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A Preliminary Simulation Study of the Impact of Building Typology on Cooling Loads and Outdoor Thermal Comfort Potential in the Tropical Context

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ABSTRACT

The tropical climate is characterized by high level of solar radiation and high outdoor temperature and relative humidity throughout the whole year with little seasonal variation. Therefore, how to minimize energy use for air-conditioning to maintain indoor comfort and how to optimize thermal comfort for outdoor spaces through architectural and urban design are crucial questions relevant to the mitigation of Urban Heat Island and the creation of sustainable city in general. This study investigates the relationship between building typology, building energy consumption and outdoor thermal comfort under a fixed density in the tropical context. Specifically, the study aims to examine the implications of different residential building typologies within in a homogeneous urban context on building cooling loads and outdoor thermal comfort potential. The implications of the findings to passive design strategies in early stage of architectural and urban design lies in that building form typology has significant impact in energy use and outdoor thermal environment especially in tropical climatic context for which reducing cooling loads and enhancing outdoor comfort are the primary concerns.

Keywords: building typology, urban form, environmental performance, UHI, Energy Use Intensity, thermal comfort, compacity, clustering, Sky View Factor, solar radiation

1. INTRODUCTION

The tropical climate is characterized by high level of solar radiation and high outdoor temperature and relative humidity throughout the whole year with little seasonal variation. Therefore, how to minimize energy use for air-conditioning to maintain appropriate indoor comfort and how to optimize thermal comfort for outdoor spaces through architectural and urban design are crucial questions relevant to the mitigation of Urban Heat Island and the creation of sustainable city in general, especially in the early stage of urban planning and urban design when architectural details are not developed, users groups and their behavioral patterns are not known, and Heating Ventilation and Air Conditioning (HVAC) technologies potentially applicable are not specified yet.

This study investigates the relationship between building typology, building energy consumption and outdoor thermal environment under a given density in the tropical context. Specifically, the study examines through simulation the implications of different residential building typologies within in a homogeneous urban context on energy consumption related to building cooling loads and outdoor thermal comfort. The research questions to address include: 1) How to quantify the geometric characteristics of various building form typologies that are not captured by commonly used geometric variables? 2) What are the key geometric factors that have significant impacts on building cooling loads and outdoor comfort in the tropical context? 3) What are the design implications of the findings?

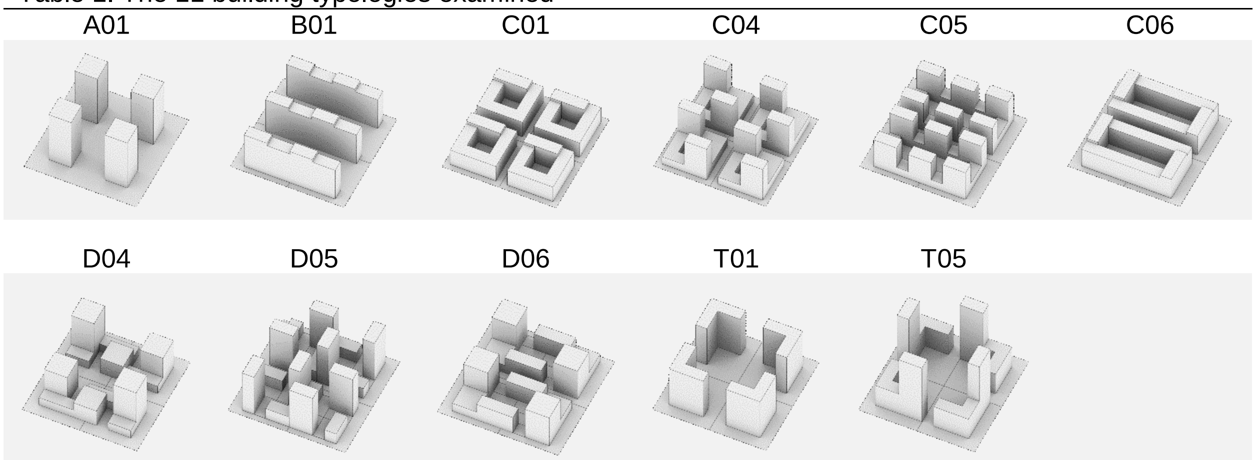
2. METHOD

2.1 Building Typologies

Eleven generic residential building typologies were selected for this experimental study, each representing a typical building form or one of its variations, such as high-rise tower block (A01), parallel slab block (B01), compact courtyard block (C01), perimeter block (C06 and T01), and several hybrid typologies derived from the above forms that are composed of a mixture of low-rise, medium-rise and high-rise blocks in different spatial configurations (C04, C05, D04, D05, T05). The purpose is to capture the geometric and spatial diversity of urban forms.

The typologies were generated with the same built density of a Floor Area Ratio (FAR) of 3 or close to it within the center of the same square-shape site (100mX100m) with equal setbacks to parallel edges of the site. This is to ensure that the building density and site area are controlled across different typologies which represent realistic medium density development in urban design.

Table 1. The 11 building typologies examined



A surrounding environment was generated for each building typology by replicating itself in a 3x3 matrix pattern with spacing between adjacent plots being 20m, the width of a typical neighborhood road. This is to create a homogenous urban context for each typology that is composed of the same building form, in the same built density and with equal spacing between plots. It is in this homogenous context the theoretical environmental performance of a given urban form typology is thus evaluated, i.e. the performance of a building form supposing it is applied uniformly to compose an entire urban district (Martin & March, 1972; Hii et al., 2011; Zhang et al., 2012). The buildings surrounding the one positioned in the center of the 3x3 matrix layout were specified as shading surfaces to emulate the urban obstructions for the center building whose energy performance wass evaluated. The geometries of the typologies examined and their respective homogenous context were modelled in Rhinoceros3D, and they were further processed by several plugins for Rhinoceros3D and the procedural modeling software Houdini[1] for simulation and performance evaluation.

[1] http://www.sidefx.com/

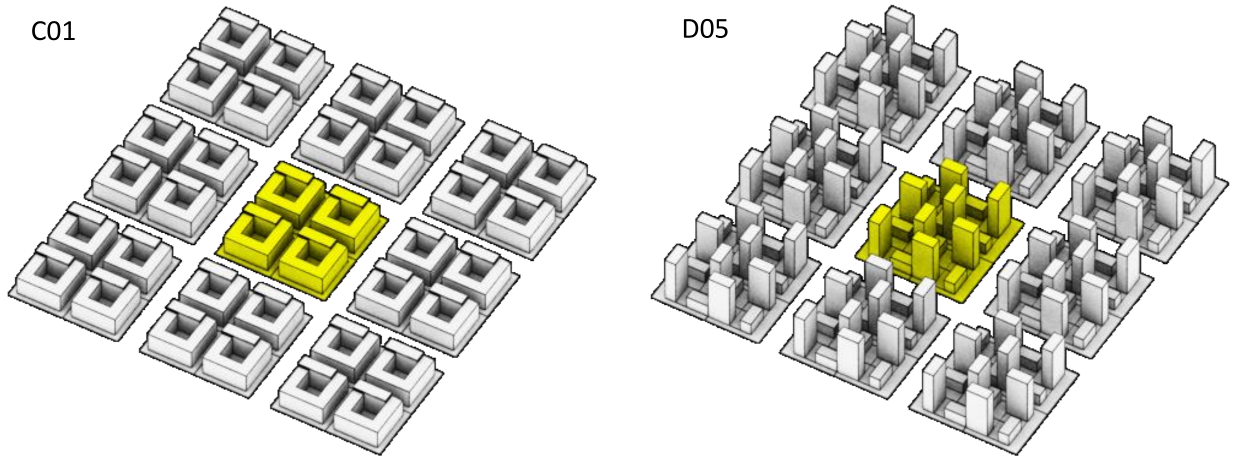


Figure 1. Examples of the theoretically homogenous study context created for a given typology

2.2 Performance Evaluation

A workflow was built using several sets of parametric modeling and environmental analysis plugins for Rhinoceros3D (v.5), i.e. Grasshopper, Ladybug and Honeybee[2], for energy consumption and façade solar radiation simulation.

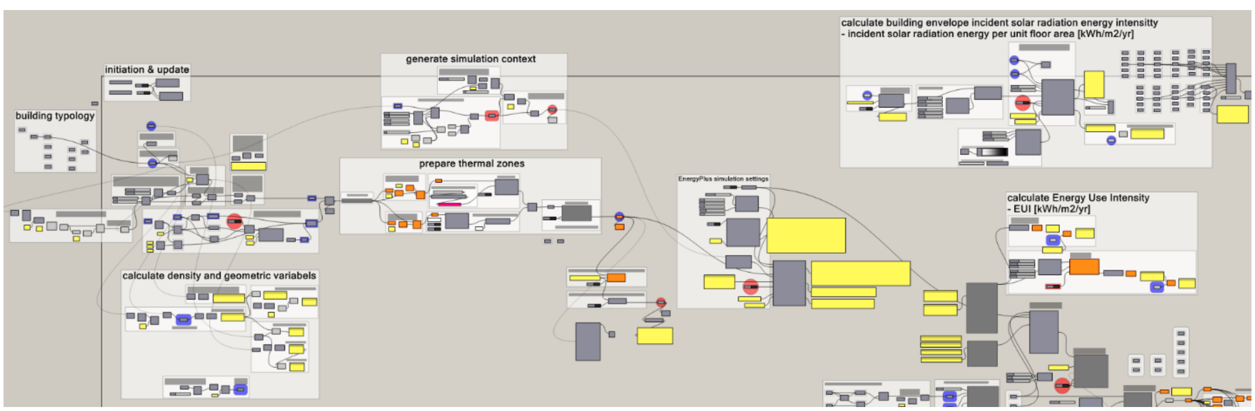


Figure 2. Workflow created for energy and solar radiation simulation using the Ladybug and Honeybee environmental analysis libraries in Rhinoceros3D+Grasshopper

For energy simulation, the building massing of each typology at the center of the 3x3 array was divided into thermal zones by a fixed floor-to-floor height of 3m with the surrounding buildings defined as shading surfaces. A typical residential apartment building program and zone program were assigned to all thermal zones under the premises that each zone is air-conditioned (setpoint=24°C) through an Ideal Loads Air System and has the same internal loads in terms of people, lights and electric equipment, and all typologies have the same building material settings. No glazing surfaces are specified so as to eliminate the impact of heat gain/loss through windows. This is to ensure that the each typology has the same internal heat gain intensity, and the difference in energy use intensity in terms of cooling loads will be primarily the results of external heat gain through building envelope in relation to the geometric characteristics of building form.

[2] http://www.grasshopper3d.com/group/ladybug

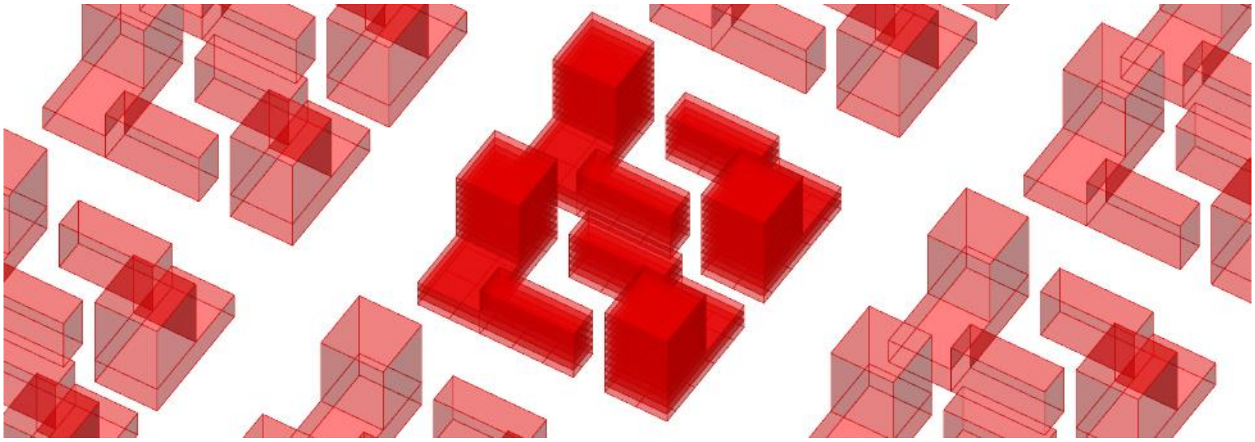


Figure 3. Example of the thermal zones and contextual shading geometries for a given typology

Annual cooling loads simulation was then conducted separately for each form in EnergyPlus (v.8.3) using Singapore's weather file in EPW format, and the resulting Energy Use Intensity (EUI), i.e. the annual total building energy use per unit floor area [kWh/m2/year], was retrieved as energy performance indicator in terms of cooling for each typology.

Solar radiation heat gain through building envelope is one of the major factor affecting cooling loads in Tropical context. The solar radiation incident on building surfaces was simulated by using a cumulative sky that merges annual hourly solar radiation into one accumulated sky radiance description. The variable "annual total building envelope solar radiation per unit floor area" was calculated for each typology accordingly as the indicator of solar radiation incident intensity.

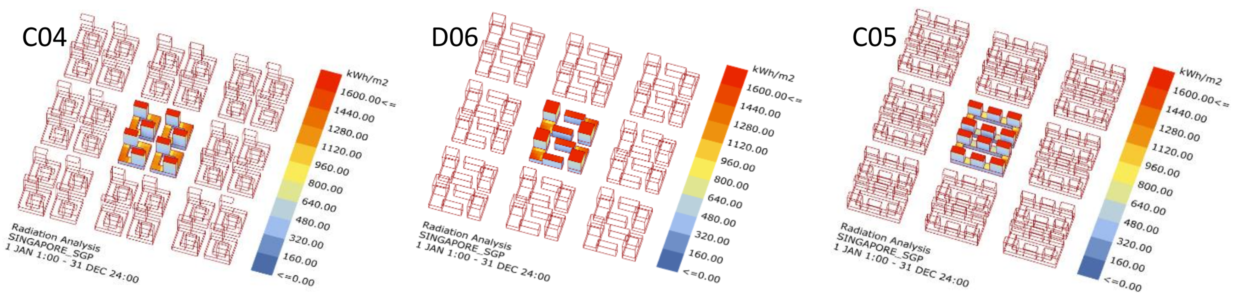


Figure 4. Visualization of building envelope annual solar radiation simulation

Sky View Factor (SVF), defined as the ratio of radiation received by a particular urban surface within an urban context to that received from unobstructed sky hemisphere, is an import parameter in urban studies on Urban Heat Island effect (Watson & Johnson, 1987). Previous studies suggest that increase of SVF is related to decrease of air temperature and mean radiant temperature, and therefore, potentially improving outdoor thermal comfort (Yuan & Chen, 2011; Wang & Akbari, 2014).

"Outdoor area-weighted average Sky View Factor" was calculated for the outdoor open spaces within site boundary at 2m height above ground for each typology as an indicator of outdoor thermal comfort potential. A workflow was created in the Houdini software (v.15) which subdivides the outdoor area into small patches of 1mX1m and the Sky View Factor was simulated by performing a radiation simulation through Radiance (v.5)[3] at the centroid of each patch.

[3] http://radiance-online.org/

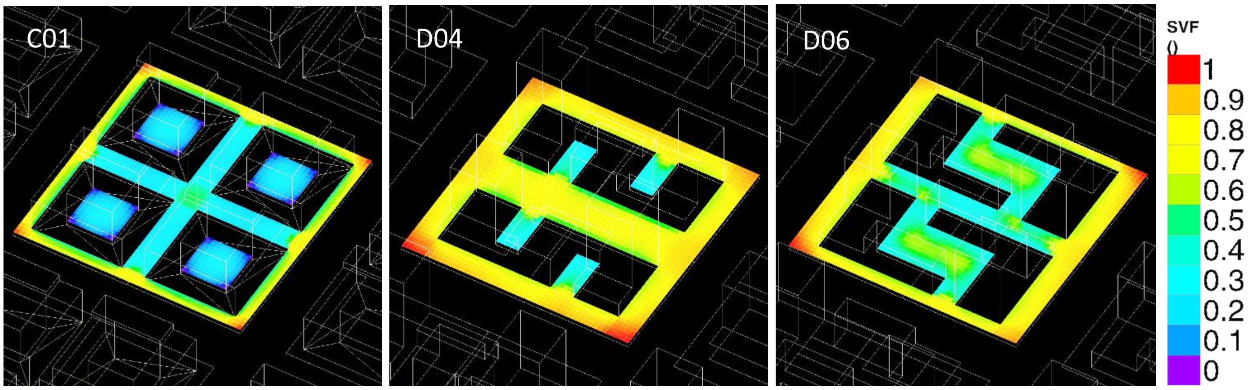


Figure 5. Visualization of SVF simulated for outdoor open spaces at 2m above ground

2.3 Geometric variables

Other than site coverage which is a planning parameter frequently used in urban scale environmental analysis, compacity was also calculated for each typology, which is the ratio of building envelope area to building volume and it is suggested to have significant implication on energy consumption on urban scale (Adolphe, 2001; Salat, 2009): the larger the compacity value, the higher the energy needs for heating in colder climates (Salate, 2009, p.601).

As indicated in a previous study (Zhang et al., 2015), compacity as a geometric variable has its limitation in differentiating different building forms and, consequently, their potential energy implications, in circumstance such as meso-scale urban analysis which involves more detailed examination of the environmental implications of relative spatial relationship between building massing volumes within an urban street block or residential precinct.

A geometric variable “clustering” was thus calculated for each typology, and a workflow was created to fill the building massing with evenly spaced points, each representing one unit building volume. The level of concentration of enclosed building volume is thus represented by the average distance between these points. The smaller the value of “clustering”, the closer spatially the different parts of a building form are to each other (Fig. 6a). Moreover, the calculation was extended to include the layer of buildings immediately around the one been examined within the homogeneous simulation context so as to take into account of the impact of the surrounding urban geometries (Fig. 6b). A clustering-weighted compacity was calculated thereafter for each typology as a composite geometric variable to quantify the spatial relationship between building volumes.

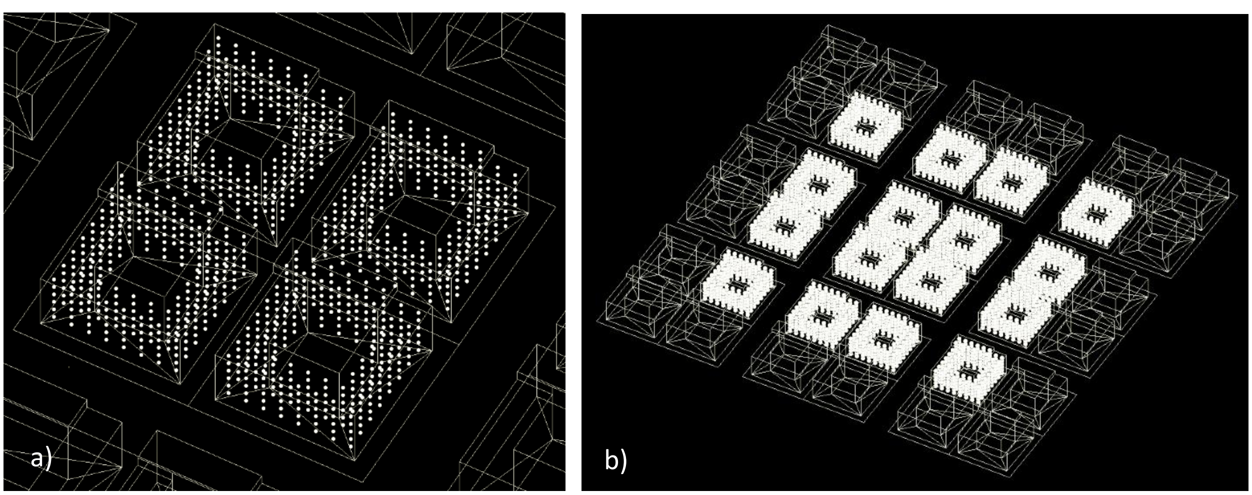


Figure 6. Visualization of the points for clustering calculation for building volumes within the site (a) and that of the buildings immediately around the site (b)

In addition, floor area normalized average building envelope Sky View Factor was calculated for each typology as a geometric variable to quantify the level of exposure to the sky of the building surfaces on average, considering the potentially strong relationship between SVF and radiation incident from sky (Fig. 7).

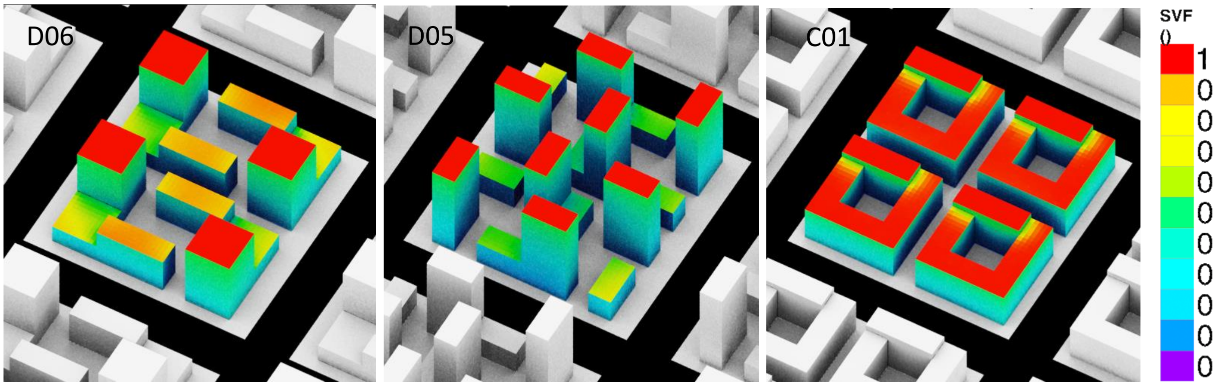


Figure 7. Visualization of SVF simulated for building envelope surfaces

3. RESULTS

Table 2 summarizes the key planning parameters, geometric variables, and performance indicators calculated for each of the 11 typologies.

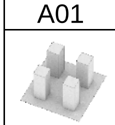
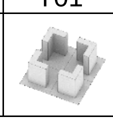
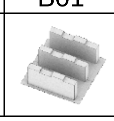
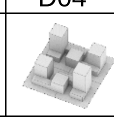
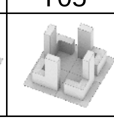
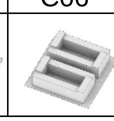
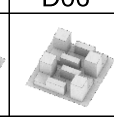
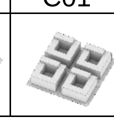
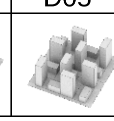
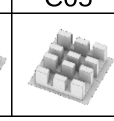
Table 2. Summary of key variables calculated for the 11 typologies

Typology	FAR	site coverage (%)	compacity	clustering (m)	clustering weighted compacity	envelope solar radiation per GFA [kWh/m2/year]	envelope SVF per GFA	EUI [kWh/m2/year]	outdoor area-weighted average SVF
A01	3.04	16	9.79	128.58	1258.77	356.91	24.57	141.31	0.533
B01	3	24	11.42	130.43	1489.51	403	28.12	144.56	0.474
C01	3	48	11.47	127.88	1466.74	493.77	31.91	147.79	0.386
C04	3.04	48	13.8	129.15	1782.21	500.46	32.22	150.34	0.404
C05	3.04	40	13.7	129.62	1775.74	465.76	30.46	149.21	0.422
C06	2.92	40	11.03	128.49	1417.20	468.22	30.69	146.65	0.434
D04	3.04	40	10.09	128.32	1294.79	414.21	27.40	145.41	0.54
D05	3.04	32	15.08	131.48	1982.67	455.82	30.08	148.78	0.406
D06	2.96	46	10.67	128.06	1366.35	461.08	29.89	147.37	0.479
T01	3	17	11.9	124.53	1481.94	411.07	27.60	144.44	0.473
T05	3.04	24	12.79	130.26	1666.01	428.19	28.85	146.05	0.447

3.1 Energy Use Intensity

The EUI of the worst typology (C04=150.34kWh/m2/year) is 6.4% higher than that of the best typology (A01=144.56kWh/m2/year). Three of the top five typologies performing the best are generic typologies (A01, T01 and B01), whereas four out of the top five typologies with the highest EUI are hybrid typologies (D06, D05, C05 and C04).

Table 3. The typologies sorted by Energy Use Intensity (in ascending order from left to right)

A01	T01	B01	D04	T05	C06	D06	C01	D05	C05	C04
										

To examine the factors that may affect EUI, linear regression analyses were conducted for some of the variables investigated here. It was found that “GFA normalized annual total building envelope solar radiation” is most strongly related to EUI (R^2=0.856, $p<0.0001$) (Fig. 8a), and this is followed by “GFA normalized total building envelope SVF” (R^2=0.845, $p<0.0001$) (Fig. 8b). This is understandable as solar radiation incident on building surfaces is the primary source of external heat gains given that the internal heat gain intensity was the same for each typology as specified early. The similarity between envelope radiation per GFA and envelope SVF per GFA in predicting EUI can be explained by the strong correlation between them (R^2=0.975, p<0.001) (Fig. 8c). Considering that SVF is a geometric variable relatively faster to calculate than annual cumulative solar radiation, it was used in the following regression analysis.

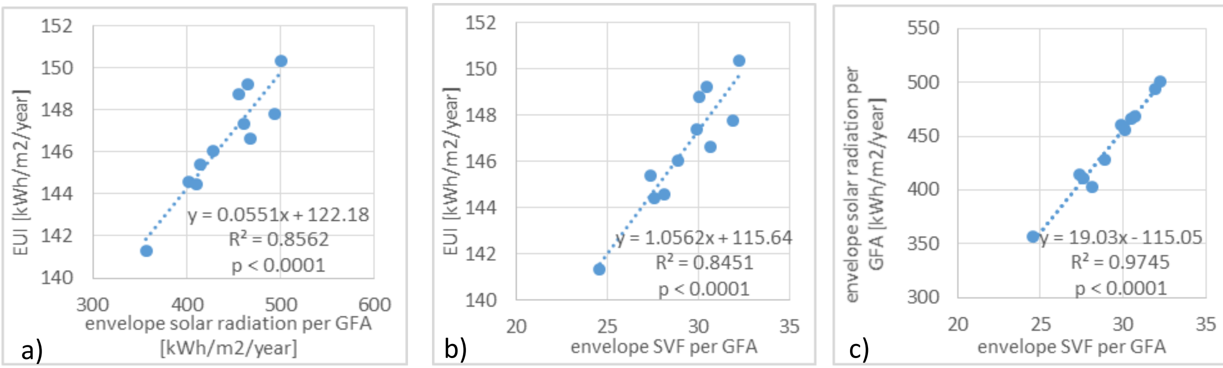


Figure 8. Correlation between Energy User Intensity and geometric variables a) envelope solar radiation per GFA and b) envelope SVF per GFA. c) The correlation between envelope solar radiation per GFA and envelope SVF per GFA

The relationship between EUI and planning parameter and geometric variables were also analyzed. Site coverage is significantly and positively related to EUI (R^2=0.6, p=0.0051): about 60% of the variation of EUI is associated the variation of site coverage (Fig. 9a). However, it can observed that there are several groups of typologies with the same site coverage but different EUI, i.e. site coverage as a planning parameter is not able to differentiate urban forms with different EUI in certain circumstance.

It was found that compacity is also significantly and positively associated with EUI (R^2=0.521, p=0.0012), i.e. it accounts for about 52.1% of the variation in EUI which is to a lesser extend as compared to site coverage (Fig. 9b), whereas clustering weighted compactiy has a slightly lower predictive power for EUI (R^2=0.512, p=0.013) (Fig. 9.c). Considering that clustering weighted compacity is able to differentiate building forms with the same compacity but different spacing between different parts of building volumes, it was considered in the following regression analysis.

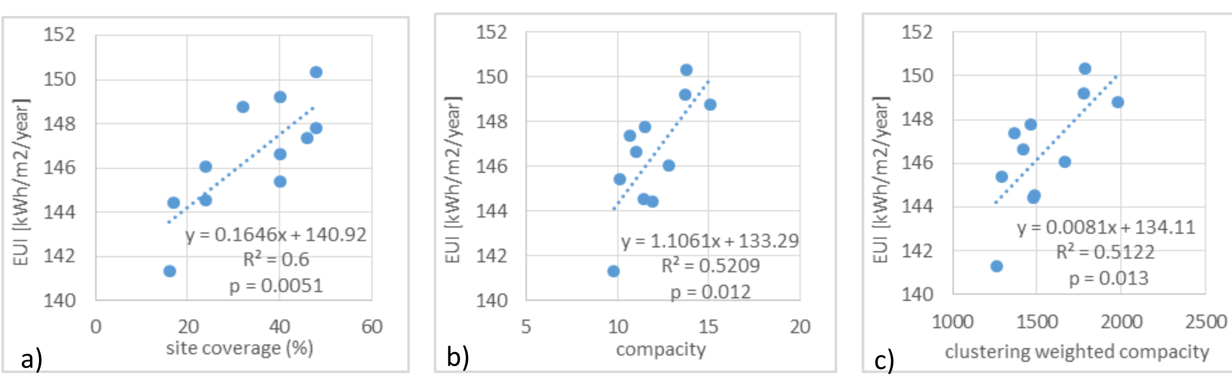


Figure 9. Correlation between EUI and site coverage (a), compacity (b) and clustering weighted compacity (c)

To understand the combined effect in predicting EUI for the planning parameter and geometric variables significantly correlated with EUI, stepwise linear regression analysis was conducted for envelope SVF per GFA, clustering weighted compactiy and site coverage, and the result is shown in Table 4.

It can be observed that by adding clustering weighted compacity to the first regression equation which involves only envelope SVF per GFA, the R^2 value increases from 0.845 to 0.913, suggesting an improved prediction for EUI. On the other hand, the third regression equation was not considered eventually, though it has the highest R2, because site coverage is significantly and positively correlated with envelope SVF per GFA (R^2=0.804, p=0.004), and it shall be removed from the equation to avoid collinearity issue.

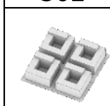
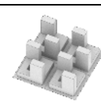
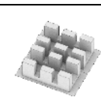
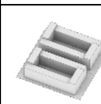
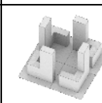
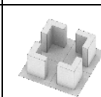
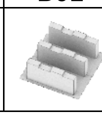
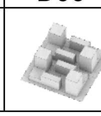
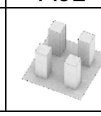
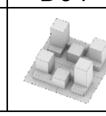
Table 4. Results of stepwise linear regression analysis for variables significantly correlated with EUI

Independent Variable	**R^2**	**Linear Regression**
Envelope SVF per GFA [SVF_GFA]	0.845 (p<0.0001)	EUI = 1.056* SVF_GFA + 115.64
Envelope SVF per GFA [SVF_GFA], Clustering weighted compacity [CW_CP]	0.913 (p=0.037)	EUI = 0.864* SVF_GFA + 0.003*CW_CP + 115.88
Envelope SVF per GFA [SVF_GFA], Clustering weighted compacity [CW_CP], site coverage [SC]	0.982 (p=0.001)	EUI = 0.223* SVF_GFA + 0.006*CW_CP + 0.115*SC + 126.8

3.2 Outdoor thermal comfort potential

The ranking of the typologies examined in terms of outdoor area-weighted average SVF is shown in Table 4. Typology D04 has the highest value (avg SVF=0.54) which outperforms the typology with the lowest value C01 (avg SVF=0.386) by about 40%. Among the top five urban forms with the highest average SVF, two of them are hybrid typologies (D04 and D06) and three of them are generic typologies (A01, B01, T01), and these building forms are expected to relatively greater potential to reduce nocturnal Urban Heat Island effect and produce a comfortable outdoor environment. On the other hand, three of the five urban forms with the lowest average SVF are hybrid typologies (C04, D05, C05) and two are generic typologies (C01, C06).

Table 4. The typologies sorted by outdoor average SVF (in ascending order from left to right)

C01	C04	D05	C05	C06	T05	T01	B01	D06	A01	D04
										

Linear regression analysis was conducted for factors that may potentially affect outdoor average SVF, and it was found that site coverage has no significant impact (R^2=0.226, p=0.139) (Fig. 10a), whereas compacity has a significant and negative impact (R^2=0.541, p=0.01) (Fig. 10b) and the impact of clustering weighted compacity is also significant, though slightly lower (R^2=0.523, p=0.012) (Fig. 10c), i.e. compacity and clustering weighted compacity account for 54.1% and 52.3% variations in average SVF of outdoor open space, respectively, for the typologies examined here.

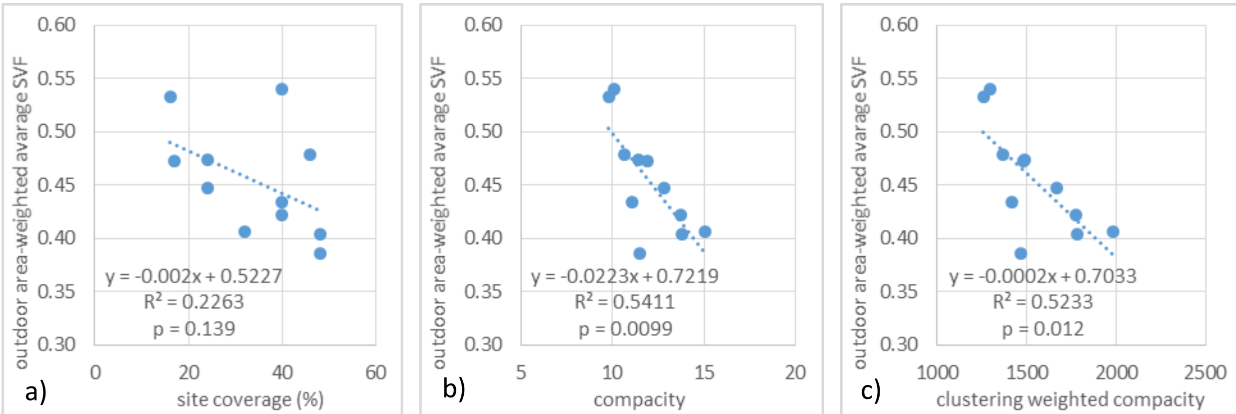
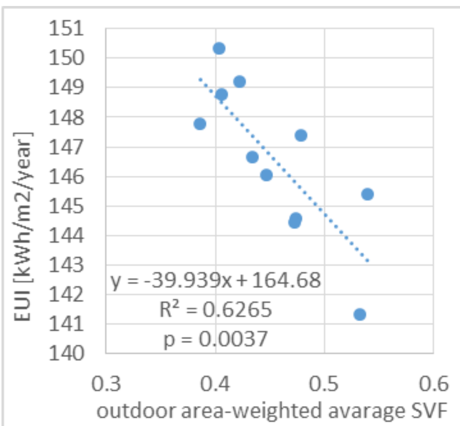


Figure 10. Correlation between outdoor area-weighted average SVF and planning and geometric variables a) site coverage, b) compacity and c) clustering weighted compacity



It is also interesting to observe that for the typologies examined in this study, there is a significant and negative correlation between the two performance indicators EUI and outdoor average SVF (R^2=0.63, p=0.0037) (Fig. 11). This suggests that, relatively speaking, for building typology with lower EUI, the average SVF of its outdoor open spaces is likely to be high, indicating greater potential in outdoor thermal comfort level.

Figure 11. Correlation between outdoor area-weighted average SVF and EUI

4. CONCLUSIONS

Using selected generic building forms and their hybrid variations, this study investigates the impact of building typology on energy consumption and outdoor thermal comfort potential under a fix density, and the planning parameters and geometric variables that may be significantly related to the performance indicators in the two areas were also examined.

It was found that, Energy Use Intensity in terms of cooling loads varied across the typologies examined here, with the largest difference of 6.4% between the worst and best performing typologies. Under the conditions specified for this study to control the impact of non-design factors, envelope solar radiation heat gains affect EUI significantly which can be approximated by GFA normalized envelope Sky View Factor. Site coverage, compacity and clustering weighted compacity are also significantly related to EUI, though to various extents in descending order. Results of linear multiple regression analysis indicate that envelope SVF per GFA and clustering-weighted compacity together can account for 91.3% of the variance in EUI. The findings suggests that building forms that is relatively compact (smaller compacity value) with smaller spacing between different parts of its usable space volumes are likely to have lower rate of energy consumption in terms of cooling loads.

On the other hand, clustering weighted compacity was also found to be significantly and negatively related to outdoor average SVF, suggesting that less compact urban form with relatively smaller spacing between different parts of the building volumes may result in larger SVF for outdoor spaces and potentially improve outdoor thermal comfort and reduce nocturnal UHI effects.

The findings implies that both geometric variables, which can be calculated efficiently, can be used to support the early stage of planning and urban design exploration and provide relatively reliable estimation of the energy impact and outdoor thermal comfort potential for various design strategies in cooling dominated climatic regions.

On the other hand, the implications of these geometric variables on other performance areas also need to be address in a comprehensive way. Compact buildings that are close to each may have relatively better energy performance and more potential to mitigate nocturnal UHI, but they may also impose negative impacts on daylight availability and penitential for natural cross ventilation that may lead to increase of energy use in artificial lighting and mechanical ventilation and decrease of indoor thermal comfort conversely. So, a holistic perspective in urban scale environmental analysis is crucial that will consider the performance implications of various design factors in different areas in a balanced matter.

The study also highlight the importance of design exploration in early stage of urban planning and architectural design in terms of their potential performance implications in energy consumption and outdoor comfort, and it also highlight the importance of comprehensive design evaluation beyond quantifiable examination.

For example, as compared to typology A01, detached tower blocks, the hybrid typology D04 offers slightly greater outdoor thermal comfort potential (1.3%) whereas its EUI is only 2.9% higher than A01. The EUI for typology D06 is 4.3% higher and its outdoor thermal comfort potential is 10.1% lower than that for A01. However, the design of both hybrid typologies might be advantageous in terms of improving daylight availability and outdoor air movement as indicated in previous studies (Ng, et al., 2006) considering their variation in building height as compare to the uniform height of the tower typology. Moreover, the two hybrid typologies can potentially contribute to the qualitative aspects of urban space in terms of the diversity in building form, ground level and rooftop open spaces, and program mixing within site that they can offer.

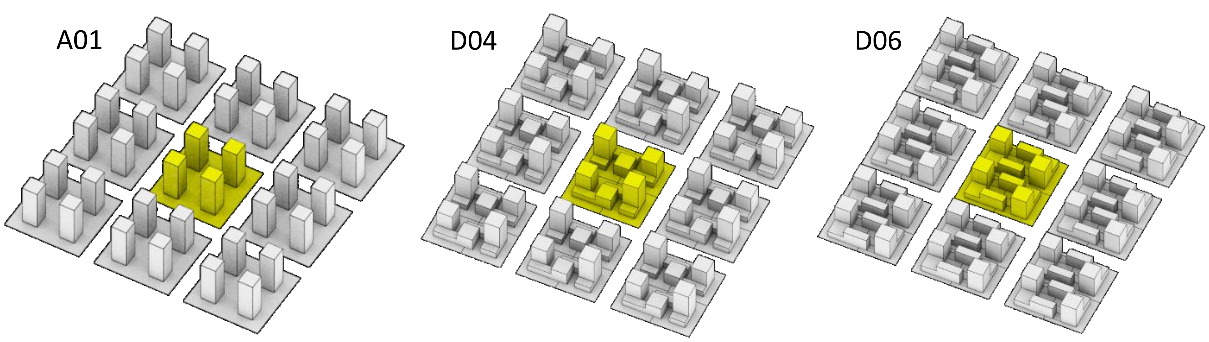


Figure 12. Tower block typology A01 and hybrid typologies D04 and D06

As a preliminary study, this study has several limitations need to be addressed in future studies: 1) The observations and conclusions drawn here based on limited numbers of building typologies under a fixed density need to be interpreted cautiously, and the methodology shall be implemented to examine more typologies and other density levels to further validate the findings; 2) In future studies, the thermal zones need to be further subdivided and specified as perimeter and core zones, and input for energy simulation such as typical schedule, internal loads, materials based on local survey shall be used in future study so as to provide more precise estimation of energy consumption; 3) SVF as proxy of outdoor comfort potential may need to be further verified, and other variable such as Universal Thermal Climate Index (Bröde et al., 2010) that may serve as more relevant indicator for outdoor thermal comfort shall be examined.

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