SOLAR RADIATION PERFORMANCE EVALUATION FOR HIGH DENSITY URBAN FORMS IN THE TROPICAL CONTEXT

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ABSTRACT

High density development in cities is a planning strategy responding to fast population growth and limited land resources. However, the agglomeration of building mass increases the solar radiation heat gain, especially in the tropics. In order to understand how various high density residential urban forms perform in terms of overall surface solar insolation, we propose a performance indicator to quantify the solar radiation performance and a methodology to evaluate and compare the theoretical insolation performance across various urban forms. The impacts of selected morphological and geometric parameters on insolation performance are analysed to identify key design attributes contributing to insolation minimization.

INTRODUCTION

The contribution from buildings towards global energy consumption in both the residential and commercial sectors has been steadily increasing, and in developed countries, such contribution has reached figures of between 20% and 40%. This has exceeded the contribution from other major sectors such as industries and transportation. For buildings, the growth in energy use in HVAC systems is particularly significant, averaging 50% of building consumption and 20% of total consumption in the USA (Pérez-Lombard et al. 2008).

High density development is implemented in many cities around the world as a planning strategy to address issues such as fast urban population growth, efficient energy consumption and dwindling supply of urban land resources. In high density cities the urban fabric consists mostly of closely positioned buildings which may affect the thermal comfort of inhabitants as the solar exposure and wind flow profile are very much altered by the building forms.

In hot and humid regions, the sun belt will predominantly fall on the east and west facades of buildings throughout the year. Our solar simulations show that the facades facing east-west get at least 4 times the value of insolation than the north-south facades. Therefore, it is crucial to minimize facades facing the east-west directions as much as possible, in particular, the west side where the hottest hours of the day are concentrated. This is to minimize solar heat gain and the thermal load which will cause thermal discomfort to inhabitants. This will also reduce energy consumption due to increased mechanical ventilation and cooling load necessary to neutralize the heat.

Objective

The research objective is to examine different high-density precincts in terms of their forms and compare their solar insolation performance across the board. Solar insolation is part of a larger research framework, which looks at sky exposure, daylighting, wind flow and noise. The research will focus on urban built forms and will not look at architectural design solutions towards reducing solar heat gain such as external shading devices and insulation materials. The scale of study is on the precinct and typology level and not the building level. As part of the research, we have also examined daylighting implications with reference to the minimum vertical daylight factor of 8% on the facade for indication of indoor daylight sufficiency without reliance on artificial lighting (Ng 2005). However, given that energy consumption for air conditioning is generally much higher than artificial lighting, we have, in this paper, focussed on solar heat gain.

Firstly, we would introduce a methodology to perform façade insolation simulation for relatively complex urban forms efficiently and for evaluation, we would propose a performance indicator to compare across different cases. Secondly, we would explore the relationship between various geometric variables and façade solar insolation to examine if certain geometric variables can be used as effective indicators to predict solar insolation performance without performing the time-consuming simulation for given built forms. The final goal is to identify appropriate built forms in terms of minimizing solar insolation so that they can be recommended for further designs explorations in new context.

Urban Morphological and Environmental Performance

Research on the morphology of building forms in terms of their implications towards urban sustainability has been done by various researchers. Studies have highlighted that building morphology plays an important role in terms of mitigating the Urban Heat Island effect (Wong et al. 2011). In this paper, the focus is on solar heat gain in relation to human comfort and energy consumption. The quest is for the most efficient urban forms in terms solar insolation will help cut down energy costs in dense environments.

In high-density environments, high-rise buildings are actually considered “good” in terms of providing shade to the neighbouring areas. However, more reflected radiation will occur as a result of the compact and high density setting. Studies have shown that the closer the building blocks are, the higher the energy consumption will be, and this is caused by the reflectivity of building facades which carries both light and heat with it (Strømann-Andersen and Sattrup 2011).

Maïzia et al. (2009) also explores the energy requirements for heating and cooling typical urban blocks in the Region Ile de France. They categorized the urban blocks into 4 categories (discontinuous collective housing, continuous collective housing, dense individual housing and dispersed individual housing), and looked at the incidence of compactness and urban organization upon energy requirements and potential solar gains. They found out that urban blocks that receive most solar gains are dispersed, individual housing types.

Other related parameters that have implications on the research in this paper include the surrounding building density, the wall surface areas and albedo. Studies have shown that urban greenery, height and density has the most impact on the temperature, which may go up to as much as 1.2°C (Wong et al. 2011). Okeil (2010) found the “Residential Solar Block” (RSB) to be the best form for temperate climates with maximum solar energy on facades, minimum solar energy on roofs and the ground surrounding the building in winter, while mitigating the heat gain through increased airflow during summer.

Adolphe (2001) proposed a number of morphological indicators of environmental performance which include density, rugosity, porosity, sinuosity, occlusivity, compacity, contiguity, solar admittance and mineralization. Among them, the most direct geometric variable that deals with solar insolation is compacity. This is the ratio of the surface area of a building to its volume or the ratio between a building’s outer skin and the heated volume it embraces, and is also known as the surface-to-volume ratio or shape factor.

Ratti et al. (2005) took the studies further by finding the relationship between surface-to-volume ratio and passive to non-passive zones on energy consumption using DEMs (Digital Elevation Model), but the tests were limited to three case studies in London, Toulouse and Berlin. DEMs have always be a favoured tool for complex urban solar envelope calculations. Morello and Ratti (2009) used the sky model from Meteonorm with DEMs to introduce the concept of ‘iso-solar surfaces’ which extend the concept of solar envelope through energy considerations. It is a fast method to quantify urban irradiation and illumination, which would be helpful for planners and architects for site studies before the design process.

Yao et al. (2011) integrated DEMs within the coupled thermal and airflow model using the *MATLAB* toolbox. It is a urban microclimate model which takes into account direct solar radiation, diffuse radiation, reflected radiation, long-wave radiation, heat convection in the air, heat transfer in the exterior wall and the ground. The model however still requires improvement as it is not accurate when simulating high-rise building blocks. These models and methods based on DEMs are fast ways to simulate the urban solar insolation condition when designing new typologies on site. They are suitable to be used at the initial stage of design exploration as well as during the parametric exploration studies of the selected typologies based on their environment performance.

METHODOLOGY

This study is part of a larger research project aims to examine the implications of high density urban forms on facade solar insolation, thermal comfort and energy consumption. The thermal comfort segment is investigated through surveys to find out the satisfaction level of residential occupants in various locations, in combination with on-site measurements of key environmental variables such as mean radiant temperature, relative humidity, light level and wind speed. Energy consumption is investigated through *EnergyPlus* simulation taking into account of users’ behavioural patterns as obtained from surveys. Essentially, both of the processes are aimed at understanding the satisfaction thresholds of occupants and linking solar insolation with potential energy costs. This paper focuses on the solar insolation of the external facades of high-density typologies.

Case Study Approach

This research will select for study high-density residential and mixed-use typologies in precincts (of at least 0.4 hectares) with Floor Area Ratio (FAR) higher than 3.0. The intention is to capture as wide a variation in urban typologies as possible at relatively high-density levels. Therefore, the collection has various forms, ranging from point, slab, perimeter blocks and hybrids of point and slab, open blocks and clusters. This paper will look at the 60 case studies s from different geographic locations around the world. The site area ranges from 1,449 m^2 to 68,216 m^2. The site coverage ranges from 10.26% to 85.35%. The FAR ranges from 2.72 to 9.02. The floor amount ranges from 6 to 46 stories.

Geometric Variables

Various geometric variables are calculated for every typology that is to be simulated. Some of them are known to be related to environmental performance like daylighting and solar insolation while others are purely geometric measurements for the built environment. They include

- Floor Area Ratio (FAR): Gross floor area / site area
- Site Coverage: Building footprint area / site area
- Open Space Ratio: Non-built ground area / gross floor area (Pont and Haupt 2010)
- Area-to-Perimeter Ratio: Floor area / floor perimeter
- Compacity: Envelope area / (building volume)$^{2/3}$ (Adolphe 2001)
- Convolution Index: (Perimeter of the building footprint – Perimeter of the smallest convex shape of the building footprint) / Perimeter of the smallest convex shape of the building footprint (Leung 2009)
- Building Height: Average building height

Performance Indicator

Solar insolation is a measurement of the solar radiation energy received on a given surface area in a given time. It is commonly known as average irradiance in watts per square metre (W/m^2). For the comparison of the typologies collected, we proposed to use the measurement "annual total solar insolation per unit floor area" as the insolation performance indicator to compare across various case studies.

Simulation Software

Ecotect, *EnergyPlus* and *Radiance* are used initially to explore the solar insolation on external building facades. However, *Ecotect*, as a 32-bit software, requires a long time to simulate façade solar insolation as well as the difficult task to map grids on facades. *EnergyPlus* can be problematic as users need to specify internal zones and cannot take very complex shapes with vertices limitations on plan. It is also takes a long time to simulate if we apply an entire precinct for simulation. *Radiance*, from our evaluation, is better than *Ecotect* and *EnergyPlus* in terms of the pre-processing stage of getting the complex 3D model and sensor points ready for simulation. The time spent for basic simulation is also much faster than *Ecotect* and *EnergyPlus*.

Solar Insolation Simulation Methods

The hour-by-hour simulation (*Gendaylit* by Jean-Jacques Delaunay) and cumulative sky (Gencumulativesky by Darren Robinson) methods were explored initially using *Radiance*. The *Gendaylit* method (Delaunay 1994) is most accurate but it requires far more computing time for simulation, especially for the diffused component. The *Gencumulativesky* method (Robinson and Stone 2004) can work well for diffused radiation but not for direct radiation. It has an average error of up to 32% against the *Gendaylit* method for the direct component and only 3% for the diffused component.

Since the direct component of the *Gencumulativesky* is yielding such a large error, we decided to use the *gendaylit* program to only simulate the direct component for 24 representative days. This brings down the direct component's error to just 1.7% and therefore is good enough for the solar insolation simulation. Figure 1 shows the graphical resolution difference between the hour-by-hour simulation and the 24-day binned suns approach for the direct component.

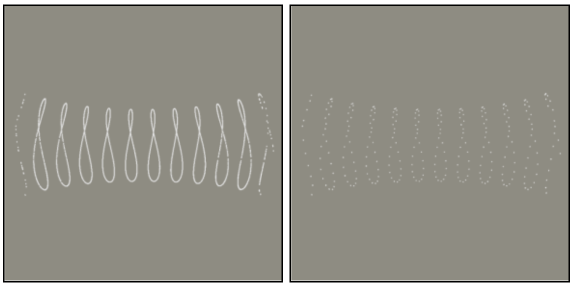


Figure 1: Hourly sun position (left) and the sun positions for the 24 representative days (right)

Workflow

Houdini, a procedural 3D modeling software with innovative data flow working pipeline is chosen as an integreated platform to build the 3D model, perform simulation and visualizing the results. The Python programming language embedded in Houdini is utilized to “glue” the 3D modeling platform and simulation software which is *Radiance* in this case (Figure 2).

Houdini ⟷ Python ⟷ Radiance

Figure 2: Houdini-Python-Radiance workflow

Houdini is used to build the 3D models for the various built forms under test, based on which various geometric parameters are calculated in order to examine their relationships with solar insolation performance. Houdini was used to extract the 3D model information and write it into files in the formats as required by *Radiance* via the embedded *Python*. Key Parameters for Radiance simulation were also built into a customized interface in Houdini to allow quick adjustment of simulation setting.

The façade surfaces for the built form under test were divided into sections of 1m (width) by 3m (height) and the centroids of the subdivided surfaces were defined as the sensors for annual total insolation simulation (Figure 3). The total insolation includes the direct, diffused and reflected components.

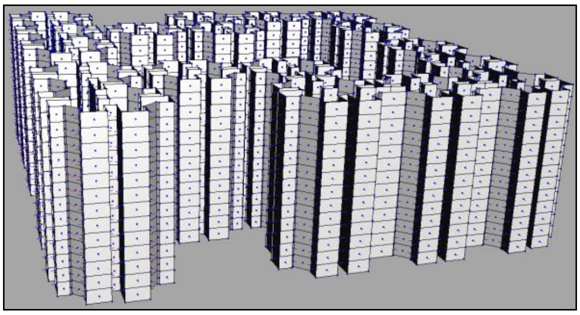


Figure 3: Subdivision of the façades with the centroids used as the sensor points for Radiance

Once the simulation is done, the results file can be retrived back in Houdini for visualization in various color legend schemes (Figure 4).

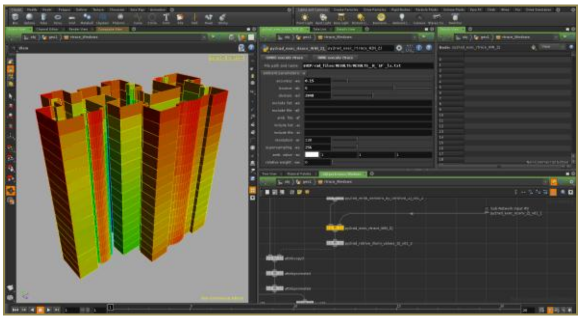


Figure 4: Houdini interface with the visualization of the results shown on the left and the parameters, results on every sensor point and the network

Normalization and Orientation

In this research, we consider that it is only fair to compare different built forms if they are simulated in a neutral environment. It is not possible to compare them if we take into context their actual site conditions with the variation of type, distance and height of neighbours. Therefore, we normalize all our cases but duplicating each unit 8 times surrounding the central typology of interest (Zhang et al. 2010). The spacing between the center typology and its neighbours is done by averaging the road widths for the real sites. During simulation, only results obtained from the typology in the centre will be taken into consideration. Figure 5 shows the typology of interest at the centre of the normalization process.

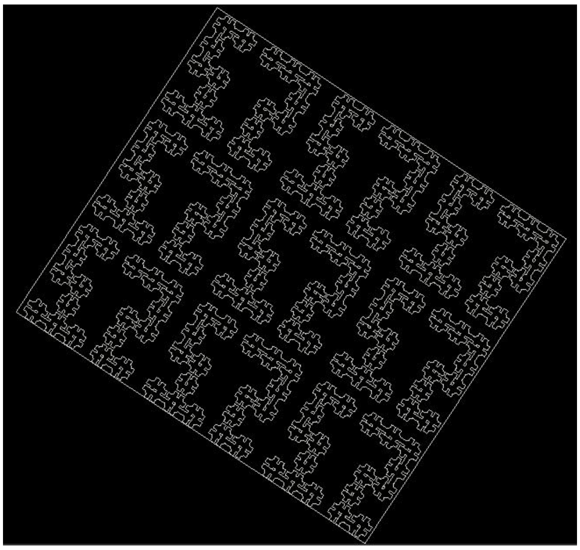


Figure 5: Normalization process

The challenging aspect of the normalization process is the shape of the irregular land plot which requires modification to enable fitting the duplicates around it. Sometimes, we may need to mirror the entire precinct to enable the normalization process to work. Whatever method we use, we make sure that the original land area is maintained so the density remains the same. Figure 6 shows some of the cases where the mirroring method is employed.

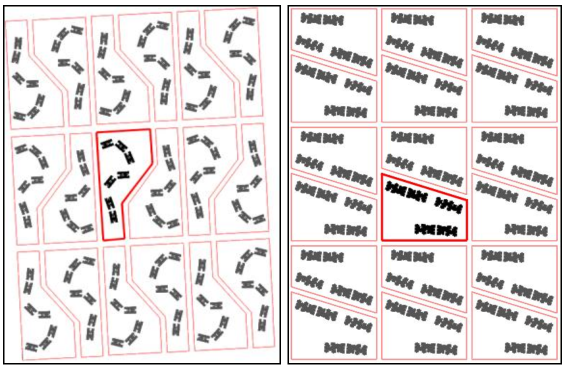


Figure 6: Normalization of irregular land plot

In addition to the normalization process, it is also not fair to compare typologies from various climate conditions around the world. We acknowledge that different typologies taken from different locations are designed to the specific predominant wind directions and sun paths. Therefore, to neutralize them under the tropical context, we have to simulate them 4 times at the original position, 90, 180 and 270 degrees and then averaging the results (ASHRAE 2004). This will give a more conclusive overall performance of every typology.

RESULTS

The *Radiance* simulation is done with zero and two bounces for the direct solar insolation as well as with one and three bounces for diffuse solar insolation for the entire year. Figure 7 shows the outcome of the *Radiance* simulation of a typology visualized in Houdini. The average total solar insolation recorded from the 60 cases are from 11,796 (Wh/m^2) / unit floor area to 58,252 (Wh/m^2) / unit floor area.

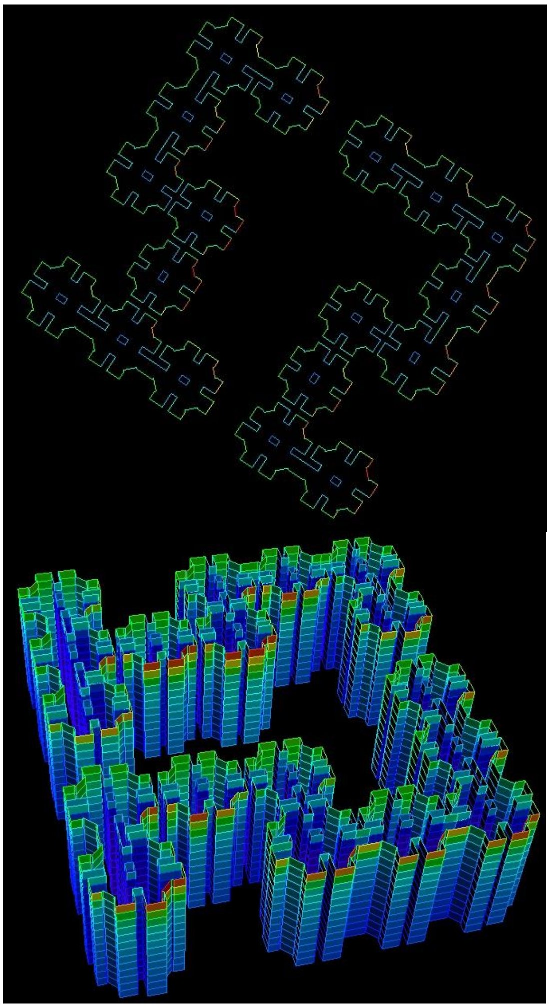


Figure 7: Solar insolation results on plan (above) and isometric view (below)

Figure 8 shows the graph which plots the 60 case studies in terms of their floor area ratio against average total insolation / floor area. The lower the typologies are located in the Y-axis, the less the solar insolation received by the facades, which is what we aim at achieving in the tropics. It is clear that for the same FAR band, the difference between two different typologies (FAR band of 3.5-4.5) can reach over to 46,000 W/m^2. Therefore, it is crucial to know how each typology fare in their respective range and to design better than the current ones. We envision this graph to be a useful chart for architects to benchmark their designs against. The ultimate aim is to achieve a design to be amongst the best in each of the FAR bands.

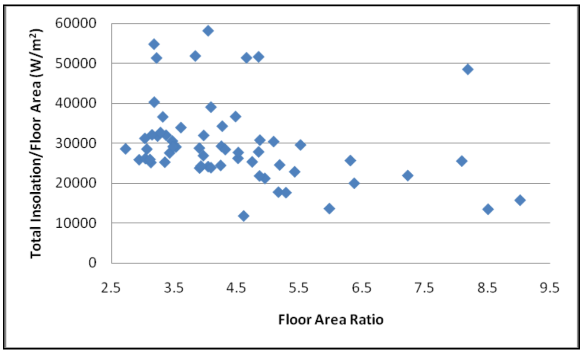


Figure 8: Average total solar insolation / floor area with FAR

We subsequently categorize the 60 case studies into different typologies of open, perimeter, point, slab and point-slab combination blocks as shown in Figure 9. The results show that perimeter blocks achieve the lowest solar insolation values while the point blocks achieve are amongst the highest solar insolation values for every FAR band. As noted earlier, it would thus be useful for an architect to see the extreme ends of every FAR band as benchmarks in the design process.

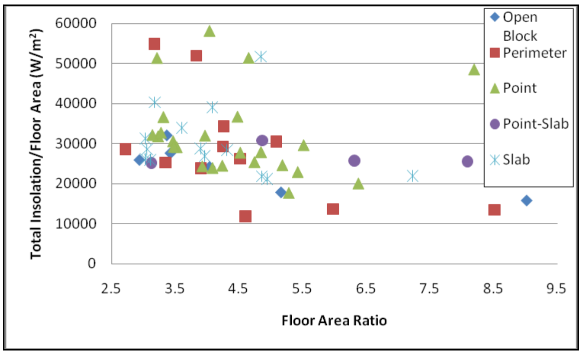


Figure 9: Average total solar insolation / floor area for different typologies

We further look at the geometric variables of floor area ratio, site coverage, open space ratio (Figure 10), area-to-perimeter ratio, compacity, convolution index and building height to plot their relationship against the average total insolation per unit floor area. Unfortunately, we are unable to isolate a single geometric variable that has a strong relationship with the solar insolation performance. Amongst them, open space ratio is probably the only candidate that shows an indicative trend but the correlation is badly affected by 8 outliers with high solar insolation.

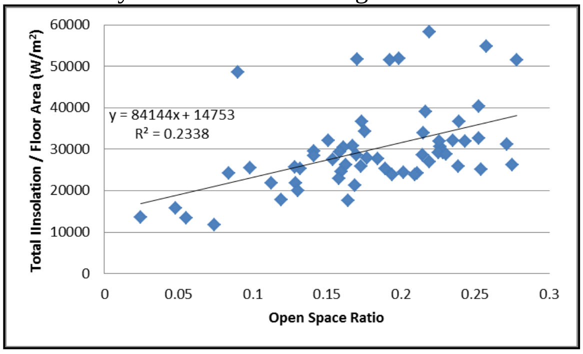


Figure 10: Average total solar insolation / floor area for different typologies

Figure 8 and 9 show the distribution of the typologies at different FAR against average total solar insolation per unit floor area. The more obvious geometric variables that are different when comparing typologies at the high and low levels of the FAR band are the Compacity and Convolution Indices. Figure 11 and Figure 12 shows the distribution of the same typologies with their respective Compacity and Convolution Index values. Typologies that tend to receive higher amount of solar insolation will have higher Convolution Index and Compacity values, which implies that they have more façade areas which are particularly prone to solar exposure. These could potentially be good indicators for architects when designing their buildings. However, the total solar insolation may be affected by self shading of adjacent façades of the typology itself.

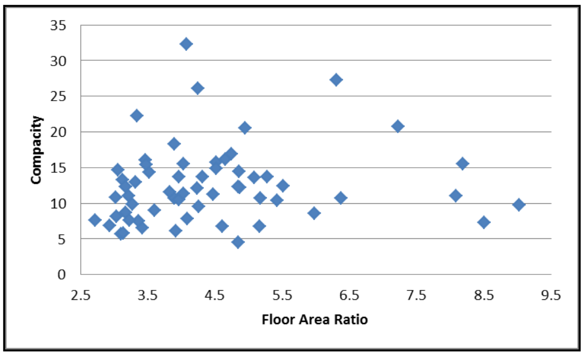


Figure 11: Average compacity

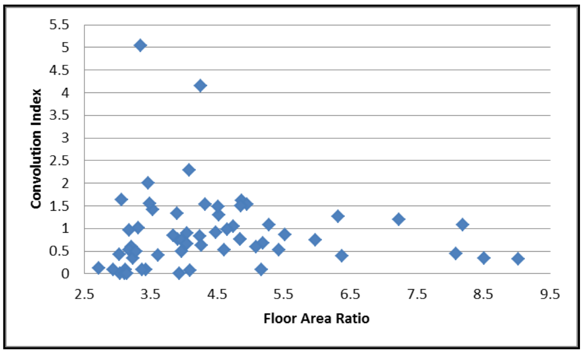


Figure 12: Average Convolution Index

We also noted that for both geometric variables, the Compacity and Convolution Index may vary as the FAR gets higher. This is an indicator that there is potential scope to explore lower solar insolation values even as we aim to build at higher density.

CONCLUSION AND FUTURE WORKS

This paper demonstrates the current research done in solar insolation on facades simulation for exploration of urban typologies. As this is an initial exploration of typologies classification, there could be more refined approaches to categorization before we can draw clear conclusions of each typology's performance thresholds at various FAR bands. We aim at collecting more high density typologies from here onwards to provide a bigger library of cases to benchmark against and to draw lessons from. Classification of typologies has always been a difficult task given that some typologies are hybrids of two or more different pure forms of point, slab and perimeter blocks. From our observations, we note that the trend is to use point blocks to push for higher densities as evident in dense cities like Hong Kong and Seoul. However, our results show that point block is a poor typology in terms of solar insolation as it receives higher solar insolation than the others. There is a need achieve the optimum spacing or combining it with other typologies to improve its performance. From the urban design point of view, it would be necessary to look for as many variations of typologies as possible in terms of environmental performance that can be adopted for high density cities.

Our present results show that the surfaces facing east and west have the highest insolation values. Generally, these values increase at the upper levels of the precincts as there is less shading from the neighbouring blocks. This is also caused by the high presence of the diffused incident radiation from the sky. The ratio of total insolation between the east-west facades to the north-south facades can be as much as 4 to 1. Since the sun belt is directional (east to west), it is certain that the distribution of direct solar insolation is not normal on the building facades.

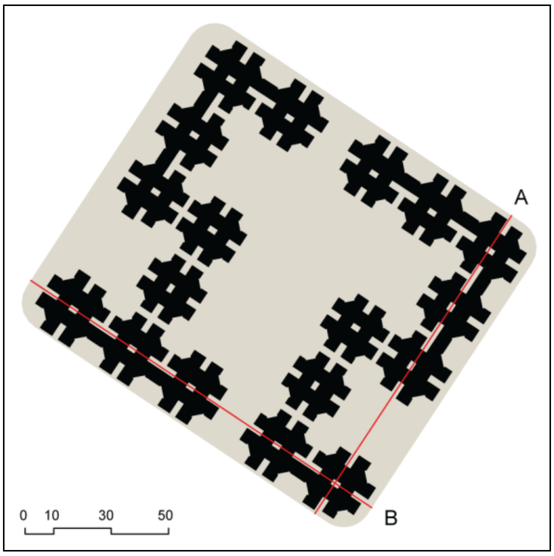
Indeed, Chow et al. (2005) explored using *DOE*, *TRNSYS* and *EnergyPlus* for the distribution of solar radiation on facades in Hong Kong and found that the south-west facades have the richest annual solar radiation despite all three recording different sloped surface irradiance models.

In our next stage of research, we will examine the outliers in the graphs to understand why they are different from the rest. There could be valuable lessons to be drawn from them.

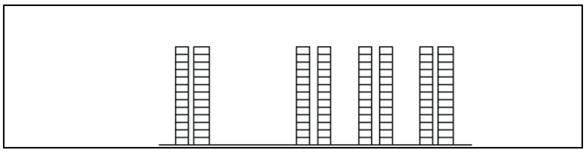
Finally, as part of this study, we will integrate the simulated results with the survey of local people's perception and behaviour toward the environment in the area of solar insolation. We can seek to match the simulated environmental performance with the respondents' satisfaction level. Potentially, we can also quantify the heat gain in terms of thermal comfort tolerance and energy costs for the building blocks surveyed so the values will be more tangible for the people living in these blocks.

Further Studies

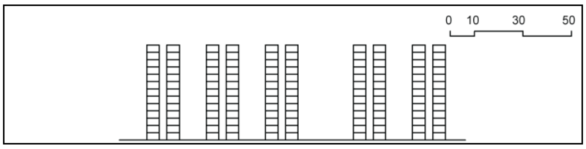
The present study shows that there is potential for research in this field for future extensions. One area for further investigation is to look at other potential variables that can best predict environmental performance (in this study, we are using average total solar insolation per unit floor area). There may be a need to explore a way to quantify average spacing of building blocks as well as building height-to-width ratio. We are aware that spacing of building blocks affects sun exposure and shading. If we build too close to each other, the reflected component will increase but if we build too far from each other, the direct component will increase. Figure 13 shows the spacing of one of the 60 case studies used for the simulation.



PLAN



SECTION A-A



SECTION B-B

Figure 13: A typology's blocks spacing to be taken into account as potential geometric variable for solar insolation prediction

Future studies may thus explore if there could be an optimum value range where buildings in high density environments can be spaced so we can control the amount of total solar insolation falling on the facades of the buildings given the land area constraints.

A further issue is to consider the implications of giving more weightage to the east and west facades as the amount of solar insolation recorded at these facades are far higher than those in the north and south facades. As pointed out in the paper, there appears to be a trend that typologies with higher Compacity and Convolution Index would receive more solar insolation. Therefore, if more weightage is given to the facade areas facing east and west, perhaps the correlations between these geometric variables and others against average total solar insolation per unit floor area could be better. This is a subject for further investigation.

We also envision that typologies with low solar insolation values can be shortlisted for further design explorations as well as parametric studies by varying different geometric variables that can be logically explored in real sites. We can learn from Kämpf and Robinson 2010 and Kämpf et al. 2010 as they coupled a multi-objective optimisation algorithm with Radiance using a cumulative sky model for computation of incident irradiation. They used the method to optimize different geometric variables as they design new urban forms that are efficient in terms of solar irradiation. They aim at integrating the algorithm with *CitySim* for simulating energy performance of urban masterplanning proposals (Robinson et al. 2009).

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As this is work-in-progress, the paper should not be quoted without authors' permission.

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