APPLYING COMPUTATIONAL SIMULATION RESULTS
TO THE DEVELOPMENT OF A DESIGN METHOD
FOR DAYLIGHT DESIGN AND REGULATION IN HIGH-DENSITY CITIES

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ABSTRACT
Daylight design for “extremely” obstructed urban environment is a relatively uncharted area of study. No city in the world has an urban density as high as Hong Kong. Designing daylight in the territory is a critical and important study. The paper attempts to develop and verify a simple method of design for architects based on theoretical formulation and results obtained using computational simulations. The Unobstructed Vision Area Method (UVA) proposed here is highly correlated to the Vertical Daylight Factor (VDF) of a building surface. This 2-dimensional plan based method is very easy to use at the early design and planning stage. The method is now under consideration by the Government for its new performance based building regulations. With small modifications to its variables, the methodology for the UVA method could also be generally used for other extreme-density cities.

INTRODUCTION

Figure 1 A typical 40 storey high housing development based on the 1959 version (current) of the building regulations in Hong Kong

Hong Kong is a city with 7.5 millions inhabitants living on a collection of islands that total 1000 square kilometers. Due to its hilly typography, only 25% of the land is built-up. Urban density is around 30,000 to 50,000 person per square kilometer. Take away the areas for roads, rails, utilities and open spaces, building sites end up with a development density of around 3000 person per hectare. This results in high rise buildings, some 40-80 storeys, built very closely together. (Figure 1) Designing and regulating the provision of adequate light and air is a difficult task.

Since 1956, the Building Regulations of Hong Kong (HKSAR 1959) prescribe a minimum distance between building blocks based on “sustained vertical angle requirements”. They are basically requirements for the horizontal distance between buildings and the permissible heights of the buildings. This antiquated law was first developed in the UK in the late 19th century. The concept has been widely used in many countries around the world.

The laws were developed in the age of low-rise terrace dwellings of constant skyines. It assumes that windows receive a good amount of Sky Component (SC). It assumes a constant value of External Reflected Component (ERC) proportional to the obstructed SC, typically 0.2 of SC. And it assumes a constant angle of obstruction opposite the building. However, nowadays, buildings in Hong Kong are much taller, they are mostly point blocks, and the windows normally face into a varying skyline and obstructed by its own block. The theoretical basis of the laws is no longer applicable to high-density cities. Forcing the outdated requirements on designers not only limit design flexibility, it encourages bad design based on illogical arguments.

In 1999, the Buildings Department of Hong Kong, commissioned a team of consultants to look into the problem with the intention to develop better, more design friendly methods to improve the situation. Researchers at the Department of Architecture, The Chinese University of Hong Kong were entrusted the task to undertake the study.

THE STUDY
Since 1999, the study has proceeded with the following workflow. (Table 1) It becomes apparent that existing rules are vastly inadequate, and over the years they have been abused with ‘ingenious’ manipulations by some architects. A performance based approach to building control was coined. The
user survey indicated that, given the cultural and contextual living conditions of Hong Kong, there exists a minimum daylight performance that people would accept or tolerate. This is found to be 8% Vertical Daylight Factor (VDF) for habitable rooms and 4% VDF for kitchens. That is to say, regardless of any method the designers use, if they could demonstrate that the said performance is achieved, the building will be given approval by the authority.

The Unobstructed Vision Area (UVA) method was coined. Basically, it is the open area that the window can ‘see’ when surrounded by high external obstruction. The UVA method was first empirically developed based on the understanding that daylight to a window comes from a 3-dimensional sky vault (Figure 4). The horizontal angle is therefore as important as the vertical angle. An embryonic idea similar to the logical reasoning of the UVA method has been used earlier in the UK (Hopkinson 1966; Crompton 1955). It was argued to be suitable for tower block urban planning. For a vertical building surface, based on the Global Illumination Model (equation 1) and CIE Overcast Sky formulation (equation 2), most of the available light comes from a cone 0˚ to 55˚ from the horizontal and 50˚ right and left of the normal to the surface. This cone of light accounts for 78% of the sky component (SC) available.

\[
E_w = \int \int_{\phi_{h} \phi_{l} \theta_{h} \theta_{l}} \cos^2 \theta \cos \phi d\theta d\phi
\]

(1)

\[
L_{\phi} = L_z \frac{1 + 2 \sin \theta}{3}
\]

(2)

\[
E_w = \text{be the illuminance on the vertical window from the sky}
\]

\[
\phi_{h}, \phi_{l}, \text{the upper & lower angles of obstruction}
\]

\[
\theta_{h} \text{ and } \theta_{l}, \text{the right and left angles of unobstructed sky}
\]

\[
L_z \text{, Zentih Luminance}
\]

\[
L_{\phi} \text{, Luminance of the patch of sky at } \theta \text{ and } \phi
\]

Equation (1) and Equation (2) could be resolved to Equation (3) for SC as well as the reflected light between buildings. (Tregenza 1989)

\[
E = L_z \left[ \frac{1}{3} (\sin \phi_{h} + \sin \phi_{l}) \times \left( \frac{\theta_{h} - \theta_{l}}{2} \right) + \frac{\sin 2\theta_{h} - \sin 2\theta_{l}}{4} + \frac{2 \cos^3 \theta_{h} - 2 \cos^3 \theta_{l}}{3} \right]
\]

(3)

\[
E = \frac{1}{1 - (0.5 \rho_b)} \times E_{\omega} \rho_b \times \left[ \frac{\pi}{2} - (\sin \phi_{h} + \sin \phi_{l}) \times \left( \frac{\theta_{h} - \theta_{l}}{2} + \sin 2\theta_{h} - \sin 2\theta_{l} \right) \right]
\]

\[
\rho_b \text{ be the reflectance of the surrounding surfaces}
\]

\[
E \text{ be the total illuminance on the window from the sky and reflected light from buildings}
\]
The amount of light receivable on a vertical window is proportional to: the reflectance of the surrounding buildings \( \rho_b \) and the horizontal angles the window can see \( \phi_L + \phi_R \). This horizontal angle is related to the amount of external obstruction the window faces. Up to a total horizontal angle of 100° left and right of the vertical surface, the available light and the angles are linearly proportioned. (Figure 3), and \( \sin \theta_L + \sin \theta_R \) could be approximated to \( \theta_L + \theta_R \). Therefore, the amount of light receivable could be appropriated to a cone shaped area in front of the window 50° left and right to the normal of the window.

Given the high rise, high density urban conditions of Hong Kong, (Figure 2) and indeed some other cities, it is possible to simplify Equation (3) to become Equation (4) as \( \theta_L \) gets larger (>70°) as follow:

\[
E = L \left[ \frac{\sin \theta_L + \sin \theta_R}{3} \right] + \left[ \frac{1}{1 - (0.5 \rho_b)} \times \frac{E_{\text{ref}} \rho_b}{\pi} \times \left[ \frac{\pi}{2} - (\sin \theta_L + \sin \theta_R) \right] \right] \tag{4}
\]

From the design point of view, this simplification is very important as it is now possible to approximate daylight performance with a 2-dimensional plan information which is readily available to architects.

Figure 2 In Hong Kong, most light of lower floor windows come from reflected light as \( \theta_L \) gets larger (>70°). The UVA is the area boundary by the tall surrounding towers.

Figure 3 \( \sin \theta_L + \sin \theta_R \) as a function of \( \phi_L + \phi_R \). When \( \phi_L + \phi_R \) is < 100°, the two are approximately linearly related.

From the design point of view, this simplification is very important as it is now possible to approximate daylight performance with a 2-dimensional plan information which is readily available to architects.

Figure 4 The amount of Sky Component receivable by a vertical window surface facing into a CIE Overcast sky. The window receives most light from the path of sky directly in front and at 30° from the horizontal. Note the horizontal spread of the available light.
early in the design process. This plan area is known as the Unobstructed Vision Area (UVA). A mathematical formulation of a perfect cone shaped area could be expressed in Equation (5). Note the coefficient \( k \).

\[
A = \left[ \frac{\pi (\theta_a + \theta_b)}{360 (\tan^2 \theta_a)} \right] h^2 \text{ or } A = kH^2 \tag{5}
\]

This mathematical formulation takes into account only the area of a cone of light and ignores other areas of an enclosed space in front of the window. When these other areas are accounted for in an area-based methodology, it is necessary to factor them in. Since the shapes and geometries of these areas are site specific, it is impossible to devise a simple formula for it. Simulation studies could be used. The hypothesis is that \( k \) could be statistically devised using block plans that are likely to be encountered by designers in Hong Kong. A number of computer software were tested and their results have been reported earlier. (Ng 2001b; Ng 2001c; Ng 2002; Ng et al 2003) For high obstruction scenarios, Lightscape 3.2 was suitable. It appears that although the software does not use a very accurate sky model, because of the limited amount of sky a surface could ‘see’, it turns out not to be a problem. On the other hand, the software appears to have good routines that accurately account for the reflected light. This is very important for high obstruction conditions. Studied earlier, the software could approximate site measurement and model study data if used with careful calibration. (Ng 2001b) 40 theoretical configurations were used to test the relationship between Vertical Daylight Factor (VDF) of windows and the Unobstructed Vision Area (UVA) (Figure 5). 25 blocks were randomly laid out on a 5 x 5 grid. The blocks were 1 unit x 1 unit on plan, and 3 units high, with a standard spacing of 1 unit. The lower portions of four surfaces of the central block (marked in Figure 6) were measured after simulation. UVA of these 4 surfaces were calculated. To provide a reasonable context to the 5 x 5 grid, it was duplicated 8 times to form a surrounding. All surfaces and the ground plane had a reflectance of 0.2.

The 40 scenarios were designed in such a way that UVA of windows at the bottom of the tower are evenly distributed. This allows UVA data points at different VDF performance levels. (Figure 7, 8 and 9) (Figure 10)
To test the sensitivity of our UVA hypothesis against the H to W ratio, two other studies were made with the H to W ratio of the blocks at 4:1 and 2:1 respectively. The results of the finding are summarized in Figure 9, 10 and 11. For the purpose of regulation, a line that represents the low quantile of the data was drawn. A relationship between VDF and UVA can be deduced. It is possible to say that: If a window has a UVA not less than X, then there is a 75% chance that the achievable VDF is Y or above.

**CONCLUSION**

Based on the study, it can be concluded that there is a good linear relationship between UVA and VDF. As the building height vs. the width of space increases, the need for larger UVA to achieved the required VDF increases correspondingly. The graphs could
be captured with the following linear regression expressions, $R^2$ could be noted:

- $H/W=2$, $VDF=0.0518 UVA + 0.0057$ $R^2=0.7358$
- $H/W=3$, $VDF=0.0163 UVA + 0.0077$ $R^2=0.7956$
- $H/W=4$, $VDF=0.0058 UVA + 0.0215$ $R^2=0.6810$

$H$ is the height of the block
$W$ is the average width of the space separating the blocks

The lines in Figure 9, 10 and 11 represent the lower quantile of the data when relating VDF and UVA. The coefficient $K$ could be deduced:

For $H/W=2$, $K = 0.40$  
For $H/W=3$, $K = 0.58$  
For $H/W=4$, $K = 0.75$

For $H/W = 3$, which is the height to space width ratio of interest here, based on Equation 5, it is now possible to relate the UVA requirement to the building height on the assumption that the designed building and the surrounding buildings are of similar heights. (Figure 14) This ‘mutually respected’ urban layout will result in a cityscape that is similar to the tested scenarios of the study.

Using Figure 14, the daylight performance of the windows could be noted very quickly. Not only that the designer could check for compliance, the method allows designer to know where he or she stands. This allows them to adjust their designs accordingly.

The tool has been proposed to be incorporated into the new performance based building regulations in Hong Kong. (Ng and Tregenza 2001) (Figure 15)

It is the first time that computational results have been ‘approved’ to be used as evidence for law making in Hong Kong. Hopefully, real design projects will result in a few years time to allow us to conduct further tests and evaluation studies. (Figure 16)
A few lessons have been learnt that is of a wider implication. Firstly, for computational study to be creditable to the eyes of the regulators, it must undergo a rigorous testing and validation procedure. Secondly, although more accurate results might be obtained using other daylight calculation methods on a case by case basis, the UVA method proposed here is more generic and therefore far more useful, especially during the early design stage, in a format that most people could understand. It is important to keep a balance between accuracy and simplicity.

The UVA method is robust when, on average, building heights are 3 times the height of its surrounding space (when $\theta_L > 70^\circ$). It is less useful when $\theta_L < 60^\circ$ as more direct sky could be seen. The method must therefore be used within its limits of assumptions.

For urban conditions dissimilar to Hong Kong, it is advised that the method be modified accordingly. But the basic methodology explained here is still applicable.

REFERENCE


Ng, E., Chan, T Y, Leung, R and Pang, P, (2003), ‘A Daylight Design and Regulatory Method for High-density Cities Using Computational Lighting plans. (Figure 17) This will further simplify the chores.

A computational drawing tool is now under development to read off the UVA directly from plans. (Figure 17) This will further simplify the chores.

Ng, E. and Tregenza, P.R., (2001), A design Tool for regulating daylight availability for high density housing in Hong Kong, Technical Report for Anthony Ng Architects Ltd. and Buildings Department, HKSAR, TA00491, (15 pages), Dec 2001.


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FURTHER INFORMATION

Since the studies have completed and proposed to the Hong Kong Government at the end of 2002, a number of developments are worth reporting. They don’t form part of the scientific content of the paper but nonetheless is valuable to note – since this paper is about establishing a legal requirement based on computational studies.

During the consultation stage of the new method, many attempts were made to ‘improve the science and accuracy’ of the method. For instance, adding correction factors, look up tables and so on. They were discussed and resisted mainly because this will significantly add to the chore of design regulations. The intention has always been to keep things very simple and ‘reasonably’ accurate.

On the other hand, there were attempts to ‘twist’ the method for some practical convenience. For instance, tilt the cone to one side, apply mirror effect to open space that does not exist, and worse still, sin against the fundamentals of the UVA method by asking for relaxations, say using multiple windows. Everytime, it has been necessary to go back to first principles and to resist any of these modifications. The task has not been easy as it is human nature, to get more with less.

The new method was heavily resisted, believe it or not, by the local architectural circle. The argument being that it becomes difficult to design. Supporters of the new method comes from other circles – planners and surveyors, and surprisingly from some developers seeing benefits.

Most recently, since May 2003, because of SARS in this region of the world, revised interests have been vested in providing healthier building designs. This gives the government an excuse to introduce the new method as ‘an alternative to design’. The saga continues.

And it the meantime, we have been doing more experiments, taking more on-site measurements to fine-tune and verify the method. Thus, the works also continues.