THE RELATIONSHIP BETWEEN BUILDING FORM TYPOLOGY AND COOLING LOADS IN THE TROPICAL CLIMATIC CONTEXT

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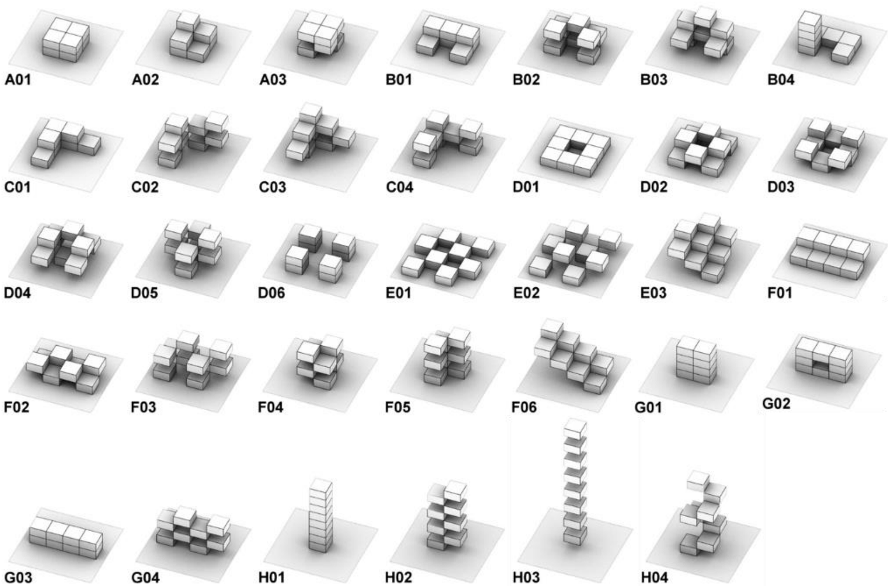


Fig 1. The 34 generic building typologies tested

Research summary

This study aims to achieve a better understanding of the impact of building form typology on building cooling loads under a given density in the tropical climatic context. A new geometric variable clustering, which quantify the level of spatial dispersion of building volumes or a group of buildings, is proposed. Utilizing a series of hypothetical generic building forms in diverse spatial configurations in a fixed built density and site, this study found that clustering-weighted compacity is a good predictor of both annual cooling Energy Use Intensity (EUI) in tropical climate and pedestrian level outdoor average wind velocity. The findings also emphasize the importance to seek innovative design solutions alternative to commonly used typologies in urban and architectural design that may have greater potential in performance improvement.

Keywords: Urban form, building typology, cooling loads, energy performance, compacity, clustering, spatial dispersion, pedestrian level outdoor air movement

1. Introduction

Building is one the major sectors of energy consumption. Previous studies revealed that, among other factors, building form and urban morphology have significant impacts on building energy consumption on urban scale (Ratti et al, 2003; Cheng et al, 2006; Salat, 2009). The relationship between urban form and energy consumption is an important subject especially in the tropical climatic context which is characterized by high level of solar radiation incident, high temperature and humidity level throughout the whole year, and where cooling loads are the primary components of building energy consumption. Therefore, it is crucial to investigate how to minimize building cooling loads through passive design strategy in the early stage of urban planning and urban design when architectural details are not developed, users groups and their behavioural patterns are not known and Heating Ventilation and Air Conditioning (HVAC) technologies potentially applicable are not specified yet.

2. Research Objectives

This study aims to achieve a better understanding of the impact of building typology on building cooling loads under a given density in the tropical climatic context. Specifically, it aims to investigate the following research questions: 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 in the tropical context? 3) What are the design implications of the findings?

3. Method

3.1 Performance Evaluation

A variety of 34 hypothetical generic building forms were used for the experimental simulation study (Fig 1), each representing a variation of one of several typical building form typologies, such as compact block (A01-A03), semi-open U-shape block (B01-B04), L-shape block (C01-C04), courtyard block (D01-D06), low-rise clustered block (E01-E03), row house (F01-F06), linear slab block (G01-G04), and high-rise tower block (H01-H04).

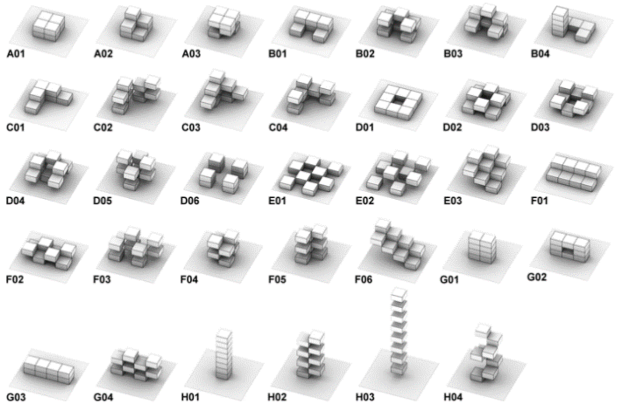


Fig 1. The 34 building form typology investigated

To emulate the composition of a typical small residential building, each form was defined as been composed of eight geometrically identical spaces (5m, 5m and 3m for width, depth and height, respectively) so that all the forms have the same total usable floor area of 200m^2 and total building volume of 600m^3. Each form is in a different spatial composition of the eight uniform spaces with no partial overlapping of envelope surfaces between adjacent spaces. Effort was made to make sure that each space has at least two surfaces exposed to the outside. The variations of the typologies examined are conceived to represent various types of enclosure and different levels of porosity in architectural form. In addition, the shape and size of the plot is also fixed as a square site of 25x25m with the building positioned in the centre of the plot and having equal setbacks to parallel edges of the site. These conditions are set so that the built density and the total usable volume of the thermal space whose cooling needs are to be dealt with for each building form are controlled to be the same.

Rather than modelling a building as standalone geometry, a surrounding is generated for each building form by replicating itself in a 3-by-3 matrix pattern with no additional spacing between adjacent plots (Fig 2). This is to create a homogenous urban context for each form 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 centre of the 3x3 matrix layout are specified as shading surfaces to emulate the urban obstructions for the centre building whose energy performance is evaluated. For simplification purpose, building structure elements such as columns and beams necessary to maintain the structural integrity of the hypothetical building forms were not modelled, althought it is acknowledged that their impacts on building energy performance in real design scenario may not be negligible.

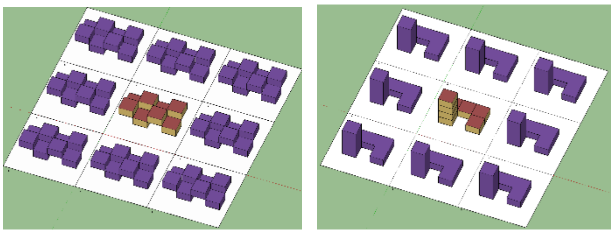


Fig 2. Examples of the homogenous context

All the building forms and their respective homogenous context were modelled in SketchUp Make 2015 with OpenStudio Plugin for SketchUp (v1.7), and each of the eight identical spaces of a form was defined as an individual thermal zone with typical HDB[1] public housing building materials and construction definitions applied to its surfaces such as exterior and interior walls, ceiling, floor and roof (Table 1).

Table 1. Material and construction definitions for typical HDB buildings.

Field	Units	Obj1	Obj2	Obj3	Obj4	Obj5
Name		F16 Acoustic tile	I01 25mm insulation board	M11 100mm lightweight concrete	M12 150mm lightweight concrete	M15 200mm heavyweight concrete
Roughness		MediumSmooth	MediumRough	MediumRough	MediumRough	MediumRough
Thickness	m	0.0191	0.0254	0.1016	0.1524	0.2032
Conductivity	W/m-K	0.06	0.03	0.53	0.53	1.95
Density	kg/m3	368	43	1280	1280	2240
Specific Heat	J/kg-K	5.90000000E+02	1210	8.40000000E+02	840	900
Thermal Absorptance		0.9	0.9	0.9	0.9	0.9
Solar Absorptance		0.3	0.6	0.5	0.7	0.7
Visible Absorptance		0.3	0.6	0.5	0.7	0.7

Field	Units	Obj1	Obj2	Obj3	Obj4	Obj5	Obj6	Obj7	Obj8
Name		HDB Exterior Door	HDB Exterior Floor	HDB Exterior Roof	HDB Exterior Wall	HDB Exterior Window	HDB Interior Ceiling	HDB Interior Floor	HDB Interior Wall
Outside Layer		I01 25mm insulation board	M15 200mm heavyweight concrete	M11 100mm lightweight concrete	M15 200mm heavyweight concrete	Clear 6mm	M15 200mm heavyweight concrete	M15 200mm heavyweight concrete	M12 150mm lightweight concrete
Layer 2				F05 Ceiling air space resistance					
Layer 3				F16 Acoustic tile					

The geometry and material information for each form was exported as IDF file from OpenStudio and then edited in IDF Editor of EnergyPlus to add other energy simulation related specifications. To understand the impact on cooling loads from building form itself, no window or door is created and the building infiltration design flow rate is set as

[1] HDB represents Housing Development Board, which is the government agency in Singapore in charge of the provision and management of the renowned public housing new town development in Singapore which houses more than 80% of Singapore's population.

zero (AC/h) to rule out the impacts of heat gain/loss due to windows or doors and infiltration. Shading surfaces such as horizontal blinds or vertical fins are not created either, and thus only the self-shading effect of a given form is considered. Definitions for internal heat gain sources such as people, lights and electric equipment were also left out to rule out the impacts of these non-building-design factors. To estimate the cooling loads for the building forms studied, an Ideal Loads Air System with a single cooling thermostat was specified for each of the eight thermal zones of a given building form with the cooling setpoint temperature set as 24C° for every hour.

These specifications are to understand the maximum energy implication of a given building form within a theoretically homogenous urban context assuming that a constant typical interior cooling temperature needs to be maintained for every air tight zone throughout the whole year regardless of its spatial function and use pattern. The cooling loads as simulated are thus primarily the results of envelope heat gain/loss, air movement around building and self-shading between different parts of the building solely due to the geometric characteristics of the building form.

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 value Energy Per Total Building Area [kWh/m2] as reported by EnergyPlus, was retrieved as energy performance indicator in terms of cooling.

In addition to annual cooling loads, pedestrian level air movement was also investigated for selected typologies to examine the impact of building form and spatial distribution of building volume on ground level outdoor wind performance. Area-weighted average wind velocity was calculated for each form within its respective homogenous urban context based on CFD simulation (ANSYS Fluent v15.4) for the plan corresponding to the shape of the site at 2m above the ground for outdoor open space areas was calculated as wind performance indicator.

3.2 Quantifying Geometric Characteristics

Regarding the variables to quantify certain geometric characteristics of urban form, previous studies have cited compacity, which is the ratio between building envelope area to building volume, as a key parameter that may have significant implication on energy consumption on urban scale (Adolphe, 2001; Salat, 2009), and it was observed that the higher the compacity value, the higher the energy needs for heating in colder climates (Salate, 2009, p.601).

However, it is not known if compacity is a significant predictor of energy consumption in cooling dominated climatic context. In addition, compacity as a geometric variable has its limitation in differentiating different building forms, 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. For example, the four building forms shown in Fig 3 have the same compacity but different spatial arrangements of their building volumes which may result in different energy performance due to their formal characteristics.

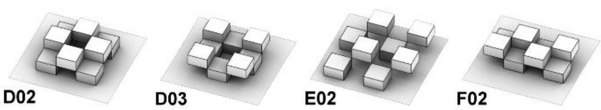


Fig 3. Example forms with the same compacity

The examples above suggest that there is the need to quantify spatial distribution of building volume in meso-scale urban analysis that is not captured by compacity. On urban design scale, if the building volume can be abstracted as been composed of uniform "volume cells", spatial distribution of the building volume in general can then be characterized as the average distance between these cells. A geometric variable "clustering" is thus proposed to quantify the level of concentration of enclosed building volume for a building form. Since each of the 34 forms tested in this study is composed of eight uniform thermal zones, the average distance between these zones can then be abstracted as the average distance between each pair of the spatial centroids of the zones. This "clustering" variable can only quantify the relative spacing between different parts of the building volumes within the building itself, and the distance between the building and its context is not taken into account that may have significant impact on the target building such as shading or obstruction of air movement. Therefore, a "clustering in context" variable is used in this study that expends the calculation of average distance between thermal zone centroids to all the building volumes within the entire homogeneous context. The smaller the value "clustering in context", the spatially closer the different parts of a building form are to each other (Fig 4).

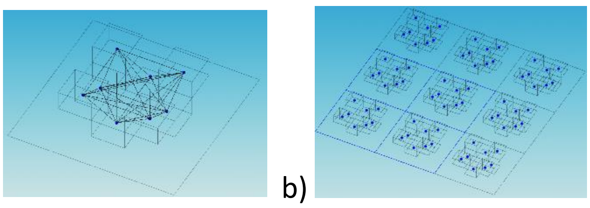
a) b)


Fig 4. a) Lines between every pair of centroids, b) Centroids for each thermal zone within the entire homogenous context.

In addition to the geometric variables, annual total building envelope solar radiation incident energy (kWh) was also simulated in Radiance v4.3 (Larson & Shakespeare, 1998) for each form as an alternative predictor of EUI since envelope solar heat gain is assumed to one of the major contributors to cooling loads.

4. Results

4.1 Energy Use Intensity (EUI)

Fig 5 shows the ranking of the 34 building forms by their annual cooling EUI which ranges from 150.65kWh/m^2 for the most compact building form A01 to 241.47kWh/m^2 for the vertically dispersed tower block H03 with enclosed thermal zones and intermittent void spaces arranged in alternating pattern, and the latter is about 60% higher than the former.

A closer look reveals that most of the forms with EUI lower than 200kWh/m^2 are relatively compact and low rise buildings, whereas the rest of the forms are ones with their building volumes distributed in more dispersed matter in various ways.

In Fig 5, if the EUI for form H01, which represents typical tower block, is set as the baseline, a variety of building forms have better energy performance, and some can achieve as large as 30% lower EUI such as form A01 and A02.

To understand the cooling loads impacts of the geometric variables, compacity and clustering within context, logarithmic regression analysis was conducted between each of the three variables and EUI. It was found that compacity is a significant and positive predictor of the EUIs of the 34 forms calculated in their respective homogenous context ($p<0.0001$, $R^2=0.827$), which indicates that the more compact a building form (indicated by a lower compacity value), the less its annual cooling EUI. The annual cumulated solar radiation energy incident on envelope also has significant and positive relationship with EUI, although with lower predictive power ($p<0.0001$, $R^2=0.357$) suggesting that only about 35.7% of the variation in EUI can be explained by the variation in annual cumulative envelope solar incident energy.

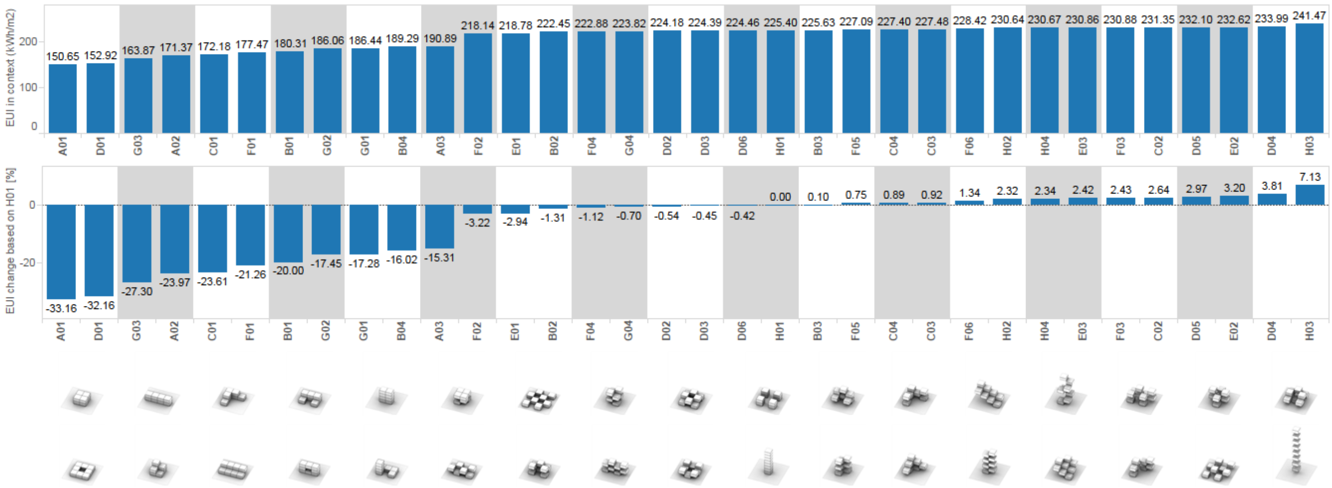


Fig 5. EUI for the 34 forms and their respective EUI change based on that for H01

Since compactity is not able to differentiate certain building forms, a clustering-weighted compacity value is calculated for each form to further quantify the level of spatial dispersion of building volume, i.e. for building forms with the same compacity, the one with higher clustering value is the one with larger average spacing between different parts of its building volume within the homogenous context. It was found that clustering-weighted compacity improved the logarithmic regression with a slightly larger R^2 of 0.838, suggesting a slightly better predictive power than compacity alone (Fig 6).

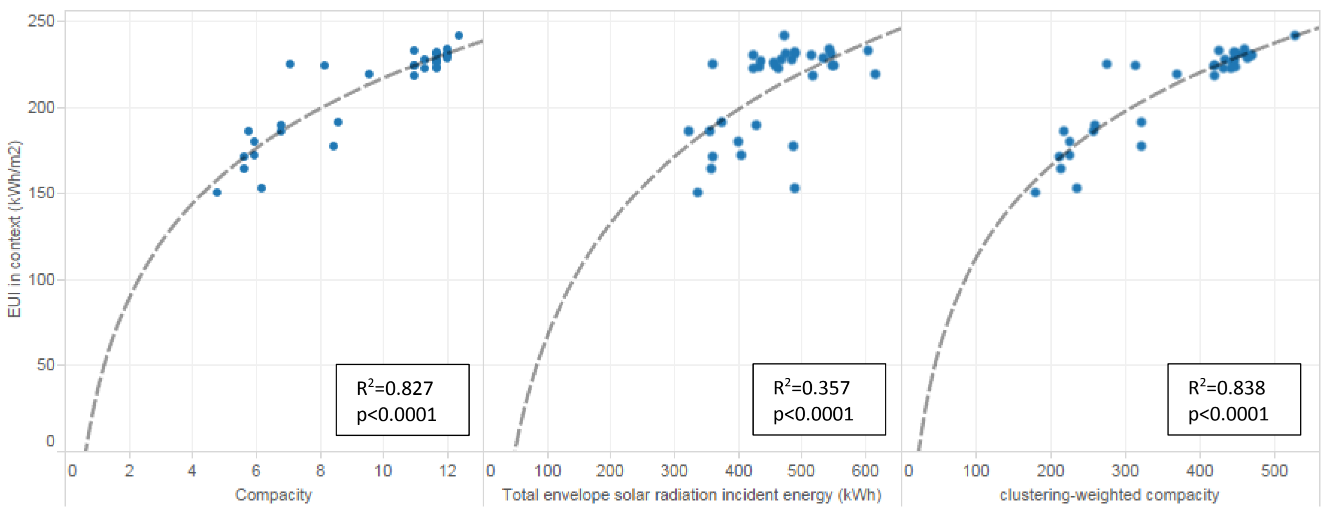


Fig 6. Logarithmic regression between the three predictor variables and EUI.

4.2 Pedestrian level air movement

To understand the impact of building form and their spatial distribution on outdoor air movement, pedestrian level wind velocity was simulated at 2m above the ground for outdoor open spaces within site for 12 selected building forms in their respective homogenous context. Due North wind profile of 2.7m/s at 15m height with suburban urban roughness context is used considering the geometrically symmetrical nature for most of the forms, and area-weighted average wind velocity was calculated as performance indicator for each form.

The results shown in Fig 7 suggest a wide range of variation in pedestrian level average wind velocity, ranging from 0.439m/s for G03 to 2.186m/s for H03. It seems that building footprint site coverage is not correlated with this performance indicator, and Frontal Area Index (FAI), which is the total area of building facets projected to plane normal facing the particular wind direction divided by the plane area (Wong et al., 2010). It is frequently used in urban scale ventilation studies, is obviously not able to differentiate the forms, either, since quite a few forms here have the identical FAI in relation to the wind direction.

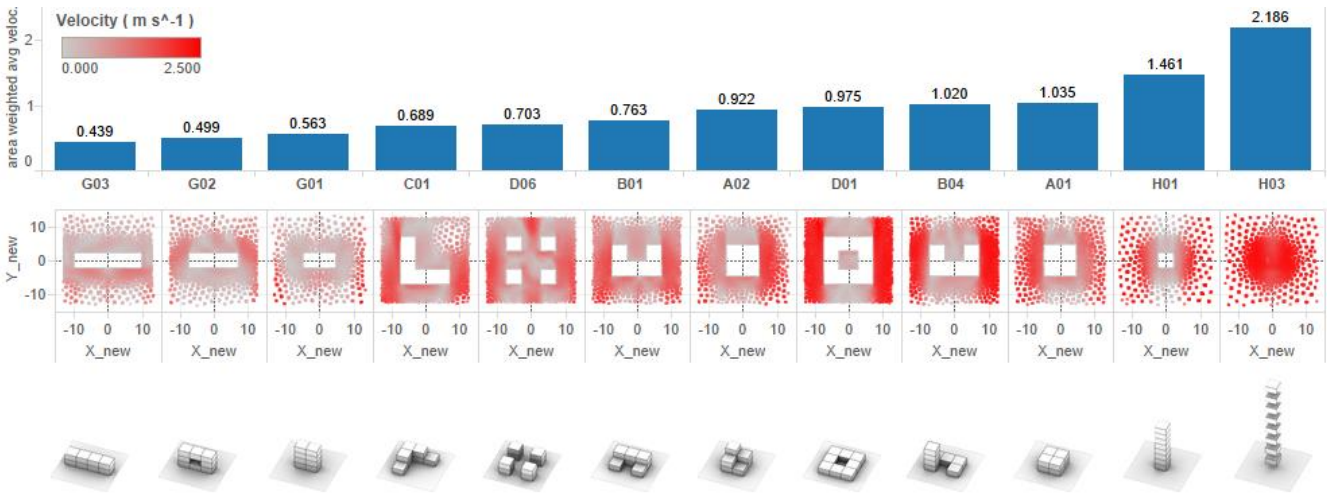


Fig 7. Ranking of the 12 selected building forms based on area-weighted average wind velocity and visualization of the velocity value based on CFD meshing.

Other than compacity and clustering-weighted compacity, an additional geometric variable, total area-weighted envelope Sky Exposure Factor (Zhang et al. 2012a), was calculated for the 12 forms that quantifies the degree of openness to the sky and is hypothesized to have potential impact on outdoor air movement. The results of linear regression analysis between each of the three geometric variables and wind performance indicator (Fig 8) show that clustering-weighted compacity is the best predictor with the highest R^2 of 0.605 (p=0.003), followed by compacity (R^2=0.569, p=0.005) and total area-weighted envelope Sky Exposure Factor (R^2=0.415, p=0.023).

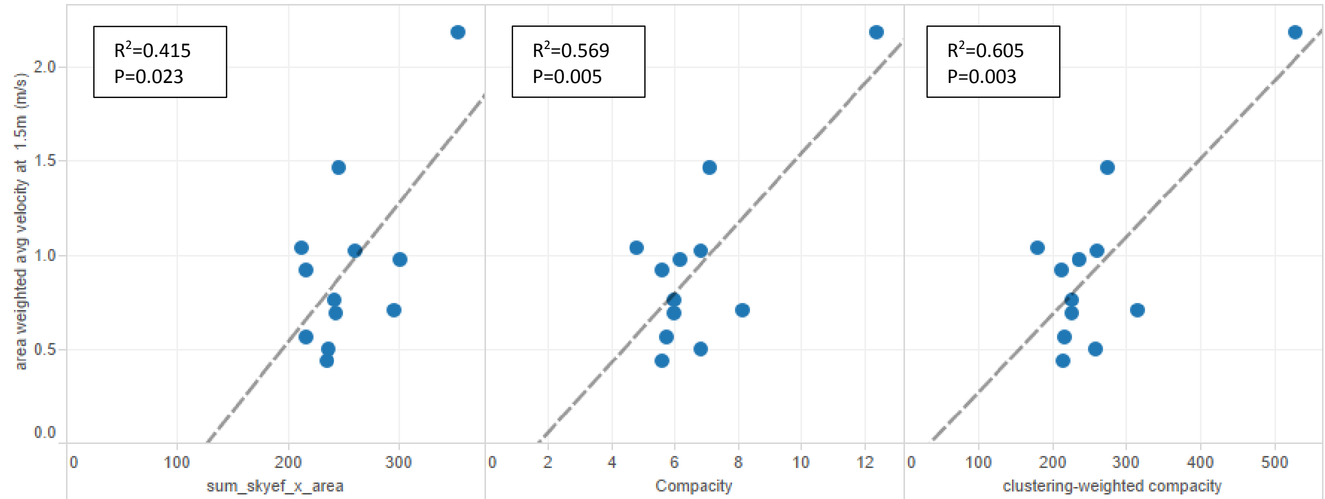


Fig 8. Linear regression between geometric variables and wind performance indicator

5. Conclusions

To describe the spatial distribution of building volumes, this study proposes the geometric variable clustering to quantify the level of dispersion of different parts of a building or a group of buildings within a given spatial boundary, and it is shown that this variable has the advantage, as compared to the widely used variable compacity, to differentiate building forms in terms of both their spatial distribution patterns and their potential energy implications. Utilizing a series of hypothetical generic building forms in diverse spatial configurations in a fixed built density and site, this study found that clustering-weighted compacity is a better predictor of the annual cooling EUI in tropical climate than both compacity and annual cumulative envelope solar radiation incident energy. It is also a better predictor of pedestrian level outdoor average wind velocity than both compacity and total envelope sky exposure level.

The findings also emphasize the importance to seek innovative design solutions alternative to commonly used typologies in urban and architectural design that may have greater potential in performance improvement. It can be observed from the ranking of the 34 forms based on EUI, there are a variety of building form typologies other than the widely used tower block typology H01 that can achieve the same density but better energy performance, each having their unique spatial and social implications both inwardly towards the local community within the neighbourhood and outwardly towards the urban space. For example, form B04 consumes 16.02% lower cooling energy than H01, and without sacrificing built density, this hybrid typology composed of both low rise perimeter block and tower block can contribute both to the local community by forming a relatively undisturbed semi-enclosed courtyard and to the city by constituting a clear and continuous interface to define and serving the street spaces.

It should be noted that the findings here are based on analysis of cooling loads under certain simplified premises to define a "worst case scenario" for cooling in tropical climate without considering impact of factors not directly related to geometric characteristics of building form. The conclusions might be different if other design factors are considered, such as building materials, fenestration design or openings on façade to facilitate natural ventilation (Hirano et al., 2006). The findings related to cooling energy use must also be considered together with examination of other performance areas such as daylight availability, noise exposure level, and implication in pedestrian accessibility and structure of public space, etc, to form a comprehensive and balanced evaluation.

Future studies should examine the relationship between building typology and energy consumption in different climatic context where both cooling and heating loads need to be considered and in scenarios with higher built density in which geometric variation will be more constrained. Alternative performance indicator should be explored to provide a more complete evaluation of outdoor air movement around building volume in its entirety rather than focusing on ground level only.

6. References

Adolphe, L. (2001). A simplified model of urban morphology: application to an analysis of the environmental performance of cities. *Environment and Planning B: Planning and Design, 28*(2), 183–200

Cheng, V., Steemers, K., Montavon, M., & Compagnon, R. (2006). *Urban Form, Density and Solar Potential*. Paper presented at the 23rd Conference on Passive and Low Energy Architecture, Geneva, Switzerland.

Hii, D. J. C., Heng, C. K., Malone-Lee, L. C., Zhang, J., Ibrahim, N., Huang, Y. C., & Janssen, P. (2011). *SOLAR RADIATION PERFORMANCE EVALUATION FOR HIGH DENSITY URBAN FORMS IN THE TROPICAL CONTEXT*. Paper presented at the BS 2011, Sydney, Australia.

Hirano, T., Kato, S., Murakami, S., Ikaga, T., & Shiraishi, Y. (2006). A study on a porous residential building model in hot and humid regions: Part 1—the natural ventilation performance and the cooling load reduction effect of the building model. *Building and Environment, 41*(1), 21-32. doi: 10.1016/j.buildenv.2005.01.018

Larson, G. W., & Shakespeare, R. (1998). *Rendering with Radiance : the art and science of lighting visualization*. San Francisco: Morgan Kaufmann. http://www.radiance-online.org/

Martin, L., & March, L. (1972). *Urban space and structures*. London,: Cambridge University Press.

Ratti, C., Raydan, D., & Steemers, K. (2003). Building form and environmental performance: archetypes, analysis and an arid climate. *Energy and Buildings, 35*, 49-59.

Salat, S. (2009). Energy loads, CO2 emissions and building stocks: morphologies, typologies, energy systems and behaviour. *Building Research and Information, 37*(5-6), 598-609.

Wong, M. S., Nichol, J. E., To, P. H., & Wang, J. (2010). A simple method for designation of urban ventilation corridors and its application to urban heat island analysis. *Building and Environment, 45*(8), 1880-1889. doi: 10.1016/j.buildenv.2010.02.019

Zhang, J., Heng, C. K., Malone-Lee, L. C., Hii, D. J. C., Janssen, P., Leung, K. S., & Tan, B. K. (2012a). Evaluating environmental implications of density: A comparative case study on the relationship between density, urban block typology and sky exposure. *Automation in Construction, 22*, 90-101. doi: 10.1016/j.autcon.2011.06.011

Zhang, J., Heng, C. K., Malone-Lee, L. C., Huang, Y. C., Janssen, P., Hii, D. J. C., & Ibrahim, N. (2012b). *Preliminary Evaluation of A Daylight Performance Indicator for Urban Analysis: Facade Vertical Daylight Factor per Unit Floor Area*. Paper presented at the SimBuild 2012, Madison, Wisconsin, USA.