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A parametric sensitivity analysis of the impact of built environment geometrical variables on building energy consumption

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Abstract: The growth of urban communities creates the need for analytical frameworks that have a multi-objective and holistic approach. It is important to integrate these frameworks within commonly used architectural tools. The urban environment is mostly designed and formed by architects and urban planners who can create more sustainable urban growth. In this paper, urban geometry will be explored as it has a significant influence on the building heat loss/gain that determines the energy demand needed to achieve indoor thermal comfort. Simulation tools have been created to analyse and optimize urban geometrical variables in a multi-objective approach. This study analysed urban geometrical variables such as (height, capacity, orientation and window to wall ratio). In addition, it gives an insight of the buildings' inter-shadowing effect by adding the context buildings' capacity in the grid.

The results show that daylighting analysis consumes almost triple the time using multi-objective, multi-zone geometrical iterations. In this set of inputs for hot arid climates there is a minor impact on cooling energy consumption, suggesting that the study daylighting distribution should be postponed to a later design stage rather being a key component of energy analysis in early design stage. This study shows that WWR has the highest impact on the building thermal cooling consumption in this urban context, then comes built area ratio and finally building height for midrise residential buildings.

Keywords: parametric simulation, energy demand, lighting control, daylighting, urban geometry

Introduction

World urbanization is expected to be continue its growth for at least the next 10 years. The UNFPA 2007 report stated, *"In developing countries, cities of 100,000 or more are expected to triple their built-up land area to 600,000 km^2 in the first three decades of this century."* By 2005, Asia had urban growth of 40% and Africa 38% which is the fastest global rates **(**Martine and Marshall, 2007)**.** In addition, due to increased global greenhouse gasses (GHG) emissions, Africa has a greater chance of increasing temperature than the world average, especially in the Sahara area (Field *et al.*, 2014). Furthermore, Africa has one of the least populated rates in its northern Sahara area. (Food and Agriculture Organization and World Bank population estimates., 2015). The building sector is responsible for the third of global energy consumption and generates 20% of man-made GHG emissions worldwide. (World Business Council for Sustainable Development (WBCSD), 2015). This is the main reason for the need to apply energy efficiency measures to buildings and urban energy assessment tools to create a new climate responsive built environment.

Climate responsive urban planning and design had some challenges. There is a need for a set of verified tools that can simplify the transfer of data and knowledge and consequently improve the designer’s decision making process especially in early design stages (Eliasson, 2000). The early design stage has gained a lot of attention recently, especially in urban sustainable simulation and optimization. The urban fabric is formed by various geometrical elements, each of which play a role in the creation of the building microclimates. The variation of these geometrical elements leads to the use of a parametric design approaches in studying the relationship between urban geometry and energy consumption in built environment.

Parametric design is a process that the uses different parameters to shape a form by manipulating its geometrical relationships (Monedero, 2000). With this impressive ability to the design in general, parametric urban design can simply represent a group of arranged buildings and urban geometrical variables that are shaped by scripted algorithms. This interpretation can provide a different vision and capability of investigating urban design, geometry and performance (Schumacher, 2009). It has made urban design more interactive and responsive with visualization of the design layout and its analytical data.

Urban modelling geometrical variables:

The parametric approach has been implemented in different studies to analyse building performance in urban contexts. (Yi and Kim, 2015) used a genetic algorithm tool on a Visual Programming Language (VPL) platform (Grasshopper) (Mcneel, 2014), Galapagos (Rutten, 2013)) to analyse solar irradiation for high rise building urban geometrical configuration. Orientation has been investigated (Panão *et al.*, 2008; Taleghani *et al.*, 2015), and (Vermeulen *et al.*, 2015) analysed it along with height, scale and position. In addition to energy analysis, (Sabry *et al.*, 2014)tried to reach for a balance between energy consumption and lighting performance by using an outdoor solar screen in hot arid zone. This coupling between lighting and energy analysis was previously recommended by (Mardaljevic *et al.*, 2009). Daylight metrics and analysis also used to predict energy consumption in urban scale in different studies (Bassett *et al.*, 2012; Dogan *et al.*, 2012; Jones *et al.*, 2013; Trigaux *et al.*, 2015; Nault *et al.*, 2016). The literature shows the potentiality of analysis tools and the usefulness of its parametric integrative approach. However, a limited number of studies investigated this holistic approach and explored the relative importance of geometrical variables on energy consumption in urban scale. Furthermore, the effect of adding daylight illuminance sensitivity to the study of the pattern of energy consumption for thermal comfort had been given little attention especially in residential context.

Objective:

This study aims to investigate a framework for running a holistic analysis with Ladybug Analysis Tools (Sadeghipour and Pak, 2013) and to run a sensitivity analysis for geometrical variables. This study will quantify the effect of the variation urban geometrical on thermal performance and to evaluate the relative importance of each variable on the energy consumption used in cooling and heating in hot arid zones.

Methodology:

(Sadeghipour and Pak, 2013) have introduced a simulation package of tools based on Rhinoceros/Grasshopper platform (Mcneel, 2014; McNeel, 2014). This package is called

Ladybug Analysis Tools, which are based on different simulation engines: Day-sim & Radiance for daylighting analysis; Open foam for Computational Fluid Dynamics analysis; and EnergyPlus for energy related simulation (Ward, 1994; ESI Group, 2004; U.S. Department of Energy's (DOE), 2016; Reinhart, 2017). Ladybug analysis tools enhance the capability of integrative simulation and design methods avoiding the use of multiple platforms for the same projects, combining multi-objective parametric performance tools into one method and in a parametric approach. . The study used two applications from these tools, Ladybug for visualizing weather files and results, Honeybee for running the daylighting and energy analysis.

The study was conducted in Aswan city in southern Egypt (24.0889° N, 32.8998° E), using the Egyptian Typical Meteorological Year (ETMY) weather file. Aswan is a target of Egyptian future urban growth (Egyptian Ministry of State for Administrative Development, no date) and it also represents an important sustainable development node for Egypt, hosting the high dam of the Nile which was a national development projects. There are governmental plans for its growth which include a twin new city. According to (Kottek et al., 2006), Aswan falls in the hot arid zone classification.

Geometrical parameters & thermal settings

The sensitivity analysis is conducted on a nine-building grid as a simple urban configuration. The building in the middle is the analysed model with the other 8 building acting as the typical grid context for it. The analysed building has a 30% core to perimeter ratio and an Energy-Plus midrise apartment zone program was chosen. The apartment program are used for the perimeter zones and corridor program for the core zones. All zones are conditioned with the default set ideal air loads system for Heating, Ventilation and Air Conditioning (HVAC).

The grid cell size is 23 by 23 metre as representation of the common size of land size in Egypt (El-deep *et al.*, 2012) with building areas varying for each cell's area as shown in table 1. In addition to scale, the height was a feature of geometrical variation in the study. Buildings' heights varied as shown in table 1 with fixed 3.5-meter floor height. To test orientation, the whole configuration is rotated by 45 degrees creating two groups. Finally, the case study building has a fixed window to wall ratio for its 4 facades. The window to wall ratios (WWR) is shown in table 1.

Table 1. Geometrical parameters for the case study.

Geometrical Variables							
Height (meters)	3.5	7	10.5	14	17.5	21	24.5
Scale (built area ratios)	50%	60%	70%	80%	90%		
Window to Wall Ratio	20%	50%	80%				
Orientation (degrees)	0	45					

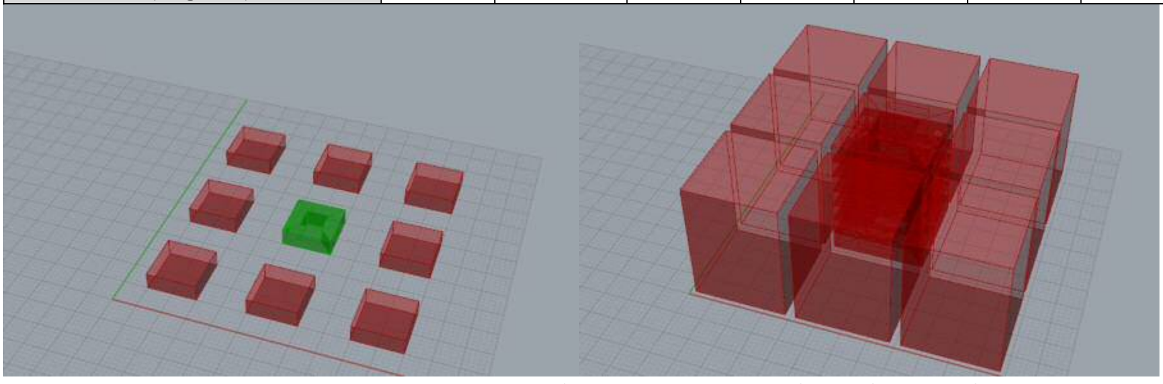

Figure 1. The tested geometrical model's examples. To the left: the first case for group A1 (20% WWR & 0 degrees' rotation) with a 3.5 meters' height floor and 50% built area of each grid cell. To the right: the last case in the same group with 7 floors, 24.5 meters' total height and 90% built area.

Material parameters & Daylighting analysis settings:

In regards to material, The material were adjusted based upon some studies made in the same geographical context (El-deep *et al.*, 2012; Attia and Evrard, 2013). The material properties were fixed for all the iterations and designed based upon the specification of the Chartered Institution of Building Services Engineers (CIBSE) Guide for environmental design (Butcher, 2006). Table 2 shows the material parameters used in the study.

Table **2**.material parameters used in the study.

COSTUMIZED MATERIALS					
External Wall		Internal Wall		Single Glazed Window	
U-Value W/m^{2}K	3.10	U-Value W/m^{2}K	5.29	U-Value W/m^{2}K	75
Internal Floor		External Roof			
U-Value W/m^{2}K	1.43	U-Value W/m^{2}K	0.36		

Daylight illuminance modelling has been included to explore the balance between the energy consumed for thermal comfort and lighting the zones. The parametric analysis creates some dense configurations that allow very little sun penetration, which was very beneficial to the cooling energy consumption, but on the other hand might result in a change in the lighting consumption. Annual daylighting analysis was conducted for each zone with a test mesh of 0.6 metre cell and one sensor point in the centre of it. The mesh is at 0.7 metre height from the floor. The lighting control system used is auto dimming with switch off occupancy sensor with 300 lux target illuminances for each zone.

The variation in the geometrical variables produces 210 different iterations. The study can be divided into 6 groups with 35 iterations each. These groups included two sets of orientations 0 and 45 degrees and three sets of WWRs .2, .5 and .8 with the full original variations of heights and building's scales. The total number of iterations was done twice one run was with basic on/off lighting controls and the other run was with dimming lighting controls based on annual daylighting profiles mentioned earlier.

Results:

The comparison is for cooling and lighting energy consumption with lighting dimming controls and with standard on/off lighting controls. Heating consumption varied between 1.7 - 8.5 kWh/m2 for the all the runs, so is considered insignificance in this comparison. The 6 groups are categorized by rotation angle and WWR for each group and each group has full heights and scales ranges mentioned earlier.

Group A1 (rotation =0, WWR=20%)

There is a change in values in cooling and lighting energy consumption between dimming and no dimming controls results. The relationship between these is quite strong with difference between them of around 1%.

Group A2 (rotation =0, WWR=50%)

The change in values for cooling is different from previous group the bigger the built area and higher the configuration the more apparent the difference. Considering lighting energy consumption, the change of urban configuration has more effect in this case on the dimming controls due to the bigger WWR ratio. This change in cooling consumption pattern is still consistent with the difference of around 3%.

Group A3 (rotation =0, WWR=80 %)

The effect of outdoor geometrical changes is more apparent in this group on lighting consumption with dimming controls applied. On the other hand, there is less difference in the cooling values for the densest configurations. The dimming applied models begin to have a fraction of higher values of cooling consumption, but this did not change the pattern of cooling consumption consistency between different lighting controls still around 3%.

Considering time consumed for the simulation for two lighting controls, the daylighting dimming control took on average triple the simulation time compared to the default on/off lighting controls. As shown in figure 2, the same patterns of cooling energy consumption are in the rest of cases, with different values due to the different angle of orientation.

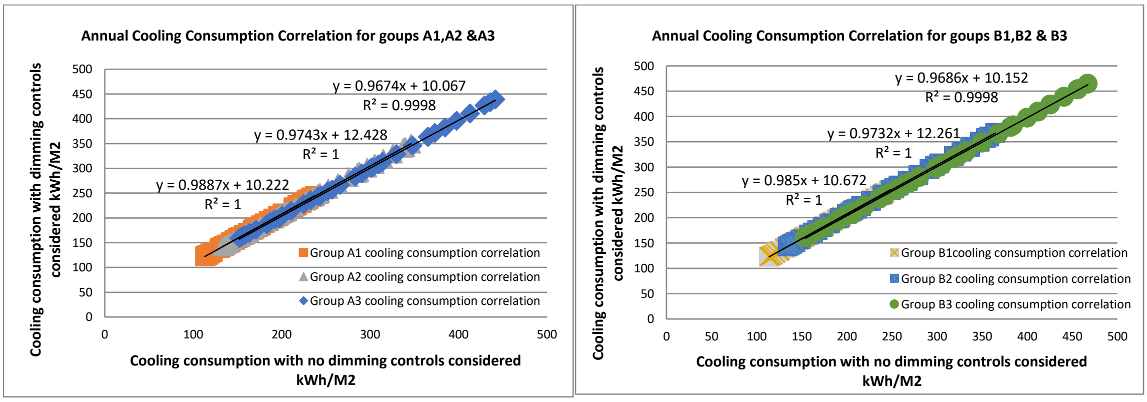

Figure 2 : Annual cooling consumption comparison between dimming & no dimming lighting controls considered for left groups A1,A2 & A3. Right, groups B1,B2 & B3

Group B1 (rotation =45, WWR=20%)

In general, the values of energy consumption for cooling and lighting are getting closer to group A1 when the configuration gets dense. Furthermore, the values are closer when it comes to one floor runs and then continue to repeat the pattern again with the repetition of heights with different scales but with a 2% difference.

Group B2 (rotation =45, WWR=50%)

The pattern and almost the same difference in consumption values are repeated in this group again with the same proximity in the lower heights lighting consumption values of group A2.

Group B3 (rotation =45, WWR=80%)

The main difference in this group is that the lighting values is almost like group A3 due to the high value of WWR. The cooling is still has the same pattern of proximity to group A3.

Variables relative importance

Heights:

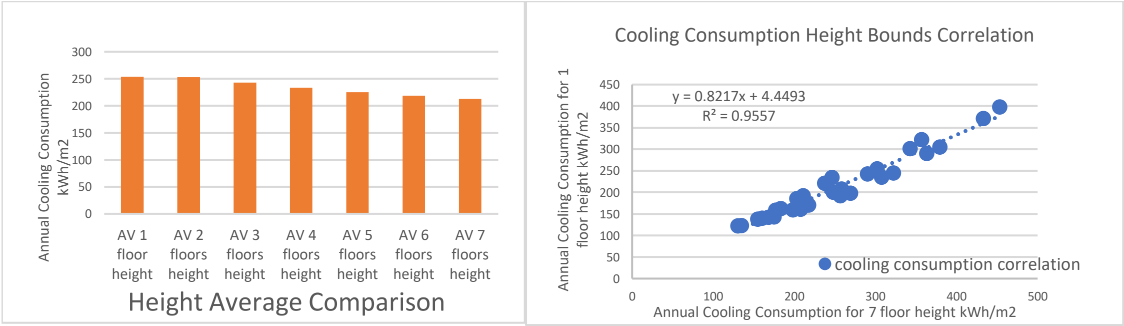

Figure 3. To the left: height variations' cooling consumption average comparison in kWh/m2, to the right: height variations' bound correlated in kWh/m2

The results imply that there was a noticeable difference in the energy cooling consumption within the building. The study shows that the relationship between height and energy cooling consumption is that of a negative correlation. It could be said that this is due to the arid conditions of the specified zone. A comparison of the calculations of the highest and lowest blocks showed that there is an 18 % difference in cooling consumption (Figure 3).

Built area ratio:

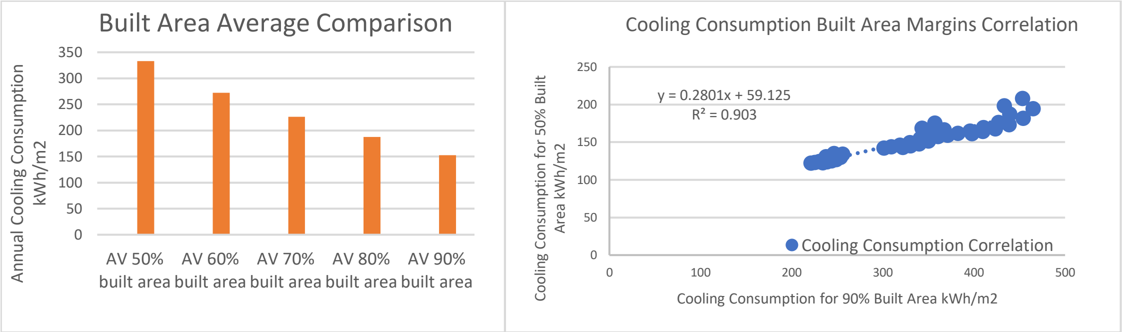

Figure 4. To the left: built area ratio variations' cooling consumption average comparison in kWh/m2, to the right: built area ratio variations' bound correlated in kWh/m2

The results imply that there was even more change in the energy cooling consumption within the building. The relationship between built area ratio and energy cooling consumption is that of a negative correlation. A comparison of the calculations of the most and least dense configurations showed that there is a 72% difference in cooling consumption (Figure 4).

WWR:

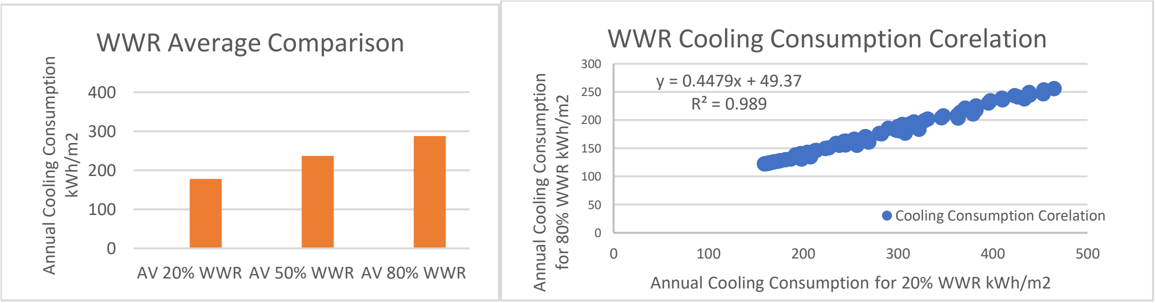

Figure 5. To the left: WWR variations' cooling consumption average comparison in kWh/m2, to the right: WWR variations' bound correlated in kWh/m2

For WWR variations, the relationship with energy cooling consumption is a positive correlation. This is can be caused also by the climate zone chosen for the study. The difference in the energy cooling consumption is more than what was shown for heights but still less than what is shown for built area ratios effect. The comparison between these variable limitations indicated that there is almost 66 % difference in cooling consumption (Figure 5).

Orientation:

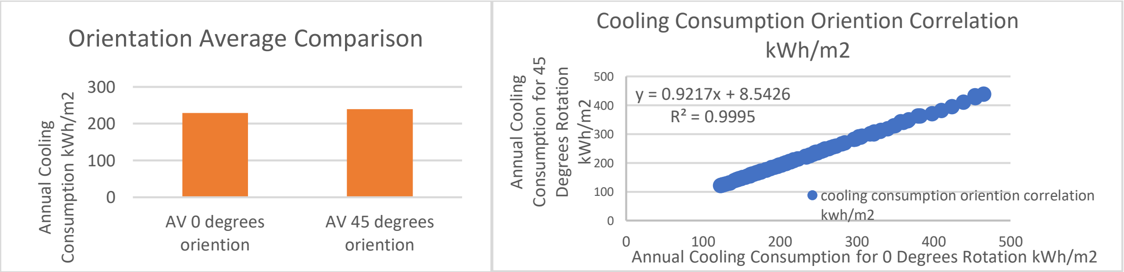

Figure 6. To the left: orientation variations' cooling consumption average comparison in kWh/m2, to the right: orientation variations' bound correlated in kWh/m2

There is a slight positive correlation for this variable, according to the results. Comparing the 2 variations it can be argued that there is an 8% of energy cooling consumption difference exists between the 2 different angles (Figure 6).

Conclusion

This study used undertook a holistic analysis to quantify the effect of the variation urban geometrical on thermal performance and to evaluate the relative importance of each variable on the energy consumption used for cooling and heating in hot arid zones.

The results show that daylighting analysis has a minor impact in comparison with cooling energy consumption in this case study based in hot arid zones. This does not imply any dependencies between cooling and lighting energy consumption. This impact varied between 2 to 4 % change in cooling consumption values due to the change of lighting controls based on daylighting autonomy. Besides, time constraints make the brute force sensitivity analysis of daylighting distribution with dimming control systems hard to be conducted in the early stage of design especially in a multi-zone, multi-object study. In this case, the difference of lighting dimming control systems is triple the time consumed to conduct a standard On/Off controls lighting analysis with the same computer specifications. Although, the need to study daylighting distribution is inevitable to achieve a comprehensive optimal building performance, it can be suggested that daylighting analysis can be postponed to a later design stage rather being a key component of energy analysis in early design stage. This study also illustrated the significance of geometrical variables' relative importance in this urban configuration. Although, height gets more attention from building regulations and decision makers, but WWR has been proven to have a greater impact on the building cooling consumption in this case study. Furthermore, the built area ratio has more impact than height, which have more impact on cooling consumption of midrise residential buildings than orientation of the configuration.

There is still a need for further studies on geometrical variables and their effect on energy consumption and its relationship with daylighting in different climatic conditions, material parameters and geometrical contexts. Although, there are tools that can conduct comprehensive energy analysis, there is more to be done to develop optimized tools for early stage design analysis on urban scale.

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