Better Daylight and Natural Ventilation by Design

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ABSTRACT: An important consideration of urban design is to provide natural outdoor conditions that are pleasant and conducive to human activities. Planning the city to cope with needs is an important task for planners and architects. There are many design parameters, for example: Development Density, Plot ratio, Site Coverage, Skyline, Building to Space Ratio, Permeability, Building Shapes and so on. This paper reports a study on how they may affect daylight and natural ventilation provisions and performance. Experiments are conducted with physical models in wind tunnel and artificial sky, as well as using CFD and computational lighting simulation. The study establishes that, for same density, by varying the skylines, the overall daylight and natural ventilation performances could be improved when compared to a city with a uniform skyline. The message of the paper is that: through better design, high density cities could be planned without losing the development efficacy of the land.

Conference Topic: Sustainability and high-rise buildings
Keywords: High Density Cities, Daylight, Natural Ventilation

1. INTRODUCTION

1.1 Background

With the increase of the world’s population, many cities are facing the problem of designing and planning to meet the demand of their inhabitants. Enlarging the city’s land boundary, building satellite towns, optimise land zone and usage, and constructing taller and closely packed buildings are some of the tactics used.

For cities with limited land area, the option opens to planners and designers is limited. Finding ways to optimise land use and designing for higher density seem to be the only options.

Land use density could typically be controlled using plot ratio, site coverage, permissible building volume, maximum building height, street width vs. building height ratio, building profile and set back, and so on. In most countries, regulatory control of most of these are prescriptive and are stated and applied with little understanding of their performance implications.

How some of these planning and design parameters affect the environmental performance of the resulting buildings is a research question. This paper reports results of parametric studies based on building density, street width and building skylines. The study investigated the sensitively and magnitude of these 3 parameters on the environmental performance of daylight and naturally ventilation of buildings.

1.2 Methodology

Many scholars worldwide have conducted researches on parametric studies that lead to simple design guidelines. Many lasting design understanding and guidelines started with the use of results of parametric studies. For example, Givoni 1969 [1] studied the use of wing walls for room air ventilation, this is now adopted by the HK Government for its new generation of performance based regulation (Figure 1). Hawkes studied the relationship between block spacing and daylight performance which later led in a site planning guide in the UK [2]; Baker studied the relationship between window size and thermal-light energy performance which resulted in the development of the European LT method [3].

Figure 1: Givoni’s parametric study of the effect of wing wall and air ventilation of internal spaces 

Parametric approach is used in this study. The advantage of using parametric study in lieu of studies based on realistic circumstances is that issues could be isolated and simplified to reduce noise and error of results. It is also much easier to design experimentally. The disadvantage is that results obtained could not be directly and readily feed back to real problems. In most cases, results could only indicate the ‘likely’ sensitivity of the performance due to the parameter.
For this study, to mimic the conditions of an urban neighbourhood, a 5x5 base plate is used. The base plate has 25 buildings on a square array. The three parameters of density, street width and building skylines were investigated using a number of simplified scenarios. The 3 parameters and 3 variables give a permutation of 27 scenarios to be studied. (Table 1). One such scenario is shown in Figure 2. This is a ‘random’ layout with ‘a density of 75 blocks’, and with ‘3 different street width to building width’ ratios.

2. DAYLIGHTING

2.1 The Scientific Basis

Daylight performance of an interior space depends on the amount of light available to the vertical surface of the window pane. In turn, the amount of light receivable on the vertical surface of the building façade depends on a number of factors. Firstly, the amount of sky the façade ‘sees’, this is the sky factor. The sky factor, the amount of sky viewable in terms of solid angle, is corrected using the sky description of the locality to become the Sky Component (SC). Typically the CIE overcast sky description is used. This description depicts the sky condition of a dull cloudy day without direct sunlight. The amount of light available under this sky is azimuth independent. Many artificial skies and computational programme are built based on this sky type.

Secondly, in dense urban conditions, most available light is reflected light (ERC) of surrounding surfaces. It depends on the reflectivity of the surfaces, as well as how well these surfaces are illuminated directly in the first place.

2.2 The Studies

Computational lighting simulation is used to conduct tests of the 27 scenarios. Lightscape has been selected. (Figure 4) The software has been calibrated to yield good results under heavily obstructed conditions [4].

2.3 Results

For comparative reasons, the base case of ‘uniform’ height, with ‘a density of 75 blocks’, and with ‘a street width to building width of 1:1’ was regarded the base case. This is the kind of urban neighbourhood most likely to have resulted in Hong Kong given current regulations and control.

To mimic the urban surroundings, the base plate is surrounded. For ventilation-wind tunnel study (Figure 3), 2 additional layers are added. For daylight study, 5 additional layers are added.

Figure 2: Diagrams show 3 scenarios tested

Table 1: Scenarios of the study

<table>
<thead>
<tr>
<th>Parameters investigated</th>
<th>Variables used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>2 blocks, 3 blocks, 4 blocks</td>
</tr>
<tr>
<td>Skyline</td>
<td>Uniform, Random, Stratum</td>
</tr>
<tr>
<td>Building to space ratio</td>
<td>2:1, 1:1, 1:2</td>
</tr>
</tbody>
</table>

Figure 3: The base plate (5x5) surrounded by 2 extra rows on all four sides for air ventilation studies using wind tunnel as well as CFD.

Figure 4: One of the 27 scenarios tested. Note that the base plate of 5x5 grid is surrounded by duplicates of itself to form an urban environment.

The geometry was modelled in FormZ solid modeller and exported .dxf into Lightscape. All surfaces are oriented and assigned reflectance of 0.2. Rendering with cloudy sky with sun illuminance set to 0, the results are picked using the Analysis Function of the programme. The illuminance of all four surfaces of all the blocks of the 5x5 grid on the base plate is recorded. Thus for a study with 75 blocks, 300 data points could be recorded.

2.3 Results

Results of the base case of 75 blocks and street width to building width of 1:1 is shown as an example in Figure 5 below. The uniform base case (graph left)
illustrates that light levels generally fall into three distinct bands: top, middle and bottom. Roughly a third of the data points (100 data points) are in the low ranges roughly in the order of 8-9% Vertical Daylight Factor (VDF).

Results of the random and stratum scenarios illustrate that light performance spread out more and distribute along the x-axis. Summing the light performance of all the surfaces reveals that the median of base, random and stratum scenarios are 15.2%, 16.7% and 17.6% respectively. This means that on the whole light performance of stratum scenario is roughly 20% better that the base case.

Figure 5: VDF performance (x-axis) was plotted against the cumulative occurrence (y-axis).

Results of the 27 scenarios tested is summarised in Table 2. It is noted that in all cases light performance of stratum scenarios exceed the random scenarios, which in turn exceed the base scenarios. For example, in very high density conditions of 5x5x4, and a street width to building width ratio of 1:1, the performance of the stratum layout is around 30% better than the base case. That is to say, given the same design density, one design is better than the other by roughly a third.

Alternatively, examining the light performance of 5x5x3 base and 5x5x4 stratum, the two set of data is very similar. That is to say, given a certain daylight performance requirements, one could build either 75 blocks all with the same building height, or 100 blocks with varying building heights.

Table 2: Medians of VDF of all 27 scenarios

<table>
<thead>
<tr>
<th></th>
<th>Street: Building</th>
<th>Base</th>
<th>Random</th>
<th>Stratum</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 x 5 x2 blocks high</td>
<td>1:1</td>
<td>21.2</td>
<td>22.5</td>
<td>23.2</td>
</tr>
<tr>
<td>5 x 5 x3 blocks high</td>
<td>1:1</td>
<td>27.3</td>
<td>27.5</td>
<td>29.1</td>
</tr>
<tr>
<td>5 x 5 x4 blocks high</td>
<td>1:1</td>
<td>23.5</td>
<td>24.5</td>
<td>25.9</td>
</tr>
</tbody>
</table>

When plotting the 27 scenarios along the VDF y-axis, it is noted that, in general, light performance shift up from base, random to stratum. (Figure 6) The improvement is roughly 10 to 30%.

3. NATURAL VENTILATION

3.1 The Studies

Wind tunnel has been used for ventilation studies (Figure 7). CFD modelling has also been done for airflow visualisation (Figure 8). For wind tunnel experiments 1:200 scaled models were used in an open circuit atmospheric boundary layer wind tunnel to gather pressure distribution data on the exterior surface of the blocks [5]. Utilizing the pressure coefficient (Cp) values obtained, the air change rates (ACH) in the selected units at different heights were calculated using a multi zone model CONTAM. The Cp values obtained were converted to wind pressure using the power law equation. The wind pressure, in Pascal (Pw) is approximated by

\[ P_w = \frac{\rho C_p v^2}{2} \]  

(1)

Where \( \rho \) is the density in kilograms per cubic metres (kg/m\(^3\)) and \( v \) represents the local wind velocity at a specified reference height which was calculated using the equation given below

\[ \frac{v}{v_m} = K z^a \]  

(2)

Where \( v_m = 2.5 \text{m/s} \) (wind speed measured at a height of 10 m at the weather station) \( z = 90 \text{m} \) (reference height), \( k \) & \( a = 0.35 \) & 0.25 (constants depend upon the terrain).

Figure 6: Medians of VDF of 27 scenarios. Note the general shift from left to right.

Figure 7: Scaled model in the wind tunnel
3.2 Results

Results of the 100 blocks with the 9 cases are shown in Figure 9. It can be seen that most of the points in the uniform base case have air change rates in the low ranges whereas random and stratum cases show a more evenly distributed ventilation performance. When compared to stratum case, random case shows less frequency of occurrence towards the lower range and more frequency towards the higher range for all the street width.

Figure 9: Air change rate (x-axis) against the cumulative occurrence (y-axis).
Figure 10: Comparing Base and Stratum cases

Figure 11: Average of Air change rate of all 27 scenarios

Table 1: Ventilation performance of different density and spacing configurations

<table>
<thead>
<tr>
<th>Density</th>
<th>Spacing</th>
<th>Uniform</th>
<th>Random</th>
<th>Stratum</th>
</tr>
</thead>
<tbody>
<tr>
<td>75 Blocks</td>
<td>1.0</td>
<td>11.03</td>
<td>18.45</td>
<td>17.59</td>
</tr>
<tr>
<td></td>
<td>1.1</td>
<td>14.28</td>
<td>19.31</td>
<td>19.28</td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td>15.62</td>
<td>22.82</td>
<td>21.36</td>
</tr>
<tr>
<td>100 Blocks</td>
<td>1.0</td>
<td>11.03</td>
<td>18.69</td>
<td>18.29</td>
</tr>
<tr>
<td></td>
<td>1.1</td>
<td>12.97</td>
<td>19.47</td>
<td>19.02</td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td>16.81</td>
<td>23.34</td>
<td>22.72</td>
</tr>
<tr>
<td>125 Blocks</td>
<td>1.0</td>
<td>11.12</td>
<td>17.33</td>
<td>16.56</td>
</tr>
<tr>
<td></td>
<td>1.1</td>
<td>12.32</td>
<td>18.94</td>
<td>17.62</td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td>17.37</td>
<td>24.31</td>
<td>22.34</td>
</tr>
</tbody>
</table>

This parametric study is a beginning. It investigated density, building skylines and street width to building width ratios. Other parameters like building shapes, gaps between buildings, permeability of the urban fabric and building surfaces could also affect daylight and air ventilation performances. They require further studies.

4. CONCLUSION

4.1 Discussions

The study demonstrates beyond reasonable doubt that for lighting and air ventilation, better performance could be obtained by varying the skylines. The improvement is around 20-30% for daylight, and 30-40% for air ventilation. Thus, it is important to capitalise this by effecting design guides, building and planning regulations to encourage that to happen.

4.2 FURTHER WORKS

This study only identifies preliminarily the quantitative effects of 3 parameters. Further studies are needed to include additional scenarios and to further investigate the precise mathematical relationship between the parameters and performance. For example, if building skyline is an important parameter as stated in this study, what is the range of building heights one should recommend? Is there is simple mathematical formula to describe the relationship? Can an optimum solution be found and expressed mathematically? This parametric study is a beginning. It investigated density, building skylines and street width to building width ratios.

REFERENCES