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Holistic sensitivity analysis on urban geometry and its effect on building performance in hot arid zones

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Abstract

There is a need to assess the growth of urban communities through analytical frameworks that have a multi-objective and holistic approach. In this paper, a sensitivity analysis was conducted on urban geometry with a holistic and integrative approach 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 that analyse urban geometrical variables are available in commonly used parametric design software. This study analysed urban geometrical variables such as (height, built area ratios, orientation and window to wall ratio). In addition, it gives an insight into the buildings' inter-shadowing effect by adding the context buildings' built area ratio in the tested grid. Furthermore, the study includes daylighting sensitivity analysis by changing the lighting control systems. Two sets of materials were used to refine the results for the study conducted for the city of Aswan in Egypt which has a hot arid climate. Additionally, the study investigated the effect of changing lighting controls (standard ON/OFF controls vs. dimmers) on cooling energy consumption. Using the Daylight autonomy results to change the lighting schedules of the tested energy zones is time-consuming, suggesting that the daylighting distribution is better suited for later design stages rather than being a key component of energy analysis in early design stages. The geometrical variables' relative importance on energy performance on the energy deman for cooling of mid-rise residential buildings in hot arid zone urban configuration are as follows: Window-to-wall ratio (WWR); built area ratios; heights; and finally orientation. The results of this study show the need for a staged approach to early stage design with increasing simulation complexity as the design develops. This can be achieved in a single environment where simulation components are carefully combined.

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

Introduction

The world urbanization is expected to continue its growth for at least the next 10 years. As it is stated by UNFPA 2007 report. *"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 are the fastest global rates (Martine and Marshall, 2007). In addition, Green House Gasses (GHG) emissions are increasing Africa's temperature because it has more than the world average of GHG emissions especially in the Sahara area. (Field *et al.*, 2014). Furthermore, one of the least populated areas are located in northern Africa (Food and Agriculture Organization and World Bank population estimates., 2015). The built environment industry sector accounts for a third of the global energy consumption and generates 20% of man-made GHG emissions worldwide (World Business Council for Sustainable Development (WBCSD), 2015). This is why there is a need for energy efficiency measures to be taken regarding building performance and urban energy assessment targeting a new climate-responsive built environment.

The early design stage has gained a lot of attention recently especially in the area of urban sustainable simulation and optimization with regard to energy consumption. Urban geometry is formed by various elements each of which play a role in not only shaping the urban geometry but also affecting the microclimate on different scales of built environment.

The variation of these geometrical elements empowered the ability of using a parametric design approach in studying this relationship between urban geometry and energy consumption in the built environment.

Parametric design can be defined as the manipulation of different associated parameters to shape a form (Monedero, 2000). Thus, parametric urban design can be represented as a group of arranged buildings and urban geometrical variables that are shaped by scripted algorithms. This interpretation provides a different vision and capability for investigating urban design, geometry and performance (Schumacher, 2009a, 2009b). It has made urban design more interactive and responsive with good visualization outputs for either the design layout or its analytical data. The literature shows that there are different approaches to modelling and simulation at an urban scale (Hosney Lila and Lannon, 2017). The geometric variables tested for these studies included height, scale, orientation, urban voids, etc. In addition to variables, the aspects simulated in building performance were also covered in many ways. Some studies focused on a single aspect simulation such as energy-only simulations while others tried to combine two or or more aspects of building performance such as studying the relationship between lighting performance and energy consumption and vice versa, or adding computational fluid dynamics (CFD) to the formula (Panão *et al.*, 2008; Bassett *et al.*, 2012; Dogan, Reinhart and Michalatos, 2012; Jones *et al.*, 2013; Sabry *et al.*, 2014; Trigaux, Allacker and Troyer, 2014; Taleghani *et al.*, 2015; Trigaux *et al.*, 2015; Nault, Rey and Andersen, 2016).

In regard to the tools used in these studies, there is a continuous development to help designers and architects conduct performance simulation and optimization at an urban scale. These tools are built using different approaches to provide a variety of functionality needed for each simulation or optimization study. Some tools are standalone software that carry out modelling, simulation and visualization tasks while others form a full suite designed only for simulation and optimization processes (© ENVI-MET GmbH *et al.*, 2016; U.S. Department of Energy's (DOE), 2016; Simulation Research Group, 2017). Yet other tools are mainly plug-ins that provide a link between simulation engines, that carry out the calculations, and modelling platforms. This link enables designers to visualise and analyse their results within the same software suites they are using to model their projects (Lagios, Niemasz and Reinhart F, 2010; Jakubiec and Reinhart, 2011; Reinhart *et al.*, 2013; Fonseca *et al.*, 2016; Reinhart, 2017). Other tools widened this spectrum of integrative simulation by creating open-source software for comprehensive modelling simulation (Sadeghipour and Pak, 2013). Adding to to the mix, some studies have merged evolutionary solvers also known as genetic algorithms to the process of optimization (Rutten, 2013; Naboni, 2014; Yi and Kim, 2015; Calcerano and Martinelli, 2016).

The literature illustrates the potential of analysis tools and the usefulness of their integrative parametric approach. However, only a limited number of studies have investigated this holistic approach using these tools and explored the relative importance of the basic geometrical variables on energy consumption and thermal performance of the built environment at an urban scale. One of the recent tools that enabled more interaction with this holistic approach is the ladybug tools package (Sadeghipour and Pak, 2013). This package of tools covers different aspects of the built environment performance and at different scales. Also, it is based on the Rhinoceros/Grasshopper parametric modelling platform (McNeel, 2014; Scott Davidson, 2017). This study was conducted using these tools to add daylight illuminance sensitivity to the modelling of energy consumption for thermal comfort in residential context.

Objective

This study aims to investigate the limits and opportunities of a framework for conducting a holistic analysis with ladybug tools, and to run a sensitivity analysis for geometrical variables.

The research quantified the effect of each geometrical variable on thermal performance and the change of consumption patterns due to the change in these variables on the energy consumption used in cooling and heating in hot arid zones. Furthermore, the study explored the correlation between lighting performance and controls and their effect on energy consumption and looked for more verification for this relationship by using standard recommended materials.

Methodology

This study is a part of an ongoing research about holistic approach of optimization on neighbourhood scale. It looks into framing the impact of different urban geometrical variables besides investigating the relationship between thermal balancing energy consumption and the consideration of lighting control systems. Understanding this relationship will provide better recognition of built environment performance and its simulation. For this simulation, the dependant parameters is the urban geometrical variables while the energy performance outcome acts as the independent parameters.

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

Geometrical parameters & thermal settings

The sensitivity analysis was conducted on a nine-building grid in a simple urban configuration as shown in figure (2). The building in the middle of that configuration was analysed with the other 8 buildings acting as a typical context. The grid cell size is 23 by 23 metre as representation of the common size of land size in Egypt (El-deep, El-Zafarany and Sheriff, 2012) with building areas varies from 50% to 90% of each cell's area with a 10% differentiation for each group. In addition to scale, the height was a feature of geometrical variation in the study. Buildings' heights varied between 3.5 metres and 24.5 metres with variation of a 3.5 floor for each group. Moreover, the whole configuration is rotated by 45 degrees creating two groups. The analysed building has a 30% core-to-perimeter ratio. EnergyPlus(U.S. Department of Energy's (DOE), 2016) *midrise apartment zone programs* were chosen for the building zones with *apartment programs* for the perimeter zones and *corridor programs* for the core zones (Figure 1 and 2). All zones are conditioned with the default set of ideal air loads system for Heating, Ventilation and Air Conditioning (HVAC). This is an hourly energy simulation with a 10 minutes time step. The simulation studied zone energy use and zone gains and losses as an output. The cooling loads are calculated from the sum of sensible and latent heat that must be removed from each zone as the HVAC is assigned to the default Ideal Air Loads.

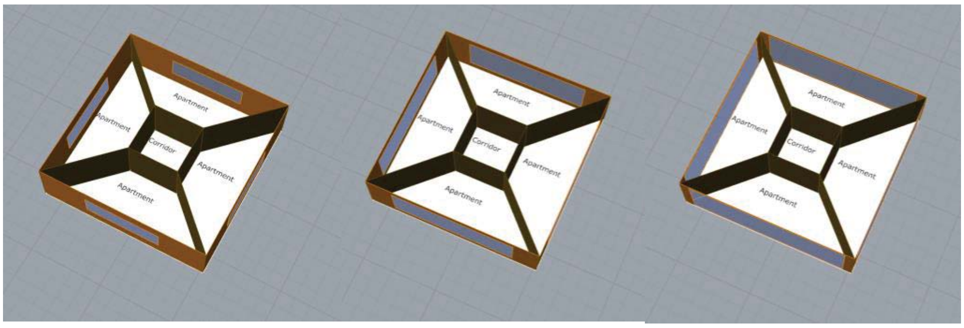

Figure 1. One floor example of different window to wall ratios and core to perimeter split and the programs assigned to different zones

Finally, the case study building has a fixed window to wall ratio for its 4 directions facades. The window to wall ratios (WWR) varied between 20%, 50% and 80% with. These variables are shown in Table 1.

Table 1. Geometrical parameters for the case study.

Geometrical Variables							
Height (metres)	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					

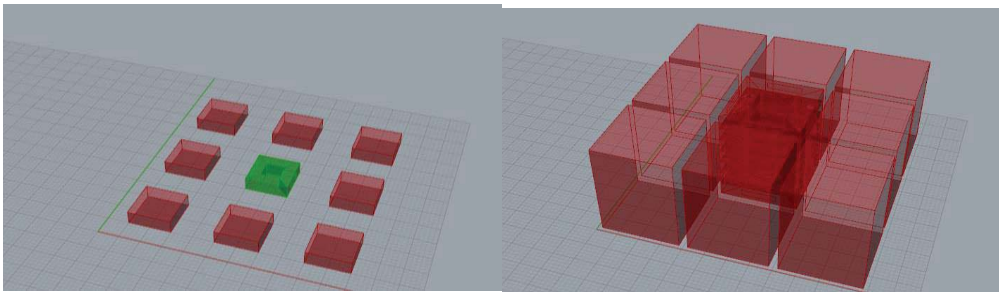

Figure 2. The tested geometrical model's examples. To the left: the first case for 20% WWR and 0 degrees' rotation with one 3.5 metres height floor and 50% built area of each grid cell. To the right: the last case in the same group (20% WWR & 0 degrees' rotation) with 7 floors, 24.5 metres total height and 90% built area.

Daylighting analysis settings:

The main goal of combining daylight illuminance in the study was to try to reach a balance between the energy consumed for thermal comfort and lighting energy consumptionof the zones. As with some of the dense configurations caused very little sun penetration which was very beneficial to the cooling energy consumption but on the other hand there was a need to know the effect this might have on lighting consumption.

For annual daylight analysis, each zone was divided into a mesh of 0.6 metre cells with one sensor point in its centre at 0.7 metre height from the floor. The lighting control system is auto dimming with switch off occupancy sensor with 300 lux target illuminance for each zone.

This algorithm cross-matched these geometrical variables, producing 210 different iterations. Thus, 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 window to wall ratios (20%, 50% and 80%) with the full original variations of heights and building's scales. The total number of iterations was carried out twice: One run was conducted with basic on/off lighting controls and the other run was conducted with dimming lighting controls based on annual daylighting profiles as mentioned earlier as shown in figure (3).

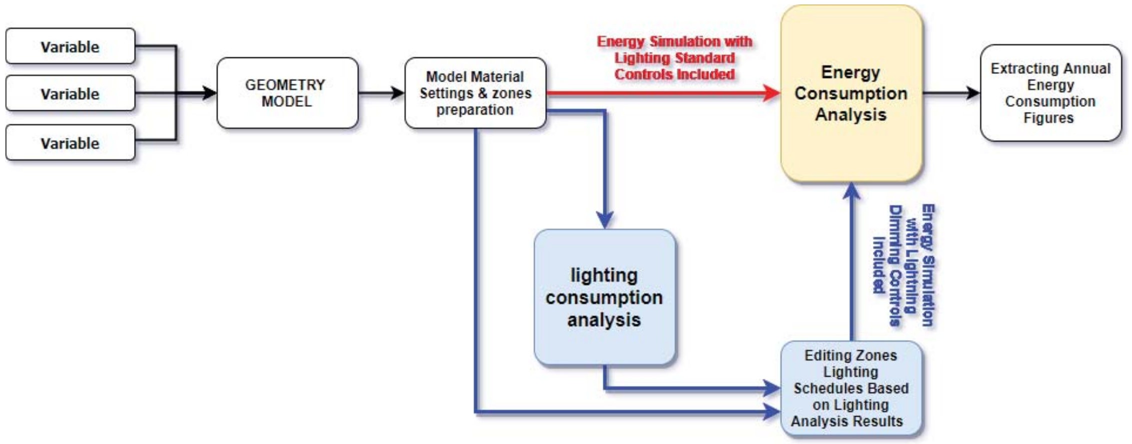

Figure (3) . Simulation methodology between the types of lighting control systems

Material parameters:

The study was then repeated twice with two different material settings. The first phase had all the afore-mentioned settings with literature review based material parameters, while the second phase used ASHREA 90.1-2010 (ANSI/ASHRAE/IESNA, 2010) material recommendation for the climate zone of the study as it was embedded in Energy Plus library for climate zone materials. For the first phase, The used material palette was adjusted based on studies conducted in the same geographical context (El-deep, El-Zafarany and Sheriff, 2012; Attia and Evrard, 2013). The material properties were fixed for all the iterations and designed based on 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 for both first & second phase.

FIRST PHASE MATERIALS			**SECOND PHASE MATERIALS**		
name	materials	U-Value	name	materials	U-Value
External Wall	• CEMENT PLASTER • BRICK (EXPOSED) • CEMENT PLASTER	3.10	ASHRAE 90.1-2010 EXTWALL MASS CLIMATEZONE 1	• 1IN Stucco • 8IN CONCRETE HW RefBldg • 1/2IN Gypsum	3.69
Internal Wall	• CEMENT PLASTER • BRICK INTERIOR (EXPOSED) • CEMENT PLASTER	5.29	INTERIOR WALL	• G01a 19mm gypsum board • F04 Wall air space resistance • G01a 19mm gypsum board	2.58
Internal Floor	• CERAMIC-FLOOR-TILES • CEMENT-MORTAR(MOIST) • CONCRETE CAST(HEAVYWEIGHT) • GYPSUM-PLASTER	1.43	INTERIOR FLOOR	• F16 Acoustic tile • F05 Ceiling air space resistance • M11 100mm lightweight concrete	1.44
External Roof	• CEMENT-MORTAR(MOIST) • EXPANDED POLYSTYRENE (EPS) • CONCRETE, CAST (HEAVYWEIGHT)	0.36	ASHRAE 90.1-2010 EXTROOF IEAD CLIMATEZONE 1	• Roof Membrane • IEAD Roof Insulation R-14.76 IP • Metal Decking	0.376
Window	• CLEAR GLASS 12MM	75	ASHRAE 90.1-2010 EXTWINDOW NONMETAL CLIMATEZONE 1	• Fixed Window 5.84/0.25/0.11	5.84

As for the second phase, ASHREA 90.1-2010 standard set materials were used for the envelop materials and for the adiabatic walls and floors the default material set offered by the ladybug tools.

Results

Show case:

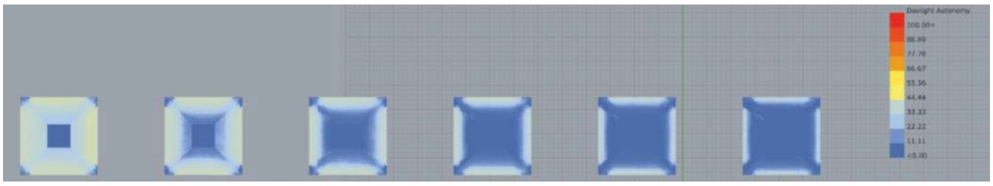

Figure (4). Daylight autonomy results illustration for 0 degrees rotation, 50% WWR, 6 floors height and 70% built area ratio showing the results of different zones. The floors order begins with the ground floor on the right up to the 5th floor on the left end

The results for each case was built to contain results for energy consumption aspects and daylighting results. This is shown in the example illustrated in Figures 4 and 5. The group results are summed up for each case. The example shown for illustration is an intermediate case with 0 degrees' rotation, 50% WWR, 6 floors height and 70% built area ratio.

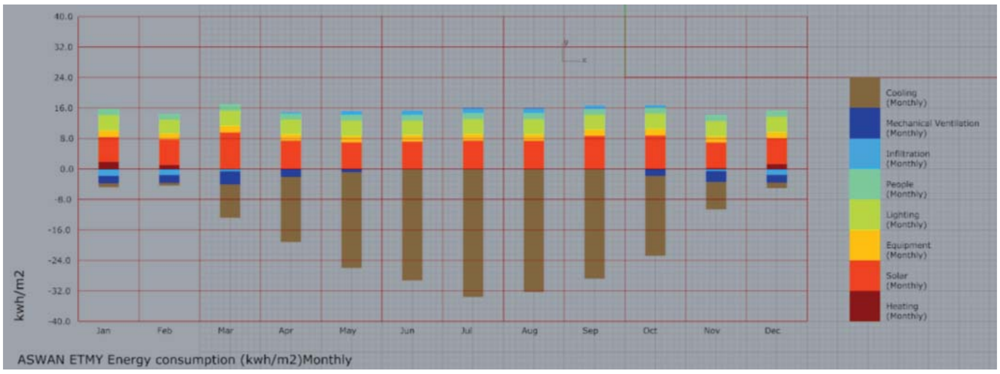

Figure (5). Total monthly consumption comparison for different aspects for the mentioned case in kWh/m^2

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 all the runs so it lacked significance to be added to the current study results as the cooling results have a much larger variance. The 6 groups are categorized by rotation angle and WWR for each with full heights and scale ranges as mentioned earlier. The categories are shown in Table 3.

Table 3. Groups' categories

Group name	Rotation angle	WWR
A1	0	20%
A2	0	50%
A3	0	80%
B1	45	20%
B2	45	50%
B3	45	80%

General lighting results remarks

The initial observation shows a direct effect on daylighting autonomy distribution in the first phase of the simulation. After the direct effect of WWR the scale and the context proximity also show a significant effect especially in the lower floors in the higher cases which leads to a rise in energy lighting consumption. It is important to mention that in the same case there are no significant differences in lighting consumption per metre square either in the different floors or in the 5 different zones within the same floor. As for cooling consumption, the pattern of does not have the same baseline of applying the on/off controls as the one existed for lighting so it will be included in the groups' results discussions. The change of material in the second phase of the simulation did not change these patterns due to the lack of shading geometries, and the low number of bounces set by default in the analysis tool.

Lighting results and its pattern of change due to the variation of geometrical variables were discussed in detail for the first phase of the study in previous publication (Hosney Lila and Lannon, 2017). One of the significant results in that publication was the linear correlation in cooling consumption patterns when compared between the two lighting controls settings. As previously described, lighting analysis results were used to change the occupancy schedule for the energy consumption zones to look for the optimal balance between lighting and energy performance. This caused a significant change in results between the cooling consumption with the use of dimming lighting controls and the same consumption values when standard On/Off lighting controls where assigned. In the second phase of the study with

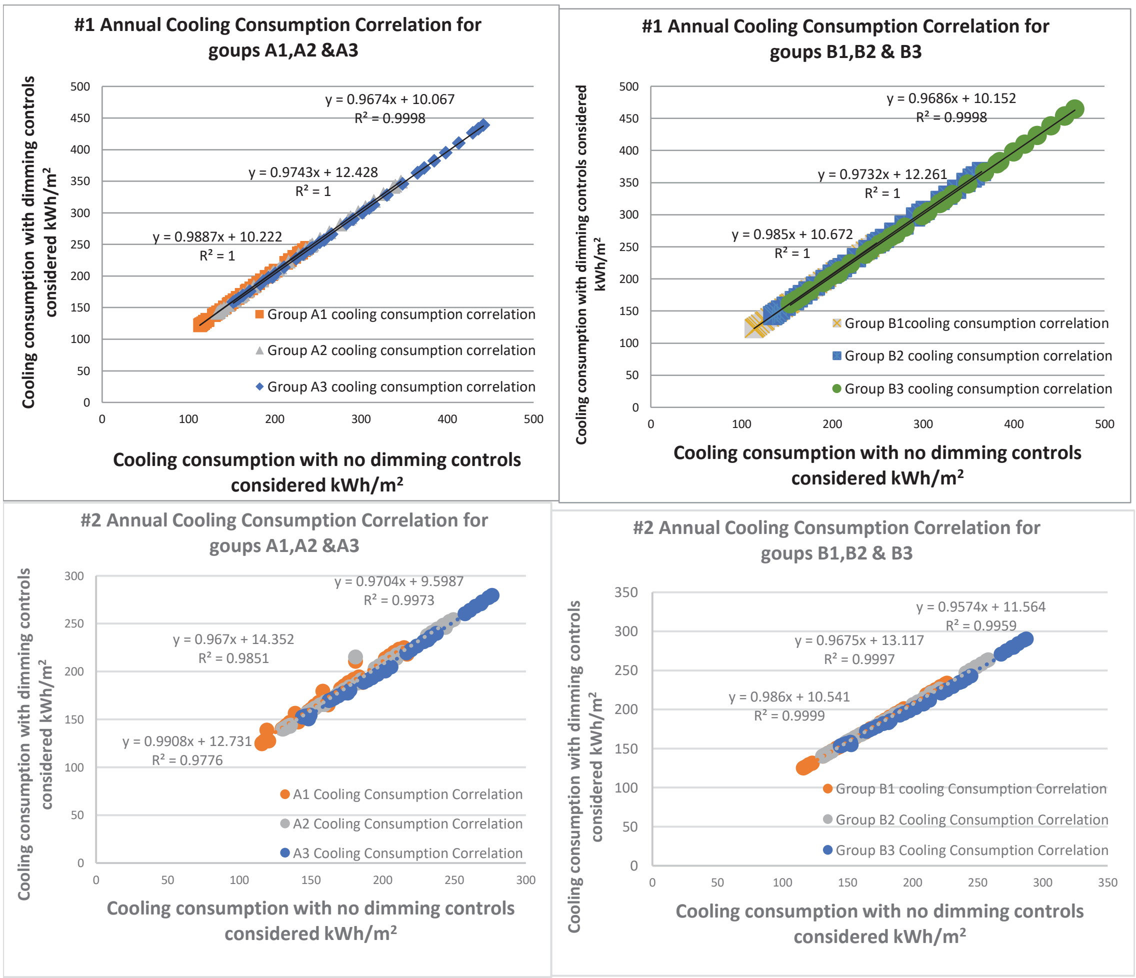

Figure 6 : (#1) indicates that the figure belongs to phase one of the study. to the left, annual cooling consumption comparison between dimming & no dimming lighting controls considered for groups A1,A2 & A3. to the right, annual cooling consumption comparison between dimming & no dimming lighting controls considered for groups B1,B2 & B3. (#2) indicates that the figure belongs to phase one of the study. to the left, annual cooling consumption comparison between dimming & no dimming lighting controls considered for groups A1,A2 & A3. to the right, annual cooling consumption comparison between dimming & no dimming lighting controls considered for groups B1,B2 & B3.

the change of material and the use of standardised materials, the correlation is not changed as it is shown in Figure 6. It is important to mention that changing the scale of the land plots will not affect this correlation due to the fixed core-to-perimeter ratio.

Variables relative importance

Heights:

In the conducted study, there were 7 height variations. 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 in both phases. It could be said that this is due to the arid conditions of the specified zone. A comparison of the calculations of the extremities (highest and lowest blocks) showed that there is an 18 % difference in cooling consumption for the first phase of the study and nearly 4% for the second phase (Figure 7).

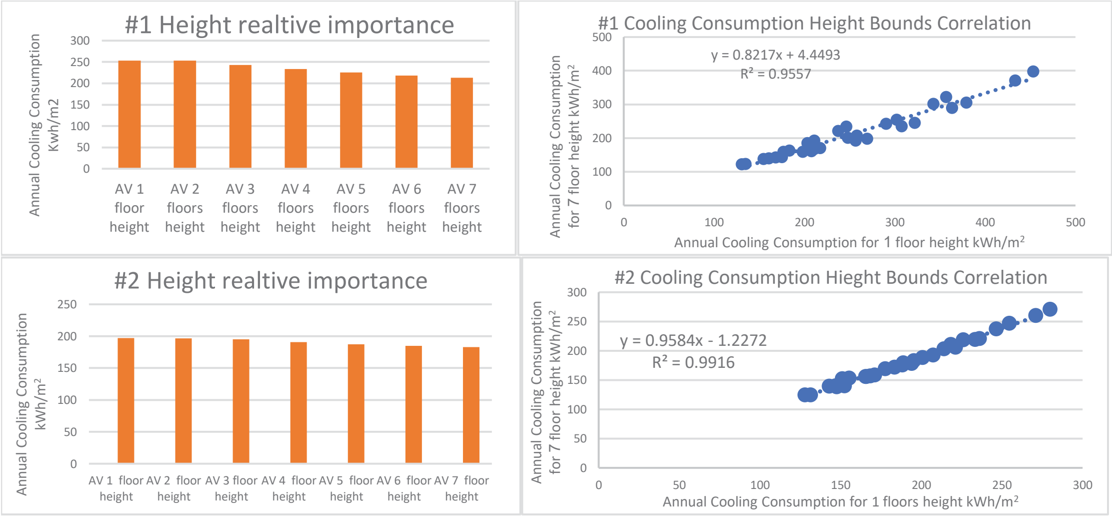

Figure 7. (#1) To the left: height variations' cooling consumption average comparison in kWh/m^2, to the right: height variations' bound correlated in kWh/m^2, (#2) To the left: height variations' cooling consumption average comparison in kWh/m^2, to the right: height variations' bound correlated in kWh/m^2

Built area ratio:

As mentioned before there were 5 built area ratio variations. The results imply that there was further change in the energy cooling consumption within the building. The study shows that the relationship between built area ratio and energy cooling consumption is a clear negative correlation as the denser the configuration the more prevention to sun penetration to the buildings. Therefore, cooling consumption is reduced heavily as shown in Figure 7. A comparison of the calculations of the bounds (most and least dense group configurations) showed that there is a 72 % difference in cooling consumption for the first phase and with the change of material for the second phase the difference reaches 54% of change between the bounds of the 5 groups (Figure 8).

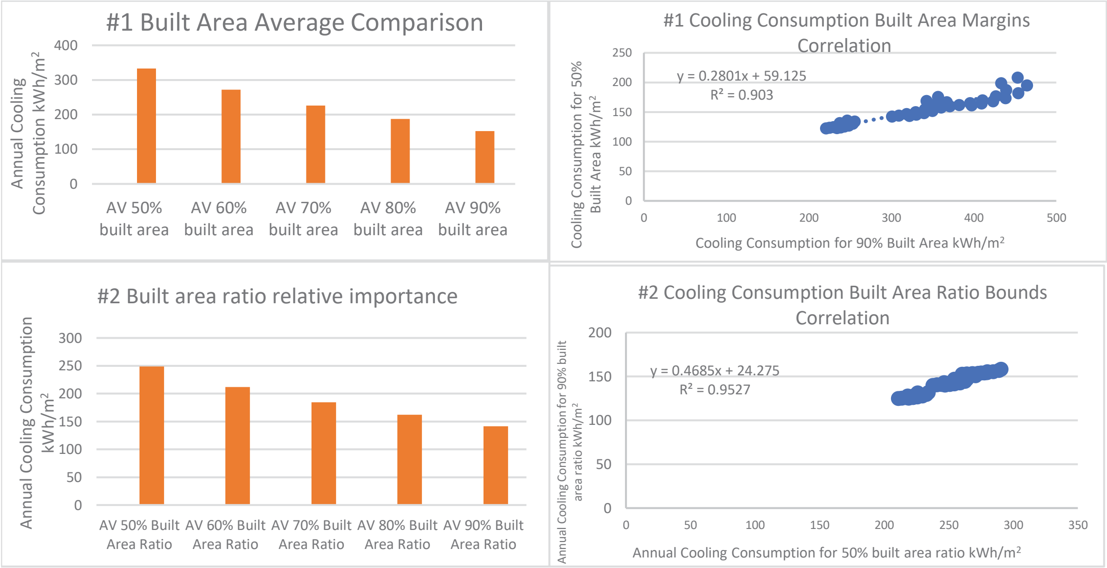

Figure 8. (#1) To the left: built area ratio variations' cooling consumption average comparison in kWh/m^2, to the right: built area ratio variations' bound correlated in kWh/m^2 for the first phase, (#2) To the left: built area ratio variations' cooling consumption average comparison in kWh/m^2, to the right: built area ratio variations' bound correlated in kWh/m^2 for the second phase

WWR:

For WWR variations, the relationship with energy cooling consumption for the first phase is a positive correlation that becomes less steady when in the second phase. This is can be caused by the climate zone chosen for the study. The difference in the energy cooling consumption is larger than what was shown for heights but still less than what is shown for built area ratios effect. The comparison between these variable limitations indicates that there is almost 66 % difference in cooling consumption for the first phase. But for the second phase this number decreases to 22% difference in consumption (Figure 9).

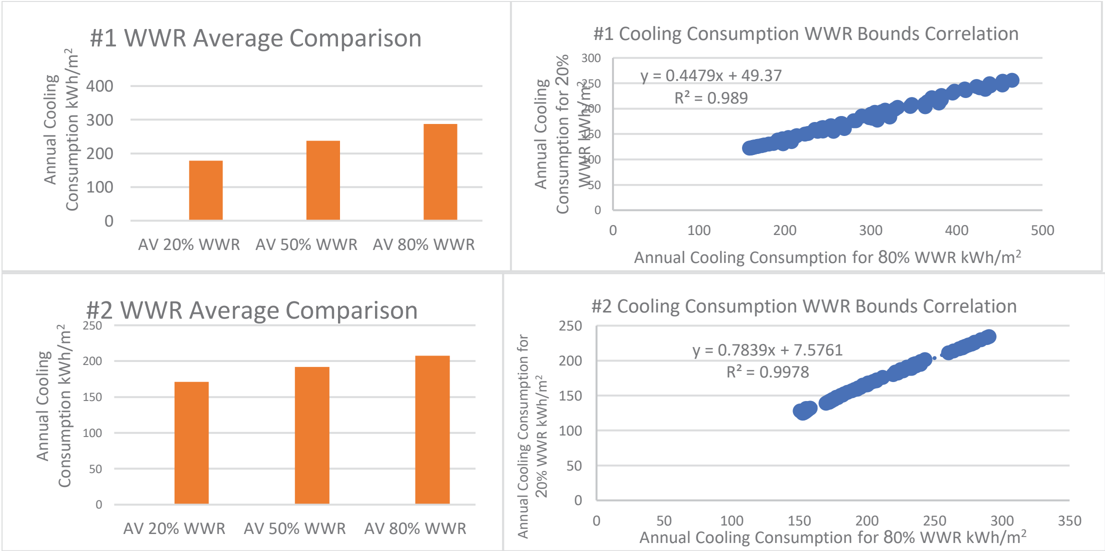

Figure 9. (#1) To the left: WWR variations' cooling consumption average comparison in kWh/m^2, to the right: WWR variations' bound correlated in kWh/m^2, (#2) To the left: WWR variations' cooling consumption average comparison in kWh/m^2, to the right: WWR variations' bound correlated in kWh/m^2

Orientation:

There is a slight positive correlation for this variable, according to the results. Comparing the two variations for both phases, it can be argued that there is an 8% of energy cooling consumption difference that exists between the 2 different angels for the first phase while, for the second phase, it decreases to 6% difference in consumption between the two different angle groups (Figure 10).

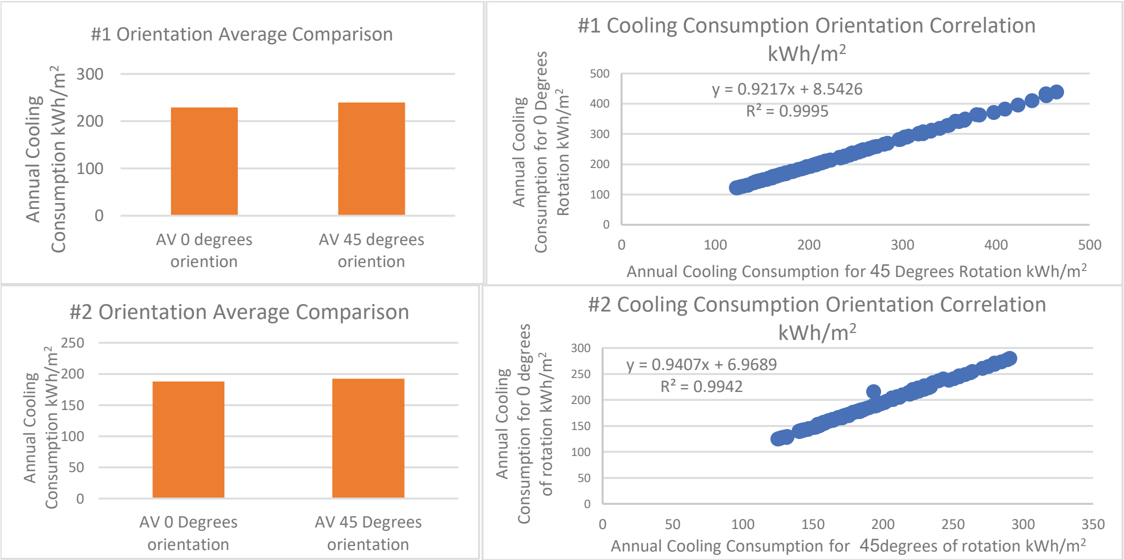

Figure 10. (#1) To the left: orientation variations' cooling consumption average comparison in kWh/m^2, to the right: orientation variations' bound correlated in kWh/m^2, (#2) To the left: orientation variations' cooling consumption average comparison in kWh/m^2, to the right: orientation variations' bound correlated in kWh/m^2

Conclusion

In addition to conducting a holistic analysis of geometrical variation and its effect on energy performance, this study used two sets of materials to assure the results of this sensitivity analysis and the variables' relative importance to energy consumption.

The results show that the thermal energy consumption has not significantly changed due to integrating the lighting control system variations to change the energy zones occupancy settings. With variation between 2%-5% change in cooling consumption correlation between using dimming in lighting control systems and using standard on/Off lighting controls, it can be argued that it is wise to delay the lighting analysis to a later stage of design specially if it is similar to the setting of this study model and limited to geometrical variables. It is important to note that the comprehensiveness of the capabilities of the Ladybug tools is still constrained by time limits when it comes to brute-force multi-iteration sensitivity analysis such as the ones used in this study. Merging different aspects of environmental building performance in the same platform and same study needs better optimized frameworks to enable this approach in the early design stage. Furthermore, this study quantified the relative importance of each of the studied geometrical variables and their effect on energy consumption in hot arid zones. Built area ratio was found to have the most significant impact on energy consumption for thermal performance while WWR followed the effect of Built area ratio in both phases of the study. Height variation was found to have a larger effect than Orientation on cooling energy consumption for midrise residential buildings in hot arid zones. The change of material settings between the two phases changed the values and pattern of energy consumption results but still assured the lighting controls minimal effect on energy consumption and the relative importance of these variables in hot arid zones climatic conditions.

Further investigation is still needed regarding the relationship between geometrical variables and energy consumption and the integration of daylighting in different climatic conditions, material parameters and geometrical contexts. Although there are tools that can conduct comprehensive energy analysis, their capabilities regarding multi-iteration simulations are limited.

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