Correlation of urban built form, density and energy performance

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Abstract. In order to optimize the energy consumption in cities and enhance the potential of using renewable energy sources, the form of the city is considered as an influential factor. Numerous indicators have been used to analyse the effect of density and other characteristics of urban form on energy use. The paper presents results of an investigation into the relationships of building energy performance with two important urban density indicators, namely site coverage and volume-area ratio. Generic mathematical model of pavilion urban built form has been developed in order to compare and contrast its land-use/density characteristics with energy performance. Energy analysis has been performed on geometrical models using urban simulation software. The relationship between energy and density indicators are compared by considering an important variables, namely plan depth, cut-off angle and number of storeys. The city of London, representing a temperate climate, is considered as a case study. According to the results, high-rise buildings with deeper plans achieve higher energy efficiency. However, in case of including PV energy generation, low-rise buildings with deeper plans illustrate better total energy performance. Graphical results provide urban planning guidelines that can be used by urban designers, planners and architects to facilitate the most energy-efficient built form density for promoting more sustainable cities.

1. Introduction

Cities are rapidly growing due to urbanization. More than 50% of the world’s population live in urban areas, and this is predicted to reach 66% by 2050 [1]. Their energy demand (encompassing building, transportation, service and commercial activities) varies with climate, energy technologies and urban form. Hence, the form of the city has an impact on its energy use [2, 3]. “*The buildings and buildings construction sectors combined are responsible for 36% of global final energy consumption*” [4]. Since urban form illustrates a significant relation with the energy demand in buildings [5], it is crucial to establish the relationship of building energy consumption with urban form in order to optimize the future development of cities in an energy efficient manner.

Urban form is composed of many attributes such as density, diversity, green areas, orientation, shading, passivity, connectivity, accessibility and centrality [6], and the impact of each attribute should be analyzed. Identifying the relationship of urban form and energy, most of the studies in the literature consider density as the main variable of interest. According to [7, 8], both higher density buildings and taller buildings can significantly increase heating energy efficiency. Internationally this has resulted in greater intensity for compact cities since urban sprawl increases the energy consumption of buildings [9, 10]. On the contrary, [11] believe that high-rise buildings are energy-intensive than low-rise buildings. A case study in Sydney has found that high-rise residential buildings consumed more energy than medium-rise which, in turn, consumed less than low-rise [12].

However, urban areas are increasingly generating their own energy from renewable energy sources [13] such as rooftop mounted PVs as well as ground source heat pumps with both requiring a larger area that cannot be achieved by compact high-rise buildings[14, 15]. Hence, there is emerging evidence challenging the compact city assumptions and shows that dispersed urban form may be more energy efficient [16, 17]. In some places the sprawl structure of city has greater advantages due to reachability of renewable energy sources [18]. It pointedly means, considering the energy supply side in addition to the energy demand side could change the equations in this research area. Although, there has been considerable research in building energy consumption and renewable energy potential (specifically solar energy [19, 20]) in cities, most are considered in isolation with little notable contributions that consider them simultaneously. Thus, the exact and true effect of city form on the energy flows (energy consumption plus renewable energy supply) has yet to be effectively addressed.

Density of urban form has been investigated by a number of researchers using a variety of indicators such as site coverage, plot ratio [21], volume-area ratio [22], building density, open space ratio [23], nearest-neighbor ratio [19], BPRU index/compactness index [24], surface to volume ratio [25], volume wall area ratio [26], urban entropy [19], form factor [27] and habitable rooms per hectare [28]. This diversity of density indicators makes a comparison of results quite challenging. Meanwhile, none of the mentioned indicators are sufficiently comprehensive to determine the true definition of urban density. Hence, a set of density indicators should be selected to make a reliable estimation of density [29]. There appears to be a lack of unifying language to express the results of urban energy analysis based on urban density.

Another critical issue in energy analysis of urban areas is a consideration of the specific impact of urban built form as they vary the microclimatic conditions [30], impacting on building energy demand [5]. It means that for energy analysis of urban areas, in addition to density, the urban built form (e.g. pavilion, court, and terrace) should be taken into account simultaneously. It is the aspect that this paper primarily addresses.

This study investigates the relationship of building energy consumption and solar energy generation in urban areas with urban built form and density. An analytical model of pavilion built form is developed to derive related equations from its geometry. Considering the climatic conditions of London, and performing energy simulation, the results are presented graphically illustrating the simultaneous relationships of urban built form, density and building energy consumption/generation. The models not only consider current conditions but also, unlike previous models, provide the potential of taking into account the impact of emerging disruptive technologies. The results can be used as decision-making tool to address the best fit between built form and density, with respect to energy optimization.

2. Methodology

Generic model of pavilion urban built form is developed in order to firstly define the true relationship of urban built form and density and secondly establish the correlation between them and energy performance of urban areas for various cases. Pavilion built form is considered as it is popular in many locations worldwide [31, 32], though slightly amended with regard to culture and climatic condition. Underpinning equations are derived from the geometrical models (Figure 1 (a)) that govern the correlation between indicators. Two density indicators, namely site coverage (the ratio of area covered by buildings on total area of the site) and volume-area ratio (the ratio between total volumes of buildings on area of the site) are selected to sufficiently determine the true concept of urban density for energy analysis. The former is selected to give land-use characteristics of plans and the later to correspond to energy analysis results given per unit volume. The idea of selecting this set of indicators is derived from the concept of Form Signature [29].

Critical variables that influence density indicators are number of storeys (n), plan depth (x) and cut-off angle (θ). The geometrical relationship of these three variables is shown in Figure 1(b). Cut-off angle is the angle between the ground and the line joining the roofline of one façade to the base of opposing façade. The storey height and distance between buildings are shown by *h* and *L,* respectively.

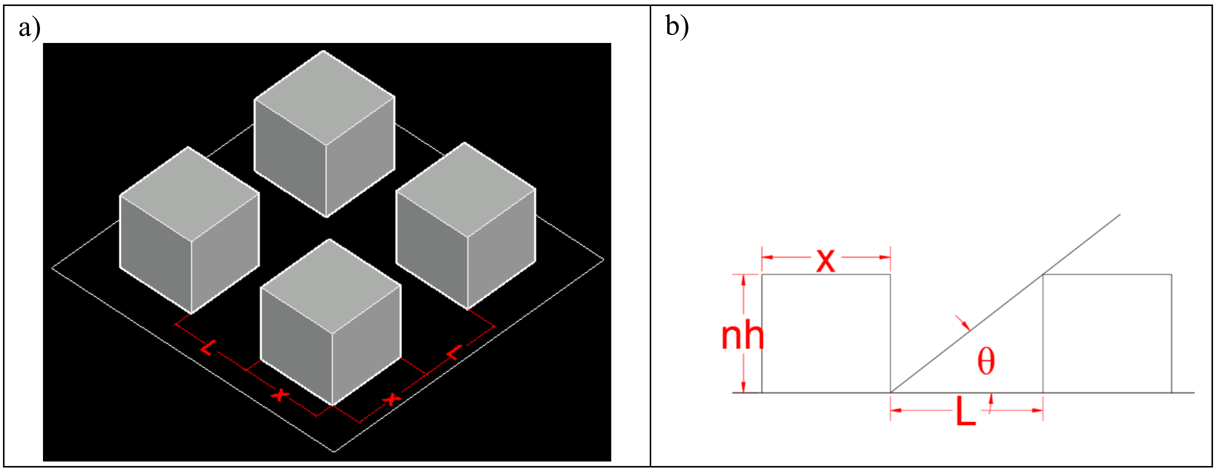

Figure 1: Generic model of pavilion built form (a), geometry of cut-off angle (b)

Energy analysis is performed on geometrical models of the aforementioned built form using urban simulation software, CitySim. This software has been chosen due to its capability for "urban" simulation rather than building simulation. It readily considers influential parameters on urban analysis such as shadowing effect and inter-reflection between external surfaces. Only heating and cooling energy demand of buildings are calculated since urban planning has a significant effect on reducing the building heating/cooling consumption [33]. Lighting energy demand has not been considered in this study that would increase the energy demand of buildings.

To ensure a like-for-like comparison between built areas with different densities, theoretical master plans are developed for energy analysis. The parameters such as building materials, isolation, glazing ratio and occupant density are kept constant in order to identify the true effect of form and density on the energy performance of buildings.

An energy indicator termed "energy equity" is introduced in this study that is an indication of building energy self-sufficiency. It is defined as the ratio of energy generation by building-mounted PVs over building energy demand. Energy equity values of higher than one means the building achieves energy surplus, while, the value of one indicates that the building is energy self-sufficient. The simulation covers annual heating and cooling energy consumption plus PV energy generation. For comparison reason, heating/cooling systems are considered for all the cases with similar heating/cooling seasons.

Geographical and climatic conditions of London, representing a temperate climate, is considered as a case study for energy simulation. The climatic data were obtained from Meteonorm software [34].

3. Results and discussion

Numerical analysis of the equations, derived from geometry of the urban built form, established the simultaneous correlation of selected density indicators considering the main influential variables (i.e. number of storeys, plan depth and cut-off angle). The investigation summarises the results as a set of graphs indicating the intercorrelation of all variables of interest. Figure 2 shows the results for the cases of cut-off angles of 25° and 45°. This graphical presentation of the results allows visual recognition of the impact of changing any of the underlying parameters. Horizontal and vertical axes represent site coverage and volume-area ratio, respectively. The diagonal lines radiating from the origin of the graph show the number of storeys starting from 1 to 30. The curve lines represent plan depths ranging from 6 to 60 m in 6 m increments.

Aggregated results of energy simulation of each model were overlaid on Figure 2 as a heat map to show the intensity of energy consumption. It demonstrates the correlation of building heating and cooling energy consumption with urban density in case of pavilion built form. Two values of cut-off angle are considered in order to examine the effect of altering distance between buildings. Unit of kWh/m^3 is used to facilitate an equitable assessment of different building plans with various dimensions, meanwhile, to take into account the effect of floor height.

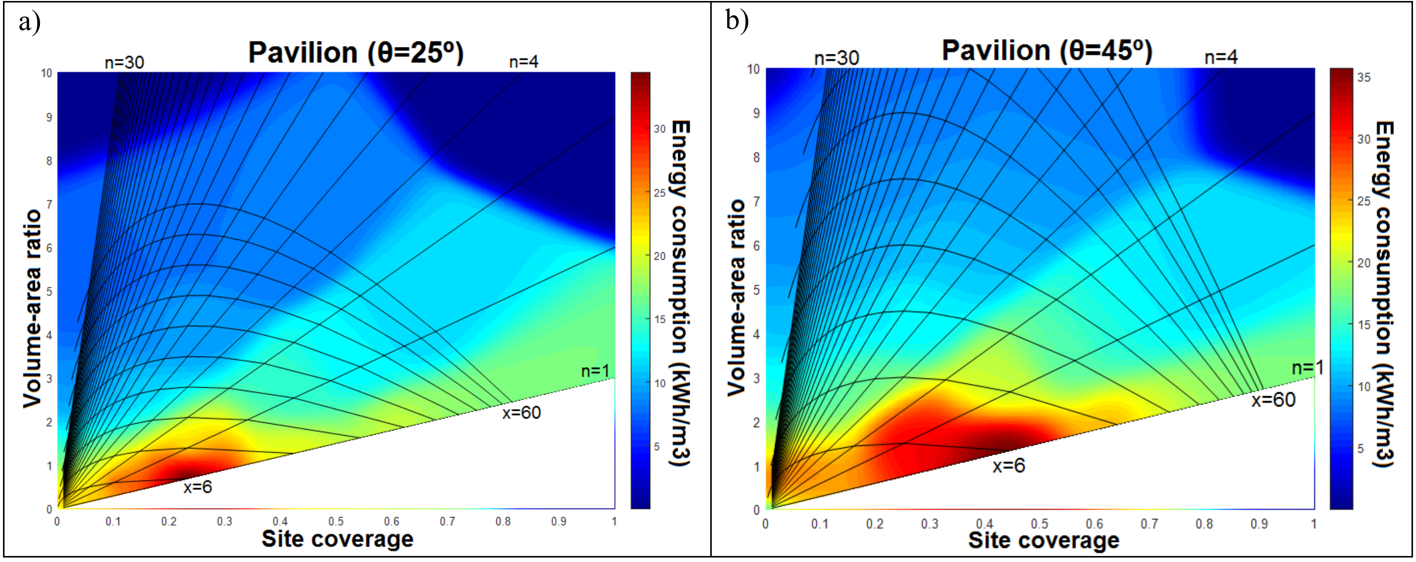

Figure 2: Correlation of building energy consumption with urban built form and density a) pavilion θ=25° b) pavilion θ=45°

It can be seen from both cases in Figure 2 that urban built areas with low-rise buildings (number of storeys up to maximum 4) and low plan depths (up to 20m) present worst case scenarios regarding energy consumption (shown in red). Conversely, urban built areas with higher number of storeys and plan depths demonstrate the lowest energy consumption per unit volume (indicated in blue). The main conclusion from these results may provide encouragement to urban planners to adopt high-rise buildings and large plan depths for new urban developments. However, as previously discussed, there are opportunities for buildings to generate their own energy from renewable energy sources. To take into consideration the potential of PV energy generation in urban built areas (i.e. PVs are mounted on building roofs), further simulations were conducted. The results are shown in Figure 3 representing the intensity of energy equity on the form-density graph.

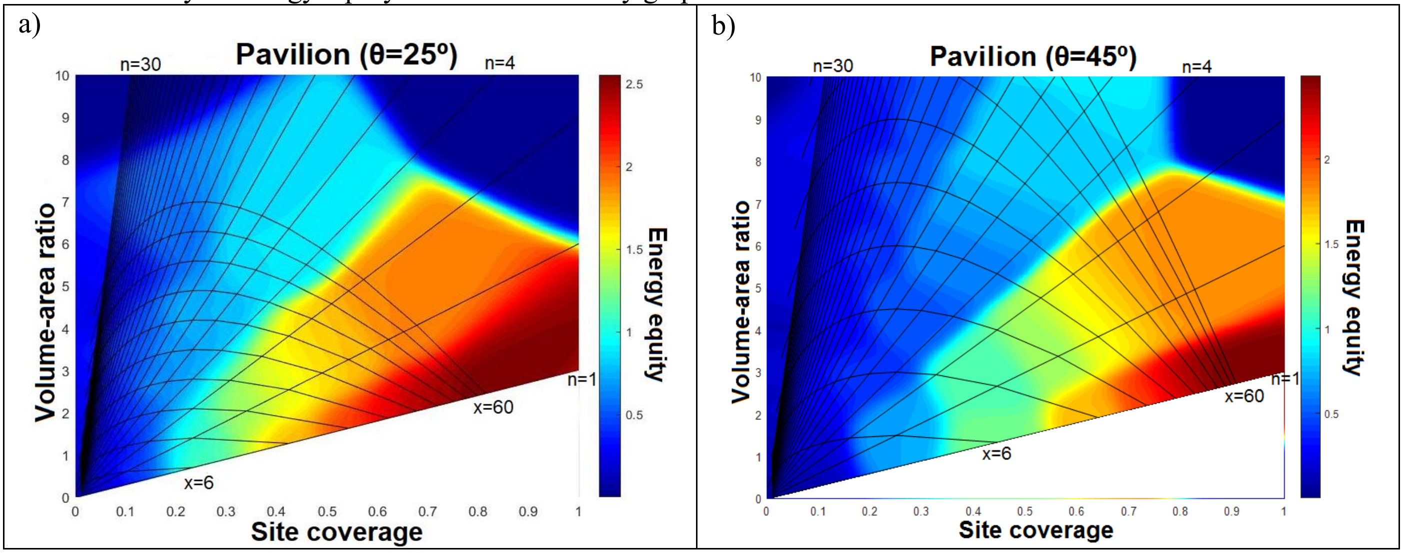

Figure 3: Correlation of energy equity indicator, considering the impact of PV generation, with urban built form and density a) pavilion θ=25° b) pavilion θ=45°

From Figure 3, it can be concluded that built areas with higher plan depths and lower number of storeys possess greater potential for solar energy generation. The red and orange areas of the graph represent the urban area that can potentially achieve greater solar energy generation compared to its energy consumption. An interesting application of this graphs is the ability to determine the appropriate urban density that buildings can energetically to be self-sufficient (this is indicated in bright blue which represents the energy equity value of one).

The results of this paper demonstrates that the high energy intensity areas of the relevant graph for each cut-off angle are approximately similar which shows the significant effect of plan depth and number of storeys. However, altering the cut-off angle certainly impact the energy performance of urban built area due to variation of the factors such as shadowing effect and interreflection between buildings external surfaces in the form of long wave radiation. The outcome of this study indicates that, having buildings farer from each other (θ=25º), lower heating load but higher cooling load are needed for buildings comparing to the case of θ=45º. It is mainly because of the lower shadowing effect as well as less infrared radiation received from adjacent buildings walls in case of positioning buildings in longer distance from each other. Another difference is that, in case of buildings with small plan depths, built areas with θ=25º consume slightly lower amount of energy (roughly 1%) comparing to areas with θ=45º, while this conclusion is opposite in case of buildings with larger plan depths. The same analysis can be repeated for other values of cut-off angle that changes the distance between buildings. The complete set of results has the potential of being an urban planning tool to be used by various stakeholders in the built environment, including urban designers, planners, architects and authorities to optimize the energy performance of growing urban areas for achieving the target of sustainable cities. The same methodology can be employed for analyzing the energy performance of other urban built forms such as terrace and court form.

In addition, this analysis showed that increasing depth of the plans, all the other variables being equal, results in a rise in the ratio of heating over cooling demand, while, increasing number of storeys leads to a fall in the ratio of heating/cooling demand.

It should be noted that although it is possible to have deep plans, it is not usually recommended as it limits the potential of passive design strategies resulting in over reliance on artificial means for environmental control of building. This may increase energy demand of buildings while having adverse effect on user comfort, wellbeing and satisfaction. Utmost increase in plan depth of pavilion form practically results in form transformation to court form requiring an independent study in future.

4. Conclusions

This paper investigated correlations between urban built form and density affecting energy consumption of buildings and their potential for solar energy generation. The simultaneous relationships of two density indicators, namely site coverage and volume-area ratio, with urban geometrical variables investigated and presented for the case of pavilion built form. Based on heating and cooling energy consumptions, the results indicated that higher number of storeys and deeper plans results in higher energy efficiency. However, in case of including PV energy generation, low-rise buildings with deeper plans illustrate better total energy performance. The results suggested that high energy-intensity areas of the graphs are roughly the same regardless of the cut-off angles considered in this analysis, i.e. 25º and 45°. The contribution of heating and cooling loads to the total demand may however be different. For example, lower heating demand and higher cooling demand are recognized in the case of θ=25º comparing to the case of θ=45º. It is mainly due to the diminished shadowing effect and limited radiation received from adjacent buildings. Adopting the same methodology for other values of cut-off angles, set of guidelines can be generated showing inter-parameter sensitivity of built form, density and energy performance. This indicates an area for future research. Furthermore, the impact of disruptive technologies such as electric vehicles can be taken into consideration for future scenarios. Although the climatic conditions of London have been used in this study, the same analyses can be done for other cities in the world. The outcome facilitates identification of optimum design conditions for developing sustainable urban built form in relation to the climatic conditions.

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