E+08	16%	5.1E+08	14%	1.00
Fabric	1.0E+09	33%	1.0E+09	29%	1.01
Ventilation	8.3E+08	27%	8.3E+08	23%	1.00
Total	3.099E+09		3.564E+09		1.15

CONCLUSION

This paper examined four different buildings' footprint aspect ratios and two orientations in order to investigate the sensitivity of site layout planning characteristics on the energy consumption of high-rise office buildings in four different climate regions. By simulating each building configuration, we were able to draw two major conclusions regarding building energy consumption.

(1) For the buildings in Cool, Arid, and Temperate climates, the energy demand may be considered slightly sensitive to changes in SAR. Our models suggest that increasing the surface area of the building envelope by 20% leads to increased energy demand by 5.1-7.9% depending on the climate zone. On the other hand, the energy demand of buildings in a Tropical climate zone appear to be insensitive to variations in SAR. For the three other climate zones, it is important to note that an increase in the surface area may lead to an increase in the materials used, may lead to an increase in the cost and embodied energy. Also, increases in the surface area may results in an increase in the area exposed to wind pressure, which might lead to the need of a larger size of structural element, which impacts the cost and embodied energy of these buildings.

(2) Our models demonstrate that the energy performance of high-rise office buildings is not sensitive to passive solar gain as evidenced by changes in orientation insofar as the buildings' envelopes are built to code. We found the greatest difference in energy demand (by 3.1%) for buildings in a Tropical climate zone. This small to negligible difference in EUI for opposing orientations can be explained by the fact that commercial buildings are typically internally load dominated, and as such, site layout planning is not as important as ensuring efficient and load reducing internal operations. For office buildings whose envelopes are not built to IECC energy standards, however, passive design strategies such as solar heating and natural cooling may have promise (Lam and Li 1999).

High quality insolated envelope provides greater flexibility to manipulate with the building site plan (geometry) without resulting in significant changes in energy demand. On the other hand, this constrains a designer's ability to take advantage of passive design strategies. Because IECC code buildings are not particularly sensitive to solar gain, this leaves little room for solar strategies to play a role in reducing energy demand.

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