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Evaluation of Urban Compactness Indicators and Solar Potential in the Urban Environment

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Abstract: One viable solution for clean on-site energy production and utilisation is Building Integrated Photovoltaics (BIPV). The available area for installation may not be sufficient to meet the building energy demand in high-rise urban buildings in tropical climates, although rooftops are ideal for photovoltaic (PV) module integration. This causes a requirement for the utilisation of facades. Furthermore, the unplanned urbanisation in Colombo has resulted in a difficulty in quantifying urban compactness and solar potential in urban environments. Therefore, there exists a requirement to assess the applicability of urban compactness indicators in quantifying solar irradiation on building envelopes in the urban contexts. This paper attempts to evaluate the credibility of several urban compactness indicators in relation to solar potential and establish the most applicable indicators in regard to the context of Colombo. The results showed that the roof to envelope area ratio provides optimum accuracy for predicting solar potential in the urban context of Colombo, Sri Lanka, whilst the average heights ratio exhibited the lowest. These results are significant for urban planners and developers when considering urban design guidelines.

Keywords: Urban; Solar Potential; Compactness

Introduction

In recent years, conventional energy saving and the use of unconventional renewable energy (NCRE) have become issues of great importance. Energy costs have increased due to the utilisation of fossil fuel or non-renewable energy, where solar energy is a renewable energy source with great potential, which may become the world's main source of electricity by 2050 (IEA, 2014). Recently, the architectural form in the urban environment has been changing to taller high-rise buildings, thereby further increasing the demand for energy. Sri Lanka's construction industry is growing and currently accounts for 35% of the country's energy consumption (Kumanayake et al., 2018; SLSEA, 2014). After realising the necessity to change to clean energy, the country has been moving towards a green economy and is implementing policies to reduce Sri Lanka's dependence on imported non-renewable energy (Ministry of Power and Energy, 2015). This tropical island is located towards the north of the equator and is on the receiving side of a lot of solar radiation all year round. In this case, building integrated photovoltaics (BIPV) are ideal solutions because they can generate electricity on-site, thereby reducing losses caused by grid conversion and transmission. In addition, they are a renewable and carbon dioxide neutral energy system (MacDowell et al., 2010). Through the use of building envelopes for photovoltaic module integration, BIPV can capture and convert solar energy on-site in urban areas. The application of BIPV on the facade of modern buildings is already common in high latitude countries (Xu et al., 2014; Zhang et al., 2012; Taleb and Pitts, 2009; Roberts and Guariento, 2009; Unnewehr et al., 2012) due to the positive inclination towards solar irradiation and the vast area available for the installation of PV modules. Office buildings are best for BIPV applications because the panels generate electricity at roughly the same time that the building is in function (Lam et al., 2003). Even when used with materials with low emissivity, it is generally not recommended to use the structure of all-glass curtain walls in tropical locations (Halawa et al., 2018), unless it is used in conjunction with additional shading strategies. Tropical areas are more suitable for rooftop photovoltaic installations, but high-rise buildings may not be able to meet the energy needs of such buildings because the roof area may be insufficient. This has brought about the need to optimise external photovoltaic integration in tropical environments.

Previously, solar potential research has been carried out based on urban form (Compagnon, 2004; Robinson, 2006; Cheng et al., 2006a; Cheng et al., 2006b; Li et al., 2015; Sarralde et al., 2015) from the building and neighbourhood scale to the urban scale (Montavon, 2010; Pessenlehner and Mahdavi, 2003; Kanters et al., 2014; Wiginton et al., 2010). These are based on the investigation of the influence of different layouts in vertical and horizontal forms of building forms on solar energy potential and solar utilization (Cheng et al., 2006a), as well as the influence of various parameters indicating the shape and density of the city, including but not limited to plot ratio, site coverage, and building density (Morganti et al., 2017). Similarly, some studies have focused on assessing the solar potential of existing urban layouts (Kosir et al., 2014), but these studies were based on characteristic architectural forms, with few variations. Others only considered residential buildings (Li et al., 2015; Hachem et al., 2011), and some of them made use of solar radiation by suggesting optimized building shapes and urban layouts, and thus proposed urban space design guidelines. (Morganti et al., 2017). However, many of these studies have been related to using general and characteristic urban layouts to explore the impact of urban form on solar energy potential (Mirkovic et al., 2017), but have not been applied to actual case studies. In addition, despite the detailed analysis of independent buildings, due to the adverse effects of neighboring buildings and mutual occlusion, urban blocks cannot capture as much solar radiation as independent buildings. Therefore, the study of the influence of urban form on the solar potential is an area that has attracted increasing attention (Mohajeri et al., 2016).

A major problem in the Colombo architectural environment is the rapid spread of urban sprawl due to rapid urbanization (Amarawickrama et al., 2015). The combination of unplanned urban development and the lack of zoning plans have led to the random development of urban areas and the randomization of urban forms throughout the city, with no quantifiable forms or functions. Urban blocks in Sri Lanka often have multiple functions, with residential, commercial, government and industrial buildings coexisting in the same urban space. Therefore, it is difficult to conduct research in the city based on the function of city blocks. One of the most commonly used indicators of urban form is urban compactness (Mohajeri et al., 2016). However, in the real built environment, research on assessing the full impact of urban compactness on solar energy potential is limited. Researchers have studied compactness in many ways, but there is a lack of knowledge about how compactness in existing communities affects the solar potential of buildings (Li et al., 2015; Sarralde et al., 2015; Tsai, 2005; Mendis et al., 2020a; Mendis et al., 2020b).

Therefore, this paper attempts to assess the solar energy incident on urban building envelopes based on urban compactness in Colombo in terms of urban compactness indicators, where ten random blocks in the city are evaluated with the goal of determining their respective urban compactness indicators, and how these indicators affect the solar energy incident upon the central building.

Methodology

A. Urban Block Type

This study made use of ten city blocks. Colombo is the financial capital of Sri Lanka, and unplanned rapid development in the past couple of decades has led to an rise in urban block functions taking on a mixed form along with urban expansion. This has brought about an inefficient use of available resources, including land, and has created an abundance of problems to the general public, including inefficient transportation means, pollution, and other services. Due to this, the city blocks that were selected are primarily of mixed form, where residential, commercial, and government regions exist together within the same urban block. However, for the purposes of this study, the focal point of analysis is upon the central building within the urban block. The definition of compactness is carried out by using the urban compactness index calculations, and these are related to the urban block's density in relation to specified standards. Several urban compactness indicators (UCIs) were used in this study, which include: (a) site coverage ratio, (b) volume to area ratio (V/A), (c) building density, (d) open space ratio, (e) building density, (f) ratio of average heights, (g) the area to perimeter ratio, (h) compacity ratio, (i) ratio of floor area to site area ratio, (j) ratio of roof area to the building envelope area. The V/A ratio is the volume of all buildings in the block against the total site area of the block; site coverage is the total building footprint area of all buildings in the block divided by the area of the block; The plot ratio is the total building floor area of all buildings in the block divided by the area of the block; the building density is the total number of buildings in the block divided by the site area of the block; the open space ratio is the open space area on the site divided by the total building area in the site; compacity is the building envelope area divided by the building volume; the ratio of the roof to the building area is the total roof area divided by the total building area; the roof and the envelope structure area is the ratio is the total roof area divided by the total building envelope area; the average heights ratio is the sum of the heights of the buildings divided by the number of buildings. Figure 1 below shows the ten urban blocks that were selected for evaluation. These were selected randomly from different regions of Colombo ranging from the city centre to surrounding areas, and Tables 1 and 2 provide a breakdown of the blocks by their parameters and urban compactness indicators from Blocks 1-5 and Blocks 6-10, respectively.

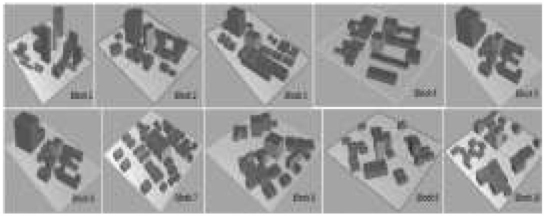


Figure 1. Urban blocks in Colombo

Table 1. Blocks 1-5 analysed by urban compactness indicators

Block Parameters	**Block 1**	**Block 2**	**Block 3**	**Block 4**	**Block 5**
Site area (m²)	108026	46689	120637	65611	36318
Volume (m³)	706025	187160	340871	188434	252883
Footprint (m²)	22283	10116	18072	16994	9576
Floor area (m²)	235342	62387	113624	62811	84294
No. of buildings	23	17	27	25	18
V/A Ratio	6.5357	4.0087	2.8256	2.8720	6.9631
Site coverage	0.2063	0.2167	0.1498	0.2590	0.2637
Plot ratio	2.1786	1.3362	0.9419	0.9573	2.3210

Building density	0.0002	0.0004	0.0002	0.0004	0.0005
Open space ratio	0.3643	0.5862	0.9027	0.7740	0.3172
Area to perimeter ratio	3.9112	3.0533	3.1919	3.1113	2.8719
Compacity	0.1650	0.2128	0.1746	0.2434	0.1654
Roof to floor area ratio	0.0947	0.1622	0.1591	0.2705	0.1136
Roof to envelope area ratio	0.1912	0.2540	0.3037	0.3706	0.2290
Average heights ratio	0.0141	0.0150	0.0058	0.0101	0.0162

Table 2. Blocks 6-10 analysed by urban compactness indicators

Block Parameter	**Block 6**	**Block 7**	**Block 8**	**Block 9**	**Block 10**
Site area (m²)	27294	28457	26477	29874	29677
Volume (m³)	56185	79853	72968	53586	62374
Footprint (m²)	6492	8810	6755	4823	6772
Floor area (m²)	18728	26618	24323	17862	20791
No. of buildings	29	31	25	21	26
V/A Ratio	2.0585	2.8061	2.7559	1.7937	2.1018
Site coverage	0.2379	0.3096	0.2551	0.1614	0.2282
Plot ratio	0.6862	0.9354	0.9186	0.5979	0.7006
Building density	0.0011	0.0011	0.0009	0.0007	0.0009
Open space ratio	1.1107	0.7381	0.8108	1.4025	1.1016
Area to perimeter ratio	1.8753	2.1682	2.0810	1.8971	2.0240
Compacity	0.3595	0.3021	0.3101	0.3263	0.3411
Roof to floor area ratio	0.3467	0.3310	0.2777	0.2700	0.3257
Roof to envelope area ratio	0.3214	0.3652	0.2985	0.2758	0.3183
Average heights ratio	0.0156	0.0148	0.0169	0.0125	0.0146

B. Solar Irradiation Analysis

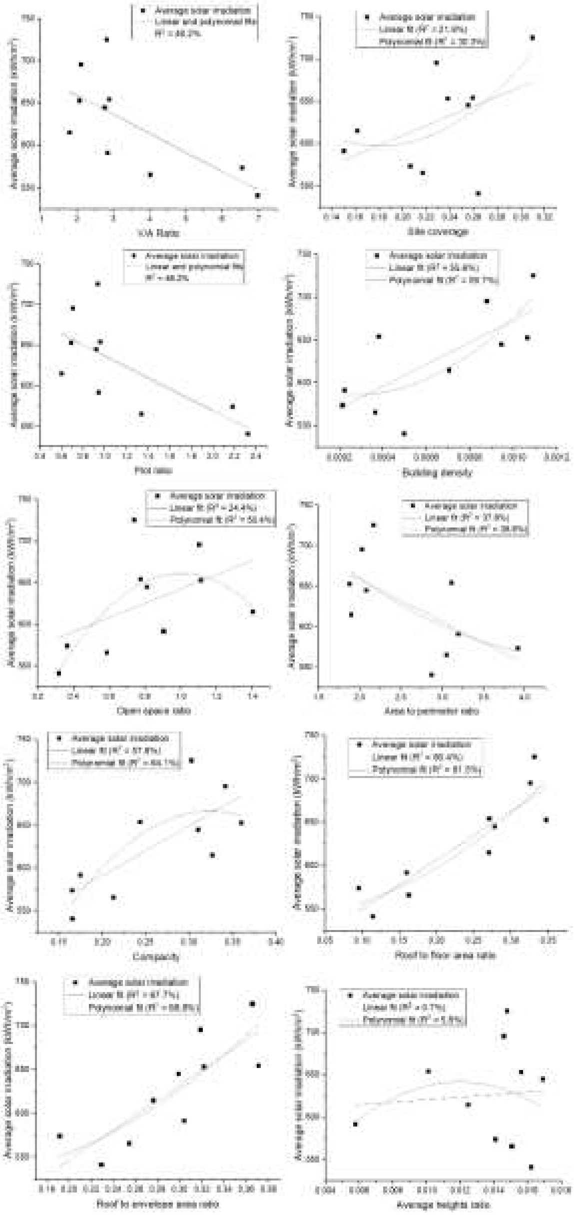
The solar radiation modeling was carried out through a proven method and model that could take into account the effects of time, location, climatic conditions and shadows. From the literature review, a variety of validated models can be found that are capable of evaluating solar radiation on the ground in urban environments. Some of these models include Daysim, RADIANCE, and ArcGIS Solar Analyst (Byrne et al., 2015; Freitas et al., 2015). RADIANCE is an accurate ray tracing software, which has been validated many times in previous research and can apply the Perez diffusion model (Perez et al., 1987; Perez et al., 1990), and considers both diffuse reflection and specular reflection. It has even been used for curved geometries (Ward, 1994), and has been successfully used in many applications to determine solar irradiation on building surfaces. The simulation engine is controlled by Rhinoceros 6, which is utilised as a plug-in. Rhinoceros is a 3D modeling software that has the ability to bring forth the Grasshopper interface - a visual programming environment and language. Ladybug and Honeybee are opensource tools which are installed in the Grasshopper environment. These help to investigate and evaluate environmental performance. Ladybug can import standard EnergyPlus weather files into Grasshopper (Roudsari, 2013). Then, the Ladybug tool maintains the initial phases of the decision-making and design procedure via the provision of a range of interactive 3D graphics. The Honeybee tool connects a visual programming language with four proven simulation engines that evaluate the building energy demand or consumption, thermal comfort levels and daylighting of buildings: EnergyPlus, RADIANCE, Daysim and OpenStudio (Roudsari, 2013). Therefore, validated environmental data sets and simulation engines are coupled with adaptable, component-based visual programming interfaces through these plug-ins. Thus, the suggested method for carrying out this study is to make use of the Rhinoceros and Grasshopper interfaces and the Ladybug and Honeybee tools, which will work as centers for radiation simulations using RADIANCE.

By using the RADIANCE simulation engine, a solar radiation simulation was performed in the urban environment of Colombo, Sri Lanka, where a selection of ten individual blocks were used, including a combination of block functions, such as commercial, residential, and government. The initial steps of the analysis include assessing the amount of solar radiation incident on the PV based on the average annual solar radiation (kWh/m2). This allows a better understanding of the solar radiation intensity available on the PV surface without having to consider the total annual solar radiation in kWh.

Results

The results found from the solar radiation simulation utilising RADIANCE demonstrate the value (kWh/m2) of the average annual solar radiation (façade) incident on the outer wall of the central commercial building in each block. Firstly, the solar energy potential of the block is analysed according to the radiation incident on the facade according to the respective city compactness indicators of the blocks. The preliminary results are based on V/A ratio, site coverage, building density, plot ratio, OSR, APR, compacity, RFAR, REAR, and the average heights ratio. The results obtained are shown in Figure 2 below.

Figure 2. Graphs of the average annual solar irradiation against the compactness indicators



The results obtained show that there is a debatable trend in the building density and site coverage graphs in comparison with those achieved in previous research, whereas those obtained for V/A ratio, plot ratio and APR appear to follow previous trends.

In addition, the coefficient of determination (R2) is calculated for the trend line of the solar potential within the block to determine the degree of fit of the model to the data. Generally, the higher the R2 value, the higher the accuracy of the data fitting the trend line. It can be seen from the obtained results that for the polynomial fit, that the roof to floor area ratio has obtained the greatest coefficient of determination, and for the linear fit, its coefficient of determination is the highest at 80.4%. This is followed by the REAR. The polynomial fit for the RFAR is 68.9%, and the compacity is 64.1%, whereas the lowest coefficient of determination is shown by the site coverage (which obtained 21.9% linear fit and 30.3% polynomial fit) and average heights ratio (which obtained 0.7% linear and 5.8% polynomial). It can be inferred that urban compactness indicators with low R2 values cannot accurately predict the solar potential in the urban environment of Sri Lanka. This research evaluates the solar irradiation in the block based on the solar irradiation incident on the central high-rise building. If the surrounding buildings are lower-rise and placed more densely (which in turn increases the site coverage and building density) in Sri Lanka, the linear fit line may not be entirely accurate. This is due to the fact that the city block with tall buildings is hemmed in by numerous low-rise buildings, which not only increases the floor space and added density of the buildings and the block, but also raises the amount solar radiation incident upon the central high-rise buildings. This could create an anomality in the results. It can be suggested that, in the setting of Sri Lanka, or rather Colombo, when taking into account the solar energy potential of central buildings in relation to a surrounding urban block, the more consistent means to assess the existing urban form based on the urban compactness indicator would be to consider the roof to floor area ratio (RFAR), since it considers for the actual verticality (i.e. building heights) of the amount of built area within the block. The RFAR also shows signs of a high coefficient of determination (R2) when compared with other urban compactness indicators (for instance, building density or site coverage), since these only account for the absolute building footprint of the total surround number of buildings within the block. It can be stablished that the latter two indicators (i.e. site coverage and building density) are not a reliable method of predicting solar potential in urban blocks with ranging levels of verticality.

Conclusions

This research was conducted to establish the ways in which different urban block types of various compactness affect the solar irradiation (which in turn affects the PV generation potential) on building envelopes within the urban block in Colombo, Sri Lanka. The means involved the evaluation of ten different urban blocks on the basis of their urban compactness indicators, where the UCIs were calculated separately for each block. Next the solar irradiation incident on each central building was simulated using RADIANCE and assessed against the respective UCI. The main contributions presented in this paper include the establishment of the most appropriate urban compactness indicators for assessment and predication of solar potential in the urban context of Colombo. It was identified that the roof to floor area ratio presents the most accurate means of predicting solar potential in the urban context of Colombo. Based on these results, further research could be conducted to estimate the solar irradiation potential of random urban blocks in Colombo and compare against simulated results in order to establish the accuracy of this method.

This research carries many benefits, including design guidelines and further understanding to aid authorities, urban planners, and designers with urban plans, in educating them on how urban compactness affects solar potential within the built environment, and how these parameters can be taken into account for sustainale urban design.

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