Compact cities in a sustainable manner

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ABSTRACT

Densification is generally assumed to exert negative impacts on urban daylight and solar potential, however, this paper demonstrates the possibilities to increase usable floor area and plot ratio without undermining the opportunities of daylight and solar applications. The paper investigates the diverse influences of built density on daylight access and the potential of two solar systems. The findings suggest that plot ratio is influential to quantities such as daylight factor, sky view factor and the potential of solar thermal and photovoltaic applications on roof, whilst the potential of solar thermal and photovoltaic applications on building facades are more dependent on site coverage and the extent of horizontal obstruction.

KEYWORDS

Compact cities, Density, Solar energy

1. INTRODUCTION

1.1 Background

Rapid urbanization in recent years has exerted tremendous pressure on urban development. To cater for the expanding urban population, densification seems to be an inevitable outcome. There is a growing concern about the environmental impact as a consequence of densification and it is generally assumed that an increasing built density would lead to deterioration of the immediate environment, in relation to solar access and urban ventilation, and lessening the potential for renewable energy application in urban scale. (Thomas, 2003)

However, these criticisms are not entirely fair as the definition of built density is often vague. In many studies, density is simply equivalent to plot ratio (ratio of total floor area to site area) and/or building height to street width ratio, which only represent two of the many manifestations of built density. This paper, by examining built density in a slightly different perspective, attempts to demonstrate that there are possibilities to compact cities in a sustainable manner, with reference to daylight and solar potential.

The paper first compares various theoretical built forms to explore the diverse effects of two different representations of built density i.e. plot ratio and site coverage (ratio of

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building footprints to site area) on urban daylight and solar potential. It then furthers the discussion by examining the performance of a range of existing building blocks in Luz, a city centre site in Sao Paulo, Brazil. Sao Paulo is now one of the biggest metropolitan areas in the world with a population of about 18 million; the case study thus puts forward the initial understandings of real urban contexts. Figure 1 shows an aerial photo and a three dimensional model of Luz.

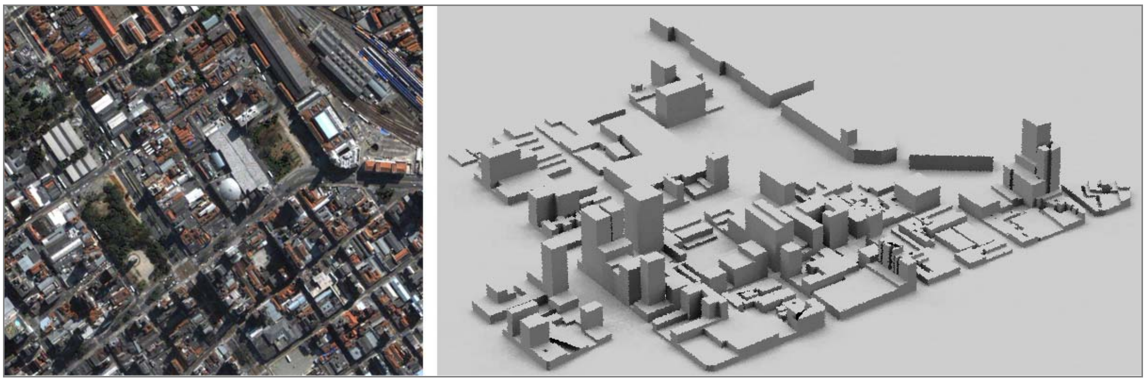

Figure 1: Aerial photo and 3D model of Luz.

1.2 Methodology

The study employs computational simulation to model sky view factor, daylight factor and solar potential in both theoretical and real existing urban built forms. Digital elevation modeling (DEM), an image processing of three-dimensional urban texture has been used to predict sky view factor at ground level. Besides DEM, a simulation tool named PPF has also been applied for daylight and solar radiation modeling; PPF is Radiance based and uses Monte Carlo ray tracing methods to calculate solar radiation availability. Both techniques have been previously employed in the EU project *PRECis: Assessing the potential for renewable energy in cities* (Steemers et al., 2000) and they also have been used in various urban form studies. (Compagnon, 2004, Montavon et al., 2005, Montavon et al., 2004, Nikolopoulou, 2004, Ratti et al., 2003, Scartezzini et al., 2002)

2. THEORETICAL STUDIES

In this study, models representing three different types of built forms i.e. uniform skyline, pyramid skyline and random skyline (as shown in Figure 2) are compared for daylight performance and solar potential. Each of the models consists of 25 buildings in a 5x5 square array. Apart from the model array, in order to imitate urban surroundings, two extra rows of buildings are placed along the peripheral; these buildings with random heights resemble the surrounding obstructions.

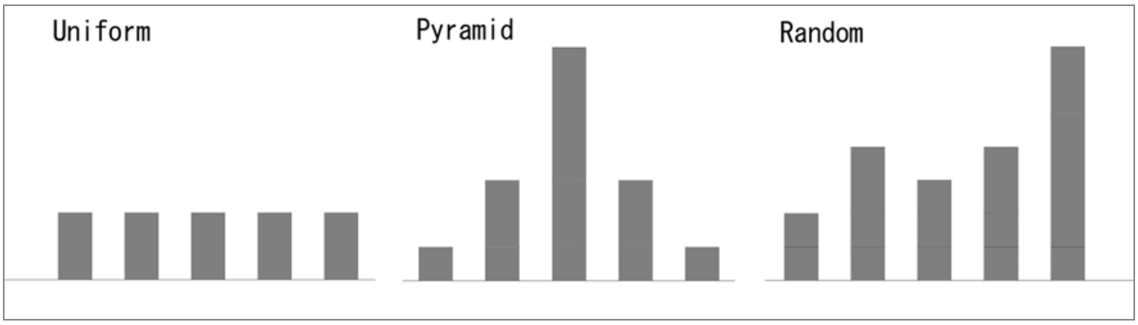

Figure 2: Built forms representing different types of skylines

In the first experimental series, all the three built form models have the same amount of usable floor area and the built density can be specified as plot ratio = 0.6, site coverage = 0.3 and average building height =2 units[*]. Figure 3 shows the generic models.

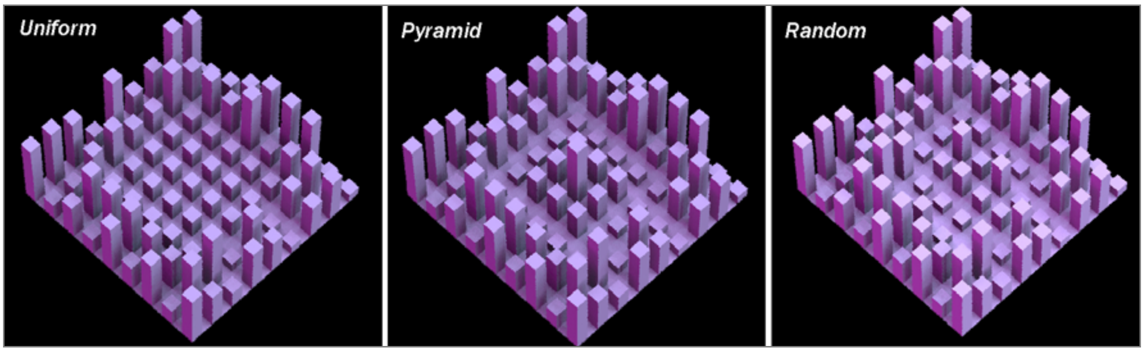

Figure 3: Generic models for theoretical studies

2.1 Sky view factor (SVF)

The average sky view factors at both the ground level and building envelope (both façade and roof) have been computed using DEM modeling and PPF respectively. The results are shown in Table 1. Sky view factor is a measure of the openness of a surface, a SVF of 1 means an unobstructed view of the sky and a SVF of 0 means a completely obstructed view of the sky. The results show that at both ground level and building envelope, the average SVF in pyramid and random skyline configurations are about 5% and 9% higher than the uniform skyline configuration. This suggests that varying skyline creates more unobstructed area, which is favourable for daylight and solar access.

Table 1: Average sky view factors

Built Forms	Uniform Skyline	Pyramid Skyline	Random Skyline
Ground SVF	0.24	0.25	0.26
Envelope SVF	0.22	0.23	0.24

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[*] One building height unit equals to the width of a building block.

2.2 Daylight performance

Daylight performance is assessed in terms of daylight factor under CIE Standard Overcast Sky condition; the daylight factor is defined as the ratio of illuminance on building envelope resulting from both skylight and reflected light, to the illuminance on an unobstructed horizontal plane. The average daylight factor of uniform, pyramid and random skylines are 0.26, 0.27 and 0.28 respectively, in other words, pyramid and random skylines provide 4% and 8% more daylight than the uniform skyline configuration.

2.3 Solar potential

Solar potential for thermal collectors (hot water supplies) and photovoltaic systems have been computed for the three skyline configurations. The solar potential is defined as the percentage of façade area that receives, on average, 400 KWh·m^{-2} (thermal collector) and 800 KWh·m^{-2} (photovoltaic systems) or more solar radiation annually. These threshold values were determined based on current technical limitations as well as economic considerations. (Compagnon, 2000) The thermal potential of the uniform, pyramid and random configurations are respectively 16%, 22% and 27%; and the photovoltaic potential are respectively 0%, 1% and 1%. In relation to solar thermal potential, the varying skylines significantly outperform an uniform skyline; the thermal potential of pyramid and random skylines are 35% and 69% higher than the uniform skyline configuration. However, the photovoltaic potential is low in all three models; this is probably due to the relatively compact setting of the model arrays and the high solar radiation threshold for photovoltaic systems.

Based on the results of the first experimental series, it could be concluded that varying skyline, preferably randomly, results in better performance in both daylight access and solar potential and therefore it should be encouraged in urban design.

In the second experiment, the usable floor area of the random skyline model is doubled and the built density can be specified as plot ratio = 1.2, average building height = 4 units and site coverage = 0.31 (unchanged). As a consequence of increasing building height and thus plot ratio, the daylight and solar potential drop; the average SVF (ground level and building envelope), daylight factor, solar thermal potential and photovoltaic potential become 0.20, 0.22, 0.24, 25% and 1% respectively, which account for a 8-23% reduction in daylight and solar potential (excludes the performance in PV). The result agrees with the conventional assumption that increasing plot ratio and hence usable floor area reduces the potential of renewable energy application.

In the third experiment, the usable floor area and plot ratio are kept as the same as those used in the second experiment, but the site coverage is reduced from 0.3 to 0.1 and the average building height increased from 4 to 11 units. The building heights in this experiment are again randomly distributed. The average SVF (ground level and building envelope), daylight factor, solar thermal potential and photovoltaic potential become 0.31, 0.31, 0.31, 52% and 5% respectively. All daylight and solar quantities increase tremendously compared to the random skyline configuration in the first experimental series. The improvement in SVF and daylight factor range from 10-30%, the solar thermal potential is doubled and the photovoltaic potential is increased fivefold.

The results of the third experiment demonstrate a means to increase usable floor area and at the same time, maintains and even improves the urban daylight and solar potential. Although increasing plot ratio might lessen the daylight and solar access, a simultaneous decrease in site coverage could compensate the drawback and add benefits to the overall performance.

Therefore, the ultimate effect of built density on urban daylight and solar potential does not purely depend on how high the buildings are or how much usable floor area it provides. Urban design details such as the openness and permeability of building layout, which are in certain extent incorporated in the evaluation of site coverage, do play a significant role. The studies suggest that tall, widely spaced and buildings of random heights perform well. However, real cities present us with more complex configurations.

Table 2: Summary of theoretical studies

Experiment	Quantity	Uniform	Pyramid	Random
1	Ground SVF	0.24	0.25	0.26
	Envelope SVF	0.22	0.23	0.24
	Daylight Factor	0.26	0.27	0.28
	Solar Thermal	16%	22%	27%
	PV Potential	0%	1%	1%
2	Ground SVF	-	-	0.20
	Envelope SVF	-	-	0.22
	Daylight Factor	-	-	0.24
	Solar Thermal	-	-	25%
	PV Potential	-	-	1%
3	Ground SVF	-	-	0.31
	Envelope SVF	-	-	0.31
	Daylight Factor	-	-	0.31
	Solar Thermal	-	-	52%
	PV Potential	-	-	5%

3. STUDIES OF EXISTING URBAN BLOCKS

Existing urban blocks in Luz (a city centre site in Sao Paulo, Brazil) have been examined using PPF simulation for daylight under CIE Standard Overcast Sky condition and solar potential under typical Sao Paulo sky condition. Figure 4 shows the 11 urban blocks being studied. These urban blocks represent a range of different built forms from compact high-rise to relatively flat and open layout, which provide a rich urban texture for understanding the influences of built density.

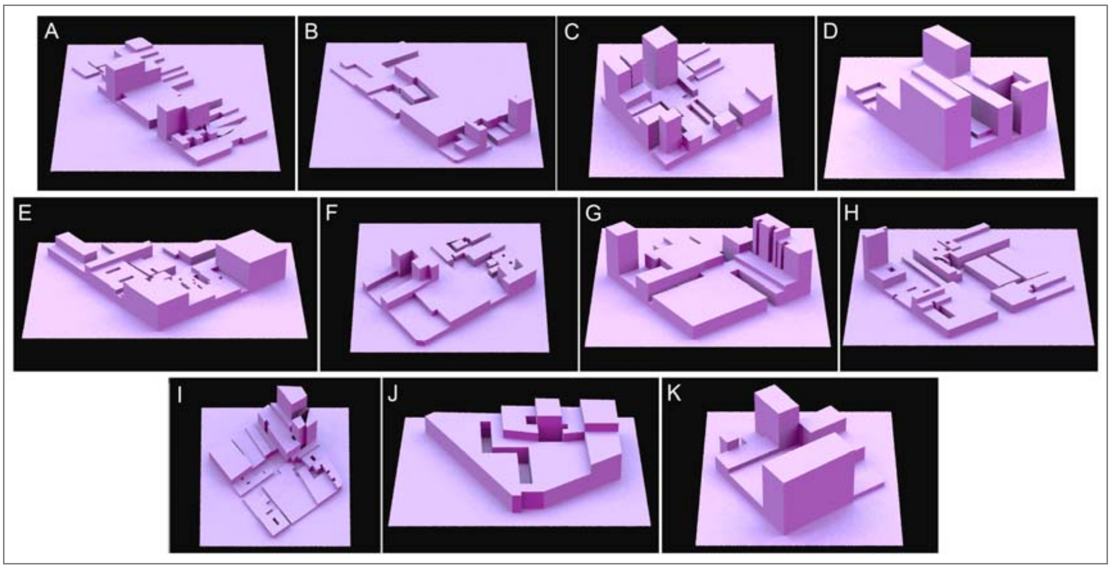

Figure 4: Existing urban blocks in Luz, Sao Paulo, Brazil

Several daylight and solar quantities including sky view factor, daylight factor on building envelope (façade and roof), solar thermal potential and photovoltaic potential have been computed and the results are shown in Figure 5. Daylight factor is calculated under CIE Standard Overcast Sky condition and the thresholds for solar thermal and photovoltaic systems are the same as those used in the theoretical studies.

As shown in Figure 5, the daylight factor and sky view factor on building envelope, solar thermal and photovoltaic potential on roof follow similar patterns, whilst the solar thermal and photovoltaic potential on facade behave diversely. In order to understand this discrepancy and its relationship with built density, daylight factors representing the former group and facade solar thermal potential representing the later group have been separately studied.

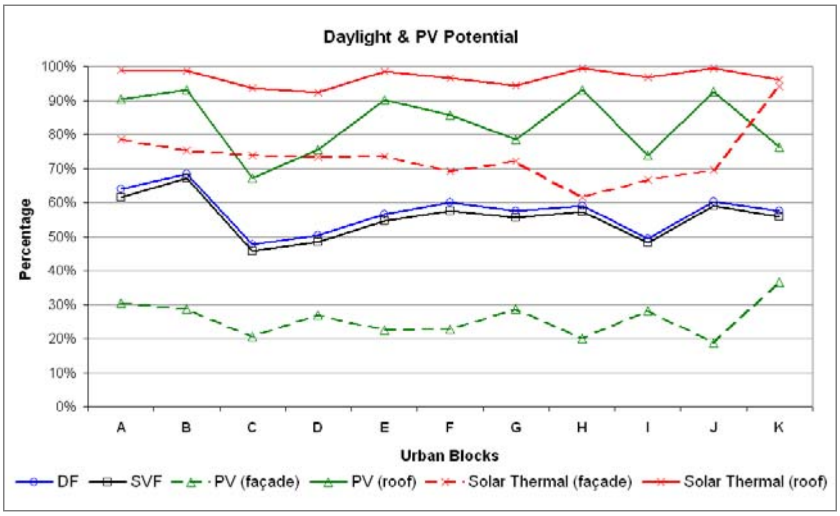

Figure 5: Daylight and solar potential of the urban blocks

3.1 Daylight factor & built density

The study first correlates the built density parameters i.e. plot ratio and site coverage with daylight factor and the results are shown in Figure 6. It appears that plot ratio has fairly good correlation with daylight factor (R^2=0.36), whilst site coverage is not relevant at all (R^2=0.001).

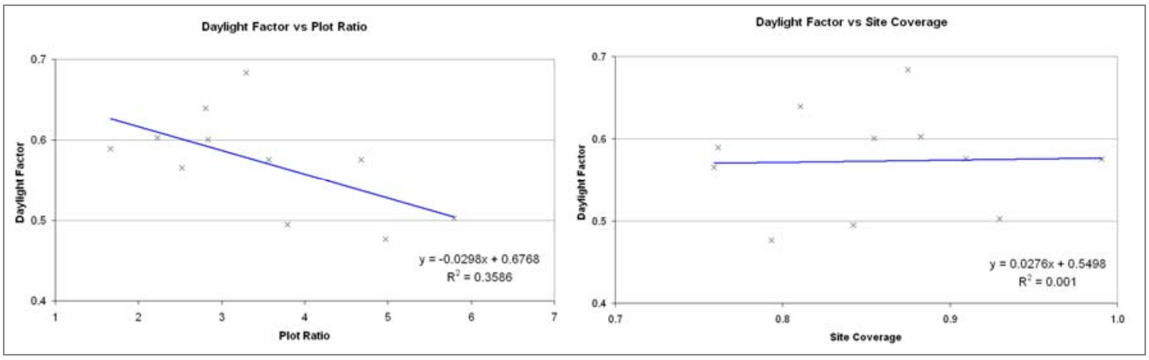

Figure 6: Daylight factor and built density

Although the result suggests that site coverage alone does not influence very much the daylight factor, it does not mean that its effect is completely negligible. To further understand the issue, a quantity known as the Compactness Index, which addresses both plot ratio and site coverage, has been introduced. The Compactness Index is defined as the ratio of plot ratio to site coverage, in other words, it represents the ratio of total floor area to building footprint i.e. the average number of floors.

Figure 7 shows the correlation between compactness index and daylight factor; the result shows good correlation (R^2=0.46) and the outcome outperforms that obtained with plot ratio alone. The same is true for sky view factor and solar thermal and photovoltaic potential on roof where R^2 equal to 0.46, 0.77 and 0.75 respectively. Therefore, the compactness index, as one of the built density manifestations, seems to be useful in predicting daylight access and solar potential on roof.

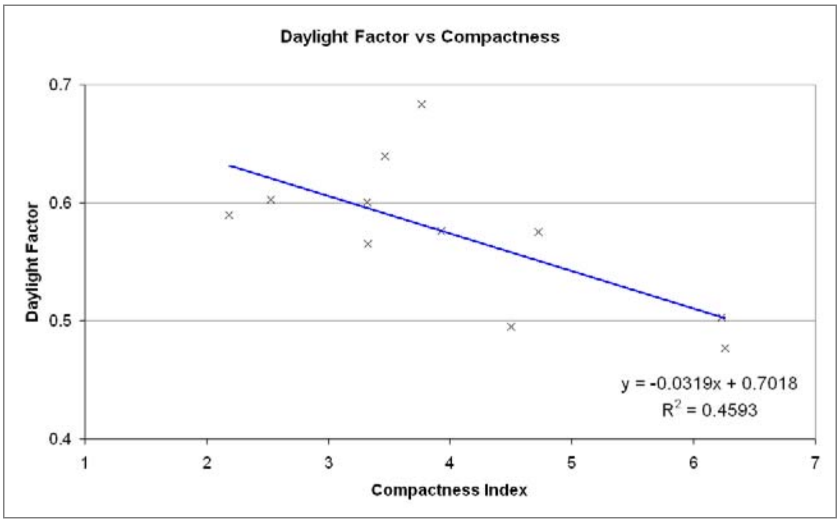

Figure 7: Daylight factor and compactness index

Figure 8 shows the comparison between predicted daylight factor using the compactness index and the simulated daylight factor using PPF. In general, the predicted daylight factors are within ±10% of the simulated results which suggests that the two sets of data are in good agreement.

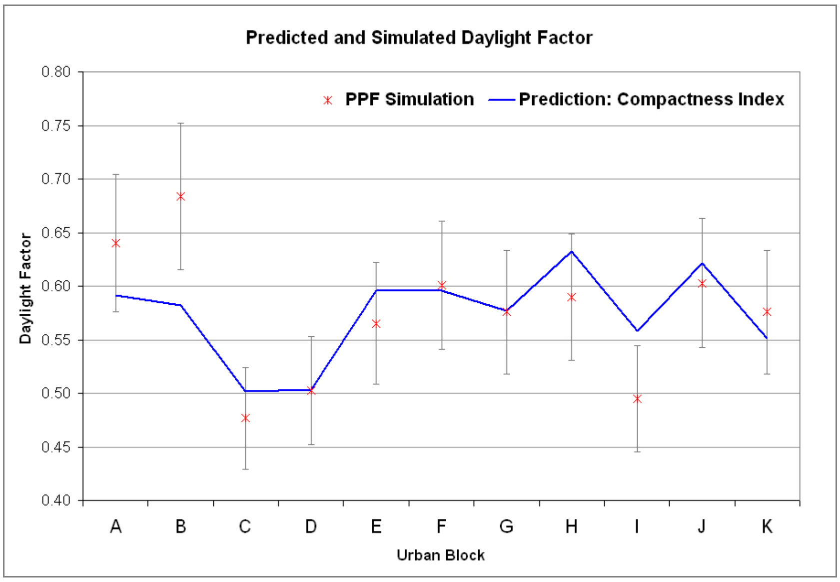

Figure 8: Predicted and simulated daylight factor

3.2 Façade solar thermal potential & built density

The correlations between façade solar thermal potential and 1) plot ratio and 2) site coverage have been studied and Figure 9 shows the results. In comparison to plot ratio (R^2=0.22), site coverage (R^2=0.37) appears to have larger influence on façade solar thermal potential; the result is opposite to that obtained with roof application. A study of the correlation between compactness index and façade solar thermal potential shows even worst result (R^2=0.13). Nevertheless, there is very good correlation between facade solar thermal potential and the percentage of weighted unobstructed façade area[*] (R^2=0.87). This close linkage with unobstructed façade, however, is not valid for daylight factor (R^2=0.07).

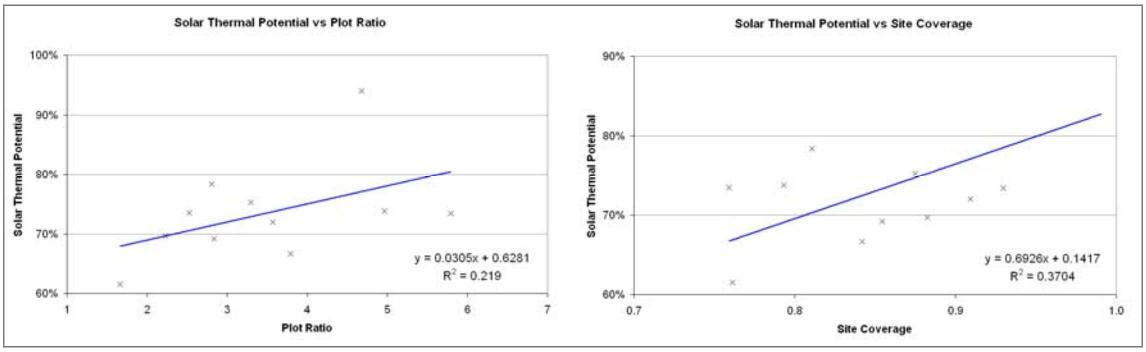

Figure 9: Façade solar thermal potential and built density

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[*] The weighted unobstructed façade area A (m^2) is defined as: $A = \sum_i \frac{SVF_i}{0.5} \cdot A_i$

where i is the total numbers of measuring points in PPF simulation and A_i is the total façade area. For a totally unobstructed façade, $SVF_i = 0.5$. (Compagnon, 2000)

4. DISCUSSION & CONCLUSION

The daylight and solar potential of an urban development are primarily determined by the amount of solar radiation that falls on the surfaces. In this sense, there are two parameters i.e. the vertical and horizontal obstruction angles, which could be influential. Vertical obstruction affects light coming from the top whilst horizontal obstruction affects light coming from the sides. Figure 10 is an illustration of the two obstruction angles in an urban setting.

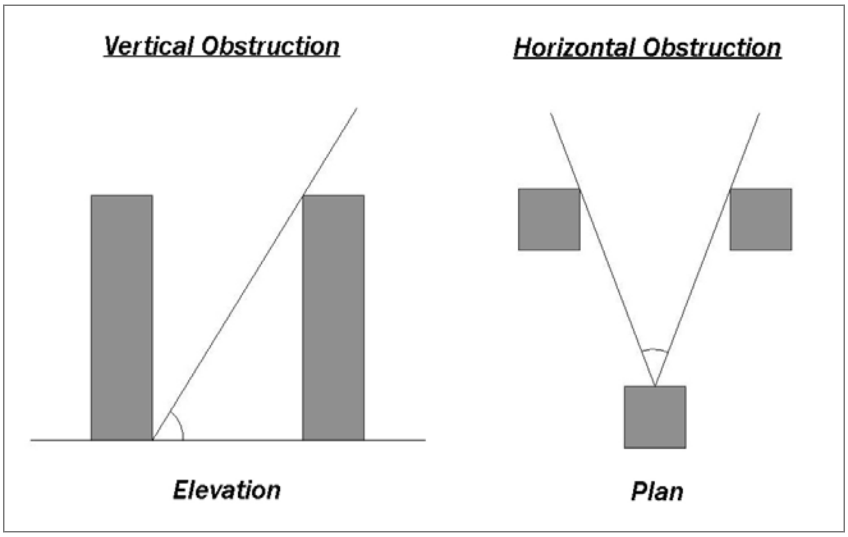

Figure 10: Vertical and horizontal obstruction in urban setting

The discussion on skylines, plot ratio and compactness index are more related to vertical obstruction whilst those studies on site coverage and unobstructed façade area are more relevant to horizontal obstruction.

According to the results of the case study in Luz, daylight and solar quantities such as daylight factor, sky view factor and solar thermal and photovoltaic potential on roofs are better correlated to plot ratio and compactness index. This suggests that these quantities are more influenced by vertical obstruction, in other words, more dependant on light comes from the top. On the other hand, solar thermal and photovoltaic potential on façade are better correlated to site coverage and unobstructed façade area, therefore these quantities are more influenced by horizontal obstruction, which means more dependant on light comes from the sides.

In conclusion, the finding of this study shows that varying skyline configuration has better performance than uniform skyline configuration, in terms of daylight access and solar potential. Furthermore, it suggests that the effect of built density on urban daylight and solar potential is not straightforward. It has been demonstrated in the theoretical studies that, with a simultaneous decrease in site coverage, it is possible to increase the usable floor area and plot ratio without reducing the opportunities of daylight and solar applications.

The case study in Luz further reveals the complexity of the issue. It appears that the different manifestations of built density i.e. plot ratio, site coverage and compactness index play different roles in determining urban daylight and solar potential. Plot ratio and compactness index are more influential on quantities such as daylight factor, sky view factor, roof solar thermal potential and roof photovoltaic potential. On the other hand, solar thermal and photovoltaic potential on façade are more dependent on site coverage and the extent of horizontal obstruction.

After all, the key message of this paper is that the intention for densification and the concept of sustainability are not mutually exclusive. Given proper urban design and layout, compact cities can be a respectable solution to rapid urbanization.

5. LIMITATIONS OF THE STUDY

As a final remark, there are some limitations of this study, which have to be observed. First, the major findings of this study are fundamentally based on computer simulation. Though the simulation programs used have been widely tested for competencies, variations in architectural features, for instance, projections from building façades could significantly affect the outcome.

Second, the urban block study in Luz is mainly for further understanding of the influences of built density and urban form on daylight and solar potential. In order to minimize the interference from other factors, the effect of surrounding obstruction has not been taken into account. Hence, the result is for comparison rather than absolute performance evaluation.

Third, the solar potential obtained from the case study in Luz is derived from typical sky condition of the region. As for the low geographic latitude of Luz (23.5^{o}S), sky condition is characterized by high solar altitudes, which results in appreciable difference between façade and roof illumination. Hence, the findings might not be able to generalize in places with different sky conditions.

Last, the analysis is basically based on first order regression analysis which might not be able to account for factors, which lie outside the scope of this study.

6. ACKNOWLEDGMENT

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