ISSN 2004-2965 Energy Proceedings, Vol. 21, 2021

International Conference on Applied Energy 2021
Nov. 29 - Dec. 5, 2021, Thailand/Virtual
Paper ID: 454

Does Urban Form Randomness Improve Indoor Daylight Duration?

Parth Bansal[1], Steven Jige Quan[1, 2, 3, *]

1 City Energy Lab, Graduate School of Environmental Studies, Seoul National University

2 Environmental Planning Institute, Graduate School of Environmental Studies, Seoul National University

3 Artificial Intelligence Institute, Seoul National University, South Korea

* Corresponding Author. Email: stevenchuan6656@gmail.com | sjquan@snu.ac.kr

ABSTRACT

Indoor daylight has significant influences on building energy use and occupant health, and studies suggest a targeted illuminance range to achieve an overall performance, the duration of which has been adopted to evaluate the urban design. In previous studies on urban form, solar availability, and daylight, there are two streams of research, namely, the parametric design, and the design optimization. As urban design often involves diverse urban form patterns, the former stream focuses on whether a uniform pattern or random pattern has better solar availability or daylight while the latter directly searches for the best performative design through optimization. However, in the parametric stream, the definitions and sampling for uniform and random design patterns were largely limited; in the optimization stream, the form parameters to optimize were often limited, and searching for the best design only provided one-sided information as design heuristics for generalization. Moreover, most of the studies in both streams focused on general solar availability and daylight, and it is largely unclear how urban form influences the comprehensive daylight duration metric. This study investigates the indoor daylight performance of different urban forms with two specific sets of questions: First, is random urban form better than regular urban form for daylight as stated in the first research stream? And second, what are the best and worst urban forms for daylight and how much performance difference they make, extended from the discussions in the second research stream? To answer these two sets of questions, this study used a grid-based hypothetical design setting as the test case. The study has two parts. In the first part, 500 parametric models were developed to compare daylight availability between five groups of urban form with different levels of uniformity/randomness. In the second part, designs with nearly best and worst daylight are generated using a genetic algorithm and compared. It was found that on average, randomness improves daylight duration, but some random forms perform poorly compared to uniform urban forms, which is echoed by a large performance variation of random urban forms from the optimization results. The findings provide a better understanding of design performance for daylight, which can be used as a general heuristic to inform urban design practice.

Keywords: solar availability, urban design, daylight, optimization, parametric design

1. INTRODUCTION

One of the major purposes of urban design and planning is to provide occupants with optimal natural daylight access. At the urban design stage, regulations are generally concerned with maximizing access to the entire design area, while individual buildings try to maximize whatever daylight is available [1]. Natural light has been linked with improved health outcomes, and increased workplace productivity [2]. Furthermore, natural lighting within an optimal range reduces building energy consumption by lowering artificial lighting energy use [3, 4].

Improving solar availability, and daylight access to an urban area has been studied by examining façade exposure, the orientation of streets, building and street shapes, courtyard styles, and building density [5]. A typology-based approach has been commonly adopted for morphology-based studies, including those concerned with solar availability and daylight access [6]. Using such a typology approach, Ng [7] studied the impact of variation in building height on daylight availability in a high-density neighborhood, composed of otherwise identical towers. Cheng, Steemers [8] expanded this concept to include both vertical and horizontal randomness in urban form. They compared tower typology models of uniformly built with those having horizontal, vertical, and horizontal plus vertically randomness and concluded that randomness improved access to daylight irrespective of site coverage or floor area ratio.

While Cheng, Steemers [8] showed the benefits of randomness in urban form for daylight access, they conceded that their parametric study relied on only 18 models of urban form. Thus, layouts generated by them for uniform or random urban forms are not sufficient to conclude that all random urban forms are equally efficient for daylight access. Additionally, this approach failed to inform which of the enormous possibilities among random urban forms produces the best daylight access results.

To address these issues systematically, this study is divided into two parts. In the first part, referred to as the parametric study, 500 models are constructed from randomly drawn samples. They are used for studying the effects of uniformness or different types of randomness in an urban form on daylight access. In the second part, referred to as the optimization study, genetic algorithm [9] NSGA II [10] is used to identify nearly best urban design models in terms of daylight access. They are then compared with the nearly worst models generated using the same approach.

Compared to previous major studies [7, 8, 11, 12], the key contributions of this study are: 1) It investigates the impact of randomness in the urban form on daylight using a large number of parametrically generated urban models. 2) It demonstrates the application of optimization for daylight maximization for preferred FAR. 3) It shows expected improvement in daylight duration using optimization over randomly chosen design and compares urban models with nearly best and worst daylight.

2. METHODOLOGY

2.1 Geometric Model

At the urban design level, buildings with a low level of detail are defined for the general layout of proposed build area. This study assumes that the hypothetical site is located in the western quadrant of Portland, US. The location is characterized by a regular square grid including the streets with the width of 20 M and blocks with the size of approximately 60 x 60 M. Based on this, a 4 x 4 grid and a single row of buildings surround it is constructed to depict a new development within a pre-existing district (Fig. 1). Surrounding buildings are defined as 18 x 18 M structures with a cover ratio of 0.72 based on the average characteristics of the selected location.

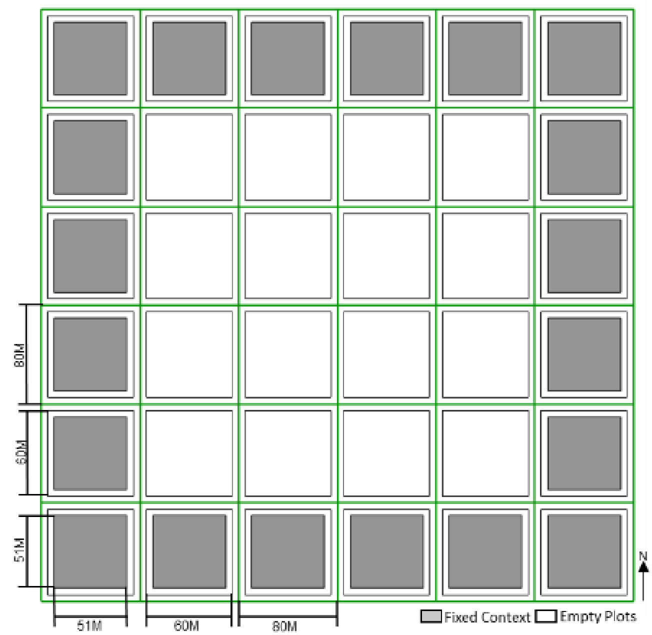

Fig. 1. Parametric design setting

For both parametric and optimization study, each of 16 buildings is defined by four parameters: length, width, location within the plot, and floor count. Length or width of each building can vary from a minimum of 20 M to maximum of 60 M (eq. 1 & eq. 2). The floor count can range from 1 to 40 (eq. 3). Building footprint area and floor count ratio of the Portland's western quadrant is estimated to range between 17.66 to 4808 with 5 percentile value of 60. Thus buildings in the study cannot have a footprint area and floor count ratio of less than 60 (eq. 4) to ensure that taller buildings are not of unreasonable dimension. Buildings can be located anywhere within the plot as long as it does not exceed the plot's boundary.

$$\text{Lenght } (L): 20 < L < 60 \quad (1)$$
$$\text{Width } (W): 20 < W < 60 \quad (2)$$
$$\text{Floor Count } (FC):\ 1 < FC < 40\ \ (1 \text{ floor} = 3.65\text{M}) \quad (3)$$
$$\text{Footprint Area–Height Ratio } (FAHR): 60 < FAHR \quad (4)$$
$$\text{Location: within plot}$$

2.2 Parametric Study

The parametric study consists of 500 models divided into five sets, each containing 100 models (Fig. 2). Each model is defined by 16 buildings following constraints defined in section 2.1. Additionally, it is assumed that a developer would like to maximize the 4 FAR allowed in the study area. Hence each parametric model generated has FAR in the range of 3.96 to 4.

Set 1 consists of uniform models, i.e., all 16 buildings have the same length, width, floor count, and location. Set 2 consists of models where floor count (and thus building height) varies randomly, but length, width, and location of 16 buildings are the same. Set 3 consists of models where length and width vary randomly, but height and location of 16 buildings are the same. Set 4 consists of models where location varies randomly, but all the heights, lengths, and widths of 16 buildings are the same. Finally, set 5 consists of models where all four aspects vary.

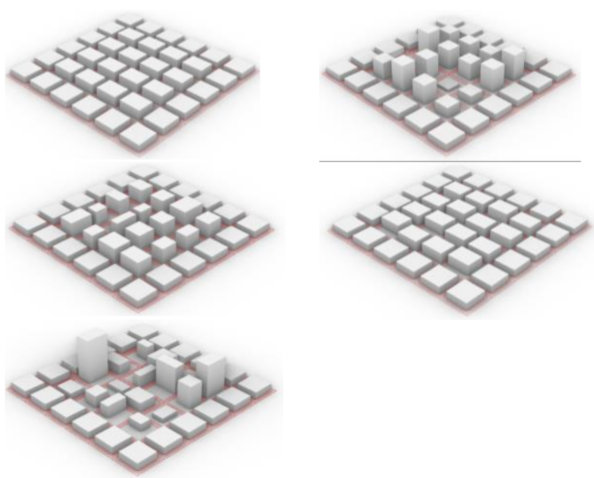

Fig. 2. Example of uniform, random height, random length and width, random location and complete random designs (left to right, top to bottom)

2.3 Optimization study

The optimization study uses NSGA-II [10], a genetic algorithm used for multiobjective optimization. Similar to parameter study, each model is defined by 16 buildings following constraints defined in section 2.1. The objective is to maximize the percentage of time when illuminance is between 300-3000 lux between 7 AM and 7 PM (eq. 6). Additionally, the second objective was to minimize the absolute difference between 4 and FAR of a model (eq. 7).

$$Minimize\ \ f(x) = \frac{\sum_{i=1}^{n} -x_i}{n} \tag{6}$$

$$Minimize\ \ f(y) = |y - 4| \tag{7}$$

Where x is the percentage of time when illuminance is between 300-3000 lux between 7 AM to 7 PM, and y is the model's FAR. Two independent optimizations with different NSGA-II parameters (table 1) are performed.

$$Minimize\ \ f(x) = \frac{\sum_{i=1}^{n} x_i}{n} \tag{8}$$

To compare models with near best daylight with those who have near worst daylight, optimization based on the same parameters as run 1 is executed (eq. 7 & eq. 8).

Table 1. NSGA-II parameters

Parameters	Run 1	Run 2
Population	100	100
Generation	100	100
Mutation Probability	0.1	0.05
Crossover rate	0.9	0.8

2.4 Daylight simulation

For daylight simulations, Radiance [13] is deployed. It is a widely used physically-based backward raytracing renderer that has been thoroughly validated [14]. Since detailed fenestration design is generally not done at the urban design stage, the two-phase daylight coefficient method is used to keep simulation time reasonable. Perez sky model [15] is generated from the luminance value of typical meteorological year's weather data for the assumed location of Portland, US.

Radiance parameters colloquially referred to as "fast" [16] are used. Sensors for measuring illuminance are set at 8x8 M density and are located at 0.8 M from the ground of each floor. Building level details (Table 2) based on the US department of energy's reference building model for a large office building in climatic regions 4C [17] is supplied into the Radiance engine. Additionally, the area not occupied by building footprint is assumed to be asphalt with the 0.2 reflectance.

Table 2. Building parameters based on DOE reference building for large office building in climate region 4C

Parameter	Value
Window to Wall Ratio	0.38
Window Material	Glass with transmittance of 0.305
Exterior Walls and Roof	Concrete with 0.3 reflectance

3. RESULTS

3.1 Parametric study

The daylight results of 500 models divided into five sets, each containing 100 models, are shown using a box plot (Fig. 3) and summary statistics (Table 3). In the case of uniform model set, the minimum and maximum percentage of time when daylight is within the range of 300-3000 lux between 7 AM to 7 PM is 18.98% and 44.09%, respectively, with a mean of 33.41%. All five statistics (Table 3) improves when height, length and width, location, or total randomness is allowed. The mean improvement in daylight duration was 5.49%, 8.21%, 3.17%, and 12.01% for height, length and width, location and total randomness, respectively. Besides the relatively lower mean improvement in daylight duration in location randomness set, the range is also relatively higher than other sets. This indicates that benefits from location randomness can largely depend on other factors held constant for this set.

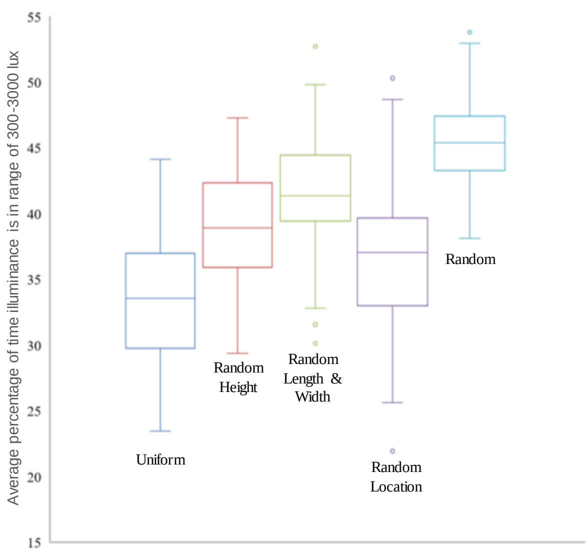

Fig. 3. Box plot of percentage of time when daylight is between 300-3000 lux between 7 AM – 7 PM

Table 3. Descriptive statistics for daylight duration in different sets of urban form

	U	RH	RLW	RL	AR
Mean	33.47	38.90	41.62	36.58	45.42
Minimum	23.42	29.38	30.12	21.91	38.09
Maximum	44.09	47.27	52.68	50.28	53.80
5 Percentile	24.76	31.11	35.59	27.11	40.32
95 Percentile	42.13	45.63	48.00	44.71	51.06

Notes:

U: Uniform, RH: Random height, RLW: Random length and width, RL: Random location, AR: All random

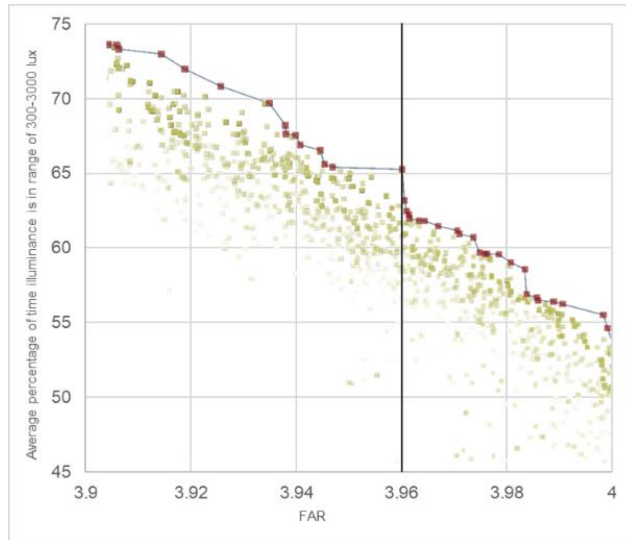

Fig. 4. Pareto front for run 1 with cutoff for FAR

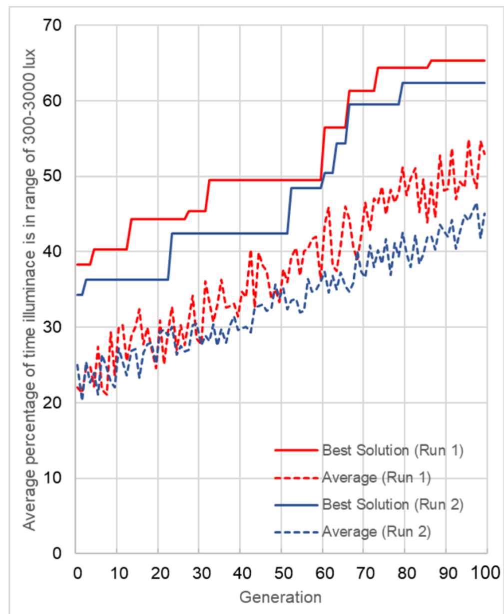

Fig. 5. Generational improvement over daylight objective function

3.2 Optimization Study

Based on the parameters described in section 2.3, optimization is performed two times. Similar to parametric study, it is assumed that development would aim for the maximum allowed FAR 4, and thus results are filtered out to only include models whose FAR is in the range of 3.96 to 4 (Fig 4).

The run 1 and run 2 of the optimizations after 100 generations produced the best solution with daylight performance of 65.34% and 62.01%, respectively (Fig 5). Additionally, the average value of population in a generation also improves faster in run 1. Fig. 6 shows examples of the best design which maximizes the percentage of time when illuminance is between 300-3000 lux between 7 AM and 7 PM.

Optimization with the same parameters as run 1 but where the objective was set to minimize daylight duration was also executed. Fig. 7 shows examples of worst designs that minimized the percentage of time when illuminance is between 300-3000 lux between 7 AM and 7 PM.

4. DISCUSSION

Despite the improvements in the mean of daylight duration from randomness, the bar plots (Fig. 3) show considerable overlap with the uniform models. Thus, while on average, randomness improves daylight duration, it is indeed possible that some uniform urban designs are better than some random urban designs. Hence while Cheng, Steemers [8] were partially correct about the benefits of randomness for better daylight, urban planners and designers need to be aware that just a label of uniform or random does not ensure relatively better daylight.

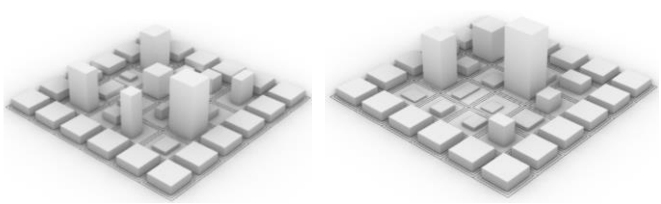

Fig. 6. Design examples with close to the longest daylight duration in desired range

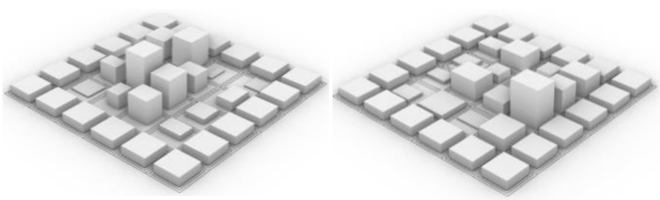

Fig. 7. Design examples with close to the shortest daylight duration in desired range

Fig. 6 & 7 further highlights how all urban models which would be considered random in terms of height, length and width, or location within plot, can both be near best or near worst. A much bigger factor than a label of random or uniform appears to be how the randomness is distributed within the 16 plots. Generally, those models with higher daylight performance have taller buildings located far from other taller buildings, which ensures that even if one side of the building is overshadowed, the other side maintains access to daylight.

5. CONCLUSION

This study investigates the impact of urban form on daylight duration within the desired range of 300 – 3000 lux. Uniform urban form models where all buildings are of the same dimension and location within plot are compared with urban form models with height, length and width, and location randomness. The parametric study concludes that on average, randomness improves daylight duration, but not all random urban form is equally good, and some random forms perform poorly compared to uniform urban forms. On average, maximum gains from randomness are observed when all three factors, length and width, floor count, and location, are random. However, even with the randomness in the three factors, some models have lower daylight duration than some uniform models.

Since mere label of randomness does not ensure maximization of daylight, urban planners and designers need to adopt a more exploratory approach for identifying ideal urban form based on a site's location. Using NSGA–II, a genetic algorithm, an approach to identifying urban form that maximizes daylight duration within the desired FAR range is developed. This approach is executed for the assumed site in the western quadrant of Portland. The results from it are compared with those generated when the objective is set to minimize daylight duration. The comparison supports the conclusion from the parametric study when both near best and near worst are random in terms of length and width, floor count, and location within the plot.

ACKNOWLEDGEMENT

This work was supported by the Creative-Pioneering Researchers Program through Seoul National University (SNU), the National Research Foundation of Korea (NRF) grant funded by the Korea government (Ministry of Science and ICT) (No. 2018R1C1B5043758), and the National Research Foundation of Korea (NRF) grant funded by the Korea government (Ministry of Education) (No. 5120200113713).

REFERENCE

[1] Strømann-Andersen J, Sattrup PA. The urban canyon and building energy use: Urban density versus daylight and passive solar gains. Energy and Buildings. 2011;43:2011-20.

[2] Boyce P, Hunter C, Howlett O. The benefits of daylight through windows. Troy, New York: Rensselaer Polytechnic Institute. 2003.

[3] Chi DA, Moreno D, Navarro J. Correlating daylight availability metric with lighting, heating and cooling

energy consumptions. Building and Environment. 2018;132:170-80.
[4] Yu X, Su Y. Daylight availability assessment and its potential energy saving estimation –A literature review. Renewable and Sustainable Energy Reviews. 2015;52:494-503.
[5] Montavon M. Optimisation of urban form by the evaluation of the solar potential. Epfl; 2010.
[6] Shi Z, Fonseca JA, Schlueter A. A parametric method using vernacular urban block typologies for investigating interactions between solar energy use and urban design. Renewable Energy. 2021;165:823-41.
[7] Ng E. A study of the relationship between daylight performance and height difference of buildings in high density cities using computational simulation. International Building Performance Simulation Conference: Citeseer; 2005. p. 847-52.
[8] Cheng V, Steemers K, Montavon M, Compagnon R. Urban form, density and solar potential. 2006.
[9] Mitchell M. An introduction to genetic algorithms: MIT press; 1998.
[10] Deb K, Pratap A, Agarwal S, Meyarivan T. A fast and elitist multiobjective genetic algorithm: NSGA-II. IEEE transactions on evolutionary computation. 2002;6:182-97.
[11] Chokhachian A, Perini K, Giulini S, Auer T. Urban performance and density: Generative study on interdependencies of urban form and environmental measures. Sustainable Cities and Society. 2020;53:101952.
[12] Vermeulen T, Knopf-Lenoir C, Villon P, Beckers B. Urban layout optimization framework to maximize direct solar irradiation. Computers, Environment and Urban Systems. 2015;51:1-12.
[13] Ward GJ. The RADIANCE lighting simulation and rendering system. Proceedings of the 21st annual conference on Computer graphics and interactive techniques1994. p. 459-72.
[14] Reinhart CF, Walkenhorst O. Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds. Energy and Buildings. 2001;33:683-97.
[15] Perez R, Seals R, Michalsky J. All-weather model for sky luminance distribution—preliminary configuration and validation. Solar energy. 1993;50:235-45.
[16] Kharvari F. An empirical validation of daylighting tools: Assessing radiance parameters and simulation settings in Ladybug and Honeybee against field measurements. Solar Energy. 2020;207:1021-36.
[17] Deru M, Field K, Studer D, Benne K, Griffith B, Torcellini P, et al. US Department of Energy commercial reference building models of the national building stock. 2011.