Suitability of neighborhood-scale massing models for daylight performance evaluation.

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Abstract: Access to daylight in buildings is the combined effect of a building's own physical attributes along with its surrounding physical context. There is thus growing interest among researchers to extend the use of building performance simulation (BPS) tools for daylight performance evaluation, not just for an individual building, but to the neighborhood scale and beyond. In the design process of neighborhoods, massing models are often utilized and are a pivotal early design-stage work-product. These models are typically simple and delineate broad geometric dimensions of built enclosures. They are thus attractive for fast early design stage assessment using BPS tools and maybe used to determine daylight access potential. However, at this stage, the designer may have limited and imprecise information regarding the building façade, the vital element for daylight intake and distribution in the building interior.

In this study, we assess the dependability of simple massing models for comparative indoor daylight assessments of neighborhood forms. Useful Daylight Illuminance (UDI) metric based performance values were calculated for five neighborhood design options using common practice for façade related inputs in early design stage simulation models and then ranked in decreasing order of performance. A virtual progression of the design-process was then carried out to develop multiple plausible façade design solutions for all proposed massing schemes. The main finding of this study is that significant changes can be observed in neighbourhood rankings when increasing the degree of detail in the façade design solutions. While the highest performing designs were found to maintain their ranks, the rankings of other projects shifted considerably when façade related information was supplied. This work informs on the possibility of erroneous design decisions resulting from simplified façade inputs in early design stage models and fosters the growing discussion on appropriate utilization of BPS tools for informing design decisions.

Key Words: BPS best practice, design process, daylight, façade details

Introduction

The world is currently witnessing the largest urban population growth in history. According to projections by the United Nations ("UN DESA 2014"), by the year 2050, the world's urban population will increase by 2.5 billion. While increasing urbanization brings about resource efficiency and economic growth, it also affects the ability of the new and existing built environment to rely on natural resources such as daylight to create comfortable spaces for habitation. The role of architects and architecture today is thus of critical importance. In his revolutionary book in the year 1923 (Corbusier, 1923), architect Le Corbusier, described a house as 'a machine to live in' and that 'architecture is the masterly, correct and magnificent play of masses brought together in light'. Growing pressures of urbanization and the urgent need to address our building use related carbon-emissions are now demanding greater precision in the building design process; and that architects be 'masterly' and 'correct' in order to deliver pleasurable, healthy, comfortable, energy-efficient urban living environments.

Daylight, a critical element of the indoor environmental quality, is modulated by each scale of the physical environment (Cammarano et al, 2015), from the urban scale right down to a single room. While the pre-existing urban context may partially determine the nature and amount of daylight access, it is up to the building design team to harvest the available resources for a given a project. In the context of the architectural design process, massing models, whether created in

sketch, 3D modeling material or computing medium play a crucial role. Early in the design process, quick and simple models are often developed to examine, evaluate and discuss design ideas (Akin and Moustapha, 2004; Kvan and Thilkaratne, 2003). Kvan et al, highlight that models in the architectural design process, especially early on, tend to be diagrammatic or representative in nature and they develop along the design process. A number of design decisions may be taken based on the exchange that happens amongst the design team while examining these models. A number of daylight researchers have thus been trying to target this design activity while the project is taking shape.

In this study, we are interested in this design activity at the neighborhood level, i.e. the intermediate scale between an individual building and the urban scale. The neighborhood scale is indeed unique as the design team has control over both the overall form of the neighborhood and also building scale decisions. In the following section, we thus discuss tools that are specifically targeted at a neighborhood scale early-design phase. These tools allow architects and designers to understand the relationship between architectural characteristics of neighborhood forms and daylight access.

Methods for evaluating daylight in early neighborhood designs

Early design tools for daylight can be divided into two primary categories 1) rules of thumb and 2) simulation based. Similar to the early rule-of-thumb based urban-scale solar design-aids developed by Knowles (Knowles, 1974, 2003), DeKay (DeKay, 2010) proposed the 'Daylight Envelope' concept as an urban scale daylight design tool. The Daylight Envelope technique produces a three-dimensional enclosure creating a permissible boundary that achieves the design goal for Daylight Factor. The model is based on empirical observations of urban block dimensions, street widths and resulting Daylight Factors achieved. However, the Daylight Factor metric itself has serious limitations. It ignores several critical factors when designing a daylit space such as the orientation of the building, climatic effects such as cloud cover and time-varying nature of sky and sun positions.

Compagnon (Compagnon, 2004) presented an indoor work-plane illuminance evaluation method for neighbourhood designs based on simulation of vertical illuminance on the exterior building facades. This computationally light method can be used to compare various neighbourhood forms. It regards window openings as daylighting devices and they are grouped under 'utilization factors' when estimating the combined effect of buildings at a neighborhood scale. In order to successfully integrate time-consuming annual daylight simulations in the transient early design phase, the speed of simulation has been one of the key concerns of researchers. For example, a fast daylight performance calculation algorithm was developed by Dogan et. al. (Dogan et al, 2012). Similar to (Compagnon, 2004), the incident illuminance on the vertical facades is first calculated. These values are then translated into indoor illuminance values using a 2-D light propagation algorithm. This method was used in the development of an interactive design tool called Urban Modeling Interface (UMI) (Reinhart et al, 2013) for rapid evaluation of massing models. Their intent was to assist architects in making connections between good daylight performance and building/urban morphology. A very different approach was used by Nault et al (Nault, 2016) in developing a tool called UrbanSOLve that also allows architects to quickly evaluate their design performance to other parametrically generated design variants. The

tool is based on a meta-model generated by collecting performance data (Spatial Daylight Autonomy) from a large set of representative neighborhood massing schemes.

While these tools are able to evaluate and compare the performance of neighborhood layouts with acceptable margins of error when compared to full-scale simulations, they take a simplistic view of the façade. Several researchers working at the urban and neighbourhood scale (Sattrup and Strømann-Andersen, 2013; Dogan et al, 2012; Compagnon, 2014) support simple façade related inputs for urban scale studies based on the idea that the influence of the volumetric and relative building layout on site tends to outweigh that of the façade composition.

However, this assumption is more likely to hold true if we assume that the windows are distributed uniformly across the façade, in which case form related factors would dominate. Both urban (Ratti et al, 2005) and room level studies (Gibson, 2014; Ratti et al, 2005; Wright and Mourshed, 2009) find that placement of windows with respect to the internal configuration of the building can have appreciable affect both quantity of daylight intake (Ratti et al, 2005) and its distribution. New climate based metrics such as Spatial Daylight Autonomy (IESNA, 2012) and Useful Daylight Illuminance (Nabil Mardaljevic et al, 2006; Mardaljevic, 2015) simultaneously evaluate the amount of daylight received indoors and also how well it is distributed (temporally and spatially) in order to support the activities of the occupants. Under these conditions, it seems imperative that we investigate the reliability of massing models that do not carry any specific information regarding the façade design.

Methodology

In this study we evaluate if ignoring façade related design information and only evaluating the massing of the neighborhood could lead to erroneous decisions when selecting the high performance designs. We tested this by carrying out annual daylight simulations for five possible neighborhood massing schemes for hypothetical project located in Geneva, Switzerland. Using the parametric modelling environment, Rhino/Grasshopper (McNeel, 2015, 2013), we add façade related information to the massing models in a step-by-step manner. Facade parameters that are included are described in the façade details section below.

Using various combinations of these façade details, we virtually propagate the design process for each of the massing schemes. Each massing scheme is taken through three explicit steps of increasing resolution in both the façade design and its representation in the simulation models. In order to represent the many possible decision-making paths that could be followed to arrive at a certain degree of definition in façade design, three scenarios are created, described in the design scenario section below. With each evolutionary step of the design process, we evaluate if the top performing massing schemes are able to retain their ranking. The façade design approach is kept strictly consistent using the same grasshopper workflow each time so as not give

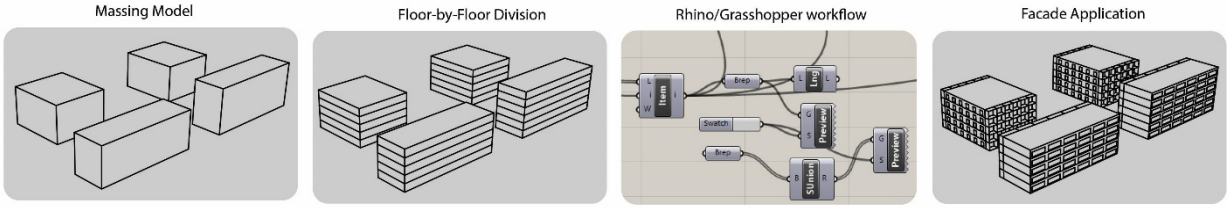

Figure 1: Sequence of transformation of massing models in Rhino/Grasshopper

unwarranted advantage to any particular neighborhood design. The façade generating grasshopper work flow is given a massing scheme which has been split into floors and one or more façade design parameters as inputs. The workflow generates a 3-D geometry file with façade elements such as windows and shading elements added to the massing scheme (Figure 1). Since the workflow remains unchanged with each massing scheme, it allows us to study if a particular façade design approach has greater synergy with a particular form more so than others.

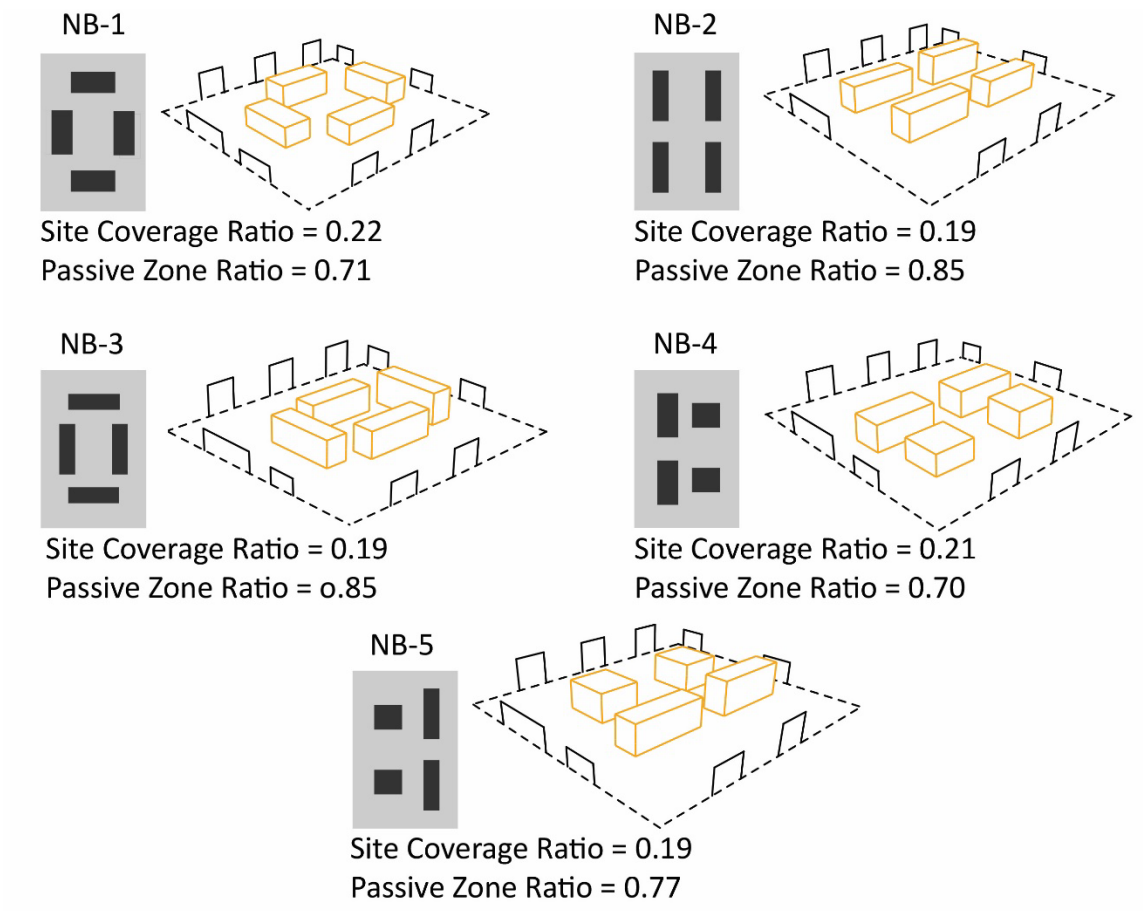

Figure 2: Proposed neighbourhood massing schemes included in the study

The proposed massing schemes are inspired largely by observations of existing neighborhoods in the Genève area. Density (built area/site area or floor-area-ratio) of 1.0 was chosen and then the number of floors, building aspect ratio and arrangement on site was drawn from observations of a set of existing neighborhoods. Given the rich variety in façade types found in residential buildings, we found it more pertinent to conduct this test on residential buildings. The schemes produced are shown in Figure 2. Site coverage ratio presented is calculated as building foot-print/site area. Passive zone ratio is the ratio of floor area within 6m of the façade to the total floor area (Baker and Steemers, 1996).

For this study, the performance evaluation criteria used is Useful Daylight Illuminance (Mardaljevic, 2015). The UDI metric is largely developed from user assessments of office spaces. It regards the range of 100-3000 lux in horizontal illuminance as useful while acknowledging that the lower illuminance range of 100-300 lux is useful but insufficient for common office related

tasks such as reading. The metric thus has provision to regard the 100-300 lux illuminance range achieved by daylight as supplementary and not fully autonomous. Since in this study the subject buildings are residential and majority of residential spaces by area (living areas and bedrooms) host several activities that are not detail oriented (social meetings, dining and household chores), the range 100-300 lux is likely to be useful in the residential setting as well. We recognize that 100-300 lux illuminance might not be sufficient for all activities in residential buildings, however we are not evaluating auxiliary artificial lighting energy use in this study and thus continue using UDI with its original intent. On the other end applying an upper limit for preferred horizontal illuminance (rather than luminance-based glare-related discomfort) is a subject of ongoing research (Kleindienst and Andersen, 2012; Wienold, 2009). It is being included here as a very appreciable proxy for visual comfort for initial investigations at this scale. Regarding shading, which greatly influences visual comfort and overheating prevention, the effect of fixed shading devices (e.g. balconies) – when appropriate to consider in a massing model (cf. façade design parameter "C" described below) – will be accounted for, but operable blinds will not be considered at this time given the scale of the daylight simulations.

Climate based annual daylight simulations were carried out in Radiance/Daysim (Ward-Larson and Shakespeare 1998; Reinhart and Walkenhorst 2001) with the evaluation period modified to 7:00 AM to 7:00 PM in the evening to reflect relevant daylit hours at home rather than at work. In the daylight simulation model, a square grid of sensors, 1 m apart was set up across all zones/spaces in the neighborhood massing schemes. These sensor points act as virtual photo-sensors. The illuminance data at each point for every hour is assessed against the pass/fail criteria of UDI (100lux-3000lux). Every hour that the illuminance falls in this range is counted as meeting the UDI criteria. Refer to Table 1 for key material parameters. Other simulation parameters such as ambient bounces and ambient divisions were kept consistent with IESNA guideline for the modelling method for climate based daylight simulation metric sDA (IESNA, 2012).

Table 1: Surface properties assigned for daylight simulations

Surface type	Property	Value
Glazing	Visible light transmittance	0.6
Internal Walls	Reflectance	0.5
Internal Floor	Reflectance	0.3
Internal ceiling	Reflectance	0.8
External Wall	Reflectance	0.3
External fixed shading devices	Reflectance	0.3

Façade details considered

In this study three kinds of façade design parameters are being considered based on the combined considerations of common modelling practices, common design features of residential building facades and the potential impact of these elements on daylight distribution.

Facade design parameter A) Window area to wall area ratio (WWR)

Facade design parameter B) Identification of a prominent façade and a secondary façade per building and including a bias in window opening area

Facade design parameter C) Presence and location of fixed shading devices.

Façade design parameter-A: In this study simple specification of WWR is being referred to as façade design parameter A (Figure 3). The only information that is passed on to the simulation model under this parameter is the percent value of glazed area at the building level. The common practice for preparing a massing model for annual daylight simulation is followed when applying façade design parameter A, and windows with arbitrary aspect ratio are input as two-dimensional openings along all faces of the buildings. Another common default input, that is also followed, placing windows at the centre of the wall surface vertically and spacing them equally, horizontally.

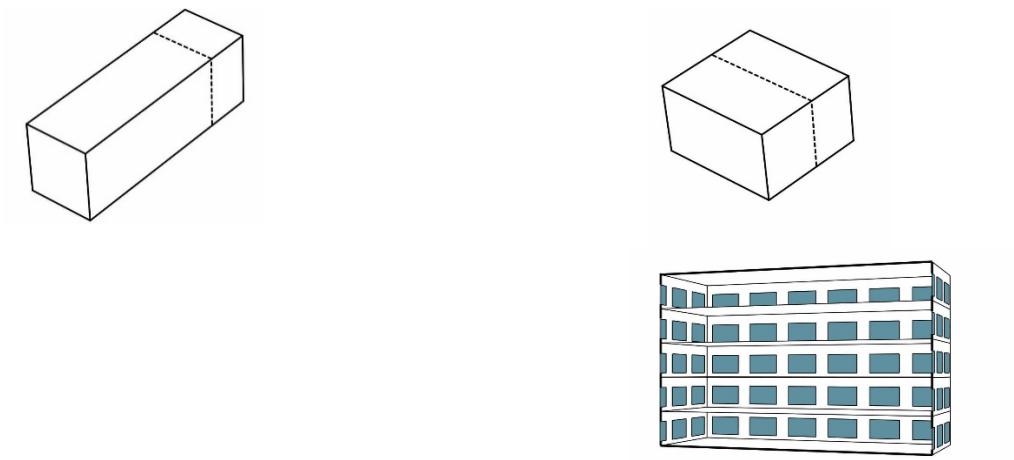

Figure 3: Example of addition of facade design parameter A using Rhino/Grasshopper to example building blocks (example on left shows sectional view of a long linear building, example on right shows a sectional view through a building with aspect ratio<1.25)

Façade design parameter-B: Under this parameter we recognize that not all building faces will carry the same WWR and that certain facades of the same building may have different WWR. Under this façade design parameter, we take the following design steps: 1) identify the prominent and secondary façade surfaces 2) define the ratio of the glazing area assigned to the prominent and the secondary façade. The selection of prominent and secondary façade is based on the orientation of facades and overall form of the building (Figure 4).

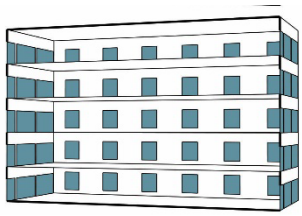

Figure 4: Examples of application of façade design parameter B (example on left shows sectional view of a long linear building, example on right shows a sectional view through a building with aspect ratio<1.25)

Façade design parameter-C: Fixed shading devices have an important role in daylight intake and distribution in the interior and improving visual comfort for the building occupant. These would also be typically excluded from early design performance evaluations. However, horizontal projections like balconies are a common design feature in residential buildings. We regard them as facade design parameter C (Figure 5). In order to test the hypothesis, an intensive version of balcony types is utilized in this study. The balconies assigned are 2.4 m deep, cover the entire

prominent facade and also have vertical elements on both sides for privacy, forming an egg crate shading device.

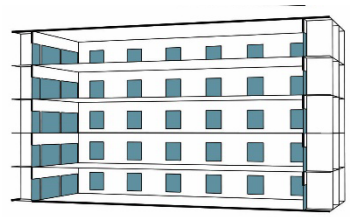

Figure 5: Examples of application of façade design parameter C (example on left shows sectional view of a long linear building, example on right shows a sectional view through a building with aspect ratio<1.25)

Design scenarios considered

We present three different scenarios in which varying degrees of information regarding the façade are input during the initial daylight assessment at the onset of the project. In scenario 1, no specific façade details are known. Default values are assumed and they are eventually corrected in subsequent design steps. In scenario 2 WWR value is known fairly accurately and other façade design details are added eventually (table 2). In scenario 3, The design team is able to specify the prominent facades but does not know the WWR to be used on the project. In each case, they would like to assess the performance of the five neighborhood massing schemes.

Table 2: Design scenarios considered

	Initial assessment inputs	**Virtual design step I**	**Virtual design step II**
Scenario 1	Only facade design parameter A is set, 40% WWR is assumed	• WWR corrected to 30% • Facade design parameter B is added	• Facade design parameter C is added
Scenario 2	Only facade design parameter A is is set, 40% WWR is assumed	• WWR unchanged • Facade design parameter B is added	• Facade design parameter C is added
Scenario 3	Facade design parameter B is specified, façade design parameter A is set to 40%	• Facade design parameter A is changed to 30%	• Facade design parameter C is added

Results

We first examine the simulation results at the space level, how the addition of various façade details changes the daylight distribution in the building interior. Two example spaces with the deepest cross-sections (20m and 26m) were chosen for further examination. We then go on to

examine the results at the neighborhood scale under the three design scenarios described above.

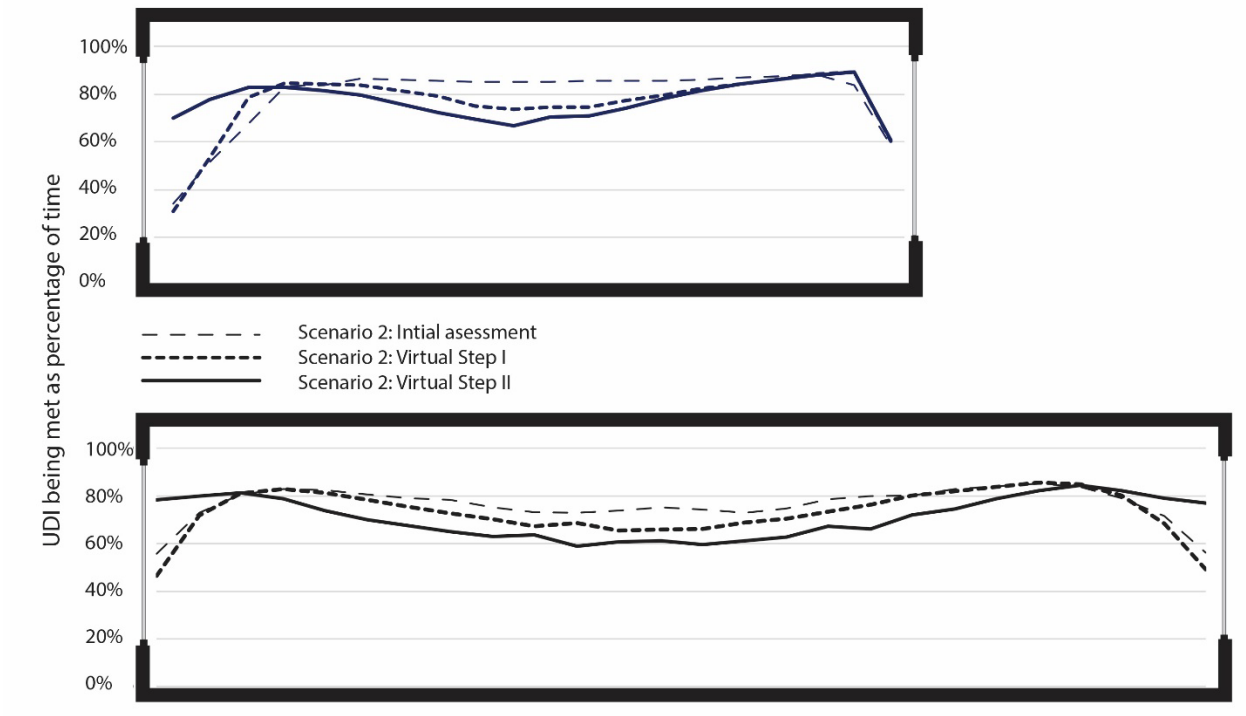

Figure 6: Percent of time UDI is met, shown in cross section of the example spaces (space proportions in section are indicative, not to scale)

Space Level Results

Figure 6. shows the variation in UDI achievement as a percentage of time over the year, across two example spaces for scenario 2. In this scenario, the WWR remains constant and the results thus show changes in performance achieved only with changes in window placement and addition of balconies. The space shown on the top in Figure 6 is 20 m deep and has East/West windows on either side. The space shown on the bottom in Figure 6 is 26 m deep and has windows on all faces with the prominent facades facing East/West.

In both examples spaces, we find that the areas near the window opening are the poor performing areas during the initial assessment phase. Understandably this changes only when the balconies are added (façade design parameter C). The addition of balconies/fixed shading brings more hours during the year under the upper limit of 3000 lux and results in the improvement of UDI achievement. The middle section of the space, farthest from the windows appears to be affected by both distribution of glazing across the facades (façade design parameter B) and the addition of balconies (façade design parameter C).

If we examine the annual average percentage of time UDI is met across the two cross-sections presented in Figure 6, we find a difference of -4.5% and -3.8% between the initial assessment and virtual design Stage I in the 26 m deep space and the 20 m deep space respectively. These differences occur by only changing the window area distribution from one façade to another. If we compare the annual average percentage of time UDI is met between the

initial assessment and virtual design step II we find greater fluctuation in the 26m deep space (-6.8%), than the 20m deep space (-2.4%).

Neighbourhood Level Results

Scenario 1: Under scenario 1, we observe several changes in performance ranking of the neighborhoods examined with incremental addition of façade details. While the top two performing neighborhoods maintained their ranks throughout the virtual progression of the design process, middle rank holding neighborhoods were found to be volatile in their rankings (Figure 7). The biggest changes in rankings were seen at the virtual design Step I when the window wall ratio was corrected and the prominent facades were identified. Virtual design Step II helped distinguish between the top performing designs suggesting that NB-3 was more sensate to placement and addition of balconies and was adversely effected in UDI evaluation. Ranking and relative performance of other neighborhoods remained largely unchanged at the virtual design Step II.

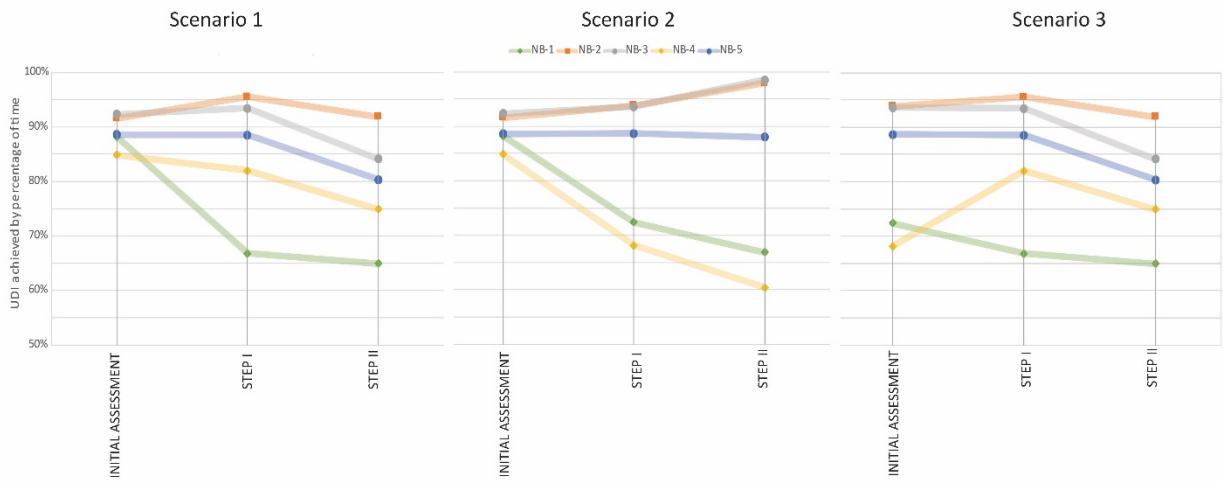

Figure 7: UDI performance values under scenario 1,2 and 3

Scenario 2: In scenario 2 also we observe one change in performance rankings of the neighborhoods examined. The initial estimate of the design team regarding the WWR here happens to be correct and remains unchanged throughout the progression shown. While the rankings, in this case, are found to be more consistent than scenario 1, we see some neighborhoods (NB-2,3,5) continue to improve in performance as more façade details are added. Performance of other neighborhoods (NB-1,4) continuously drops. In other words, a decision which would seem somewhat irrelevant in terms of daylight performance in the absence of façade design details (e.g. choosing between NB1 and NB2) can become of significant influence should one consider certain façade parameters (only revealed in steps I and II).

Unlike scenario 1, one can note that the performance of the top two performing neighbourhoods (NB -2,3) remains within 1% of each other even at virtual design step II. This could be explained due to the fact that in this case the WWR ratio remained high and thus neither neighbourhood is affected unfavourably with the addition of shading devices. In scenario 1, the

performance of NB-3 (neighbourhood with courtyard layout) drops with addition of virtual design step 3 at 30% WWR.

Scenario 3: In scenario 3 we start the assessment from a point where the design team is able to include façade design parameter B (location of prominent facades) from the very onset of their evaluations. In this case, the neighborhoods with low performance at the initial assessment are found to be volatile in their rankings. Addition of balconies (façade parameter C) helps in differentiating between the top two performing neighborhoods (NB-1,2). It is also noteworthy that in this scenario, the performance of NB-4 improves with the reduction in glazed area, contrary to other neighbourhood schemes, where the performance either drops or remain nearly constant. While the overall WWR applied to all the neighbourhoods at a certain design step is kept consistent, the amount of glazing per façade, especially after inclusion of design parameter B depends on the total available surface area per building and proportion of area of the prominent façade. For example, in Scenario 3, at the initial assessment stage, while the overall WWR is 40%, the prominent façades of the long linear building in NB-1 carry 45% WWR but in NB-4 the long linear buildings carry 60% WWR on the prominent facades. NB-4 then appears to benefit from a reduction in the overall WWR in the virtual design step I. Existing parametric studies (Berardi and Anaraki, 2015; Cammarano et al, 2015) involving design factors such as WWR, room depth when evaluating UDI show that increasing WWR results in lower UDI levels near the window while increasing the UDI levels in the back of the room. However, to further understand the inter-relationship between other factors included this study, such as building placement, orientation, passive zone ratio and daylight performance, a parametric approach is needed which we hope to address in future studies.

Summary

Rank changes were found to be most severe when information input at the initial assessment was limited to WWR and if the default value chosen was not adhered to later on in the design process. However, the two high-performance cases were able to retain their rank in all cases. The top-performing cases were neighborhoods composed of buildings with the highest passive zone ratio. No clear trends were observed with regards to the site coverage ratio. It became possible to distinguish between the top performers only upon addition of balconies in the low window-wall-ratio case (30% WWR). At 40% WWR their performances remained within 1-2% or each other. Thus it appears that change in rank and relative performance is not only subject to differences in form but also the façade parameters.

Active shading devices such as internal or external blinds/drapes are a common feature of window openings in residential buildings and play an important role in maintaining visual and thermal comfort indoors as per the occupant's needs. While occupant behaviour plays a large role in how they are used and operated, their use is also affected by design choices such as presence or absence of fixed shading devices or self-shading. The use of blinds for alleviating conditions of glare has been ignored in the study. It has been considered in a very simplistic manner in this study using the contentious upper limit of horizontal illuminance included in the UDI metric. We hope to address this in future in future studies.

Conclusions

In this study, we wanted to test if massing models could be reliably ranked in order of performance during the early design stage. By incrementally adding façade related information we tested if a minimal amount of specificity in the façade inputs could improve the reliability of massing models.

Initial assessments done using only WWR input, resulted in a relatively small spread in performance values across the proposed massing schemes. The overall range in performance at the initial assessment stage (Scenario 1 and 2) was found to be 7.4% (in annual average UDI). Adding information regarding the prominent facades in scenario 2 substantially expanded the range of performance to 25.6%. This large spread in performance allows for more confident early design stage performance evaluations when a large number of other design parameters are still unknown.

Current findings suggest that adding one or more façade details can greatly improve the reliability of massing models for daylight performance evaluations. However, they are hard to generalize as only limited façade design possibilities were tested. In future studies, we would like to explore multiple design possibilities resulting in a probability of rank changes rather than single observations.

Façade details were found to not only aid in clearly distinguishing the performance of the various massing schemes, but in some cases the design decisions could be different depending on the knowledge of the architect regarding the façade. The performance rankings were found to differ based on the chosen value of WWR per building, WWR per facade and location of fixed shading. The effect of these factors on rankings was also found to vary between the neighbourhood schemes evaluated. Thus the design decision related utility of the façade design factors in the early design performance evaluations was found to be contingent upon the subject neighbourhood(s) being evaluated. We propose a parametric approach to further understand the relationship between neighbourhood form characteristics, the resulting massing schemes and the need for façade related information for robust performance evaluation.

While findings in this paper are drawn from an example project and are empirical in nature, they inform the growing debate on robust early design phase performance evaluations using simulation tools. We find that daylight performance evaluations may not only be subject to modelling practices and evaluation criteria, but also the design process followed and degree of integration of performance evaluations into the design process.

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