Informing the design of courtyard street blocks using solar energy models: a case study of a university campus in Singapore

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Abstract. This study discusses the interplays between urban form and energy performance using a case study in Singapore. We investigate educational urban quarters in the tropical climate of Singapore using simulation-based parametric geometric modelling. Three input variables of urban form were examined: street network orientation, street canyon width, and building depth. In total, 280 scenarios were generated using a quasi-Monte Carlo Saltelli sampler and Grasshopper. For each scenario, the City Energy Analyst, an open-source urban building energy simulation program, calculated solar energy penetration. To assess the variables’ importance, we applied Sobol’ sensitivity analysis. Results suggest that the street width and building depth were the most influential parameters.

1. Introduction

The building and construction sector accounts for one-third of rising global energy use [1] and hence has a significant energy efficiency potential. To unlock this potential, considerations of energy systems could be implemented in the early urban design stages. This study focuses on the relationship of urban form and energy in the hot and humid tropical climate, taking Singapore as a case study. Being located near the equator, it has a tropical climate, rich in solar radiation, with high and uniform temperature [2]. The relatively small territory of the city state as well as its natural and climatic conditions limit the potentials to deploy renewable energy sources. There are no hydro resources, the wind speed and tidal ranges are low, and geothermal energy is not economically feasible. However, its location in the tropical sunbelt provides Singapore with a high annual solar irradiance of 1,580 kWh/m²/year [3]. Therefore, at present, solar energy is Singapore’s main opportunity for renewable energy, and the country is taking action to allocate solar energy production on every type of suitable surface, including floating PV farms on its coastal waters and PV systems on building envelopes. In this context, new urban development projects can respond to this trend. For this paper, we selected one such urban development proposal, the
‘Punggol Digital District’, as a case study to demonstrate the principles of energy-driven urban design. It is envisioned to become an energy-efficient district, and is primarily zoned for educational use [4]. The study of urban form and types in relation to energetic performance can inform urban design. Earlier research has shown an interplay between urban form and energy [5–8], including studies in tropical climates [9–11]. Possibly because they typically do not offer good ventilation, courtyards are not as predominant in Singapore as elsewhere. However, a recent review of local university campuses [9] shows that it is a common type used in educational complexes (Fig. 1). Research of Shi et al. [10] on high-density districts investigated the energy performance of different street block types but did not consider courtyards nor studied university campuses. A typological study by Zhang et al. [11] did include on-site solar energy use for the courtyard types but did not include university campuses. However, the consideration of this use-type is important since it has a unique pattern of energy use and urban form properties.

2. Methodology

2.1. Data collection
Geographic data was extracted from the Singapore Master Plan 2019, provided as open data by the Urban Redevelopment Authority of Singapore [12], complemented with building polygons retrieved from Open Street Map [13]. We imported all the datasets into Rhinoceros 3D [14].

2.2. Case study - Punggol Digital District
As a part of the Singapore Economic Gateways, the case study site - Punggol Digital District intends to boost the innovation economy of Singapore and facilitate the synergies between educational, research and business uses that it will accommodate. By promoting sustainable modal split, reducing the energy demand of the neighbourhood, deploying renewables, district cooling system implementation and smart energy grid management, the district aims at carbon footprint reduction [4].

2.3. Courtyard-block-typology design

2.3.1. Overview of the parametric model.
We extracted Energy-driven design principles from the literature review to create a parametric model of the urban block, that consists of two courts forming a connected university cluster, local streets inside the block and larger medium streets between blocks. The values for urban morphological properties are based on a survey of Singapore’s educational urban quarters [9]. We created a homogeneous environment with a simple street network grid structure.

Figure 1. Examples of courtyard typologies in university campuses of Singapore

Figure 2. Three input variables for courtyard block type generation.
and repetitious block configuration. This setup allows evaluating the influence of the specific input parameters on the performance of given types of built form within a block [15]. We selected an urban block as a basic unit to enable us to run time-efficient simulations. In addition, the buildings in the closest vicinity to this block were integrated into the model, due to the shadowing effect.

2.3.2. Design inputs - variables and constants. We selected three input parameters to be varied in this study: \( X_1 \) = street network orientation [0-90] degrees; \( X_2 \) = local street width [6-20] m and \( X_3 \) = building depth [10-20] m (Fig. 2). The input \( X_2 \) also defined the medium street width as a dependent variable, that was set to be two times larger than the local \( (X_2 \times 2) \). We set other properties of the urban form to remain unchanged. It included the Floor Area Ratio (FAR) = 3 (defined in the Singapore Master Plan), building typology, the land-use ratio of: 50% - university, 25% - office, and 25% - residential programmes. Furthermore, the plot area and elongation of the urban block were uniform: a square shape of 8000 m².

2.4. Sampling for Sensitivity analysis
The link between urban form and energy performance relies on multiple variables. To evaluate the weight of each input parameter, one of the commonly applied methods is sensitivity analysis [16], [17]. Following the methodology from Shi et al. [18], this study uses the quasi-Monte Carlo Saltelli sampling technique via the SALib - Sensitivity Analysis Library in Python that generates model inputs with Saltelli’s extension of the Sobol’ sequence [19, 20]. This sequence produces a more uniform filling of the design space than the random sampling. We set the number of samples at 35, which together with 3 input variables (\( k = 3 \)) resulted in 280 combinations of variable values, according to the theorem “cost = \( n(2k + 2) \)” [21]. We use those sampled input combinations to define an input for the parametric model in Grasshopper [22]. After the 280 simulations had been run, we conducted the Sensitivity Analysis. This study looks at the Total Order Effect, which quantifies the impact of input parameters with the interaction between them. One of the major challenges regarding the applicability of the Sensitivity Analysis is the large number of output samples required to obtain accurate estimates. To extend the dataset of simulated results, the Artificial Neural Network (ANN) tool from data analysis software JMP was applied [23]. It augments the size of the simulated datasets as the input of sensitivity analysis. Three input variables were used as an input layer. Similar to a previous study [18], K-Fold clustering was applied as a cross-validation method to make efficient use of limited data. The neural network had 1 hidden layer, consisting of 3 nodes, with the number of K-folds = 7. This combination was defined after several trials; it results in the best values of \( R^2 = 0.979 \) and Mean Absolute Deviation = 0.003. It indicates that the model creates reliable predictions regarding solar energy penetration output. Using the predicted results, the sensitivity indices were calculated.

2.5. On-site solar energy use assessment

2.5.1. Tool - CEA (City Energy Analyst). For energy modelling, we used the CEA, an open-source urban building energy simulation program [24]. It allows analysis and optimisation of energy systems on the neighbourhood and district levels. It has been successfully applied in various studies tackling the link between urban form and energy systems, renewable energy production, energy usage profiles, etc. [25, 26]. In this study, CEA and its Grasshopper plugin [27] in version 3.4 were used.

2.5.2. Metrics - solar energy penetration. Following the method described in the research by Shi et al. [10], this study is adopting its metric of solar energy penetration to evaluate district energy performance, with metric values from 0 to 1. It is calculated as the fraction of cumulative annual PV yield of the total
annual electricity demand [kWh/yr]:

\[ \text{Solar energy penetration} = \frac{\sum E_{PV}}{\sum E_{grid}} \] 

with \( E_{PV} \) representing PV yields [MWh] from all buildings inside the block, and \( E_{grid} \) representing the block’s total electricity demand from the city grid [MWh] [10, 28]. Both energy demand and PV yields were calculated using CEA [27].

3. Results

Sensitivity analysis results show that the inputs of variables building depth and street width were the most influential, with similarly high importance (with building depth slightly higher). They received Total Effect indices of 0.545 and 0.46, respectively. Interestingly, the influence of street network orientation was almost negligible, with a Total Effect value of 0.008.

The graphs in Fig. 3 plot the three input variables and the solar energy penetration output of the 280 simulated results. For the \( X_1 \), street network orientation, the graph does not show a strong trend (top graph), with orientations closer to 0 and to 90 degrees resulting in slightly higher performance. When it comes to \( X_2 \) and \( X_3 \), a stronger trend is observed. In the case of street width (middle graph), the increase of the variable values had a negative relation with the solar energy penetration value. In contrast, higher values of building depth correspond to better solar energy penetration (bottom graph).

The best-performing scenario has a narrow street canyon (7 m for the secondary street, and 14 m for the main), the largest possible building depth (20 m) and a street network orientation close to cardinal (2°). The value of solar energy penetration achieved in this scenario is 0.21. The worst performing case has a lower solar energy penetration of 0.06 – this courtyard type scenario has a wide street (19 m for the local street; 38 m for the medium), the buildings are only 10 m deep, and the street network is rotated to 54 degrees.

The influence of street width, building depth, and street orientation can be explained by four factors. First, narrower streets decrease the solar heat gain and reduce the cooling demand by having more shading effects in the street canyon. Second, high building depth and low street width both lead to a bigger building footprint and roof, which is the predominant source of PV yields. Third, high building depth results in fewer building surfaces for solar heat gains. Fourth, the street orientation has a low impact as it mainly affects the building façade, a much less important source of PV yields compared to the roofs.

Figure 3. Solar energy penetration in relation to input variables
4. Discussion
The high impact of building depth and street width indicates a positive relation between solar energy penetration and site coverage. In this study, the footprint equals the roof area, and one of the most significant results indicated that options with a larger footprint are associated with higher solar energy penetration. This is aligned with the conclusions from other research [10]. For PV yields, only the larger roof surface is valuable. Distinguishing between the footprints and roofprints at the urban design level could increase the solar energy penetration and provide other benefits. The roof surface could be bigger than the footprint, such as an overhanging roof, for PV yields. To enlarge the roofprint, the design can even use a transparent PV covering the courtyard space and allowing sunlight to penetrate. A smaller footprint can increase indoor sunlight accessibility and decrease the impervious surface at the ground level, helping mitigate the urban heat island effect. Meanwhile, as the FAR remains constant, a smaller footprint will increase the building’s surface-to-volume ratio and increase the façade surfaces exposed for solar heat gain. Potentially, a calculated large roofprint may have some shading effects onto the building surfaces to mitigate this additional solar heat gain and allow accessibility to natural lighting.

This study has several limitations. Firstly, it is focused only on Singapore and its tropical climate and the results are location-specific. Secondly, it accounts for one aspect of urban form and energy, whereas there are interdependencies on multiple levels (mobility systems, different programs, construction materials or architectural details). Thirdly, the study does not consider embodied energy as well as the temporal gap between the PV supply and energy demand. Furthermore, the deployed energy model does not include other environmental factors, such as wind, which is of significant importance in tropical climates.

5. Conclusions
In this paper, we examined the courtyard street block type for educational uses through a case study in Singapore. The results show that the contribution of façade PV yields is limited compared to that from the rooftop. We discussed a potential plan to separate the roofprint with the footprint to maximize the PV yields and provide shades. Orientation and façade design are less important for PV yields and can be informed by other urban qualities like natural ventilation. Future research could extend this study by accounting for different aspects of urban form, other forms of energy production, and the PV temporal supply gap. Further studies could also focus on other methods for design space exploration (for instance – evolutionary algorithms) and semantic knowledge management techniques (for example – Knowledge Graphs).

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