PRELIMINARY EVALUATION OF A DAYLIGHT PERFORMANCE INDICATOR FOR URBAN ANALYSIS: FACADE VERTICAL DAYLIGHT FACTOR PER UNIT FLOOR AREA

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ABSTRACT

Daylight potential for interior spaces has been one of the primary concerns of building performance simulation and various performance indicators have been proposed for interior daylighting quality evaluation. However, interior daylight simulation on urban scale is time consuming and might be affected by a variety of factors. There is the need for measurement on urban scale that can provide relatively efficient and precise estimation of interior daylight potential. A daylight performance indicator for urban analysis was proposed: facade Vertical Daylight Factor per unit floor area, which is calculated as area-weighted total facade Vertical Daylight Factor divided by total floor area. Numerical simulation was conducted across 20 generic forms and 4 different density scenarios. The results showed a strong and positive correlation between the proposed indicator and the reference indicator of interior daylight potential, i.e. area-weighted average horizontal Daylight Factor at work plane height. The utility of the proposed daylight performance indicator lies in its efficiency of simulation for urban scale of analysis and, therefore, the impacts of geometry, spatial arrangement and envelope material properties of urban built forms on interior daylight potential can be evaluated efficiently in the early planning stage. The limitations of this study and potential future explorations are also addressed.

1. INTRODUCTION

Urban morphology and building typology have significant impacts on a variety of environmental performances of urban built forms, such as energy consumption (Ratti, Baker, & Steemers, 2005; Salat, 2009) and incident solar radiation (Kämpf, Montavon, Bunyesc, & Bolliger, 2010; Robinson, 2006). Daylight is one of the primary concerns in architectural design and urban planning regarding the urban sustainability agenda as it has multifaceted implications on human physiological and psychological well-being and building energy consumption.

Research Question

Various performance metrics have been proposed to evaluate interior daylighting quality on building level (Christoph F. Reinhart, 2006). However, these metrics are primarily developed for interior spaces and they are not efficient to apply in urban studies. For example, supposing three building mass designs are proposed under the same design conditions. The interior daylight level of the primary interior spaces for these designs may depend on a variety of factors, such as the spacing to obstruction, fenestration design, building material properties and interior spatial layout. Site level evaluation of the daylight performance for all the individual interior spaces across the three design options may become impractical to manage. The question is whether we can develop measurement for urban scale comparative analysis that allows relatively efficient and precise estimation of interior daylight potential in the early stage of urban planning and architectural design for various design options so that their relative performances can be assessed. A variety of studies have attempted to address the issue of daylight potential as a function of built form in this regard.

Relevant Studies

In Ratti et al’s (2003) study, daylight availability, which was measured indirectly through average Sky View Factor (SVF) on building facade and ground surface, was examined for different building typologies regarding their suitability in hot-arid climate. The results suggested that courtyard configuration seems to perform better than pavilion types.

Cheng et al (2006) explored the relationships between urban built form, density and solar potential in a parametric study which examined a series of generic urban forms in different densities and spatial layouts. It was found that built form may have significant impacts on daylight availability as indicated by average facade Daylight Factor, and the effect of horizontal randomness was stronger in high density scenario than for low density scenario whereas the effect of vertical randomness was significant across all density scenario. The implications are that daylight availability might be significantly improved by changing the spatial layout of urban geometries without compromising the density, and increasing built density may not necessarily lead to the decrease of daylight availability, depending on how the built forms are arranged. Similar findings have been reported in early parametric studies by Ng (2004, 2005b).

Montavon et al (2006) examined the daylight viability for the built forms in *La Ville Radieuse* as proposed by Le Corbusier for Paris. Using the indicator of percentage of facade area receiving, on average, 10klux or more daylight annually, they found that the daylight performance for the cross-shape high-rise building was inferior to that for the traditional low-rise compact Parisian urban street blocks, whereas the low-rise perimeter blocks as proposed in Le Corbusier's design seem to perform better than the tradition Parisian blocks. Their findings also suggested that built form may have significant impacts on the effectiveness of heliothermic axis which represents the most desirable orientation for buildings in a given geographic location regarding solar access.

In a series of studies on daylight quality in high density urban environment, Ng (2003a, 2003b, 2005a, 2010; Ng & Cheng, 2004) proposed the concept of Unobstructed Vision Area (UVA), which is measured as the area of a horizontal vision cone unobstructed by buildings in from of a vertical window, as an indicator for facade daylight level. Parametric studies utilizing generic square blocks in typical spatial configuration in Hong Kong suggested that UVA is positively correlated with Vertical Daylight Factor. Depending on the minimum VDF required and location of windows, minimum UVA can then be specified for a given design scenario, therefore, facilitating the adjustment and regulation of the design.

An Alternative Thinking

For the studies mentioned above analysis on urban level daylight potential seemed to focus on comparing the overall quantity of daylight on building facade, either through measuring via a proxy variable such as SVF, calculating average VDF, or percentage of facade achieving certain level of daylight intensity for various urban forms, or on describing the probability of a specific point on facade to achieve a required daylight level within a given physical context (Ng, 2009, p. 189). An alternative thinking might be linking the quantity of daylight receivable on facade with usable floor spaces associated with a given form under a given density in that the daylight distribution across the floor spaces at a given height (e.g. at work plane height) is what ultimately concerns the users.

For example, there're two buildings with the same form and same physical context. One has only one story whereas the other has two stories within the same built volume. They may have the same score if average VDF or percentage of facade with VDF above certain threshold value is calculated for them because they have the same facade area. However, the amount of daylight penetrating the facade and shared by each floor will be different for the two buildings, assuming the fenestration design is the same in both cases. The floor of the one-story building may receive higher level of light through the entire facade whereas each floor in the two-story building may receive lower level of daylight as a result of the light coming from only half of the facade. Obviously, the difference in the implication of facade daylight level on interior daylight level can be attributed to the difference in the amount of usable floor spaces. Another example is what was discussed in Montavon and colleagues' (2006) study. As they pointed out, although the overall daylight performance of the high-rise tower proposed by Le Corbusier was inferior to the typical Parisian blocks according to the performance indicator used in the study, the facade convolution implemented in the "deeply serrated" design may actually increase facade area, allowing light coming from side to penetrate deeper into the rooms behind the facade and thus increase the light level at the inner part of the interior spaces.

The Proposed Indicator

It is argued that in urban scale analysis the quantity of an environmental variable, be it solar radiation or daylight, as aggregated or averaged for building surfaces may only capture one aspect of the story about the overall environmental performance of urban forms. In order to obtain the first level of understanding on the implications of facade-level environmental quantity to interior-level environmental potential by taking into account the built density, accumulated environmental quantity on facades as shared by usable floor spaces may need to be measured for different urban forms.

An urban scale daylight performance indicator, "facade Vertical Daylight Factor (VDF)[1] per unit floor area" which is calculated as area-weighted total facade VDF divided by total floor area or Gross Floor Area (GFA), is proposed in this regard (Figure 1).

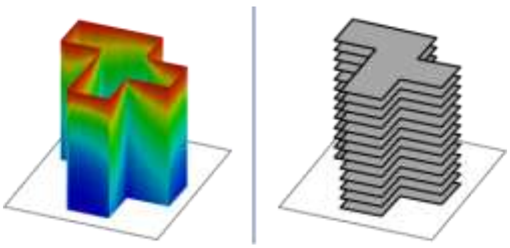


Figure 1. The proposed urban scale daylight performance indicator

Similar to the concept of Floor Area Ratio (FAR) or plot ratio in urban planning, which is an indicator of built density that prescribes the amount of usable floor spaces buildable per unit area of the site, the proposed indicator measures the average amount of daylight falling on facade that may eventually affect every unit area of usable floor space.

The basic assumption of the proposed indicator is that interior daylight potential is primarily dependent on the amount of daylight receivable on building facade in the first place (Ng, 2004; Ng & Wong, 2004), other than been affected by factors such as obstruction, fenestration, material properties and interior layout. And facade daylight level is primarily affected by geometries of building mass, facade material properties and site-level spatial arrangement of built forms and therefore can be adjusted through design intervention in the early stage of planning.

Objectives

This paper reports the methods and results of evaluating the proposed daylight performance indicator in relation to interior daylight potential, which is measured by a reference indicator "area-weighted average horizontal daylight factor at work plane height (0.85m)", assuming the respective facade is fully open (Figure 2). This reference indicator captures the maximum potential of daylight penetration for a given form by opening up its facade and calculating the average level of daylight distributed across the entire floor space.

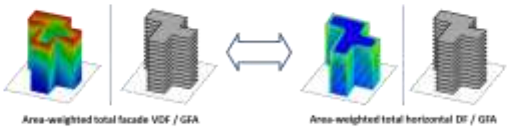
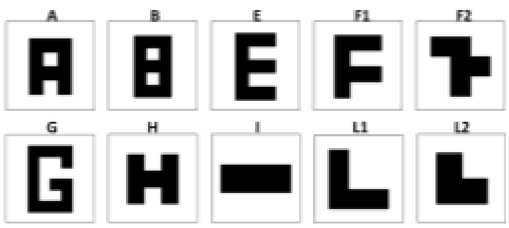


Figure 2. The proposed indicator and the reference indicator (colors indicate different Daylight Factor values as simulated)

2. METHODS

The Forms

Twenty generic forms with the same foot print area (625m^2) which capture a wide range of planar geometric characteristics were selected for simulation studies (Figure 3). They represent some of the typical building forms according to preliminary review of a pool of real urban built forms. Each form was positioned at the center of a square-shape site (50x50m, site coverage = 25%). The architectural dimensions of the forms and site were controlled to be realistic in terms of width and depth. The purpose was to examine if the relationship to be tested may vary significantly across different forms under a given density.



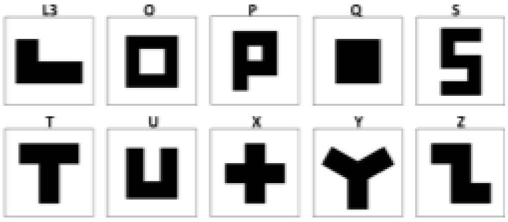


Figure 3. The 20 generic forms tested

The Context

Instead of being simulated in a fixed physical context, each form and the site was surrounded by two layers of replications of itself. In this regard, a theoretically homogenous context composed of the same form and in the same spatial layout unique for each form was created[2]. The theoretical performance for the center block in this theoretical context was thus simulated and compared (Figure 4).

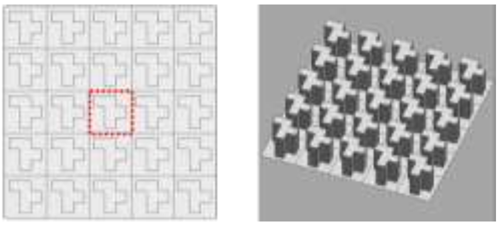


Figure 4. An example of the theoretically homogenous simulation context (the plot from which data was extracted is marked in dotted line)

The Densities

To examine the sensitivity of the relationships to be tested to the variation of density, four different density scenarios were tested for each form by increasing the height of the forms (Figure 5) from 4 stories to 12, 24 and 36 stories, resulting in densities ranging from low (FAR=1), medium (FAR=3) to high (FAR=6 and 9).

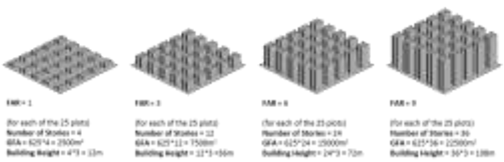


Figure 5. The four density scenarios tested

Simulation

The simulation was performed floor by floor, form by form and density by density in Radiance. VDF for the facade of a given floor was simulated by setting sensors on facade in 1x1m spacing with normal perpendicular to facade. Interior horizontal DF for a given floor was calculated by removing the facade surface of the respective floor and setting upward sensors at work plane height (0.85m) in 1x1m spacing (Figure 6). The floor by floor data was then aggregated for the analyses related to the entire facade surfaces and the entire floor spaces (Figure 7).

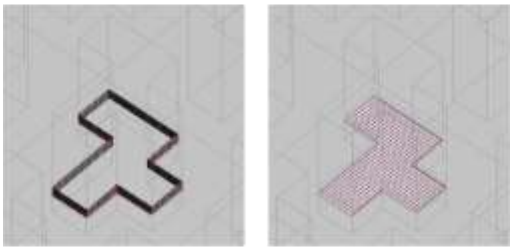


Figure 6. An example of the location of light sensors on façade and that on work plane height for a given floor

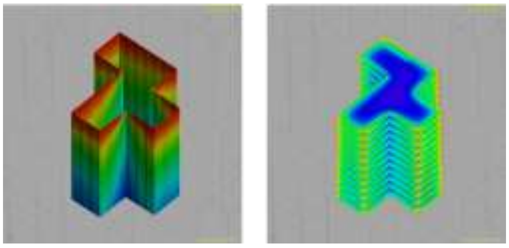


Figure 7. An example of the façade VDF and interior horizontal DF as visualized

Analysis

The bivariate correlation analyses conducted were illustrated in Table 1. Other than the relationship between the proposed indicator and the reference indicator (IV), three other analyses were performed to examine: I) if the average amount of light received on facade and that of the entire floor space is correlated on a floor-by-floor basis; II) if the average amount of light received on the entire facade is a good predictor of the average daylight level calculated for all floors (the reference indicator); III) if the total amount of light received on the facade and that for the entire floor space is correlated on a floor-by-floor basis. Each of the four relationships were also further examined to check its sensitivity to the variation of form and density.

Table 1. The relationships examined

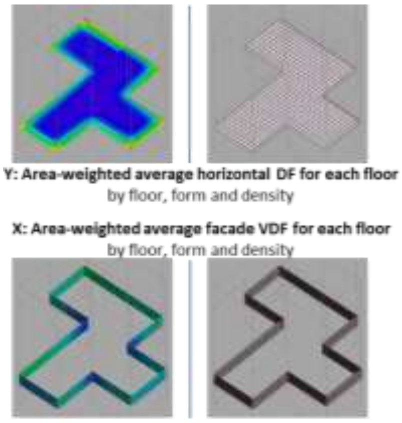
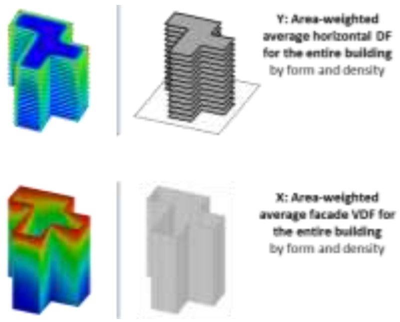
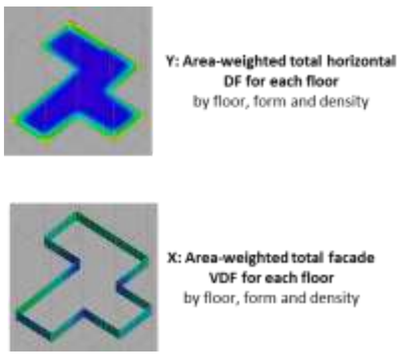
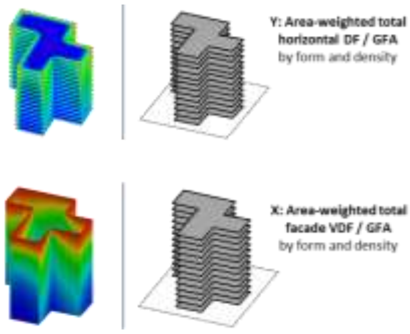
	Average amount of daylight
Floor by floor comparison	I). 
Entire surfaces comparison	II). 

Table 1. (Continued)

	Total amount of daylight
Floor by floor comparison	III). 
Entire surfaces comparison	IV).  (Note: Since the denominators for both variables are the same, this analysis is actually comparing the total amount of daylight for the entire facade vs the total amount of daylight for all floors.)

3. RESULTS

I) Generally speaking, the average facade VDF for a given floor was significantly correlated with the average horizontal DF for the respective floor (R^2=0.895, p<0.0001) across all 20 forms and all 4 density scenarios (Figure 8).

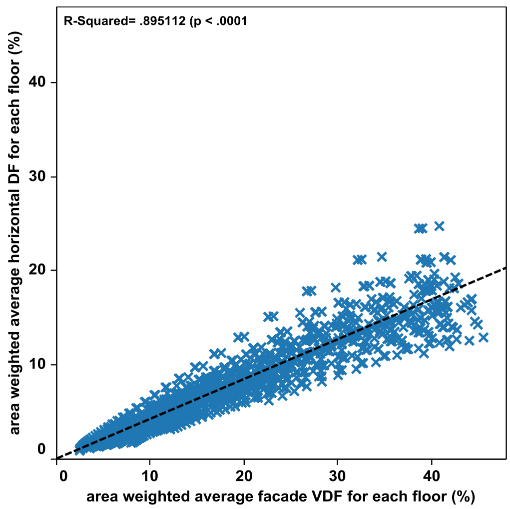


Figure 8. Average facade VDF of a given floor vs. average horizontal DF of the floor across all forms and densities

This relationship didn't vary much across different forms, as indicated by R^2 calculated for each form which ranged from 0.9932 for form Q to 0.9964 for form S (Fig 9, left). The relationship tested seemed to become stronger as density increased, as indicated by the R^2 calculated for each density scenario which increased from .075 for FAR1 to .918 for FAR9 (Fig 9, right).

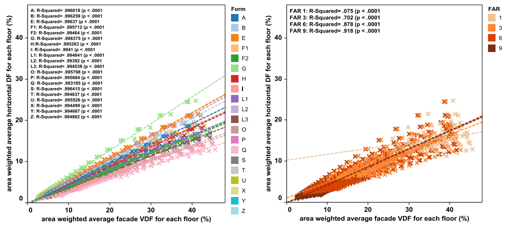


Figure 9. Average facade VDF of a given floor vs. average horizontal DF of the floor by form (left) and by density (right)

II) The average VDF calculated for the entier facade seemed to have a significant but relatively weaker corrlation with the average horizontal DF for all the floors (R^2=0.795, p<0.0001) across the 20 forms and 4 density scenarios (Fig 10). The clusters as shown in the graph is due to the incontinuity of the density scenarios tested here.

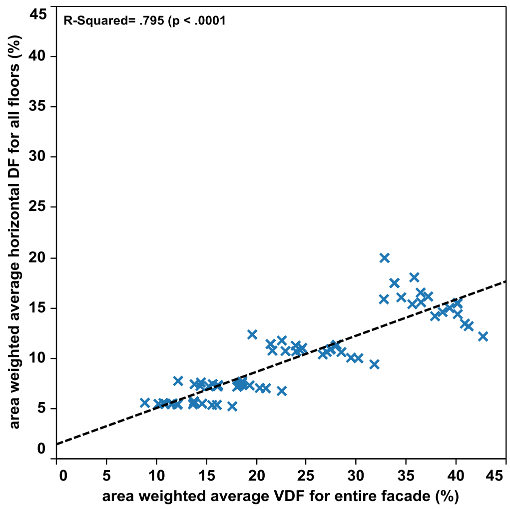


Figure 10. Average VDF of the entire facade vs. average horizontal DF for all the floors

The relationship tested also didn't vary a lot across different forms, with the R^2 calculated for each form ranging from 0.9985 for form Q to 0.9996 for form A (Fig 11, left). However, as density increased the correlation between these two variables become weaker and weaker and less and less significant, as indicated by the R^2 calculated for each density scenario which dropped significantly from .671(p<0.001) for FAR1 to .149(p=.092) for FAR9 (Fig 11, right). The results suggested the relationship between average VDF as calculated for the entire facade and average DF for all floors might be significantly affected by density.

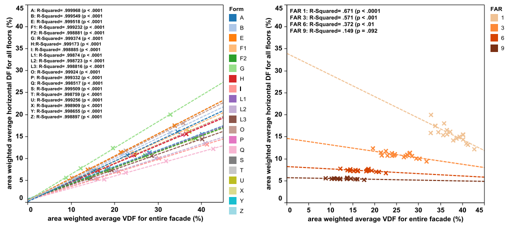


Figure 11. Average VDF of the entire facade vs. average horizontal DF for all the floors by form (left) and by density (right)

III) The total VDF for the facade of a given floor was significantly and strongly correlated with the total horizontal DF on work plane height for the entire floor space of the given floor (R^2=.991, p<.0001) across all forms and densities (Fig 12).

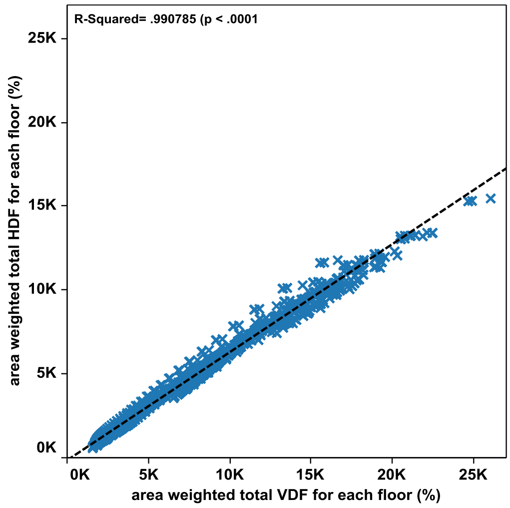


Figure 12. Total VDF for facade of a floor vs. total horizontal DF for the floor across all forms and densities

This relationship varied little across different forms, as indicated by the R^2 calculated for each form which ranged from .9932 for form Q to .9964 for form S (Fig 13, left). The correlation between the two variables seemed to become stronger as density increased, as indicated by the R^2 calculated for each density which increased slightly from .943 for FAR1 to .995 for FAR9 (Fig 13, right).

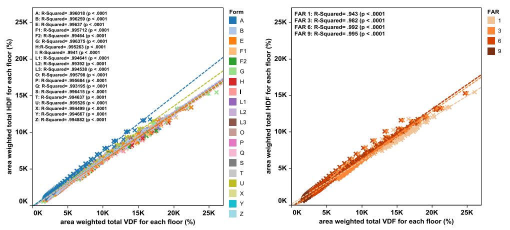


Figure 13. Total VDF for facade of a floor vs. total horizontal DF for the floor by form (left) and by density (right)

IV) The facade VDF per unit floor area was significantly and strongly correlated with the horizontal DF per unit floor area (R^2=.997, p<.0001) across all 20 forms and 4 densities (Fig 14).

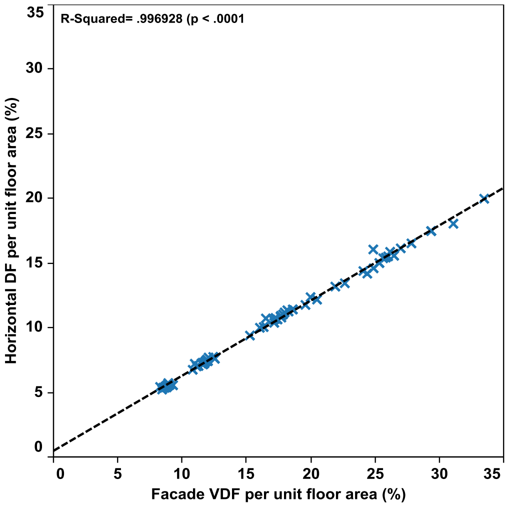


Figure 14. Facade VDF per unit floor area vs. horizontal DF per unit floor area across all forms and densities

This strong correlation only slightly varied across different forms, as indicated by the R^2 calculated for each form which ranged from .998 for form Q to .999 for form A (Fig 15, left). However, the correlation seemed to decrease as density increased, as indicated by the R^2 calculated for each density which dropped from .966 for FAR1 to .437 for FAR9 (Fig 15, right).

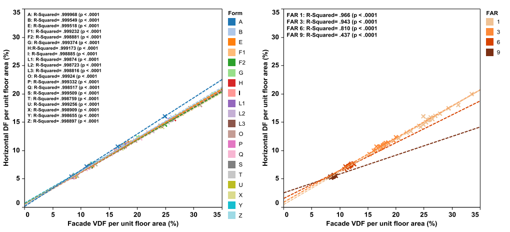


Figure 15. Facade VDF per unit floor area vs. horizontal DF per unit floor area by form (left) and by density (right)

4. CONCLUSIONS

The proposed urban scale daylight performance indicator is intended to allow planners and architects to do relatively quick and precise estimation of the interior daylight potential across various design scenarios during the early design stage when different spatial arrangements and geometric characteristics of simplified building masses of different built forms can be tested.

On a floor-by-floor basis, the results indicated that amount of light falling on facade is highly correlated with the amount of light distributed across the entire floor space in terms of either the average or the total (Fig 8, 12), and the effect of from and density on this relationship is quite small (Fig 9, 13).

Taking the entire facade surfaces and the usable floor spaces as a whole, the relationship between average VDF for facade and average horizontal DF for all floors was relatively weaker (Fig 10) and it may be affected by density (Fig 11). On the other hand, the significant and strong correlation between the proposed indicator and the reference indicator across different forms and densities suggested that the floor area normalized facade daylight quantity can be used as a relatively precise and efficient indicator of interior daylight potential (Fig 14). However, the percentage of variations in horizontal daylight potential that can be explained by the variation in the proposed indicator seemed to decrease as density increased (Fig 15). Therefore, cautions may need to be taken when apply the proposed indicator in extremely high density situation.

Limitations and Future Studies

The generic built forms tested in this study were intended to be representative. However, they're not exhaustive and the results might be different if other generic forms are considered. Further parametric studies may consider covering a wider range of generic forms. In this study the variation of density was achieved through increasing building height solely. Future studies may need to consider other approaches to vary density such as varying site coverage and their respective impacts on the sensitivity of the proposed daylight performance indicator. The experiment of this study was conducted only for four typical density levels. To further test the sensitivity of the proposed indicator to the variation of density, more levels of built density may need to be considered. The impacts of other factors such as spacing between buildings and reflectivity of facade material on the effectiveness of the proposed performance indicator may also need to be further explored in a systematic way.

The proposed indicator is based on the calculation of daylight factor which is a static daylight metric. Many studies related to interior daylight potential have addressed the limitations of using daylight factor as an indicator of daylight quality (C. F. Reinhart, Mardaljevic, & Rogers, 2006) and suggested several climate-based daylight metrics (Architectural Energy Corporation, 2005; Nabil & Mardaljevic, 2006; Christoph F. Reinhart & Andersen, 2006). Further studies may need to explore if alternative dynamic daylight metric can be used so that the annual variation of daylight on facade can be captured in a precise way.

ACKNOWLEDGMENT

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[1.] Instead of using proxy variables such as SVF, VDF is calculated in that it is widely used in daylight studies as indicator of facade daylight level and it was suggested to be a more appropriate variable for studies related to urban and inter building daylight evaluation (Ng, 2010, p. 67). Based on the contemporary development of numerical simulation software and computer hardware, precise simulation of VDF for complex urban geometries can now be achieved in relatively efficient ways.

[2.] Similar understanding can be referred to in other studies related to environmental performance simulation for a given piece of urban fabric (Ratti et al., 2005; Ratti et al., 2003; Salat, 2009), in which the hidden assumption is that the urban fabric being analyzed is relatively homogenous in terms built form.

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