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Integrating energy and wind performance reasoning in urban form type design for an educational district in Singapore

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Abstract

Climate emergency urges the reduction of CO2 emissions. Energy is the major contributor to climate change, and the building sector accounts for a large share of rising global energy consumption. Previous research has shown a strong interplay between urban form and energy consumption. The transition towards net-zero cities is challenged by the space required for renewable energy production, especially in a dense urban context such as Singapore. This study investigates the relationships between the urban morphology characteristics and the energy performance of educational districts in the tropical climate of Singapore, using simulation-based parametric geometric modelling as a method. We based morphological properties on an analysis of existing educational urban quarters in Singapore and related literature on energy-driven urban design in tropical climates. Based on that, a parametric model for a new hybrid typology was created to evaluate different configurations of it using urban energy and wind simulations to inform the design process. The scenario with the best performance was developed further and applied to a case study site in Singapore. The findings of this study could inform planning processes where design decisions can influence, or are driven by, energy performance and energy-driven design concepts.

Keyword: *Urban form, Solar Energy Penetration, Natural ventilation, Energy-driven urban design, Tropical climate*

Introduction

Rapid global urban growth has the potential to support the emergence of more self-sufficient, resilient, and intelligent energy systems. In contrast to conventional centralised urban energy structures, often powered by fossil fuels, new distributed systems offer more efficient and sustainable solutions satisfied by the on-site renewable energy use. In this context, urban form design could respond and facilitate this transition towards carbon neutral and ecologically sustainable cities. Singapore is limited in spatial and natural resources. The equatorial location of the country makes solar power the most viable renewable energy source (Energy Market Authority (EMA), 2021). The high density of the city state is associated with a large energy demand on the one hand and is coming into competition with the considerable space needed for the solar energy harvesting on the other. In an attempt to address this seeming contradiction, Singapore is exploring utilizing unused spaces such as water surfaces and building envelopes for photovoltaic (PV) installations (Chong, 2021; Liu, Krishna, Lun Leung, Reindl, & Zhao, 2018). Meanwhile, natural ventilation passing through the dense urban contexts is much preferred for improving both the indoor and outdoor thermal comfort. This paper focuses on an urban design case study in Singapore. Our case study aims to integrate multi-disciplinary knowledge from the domains of energy and wind into the parameters of a typological design of urban form, implementing the considerations of the energy system into the urban form design.

Objectives

This design-oriented study aims to propose a new hybrid urban form type synthesizing the existing heuristics for energy efficiency for an educational campus in Singapore. Singapore has a tropical climate with high uniform temperature and humidity, abundant annual solar irradiance of 1,580 kWh/m2/year and light winds of less than 2.5 m/s except the Monsoon season (The Meteorological Service Singapore (MSS), 2021). For the urban form that strives to achieve synergies with energy systems, it could be translated in the following objectives: minimize cooling energy demand, facilitate natural ventilation, and provide surfaces for the PV in the most efficient manner. As a case study to demonstrate the potential of such energy-driven design logic, the planned development site 'Punggol Digital District' in Singapore was selected (Urban Redevelopment Authority (URA), 2020). The Methodology section presents the workflow to formulate the urban form type for educational uses. The outcomes and final design application are presented in the Results and Discussions.

Methodology

This study was divided into several steps. Firstly, we reviewed the energy-driven urban design heuristics in literatures. Next, we surveyed Singapore's local university campuses to inform our model with the spatial characteristics of urban form common for the educational use. Based on that, we created the parametric model and ran the energy study to demonstrate the advantage of the generated scenario in comparison to the surveyed benchmarks in the solar energy use. Finally, this scenario was elaborated further, introducing urban porosity to improve natural ventilation, the effect of which was demonstrated with wind simulations.

A review of the energy-driven urban design heuristics

The relationship between urban form and energy use is context and climate-specific. What might be relevant in one climate zone and culture could have an inverted effect in another. The following list combines urban design solutions that could improve energy performance in the tropics and Singapore in particular. Firstly, on the macro-scale, previous studies suggest having a high density distribution gradient as well as considerable share of residential programme in the mixed-use developments to balance the energy profile and facilitate the district cooling system's efficiency (Hsieh et al., 2017; Shi, Fonseca, & Schlueter, 2021). Secondly, on the meso-scale concerning street network and plots, street network orientation design can be guided by the conditions of either the solar radiation or the wind direction (Ruefenacht & Acero, 2017; Tao, Lau, Gou, Zhang, & Tablada, 2019). Another recent research has linked street grid design and district cooling system's efficiency (Shi, Hsieh, Fonseca, & Schlueter, 2020, p. 11). Thirdly, on the micro-scale concerning building types and street canyon, the benefit of courtyard block types was demonstrated by Zhang et al. (2019, p. 523). However, courtyard types are not ideal air-movement and wind permeability. Regarding the street canyon width, there is another trade-off between wide streets that will facilitate wind movement and narrow streets that will provide shade (Ruefenacht & Acero, 2017, p. 43).

A survey of the local educational urban form

The largest part of Punggol Digital District is envisioned to be a new campus for Singapore University of Technology (SIT). To inform the parametric model with properties common for Singapore's local campus typology, a survey of university and research campuses in Singapore was done. As a reference of campus typologies in Singapore, 8 university buildings with distinctive urban form were selected (Fig. 1). While being

Figure 1. *University type survey among Singaporean campuses*

integrated into the dense urban fabric of Singapore, most of the reviewed campuses form separate functional clusters. Regarding the level of the street network and plot subdivision, it could be noted that it is rather typical for many of them to occupy a large plot with no or limited road access inside. Many of the reviewed campuses also have a massive green and public space allocated around them. Only the campus of Singapore Management University (SMU) is located more densely and on a smaller plot, since it is situated near the Singaporean Central Business District (CBD), where the masterplan for Singapore indicates higher urban density. When it comes to the level of buildings, a wide diversity of types across Singaporean universities was observed, which could be generalized to 3 main archetypes. Similarly to the classical work of Martin & March (1972), those include: solitaries (or "pavilions"), slabs (or "streets") and courtyards. Some campuses may represent a cluster of slabs following one direction (for instance, this pattern could be observed on the fragment of the NUS), whereas others are freely distributed solitaries Republic Polytechnic (RP), or, even more commonly, – a mix of all types. Examples of the courtyards include Singapore University of Technology and Design (SUTD), Singapore University of Social Science (SUSS) and, partially the CREATE campus on the

National University of Singapore (NUS), Nanyang Technological University (NTU) and Singapore Institute of Technology (SIT). Therefore, the courtyard is a common type for the educational use in Singapore.

Experimental design workflow

For this study, the courtyard type was selected as a base for the following design-space exploration (Fig 2), as the literature review has shown that it could benefit the energy performance. To satisfy the scale requirements for the campuses, this archetype was modified for the larger plots by adding the internal courtyard ring. Moreover, based on the surveyed campus types as well as the literature review on the tropical climate planning, several objectives for the new typology were extracted. They include spatial programme requirements, shading, the use of natural ventilation for cooling, on site solar energy production and the emphasis on greenery.

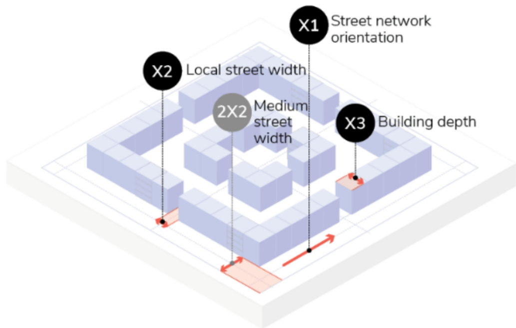

***Figure 2.** Three input variables for courtyard block type*

Energy study

A detailed energy study is described in a recent paper (Anonymous, 2021). There, the influence of three urban form variables (street network orientation, street width and building depth) on the solar energy penetration was examined using the City Energy Analyst (CEA), an open-source urban building energy simulation program to model the energy demand of each together with the PV electricity yields. Variable importance assessment done with the Sobol' sensitivity analysis suggested the street width and building depth had the highest influence on the result. The best performing scenario had a narrow street canyon and a deep building block.

To compare the results of the above-mentioned energy study to the performance of the existing urban form in Singapore, 8 campuses from the survey sections were simulated with CEA to get the same metrics: PV electricity yields and energy demand, and their ratio equals the solar energy penetration. All the input parameters, apart from geometry, were kept the same in all CEA simulations.

Wind study

The previous study was based on the energy model that includes solar radiation as an environmental factor. Another important climate feature that with an influence on energy is wind, especialy in the the hot and humid tropical climate. Schulze & Eicke (2013, p. 231) have proven that passive cooling and ventilation strategies could bring significant energy savings. Furthermore, airflow around buildings effects not only the energy aspect but also thermal comfort and occupant health (Waibel, Bystricky, Kubilay, Evins, & Carmeliet, 2017, p. 2). Therefore, after the outperforming configuration of the generic urban form has been found, it has been developed further, by opening the building block with voids to make it porous. Ruefenacht & Acero

(2017) mention it as one of the strategies that will improve the natural ventilation and pedestrian's thermal comfort

The benefits of improved natural ventilation by creating voids could be demonstrated by running the Fast Fluid Dynamics (FFD) wind simulation on the neighbourhood level. As a base case, the outcome of the energy study was taken, which was a completely solid block without any voids inside. With the use of the parametric model, 3 other options were generated with different degree of porosity that could be rounded to 15%, 30% and 45% respectively. Porosity level was calculated as the ratio between useful open volume to the total volume of the urban block, based on the definition of A.L. Martins et al. (2014, p. 45). To conduct the FFD simulation, the Grasshopper plugin, developed by Waibel et al. (Waibel et al., 2017), was adopted. The simulation was run in the domain of 500 x 500 x 500 m, with a cell size of 4m in a regular Cartesian grid; the wind speed was set to 5 m/s at 10 m above the ground; the wind direction was set to the Southwest (observed in Singapore mainly during the June-September Monsoon). Other FFD solver parameters, including kinematic viscosity, tolerance, etc. were set according to the reference study (Zhang, Waibel, & Wortmann, 2020).

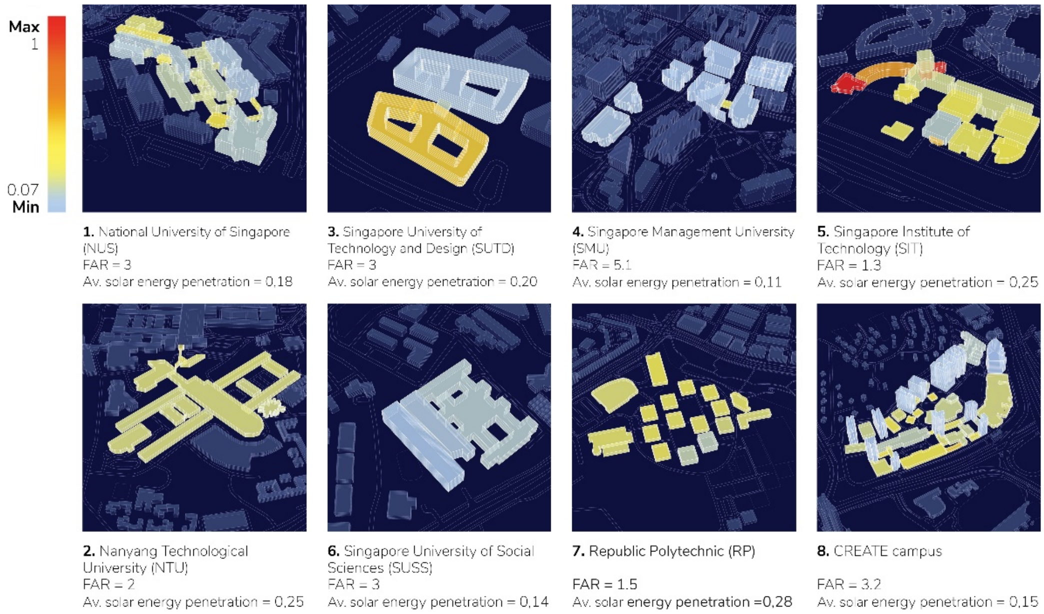

Figure 3. *Benchmark study results; coloured by the solar energy penetration by building, (-)*

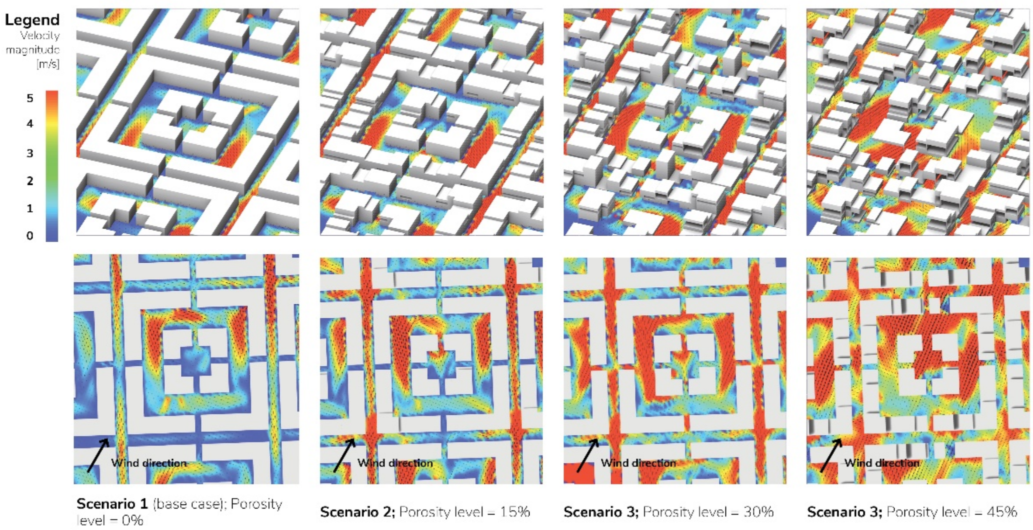

Figure 4. *Wind simulation results; colour-coded by velocity magnitude, (m/s)*

Results and Discussions

Energy study results

From the solar energy penetration perspective (Fig 3), it could be observed that all options, which have the same Floor Area Ratio (FAR ≈ 3) as the Punggol study perform worse than the best scenario, which has shown solar energy penetration = 0,21. However, in the case of the SUTD campus, the difference is insignificant - around 20 per cent of the energy demand it could be covered with PV electricity.

Wind study results

The following figure (Fig. 4) presents the flow field results of four scenarios on a z-section plane 10 m above the ground from the FFD simulations. It could be observed that the 1st scenario with a completely solid block shows low or almost no wind velocity in several areas of the block. Scenarios 2 and 3 show the gradual improvement in the wind velocity: now larger areas of the courtyard are covered with higher velocity levels. Finally, in the most permeable scenario 4 with 45% of porosity, there are almost no blue segments, with that the whole courtyard area having a medium or high degree of wind velocity.

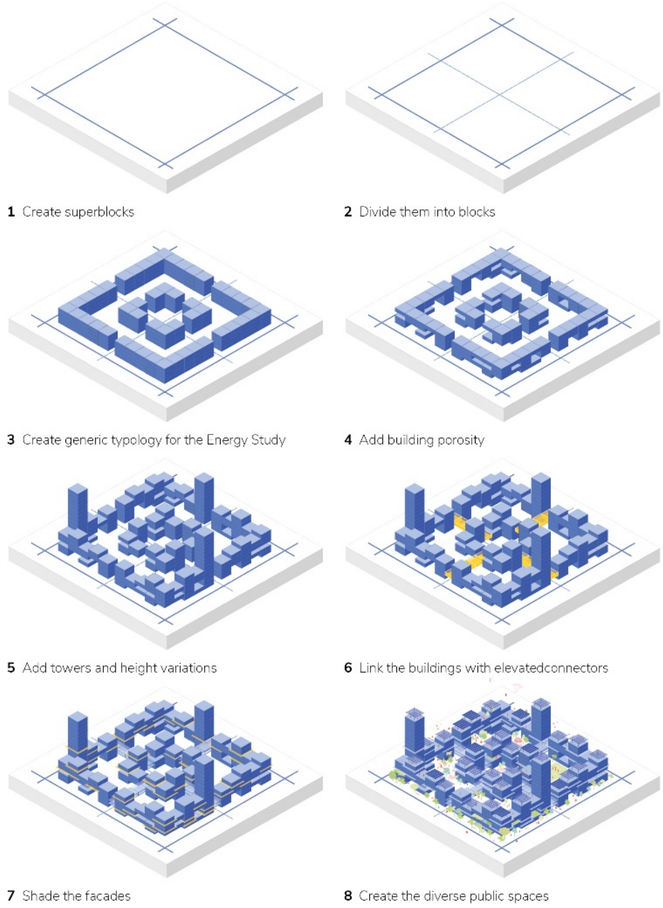

Figure 5. *Punggol campus type step-story*

An application of the type design

We modified the generic grid from the initial parameter study to make it better integrated into the context as well as to remove unnecessary street segments. Furthermore, we applied the largest density to those plots which are allocated within the shorter distance to both Light Rail Transit (LRT) and Mass Rapid Transit (MRT) stations. After defining the basic form as a result of the energy study and making it porous during the wind study, we took the following steps to further develop the most performant case study (Fig. 5):

Figure 6. *Urban design application on Punggol site*

1. **Towers|** To guarantee the high-density gradient around the transit hubs, following the logic of district cooling system efficiency, defined

by Shi et al. (Shi et al., 2021), the density gradient could be also controlled by the planner with the towers. Apart from allowing the user of the parametric model to control the density gradient, the towers facilitate the natural ventilation on the lower levels of typology by creating the downwash effect (Fig. 5.5).

2. **Connectors|** Next, we added the elevated green and shaded pedestrian bridges in the middle of each side to connect the buildings of the block in one entity while keeping this semi-outdoors transition climatically friendly for the occupants (Fig. 5.6).

3. **Large-scale programme|** For the special university functions, that require more space than the standard 20 m deep block, we dedicate a special part of the building. Where needed, we allocated it in the centre of the inner courtyard of the larger plots. In this way, the most important functions are placed in the most integrated parts of the campuses.

4. **Façade shaders|** As the last step, to reduce the cooling energy demand and increase the indoor thermal comfort, we generate the façade shading system. It will still be allowing the sunlight to be reflected and bring the natural light inside (Fig. 5.7).

5. **Public space|** The created block type (Fig. 6) forms a variety of public spaces with diverse character: the well shaded streets are linking the network of community plazas in the courtyards (Fig. 5.8), complemented by the semi-outdoor spaces with green and well-ventilated terraces inside the voids, that could be successfully used for educational purposes in Singapore (Tao et al., 2019). At the same time, they do not require any artificial cooling and do not compete for rooftop space with the PV.

Conclusions

The presented work addressed the relationship between urban form and energy and illustrated how principles of energy-driven urban design could be applied to a practical case study in Singapore. This study applied a combination of the parametric design space exploration and urban building energy modelling to quantify the impact of several urban form parameters on solar energy penetration in the context of the hot and humid tropical climate of Singapore. This was further supported by additional study to demonstrating the benefits of porosity. Based on this, we developed a parametric model for a new energy-driven campus courtyard typology, evaluated the different types that can be generated with the model, and applied it to the site of the Punggol Digital District. The selected type enabled us to achieve high solar energy penetration of 0,21 for the selected density and, at the same time, remain porous and facilitate natural ventilation and cooling. The energy and wind simulations have informed the design process and provided the insights on several design steps. Future studies may include other urban form scales, consider PV panels' embodied energy, couple the wind and the energy simulations, and deploy different design space exploration methods and knowledge management tools.

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