Adaptive Parametric Algorithm for Optimizing Non-Conventional Solar Screens for South-Oriented Office Façades in Cairo, Egypt

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Abstract

Parametric approach proved great potentials in generating various alternatives and overcoming traditional scenario-by-scenario limitations, especially when combined with simulation tools. Parallel parametric simulation was suggested as generative-evaluated tool to optimize solar screen driven by daylight and thermal performance in 8 times faster than default runs. This paper proposes an Adaptive-Parametric-Algorithm (APA) for Grasshopper (GH) based on parallel parametric simulation to directly generate optimized alternatives of non-conventional solar screen for specific target performance. APA uses Diva-for-GH to optimize various screen parameters for south-oriented office space in Cairo, Egypt. The results proved APA ability to achieve numerous screens alternatives efficiently that all comply with both LEED-V4 and IES within optimal thermal performance. Moreover, a selection criteria was proposed, that could indicate optimal screen configurations which balance daylight and thermal performance based on daylight simulation only.

Introduction

Building façade plays a significant role in architecture; it is not only a mean to express the design concepts but it is the main moderator between interior spaces and exterior environment. The increasing reliance of office buildings on air conditioning and artificial lighting systems indicates the failing role of the building facade to perform its function as a moderator. Within this context, ecological facades and the use of solar screens have proved their potentials for enhancing buildings' environmental performance in arid climates.

Parametric generative modeling tools with their ability to be linked with performance simulation tools have gained momentum over the past few years. Parametric generative systems have made a major shift in the design process from designing an 'object' to design the 'logic' of the object, considering parametric optimization approach as a generative-explorative tool (Leach, 2009).

A research by (Ayman Wagdy & Fathy, 2015) presented a methodology that could made use of the Radiance potentials to run parallel simulation according to the available CPU cores of the used computer resulting in significant time savings in the total running time. Thus, one of the main limitations of using parametric runs, over wasting running time, could almost be overcome. Similar studies that focused on exploring the effectiveness of

parametric simulation in exploring and optimizing different shading devices and designs for daylight and/or thermal analysis with various other performance aspects could be found in (Hegazy & Wagdy, 2016; Naboni, Zhang, Maccarini, Hirsch, & Lezzi, 2013; Sherif, Sabry, Wagdy, Mashaly, & Arafa, 2016). Focusing on the scope of this paper, a study by (Elghazi, Wagdy, Mohamed, & Hassan, 2014) conducted an exploration for a non-conventional solar screen based on origami: kaleidocycle rings that could be morphed to enhance daylight performance in residential spaces. Diva for Grasshopper (GH) was used as a daylight simulation tool, results demonstrated the optimal Kaleidocycle configurations that exceed LEED v4 requirements while passing Daylight availability standards. Further exploration for the same research projects we conducted by (Elghazi, Wagdy, & Abdalwahab, 2015; A. Wagdy, Elghazi, Abdalwahab, & Hassan, 2015). Another important study that addressed the limitation of simulating complex geometric screens in energy simulation software such as Design Builder and EnergyPlus was (Omidfar, 2011). As directly, creating a complex surface geometry is infeasible using current simulation tools. This paper suggested that, to model the effect of a sun shading screen based on Sculptor Erwin Hauer's design, specific performance criteria of the screen had to be measured using the daylight simulation firstly. These should include the screen shading coefficient and a yearly electric lighting schedule based on daylight performance metrics, which was Daylight Autonomy (DA). The results were then synchronized with thermal analysis performed in Design Builder. This paper proved that, a building's shading device can be both a complex geometry that satisfies the aesthetics desires for ornament, while also fundamentally addressing building performance and user comfort. Another study for the same author (Omidfar, Torghebehi, & Buelow, 2014), introduced an integrated methodology that allows designers to find solutions which yield good performance over a range of criteria to evaluate a design both aesthetically and performativity. The daylight was evaluated based on Daylight Autonomy (DA) and Solar Radiation (RAD) penetration through the skin as it could give an indication about the cooling load of the space. RAD was calculated using a set of sensors or nodes located on the exterior walls directly behind the skin to measure Radiation penetration through the unit modules. RAD results showed 70% to 96% reduction in direct radiation, which would ultimately reduce the

overall cooling demand and therefore reduce the energy consumption during the summer months.

On the other hand, a study by the authors presented the parallel parametric simulation approach for a non-conventional solar screen driven by daylight and thermal performance (Hassan, Abdin, & Ezzeldin, 2017). Parallel Radiance simulations saved time by 8 times more than the default parametric runs for 1875 solutions, by making the maximum benefits of the available CPU cores, which were 8 in this case. The only remaining problem was that this parallel simulation could not be applied for thermal simulations, as EnergyPlus could only be runs for one case at a time unlike Radiance/DAYSIM for daylight simulations that has the ability to calculate the daylight performance for more than one cases at the same time. However, to overcome this limitation an original algorithm inside GH was specially developed for this study to achieve the maximum benefit of the parallel simulations' potentials for both daylight and thermal parametric simulations. The paper presented a comprehensive analysis using an exhaustive search method for the effect of the screen parameters on daylight and thermal performance.

The work presented here is a part of a comprehensive study that aims to define the effectiveness of both parametric design and Genetic Algorithms approaches for assessing and optimizing non-conventional solar screen configurations to improve daylight and thermal performance in arid climates such as that of Cairo, Egypt. However, the aim of this paper is to propose a new methodology called Adaptive Parametric Algorithm (APA) that could make a worthwhile benefit from parallel parametric simulation approach and help architects efficiently optimizing non-conventional solar screen driven by daylight and thermal performance. Optimal solar screens are identified, and evaluation criteria are refined. Moreover, specific evaluation criteria will be addressed that could give an indication about cooling loads based on daylight simulation hence, daylight optimum cases can be sorted regarding thermal and energy performance without even being calculated.

Adapted Parametric Algorithm (APA) Concept

Adapted Parametric Algorithm (APA) is a parallel-parametric-based approach that aims to expand the benefits of the previously explored parametric simulations presented in (Hassan et al., 2017) to make a worthwhile investment of the screen parameters exploration. Figure 1 shows the advantages and limitations of using parallel parametric simulation where relatively limited number of the screen variations could be explored with limited variations of the screen configurations. Thus, APA approach aims to overcome these limitations by generating various combinations that could satisfy daylight and thermal performance as well as the designer's intents. Hence, by this approach a wide range of optimized solutions can be directly generated that all comply with both LEED V4 and IES requirements

while ensuring the optimal thermal performance with efficient energy consumption.

Figure 1: The potential of the new approach, APA.

Methodology

The methodology implemented here was divided into two consecutive phases. Firstly, further explorations of the previously analyzed parallel parametric simulation conducted in (Hassan et al., 2017) will be presented. Secondly, the Adapted Parametric Algorithm (APA) methodology will be proposed as a parametric based optimization method that rely on the parallel parametric analysis of phase one. Finally, from the analysis of the correlations between daylight performance and thermal performance results, a workflow of proposed selection criteria that could indicate the optimal balance between daylight and thermal performance based on daylight simulation only was presented.

The screen various parameters; module sizes, rotation angles, scale ratios, and protrusion values with their predefined configurations were modelled parametrically and aligned to this façade. Daylight analysis was conducted using Daylight Dynamic Performance Metrics (DDPMs); Daylight Availability, Spatial Daylight Autonomy (sDA_{300/50%}) and Annual Sunlight Exposure (ASE_{1000/250hr}) that comply with both LEED-v4 and IES approved method. While thermal analysis was based on a comparison approach to a specific base case.

Simulation framework

The realization of various parameters that control the screen geometry required the geometry to be modelled in GH as a mean to control each variable parametrically. The simulations were conducted by integrating simulation tool with parametric modelling using DIVA and GH respectively. DIVA interfaces with Radiance/Daysim and EnergyPlus for daylight and thermal analysis respectively. The overall definition of solution was generated in GH and divided into three main sets as shown in Figure 2; Parametric modeling, Performance simulations and Performance evaluation.

Firstly, two 3D models for a hypothetical office space with a south side-lit façade were modelled within GH, one with full details and thicknesses for daylight simulations and another one of singular surfaces for thermal simulations. Then the proposed screen was parametrically modelled and applied to this south façade. After that, each

alternative was linked to DIVA Daylight Analysis component within GH to firstly, measure the daylight performance inside the office space. Secondly, generate the electric lighting schedule and to calculate the screen shading coefficient to be linked to the thermal simulation later. Then the thermal simulation was conducted using Viper Thermal Analysis component within GH. Finally, the simulation results aligned with their specific configurations are collected and exported to a Microsoft Excel sheet using TT Toolbox plugin for GH that contains a fast Excel Writer which can transform results' numbers into excel to be analyzed and evaluated.

Base Case Parameters

The case study was chosen to be located in Cairo, Egypt (30°6'N, 31°24'E) a subtropical hot arid climate according to Köppen's climate classification (Peel, Finlayson, &

McMahon, 2007). Cairo is characterized by high direct solar radiation and clear sky that demands special façade treatments to minimize solar heat gain while providing appropriate daylighting. A south-oriented side-lit space has been defined as a hypothetical office space of 24m² area. It is assumed that the space is bordered on five sides by similar spaces with no external obstruction and located at a mid-floor (Figure 3). The external façade has a 90% WWR as most of the curtain walls applied to office buildings in Cairo. The proposed screen will be applied to this façade. The office space is considered to be occupied daily from 8 AM to 6 PM which agree with IES approved method (IES, 2012). The thermal properties were assigned according to ASHRAE90.1-2007, which complies with the Egyptian codes. Optical and thermal properties of all building components are listed in Table 1.

Figure 2: Main simulation process workflow and supported tools (Source: by the authors).

Figure 3: Base case 3D model showing its dimensions and location in the building.

Table 1: Base case's parameters.

Office room Parameters			
Office room Usage pattern		Thermal properties	
Occupant Load	0.17 occupant/m ²	External wall U-Value	0.26 W/m ² K
Heating set point	22°C	Internal wall /Ceiling / Floor	Adiabtic
Cooling set point	26°C	Optical properties and reflectance	
Infiltration rate	0.5 ac/h	Walls Reflectance	50%
Lighting Type & Load	(Recessed fluorescent luminaires) 11.74 W/m ²	Ceiling Reflectance	80%
Equipment Load	4.0 W/m ²	Floor Reflectance	20%
		Screen Reflectance	Metal diffuse
Window optical and thermal properties			
Glazing type & Visual Transmittance (VT)	Double pane clear 80%		
Window U-Value	2.61 W/m ² K		
Window Solar Heat Gain Coefficient (SHGC)	0.60		

Screen design logic and parameters

A parametric diagrid-based screen was generated by series of commands; rotate, scale, protrusion and surfaces' filling (Figure 4). Four variables; size, rotation angle, scale ratio and protrusion values, were the main parameters of the proposed screen. The screen parameters and values (Table 2) were controlled with numeric sliders and gene pool components within GH. However, the scale range of each cell varies were depending on its rotation angle. As only screen module with 0° rotation angle could be scaled to 80% while other screen module with larger rotation angles could only be scaled to 65%. Furthermore, the protrusion values were grouped into two sets, horizontal points and vertical points that took the same protrusion values.

Figure 4 : Main screen module form generation workflow.

Table 2: The proposed screen's parameters.

Parameters	Values
Size (cm)	120, 60, 30
Rotation Angle (°)	0° to 75° with 15° increments
Scale ratio (%)	For 0°: 20% to 80% with 15% increments For 15° to 75°: 20% to 65% with 15% increments
Protrusion value (cm) (for each point)	5, 15, 30, 45, 60

Phase one: Analysis of Parallel Parametric Simulation

As the aim of the paper is to expand the benefits of the parallel parametric simulation explorations conducted in a previous research by the authors in (Hassan et al., 2017), a conclusion of the important findings that will be used in this paper will be presented in this section.

In (Hassan et al., 2017) the interactions of all screen variables were explored using an exhaustive search method. Hence, the general tendency of each parameter and the impact of the interaction between them on the overall daylighting, thermal and energy performance were explored. The results showed that the rotation angle had no relevant effect on daylight performance. However, using 0° rotation angle was recommended, as it gave better daylight performance due to its ability to have larger scale ratios than others. Generally, the integrated effect of screen module size and protrusion values had a remarkable outcome in converging solutions at large scale ratios where the accepted daylighting performance could be reached. Moreover, in order to find the optimal alternative for each screen size that could balance daylight and thermal performance with the maximum possible energy savings, the thermal parametric simulations were analysed. Hence, the optimum alternatives for each size from the previous daylighting analysis and their corresponding thermal loads were explored in details and the optimum alternatives for each size were analysed. The optimal cases for each screen units' size, 120cm, 60cm and 30cm are shown in Figure 5, Figure 6 and Figure 7 respectively.

Figure 5: The optimal configurations for 120 cm size.

Figure 6: The optimal configurations for 60 cm size.

Figure 7: The optimal configurations for 30 cm size.

Phase two: Adapted Parametric Algorithm (APA) methodology

Adaptive parametric algorithms was specially developed based on the optimal solutions of the previous parametric simulations presented in (Hassan et al., 2017) and shown in Figure 5-7. APA not only offers relatively unlimited number of optimized non-conventional solar screen alternatives but also offers multi-configuration modules instead of the parallel parametric simulation where all the screen modules had to take the same values. Thus, APA approach has the ability to generate various combinations that all can satisfy daylight and thermal performance as well as the designer's intents. Thus, by this methodology can directly generate a wide range of well performing solutions that all comply with both LEED V4 and IES requirements while ensuring the optimal thermal performance with efficient energy consumption.

Figure 8: Difference between the alternatives of solar screen configuration for Parallel parametric simulation and APA approach.

Firstly, any combinations of three units' sizes, 120, 60 or 30 cm, generated the base module by changing size parameters in GH using Gene pool component. Secondly, each unit size was classified through its area to be divided into three groups representing the three-unit sizes. Thirdly, each group of the same units' sizes were applied its optimal parameters according to the parametric simulations results shown before. After that, the final screen configuration is connected to DIVA Daylight Analysis for GH for daylight simulation and then to Viper for thermal simulation. Finally, the results were visualized in Rhinoceros and exported to Excel sheet using TT Toolbox for GH. The adapted algorithm workflow is illustrated in Figure 9 and the grasshopper script specially developed for APA approach is shown in Figure 10. Thus, for each screen unit's size best configurations that attained the optimal required performance were chosen to be applied to this new group-based parametric algorithm

(Table 3). Note that for screen units with 120 cm size the extrude value of the vertical points were redefined to be 120 cm. One of the main potentials of the results of this approach is that the units standardizing into 3 main configurations could facilitate the final fabrication process by providing the exact dimensions of the selected case.

Figure 9: Adapted Parametric Algorithm workflow.

Table 3 : Optimal configurations assigned for the APA.

Unit's Size	120x120 cm	60x60 cm	30x30 cm
Rotation Angle	0°	0°	0°
Scale Ratio	80%	80%	80%
Vertical Protrusion	120 cm	60 cm	30 cm
Horizontal Protrusion	15 cm	15 cm	15 cm

Figure 10: Adapted Parametric Algorithm script in Grasshopper.

Results of APA simulation runs

Unlimited number of solutions could be achieved using this Adapted Parametric Algorithm (APA) methodology by a direct parametric simulation. All solutions were able to obtain 3 credits in LEED v4 and IES approved method with an acceptable thermal balance as well as achieving sufficient energy savings.

Adapted Parametric Algorithm (Case A)

In this case, the main diagrid module was generated randomly using Gene Pool components within GH (Figure 11). APA approach was applied to this base grid to analysis their modules' areas and assigned the appropriate configurations for each modules' size. Result showed that 100% sDA with 1.5% ASE was achieved that complies with both LEEDv4 3-credits and IES, it also showed 78% daylit area, 22% overlit area and 0% partially daylit. The results also proved that the total energy consumption was dropped obviously to 137.9 kWh/m² from 296 kWh/m² in the base case resulting in about 53% energy savings as shown in Figure 11.

Adated Parametric Algorithm (Case B)

In case B, another diagrid based cells was generated using Gene Pool within GH (Figure 12) to ensure the validity and efficiency of the proposed APA methodology. The result approved with the previous case A as, 100% sDA with 2% ASE was achieved that complies with both LEED v4 3-credits and IES criteria. The result also proved that total energy consumption was decreased and showed results similar to the previous case, as the total energy consumption dropped obviously to 138.3 kWh/m² instead of 296 kWh/m² in the base case resulting in about 53% energy savings (Figure 12).

Figure 11: APA- Case A simulation results.

Figure 12: APA- Case B simulation results.

Selection criteria indicating optimal thermal performance based on daylight simulation

From the thermal analysis conducted in (Hassan et al., 2017), the optimum alternatives for each size from the daylighting analysis and their corresponding thermal loads was explored in details and the optimum alternatives for each size were ordered ascending according to their cooling loads Table 4. A correlation between ASE, overlit area and increasing cooling loads was deduced. In addition, it was also shown that for the alternatives that had the same ASE value with convergent sDA values, higher overlit area indicated increasing in cooling loads. For example, by comparing cases no. 2 and no.3 with 60 cm units' sizes shown in Table 4, both of them had 0.8 ASE value while the first one had 9.7% overlit area and the second one had 13.4% overlit area indicating 134.85 kWh/m² and 135.18 kWh/m² respectively. The same results could be conducted by analyzing cases no.4 and no.8 with 30 cm units' size. Another correlation between partially daylight area increasing lighting loads was deduced. As shown in the above Table 4, the highest partially daylight areas indicated the highest lighting loads for each size as shown for case no.1 for 120cm units' sizes, case no.6 for 60cm units' sizes and case no.10 for 30cm screen units' sizes. It was also shown that alternatives that comply with IES criteria mostly indicated better cooling loads than others did. Therefore, calculating Daylight Availability, sDA and ASE could give an indication about cooling loads. Hence, daylighting optimum cases can be sorted regarding thermal and energy performance without even being calculated. The optimal cases for each screen units' size, 120cm, 60cm and 30cm, which were shown in Figure 5, Figure 6 and Figure 7 respectively, were highlighted with red dashed boundaries in Table 4.

From the above correlations, it could be proposed that the optimal cases that could balance daylight and thermal performance with maximum possible energy savings could be indicated based on daylight simulation results only by selecting the case that comply with the following workflow, descending in its impact (Figure 13). In other words, the optimal cases that could balance daylight and thermal performance with highest possible energy savings could be mostly achieved by the following selection criteria; firstly define the alternatives that comply with IES and optimal requirements. Then select the case with the highest sDA value among them. If there are similar cases, choose the case with lowest ASE value. In case of similar ASE values, select the case with the lowest overlit area. Finally, if there are similar cases, indicate the case with the lowest partially lit area as the optimal case.

Conclusion

This research presented a simulation-based study for generating and evaluating non-conventional solar screen design driven by daylight and thermal performance. The research is a part of a comprehensive study that aims to define the effectiveness of both parametric design and Genetic Algorithms approaches for assessing and optimizing various solar screens' parameters to improve

both daylight quality and thermal. However, this paper presented a new Adaptive Parametric Algorithm (APA) based on the parallel parametric simulation approach that was presented by the authors in a previous publication (Hassan et al., 2017) as way to make a worthwhile investment from this approach. The results proved its ability to achieve large number of solar screens alternatives efficiently for specific target performance.

The solar screen various parameters; size, rotation angle, scale ratio, and protrusion value, were modelled parametrically using Grasshopper (GH). This screen was aligned to a south-oriented side lit façade of a typical office space in Cairo, Egypt. Daylight analysis was conducted using Daylight Dynamic Performance Metrics (DDPMs) while thermal analysis was based a comparison approach to a specific base case. Finally, based on the analysis of the parallel parametric simulations results, various correlations between daylight performance, using daylight dynamic metrics, and thermal performance were founded. They showed that Daylight Availability, sDA and ASE could give an indication about cooling loads. Hence, a selection criteria were proposed, that could indicate the optimal screen configurations that could balance daylight and thermal performance based on daylight simulation only.

Table 4: 120cm, 60 cm and 30 cm units' size optimum alternatives thermal and energy performance.

No.	Screen Parameters						Daylight Performance				Energy consumption				Daylight criteria		
	Size cm	Rotation angle	Scale ratio %	Vertical Extrude (cm)	Horizontal Extrude (cm)	Extrude (cm)	Daylight Availability				Lighting Load (kWh/m2)	Thermal Performance			IES	3 credits LED v4 LED v4 2 credits	
							Partially	Daylit %	Overlit	sDA %		ASE %	Cooling Load (kWh/m2)	Heating Load (kWh/m2)			Energy saving %
1	120	0	65	60	60	30.8	59.5	9.7	69.2	3.2	8.02	115.61	11.49	54.4		●	
2	120	0	65	60	45	25.5	58.3	16.2	75.0	6.5	6.49	117.21	11.48	54.4	●		
3	120	0	65	45	60	26.3	55.9	17.8	73.7	7.3	8.03	118.89	11.39	53.3		●	
No	Screen Parameters						Daylight Performance				Energy consumption				Daylight criteria		
	Size cm	Rotation angle	Scale ratio %	Vertical Extrude (cm)	Horizontal Extrude (cm)	Extrude (cm)	Daylight Availability				Lighting Load (kWh/m2)	Thermal Performance			IES	LED v4 3 credits LED v4 2 credits	
							Partially	Daylit %	Overlit	sDA %		ASE %	Cooling Load (kWh/m2)	Heating Load (kWh/m2)			Energy saving %
1	60	0	80	60	45	10.9	83.0	6.1	89.1	0.4	4.78	134.73	11.17	49.1	●	●	
2	60	0	80	45	60	10.1	80.2	9.7	89.9	0.8	5.00	134.85	11.07	49.0	●	●	
3	60	0	80	60	30	2.4	84.2	13.4	97.6	0.8	4.86	135.18	11.09	48.9	●	●	
4	60	0	80	45	45	4.5	79.4	16.2	95.5	1.2	4.09	135.27	11.16	49.1	●	●	
5	60	0	80	60	15	0.4	80.2	19.4	99.6	1.6	3.41	135.81	11.00	49.2	●	●	
6	60	0	80	60	5	0.0	73.3	26.7	100.0	5.3	3.54	136.90	10.95	48.9	●	●	
7	60	0	80	45	30	1.6	73.3	25.1	98.4	4.0	4.07	137.39	10.99	48.5	●	●	
8	60	0	80	30	60	3.6	76.5	19.8	96.4	3.2	4.19	137.57	11.13	48.3	●	●	
9	60	0	80	30	45	0.0	75.3	24.7	100.0	4.5	3.02	138.41	11.07	48.5	●	●	
10	60	0	80	15	60	3.2	68.4	28.3	96.8	6.5	4.26	139.07	11.03	47.9	●	●	
No	Screen Parameters						Daylight Performance				Energy consumption				Daylight criteria		
	Size cm	Rotation angle	Scale ratio %	Vertical Extrude (cm)	Horizontal Extrude (cm)	Extrude (cm)	Daylight Availability				Lighting Load (kWh/m2)	Thermal Performance			IES	LED v4 3 credits LED v4 2 credits	
							Partially	Daylit %	Overlit	sDA %		ASE %	Cooling Load (kWh/m2)	Heating Load (kWh/m2)			Energy saving %
1	30	0	80	45	15	23.1	76.9	0.0	76.9	0.0	4.96	156.09	10.82	41.93	●	●	
2	30	0	80	30	30	22.7	74.1	3.2	77.3	0.0	5.49	156.58	10.83	41.59	●	●	
3	30	0	80	30	15	5.3	80.6	14.2	94.7	2.0	4.04	156.76	10.81	42.02	●	●	
4	30	0	80	45	5	15.4	82.2	2.4	84.6	0.4	5.43	157.03	10.79	41.47	●	●	
5	30	0	80	30	45	38.9	60.3	0.8	61.1	0.0	7.18	157.77	8.97	41.24	●	●	
6	30	0	80	60	5	35.6	64.4	0.0	64.4	0.0	7.39	158.00	10.73	40.50	●	●	
7	30	0	80	60	15	43.7	56.3	0.0	56.3	0.0	7.45	158.03	8.94	41.07	●	●	
8	30	0	80	15	45	21.5	74.1	4.5	78.5	0.4	6.69	158.66	10.78	40.50	●	●	
9	30	0	80	45	30	39.3	60.7	0.0	60.7	0.0	8.14	158.69	8.96	40.61	●	●	
10	30	0	80	15	60	40.5	58.3	1.2	59.5	0.4	8.16	159.21	10.76	39.82	●	●	
11	30	0	80	5	45	16.6	69.6	13.8	83.4	1.6	5.24	159.74	10.73	40.64	●	●	
12	30	0	80	5	60	34.0	62.8	3.2	66.0	0.4	7.38	159.76	10.68	39.93	●	●	
13	30	0	80	30	5	1.2	71.3	27.5	98.8	7.7	4.28	160.43	10.69	40.74	●	●

Figure 13: The proposed selection criteria indicating the optimal balance between daylight and thermal based on daylight simulation only.

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