



# Characterizing the Solution Space of Building Shading System Through Computational and Parametric Feed-Forward Design Approach

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**Abstract.** Building shading systems play an important role in controlling solar heat gains, which can mitigate the impact of climate change on indoor environment. Effectively reducing cooling demand in summer and heating demand in winter requests further development of seasonally regulated shading systems. The main problem is to find a way that consumes less energy while reaching better comfort, which demonstrates potential for conducting an extensive search to parametrize configuration of shading. This paper aims to investigate the effects of building shading systems on energy and thermal performance in different seasonal conditions through a parametric design method, using Baoshan station in Shanghai, China as a case study to establish a baseline model and test different shading components' direction, depth, spacing, and tilt angle. The method explores a large solution space at the beginning of design, establishing a variety of approaches that can inform the architectural design team. The results showed that a proper passive shading system can reduce energy consumption by about 13% while thermal comfort meets ASHRAE 55 standards. This finding indicates the possibility of improving the indoor thermal comfort while lessening building energy consumption.

**Keywords:** Shading system · Building energy consumption · Parametric design · Solution space · Seasonal regulation

## 1 Introduction

The IPCC report shows that the average global temperature increased by about 1.09 °C between 2011 and 2020. The frequency of heat wave events tends to increase along with climate change [1]. High temperatures can cause an uncomfortable indoor environment and threaten human health, while also causing increased use of air conditioning and increased energy consumption. To mitigate this impact of global warming on indoor thermal environment, building shading systems play an important role in controlling

solar heat gains [2]. However, building heating and cooling demands vary from different seasons. More sun exposure is needed in winter compared to in summer. Effectively reducing cooling energy usage in summer and heating energy usage in winter requests further development and adoption of seasonally regulated shading systems.

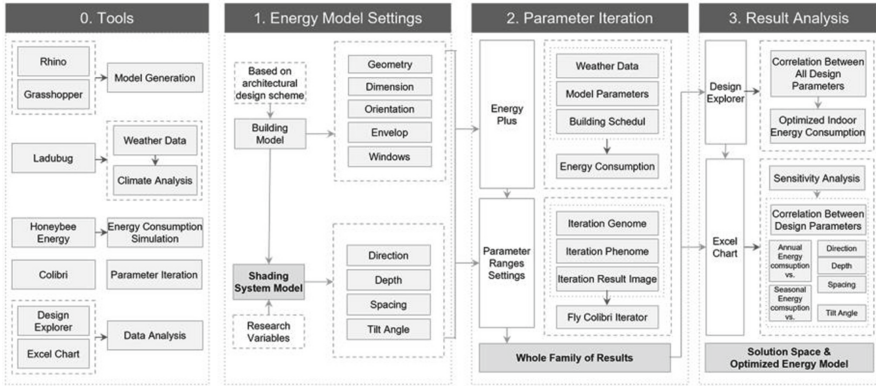
This gap has been receiving increasing attention in the archived literature which tends to be solved by using smart control with automated shading system. Experimental studies have shown that shading systems integrated with lighting controls have a potential of more than 30% energy consumption savings in commercial office spaces [3]. Simulation studies have also shown that solar shades can reduce cooling energy savings by up to 50% [4]. The main problem, however, is to find a way that consumes less energy while reaching better indoor thermal conditions. The increasing complexity of building systems and growth of high performance computing capabilities has increased the use of computer simulation programs for the prediction of building energy consumption [5]. This demonstrates potential for conducting an extensive search to parametrize configuration of external shading system via digital modelling and simulating the energy consumption and daylighting, to identify the most appropriate solution family.

Based on this, this paper aims to investigate the effects of building shading systems on energy and thermal performance in different seasonal conditions through a parametric design method using Rhino, Grasshopper, and its plug-ins Ladybug and Honeybee. It focuses the design method on the features that architects control early in the design process. Preparing a large family of studies informs the architect about different successful approaches in the climate in a process sometimes called “feed forward” [6].

## 2 Method

The study introduces a “feed-forward” design method for modeling and iterative optimization of building shading systems through parametrization. The method is based on the generative design tool Grasshopper, which has been widely used for parametric modeling in the architectural field. In particular, a large number of design scenarios for shading components models are parametrically investigated using the Ladybug and Honeybee environment plug-ins that are shipped with Grasshopper. Ladybug can import standard EnergyPlus weather files, providing interactive visual graphics that enhance the integrated decision-making process, while Honeybee gives the same design options as EnergyPlus, Radiance and Daysim, among other proven energy and daylighting engines that integrate with the Grasshopper interface to provide instant feedback on designs.

The workflow is that, firstly, a baseline building model is established based on the preliminary architectural design scheme, and all the parameters including geometry, orientation, thermal performance of the envelope are set, and simulations are run to obtain energy consumption results as the baseline reference. Then, based on the baseline model, the shading system model is established with design parameters including components' direction, depth, spacing and tilt angle, and the range of variables is set for parametric iterative study. Finally, sensitivity analysis is conducted based on the simulation data to find the relationship between design variables, energy consumption and thermal comfort (Fig. 1).

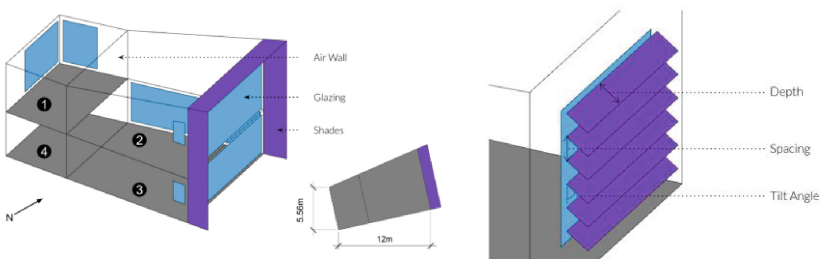


**Fig. 1.** The workflow of parametric design method for modeling and iterative optimization of building shading systems.

### 2.1 Build the Model

This study uses Baoshan station in Shanghai, China as a case study to establish a baseline model, which has a total of two floors with the footprint of 76.6 m<sup>2</sup>. The study simplified the building to the most basic box model, containing only the basic components such as walls, floors, roofs, and windows (Fig. 2).

The shading system in this study is external panel shading, modelled as shown in the Fig. 1, with adjustable rotation angle of the shade panels. In addition to the horizontal shading shown in the figure, vertical shading is also considered in this study. The set parameters of the model include depth, spacing and tilt angle, where depth represents the width of each panel, spacing represents the distance between two panels, and tilt angle represents the rotation angle of the panels. Take horizontal sunshade as an example, the panel is horizontal when the angle is 0°, rotates downward when the angle is greater than 0°, and rotates upward when it is less than 0°.



**Fig. 2.** Baseline building model and shading components model.

## 2.2 Parameter Variables and Metrics

The parametric iterative study process includes testing different shading panels' direction, depth, spacing, and tilt angle. Table 1 shows the setting of parameter variables and their range. The depth and spacing both range from 0.2 to 1.0 m, with tilt angle ranging from  $-75^{\circ}$ – $0^{\circ}$  to  $75^{\circ}$ .

**Table 1.** Parameter variables and ranges

Window	Shading component			
	Direction	Depth (m)	Spacing (m)	Angle ( $^{\circ}$ )
East	Horizontal	0.2	0.2	$-75$
North	Vertical	0.4	0.4	$-60$
West	–	0.6	0.6	$-45$
–	–	0.8	0.8	$-30$
–	–	1.0	1.0	$-15$
–	–	–	–	0
–	–	–	–	15
–	–	–	–	30
–	–	–	–	45
–	–	–	–	60
–	–	–	–	75
Number	2	5	5	11
3				550

According to the building design scheme, there are three directions of windows, east, north, and west, and the study tests the effect of different directions of shading system on the building separately. There are 550 combinations of simulations in each direction, for a total of 1650. Through parameterizing a variety of design variables, we use the following evaluation metrics to assess the performance of shading system: energy consumption, thermal comfort.

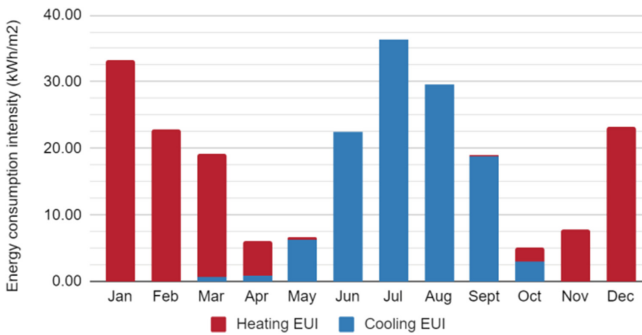
## 3 Results

### 3.1 Parameter Iterative Studies

#### 3.1.1 Baseline Results

Firstly, the energy consumption of the baseline model without shading system was simulated, and the results are shown in Fig. 3. The annual energy consumption intensity (EUI) is  $297.70 \text{ kWh/m}^2$ , of which the cooling EUI is  $118.48 \text{ kWh/m}^2$ , mainly concentrated from June to September, and the heating EUI is  $123.90 \text{ kWh/m}^2$ , mainly concentrated

from December to March. Therefore, this study will mainly focus on the cooling energy use from June to August and the heating energy use from December to March.



**Fig. 3.** Monthly heating and cooling energy intensity of baseline model without shading system.

### 3.1.2 Solution Space

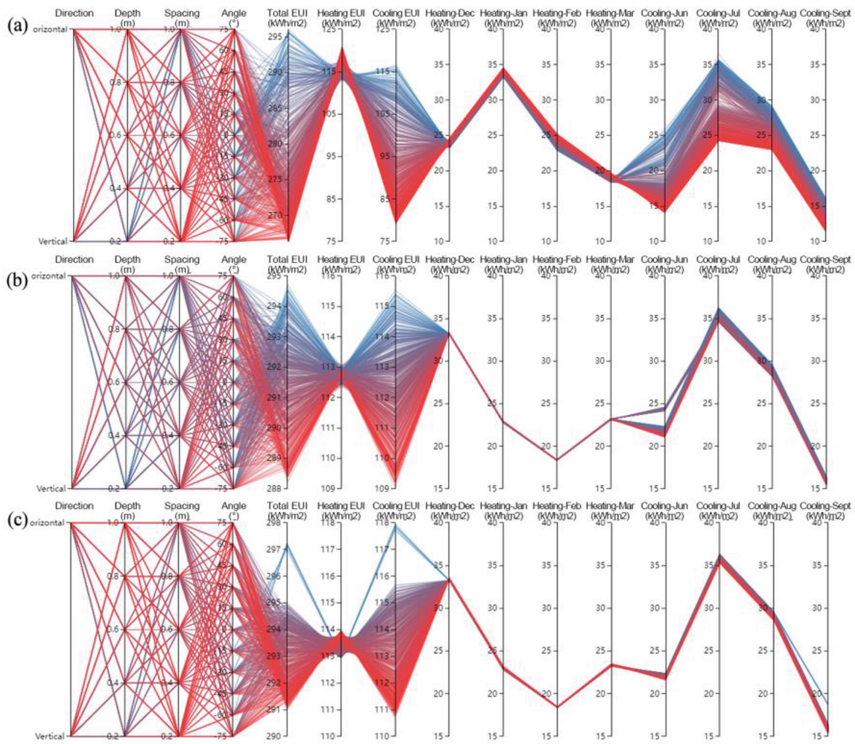
In order to integrate all results into one large solution space and analyse design variables, the open-source tool Design Explorer was used to exploring multidimensional parametric studies, thus can meet the design needs of different architects facing different design scenarios. Figure 4 shows the whole result sets for (a) east, (b) north and (c) west, for a total of 1650 cases. The first four items are the input variables, solar panel orientation, depth, spacing and angle, while the last 11 items are output results, including annual total EUI, annual heating and cooling EUI, monthly heating EUI from December to February, and monthly cooling EUI from June to August.

The result shows that shading on the east direction has the most significant impact due to the larger window area, with a minimum annual energy consumption intensity of 266.356 kWh/m<sup>2</sup>, a 10.53% reduction. The minimum value of annual energy consumption simulated for the north shading is 288.21 kWh/m<sup>2</sup> and the minimum value for the west is 291.01 kWh/m<sup>2</sup>. The three groups of results showed a common feature that the shading system had a much greater effect on the cooling EUI than the heating EUI.

## 3.2 Sensitivity Analysis

### 3.2.1 Effect of Depth and Spacing

The results of the parametric studies allowed us to figure out the effect of each variable on energy consumption and thermal performance. Figure 5 provides correlation between shading panels depth, spacing with energy consumption. Seasonal regulation is not considered in this section and annual total EUI is selected as the evaluation index for analysis, due to the dimensions of shading panels are generally fixed and do not change with the season. In this parametric study, keep the tilt angle is 0°, and the depth and spacing variables are shown for 0.2, 0.4, 0.6, 0.8 and 1.0 m. A total of six scenario were

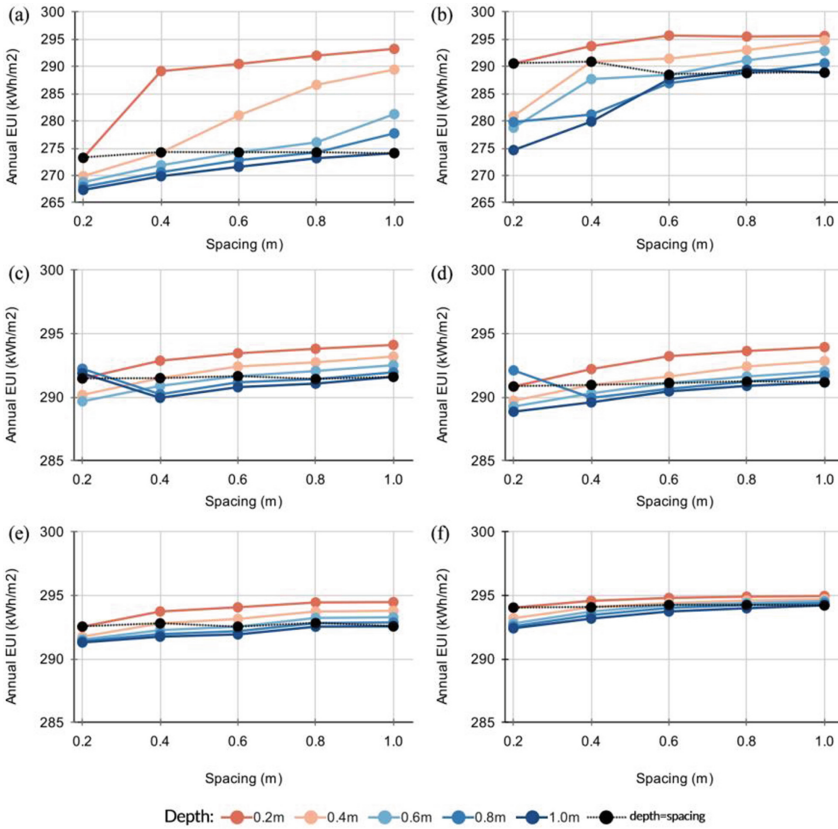


**Fig. 4.** Simulation results set: **a** East direction. **b** North direction. **c** West direction.

considered, including horizontal shading and vertical shading in the east, north and west directions.

The result shows that for the same depth, an increase in spacing leads to an increase in energy consumption. The impact is much greater on the east side than on the north and west sides, due to the large window openings on the east in the case chosen for this study. Horizontal shading and vertical shading also exhibit different characteristics. For horizontal shading, as the spacing becomes larger, the effect of depth also becomes larger. The opposite is true for vertical shading, as the spacing increases, the effect of depth changes decreases.

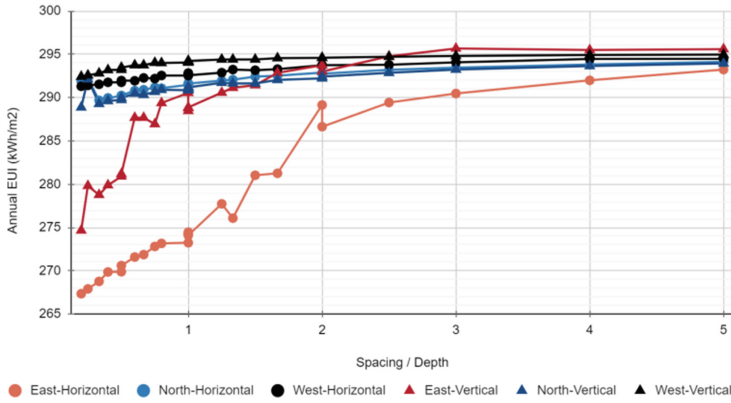
In order to study the correlation between depth, spacing and annual EUI more accurately, the study used the spacing to depth ratio ( $S/D$ ) to evaluate, and investigated the correlation between  $S/D$  and total EUI. Figure 6 shows the results. When the  $S/D$  is the same, the energy consumption is basically the same despite having different depth and spacing. The results indicate a consistent trend that as  $S/D$  increases, the annual EUI also increases, and the increase gradually decreases. When the value of  $S/D$  is between 0 and 2, its impact on energy consumption is greater, and the curve gradually flattens out when it is  $>2$ . Therefore, architects should control the  $S/D$  of the shading system to be less than 2 or even  $<1$ , and reduce it as much as possible under the premise of meeting users' lighting requirements.



**Fig. 5.** Correlation between horizontal and vertical shading panels’ depth, spacing and annual EUI in three orientations: **a** Horizontal shades on east side. **b** Vertical shades on east side. **c** Horizontal shades on north side. **d** Vertical shades on north side. **e** Horizontal shades on west side. **f** Vertical shades on west side.

### 3.2.2 Effect of Tilt Angle

In this section, the correlation between shading panels’ tilt angle with energy consumption was investigated. Seasonal regulation is considered in this section, as the angle of the shading panels is adjustable. Annual heating EUI and cooling EUI, monthly heating EUI and cooling EUI, were all used as evaluation metrics. On the one hand, heating and cooling demands in summer and winter are different and the requirements of shading system are different, when more solar energy is desired in winter, while more heat blocking is needed in summer. On the other hand, as the seasons change, the sun height angle changes, which leads to a change in the angle of the effective shading panels. In this parametric study, keep both the depth and spacing are 0.6 m, and the tilt angle variables are shown for  $-75^\circ$ ,  $-60^\circ$ ,  $-45^\circ$ ,  $-30^\circ$ ,  $-15^\circ$ ,  $0^\circ$ ,  $15^\circ$ ,  $30^\circ$ ,  $45^\circ$ ,  $60^\circ$  and  $70^\circ$ . A total of six scenario were considered, including horizontal shading and vertical shading in the east, north and west directions.



**Fig. 6.** Correlation between horizontal and vertical shading panels’ spacing to depth ratio and annual total EUI in three orientations.

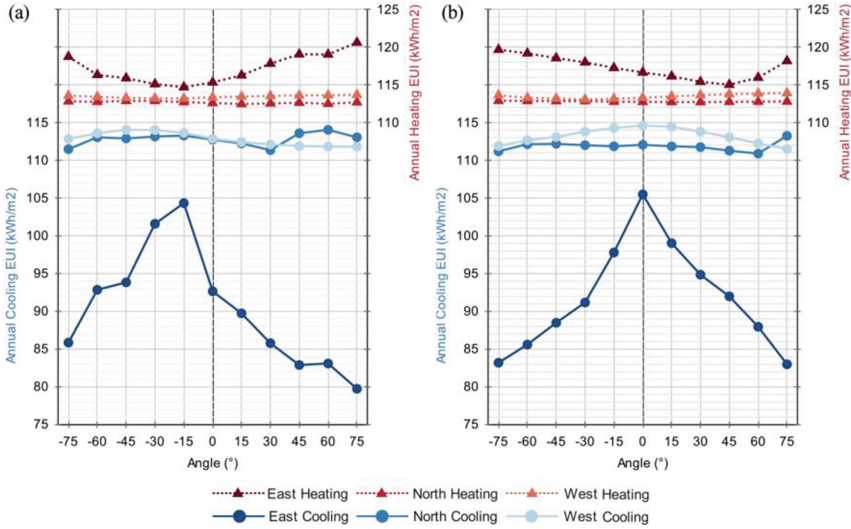
Figure 7 indicates the correlation between tilt angle with annual heating and cooling EUI. The effect of tilt angle on cooling EUI in summer is much greater than that of heating EUI in winter, with cooling EUI varies in the range of 35 kWh/m<sup>2</sup> and the difference in heating EUI is only about 7 kWh/m<sup>2</sup>. EUI varies with angle, and heating and cooling EUI show opposite trends.

For horizontal shading, in the east side, the lowest cooling EUI and highest heating EUI are achieved at an angle of 75°, and the highest cooling EUI and lowest heating EUI are achieved at -15°. When the angle is 45° the energy consumption is the second lowest, and at the same time, the indoor light quality can be guaranteed. Therefore, when the angle of sunshade is adjustable, it is a better design choice to set the angle at -15° in winter and 45° in summer. The change of angle between north and west facing shading indicate a smaller change in energy consumption, However, we can still see the lowest cooling EUI when the angle is 30°.

For vertical shading, in the east side, the lowest cooling EUI is at an angle of 75° and the highest is at 0°. The heating EUI is the lowest when the angle is 45° and the highest when it is -75°. When the angle is 60°, the energy consumption is low and the quality of light in the room can be guaranteed at the same time. Therefore, when the angle of sunshade is adjustable, setting the angle at 45° in winter and 60° in summer is a better design choice. Similarly, north- and west-facing shading brings less impact.

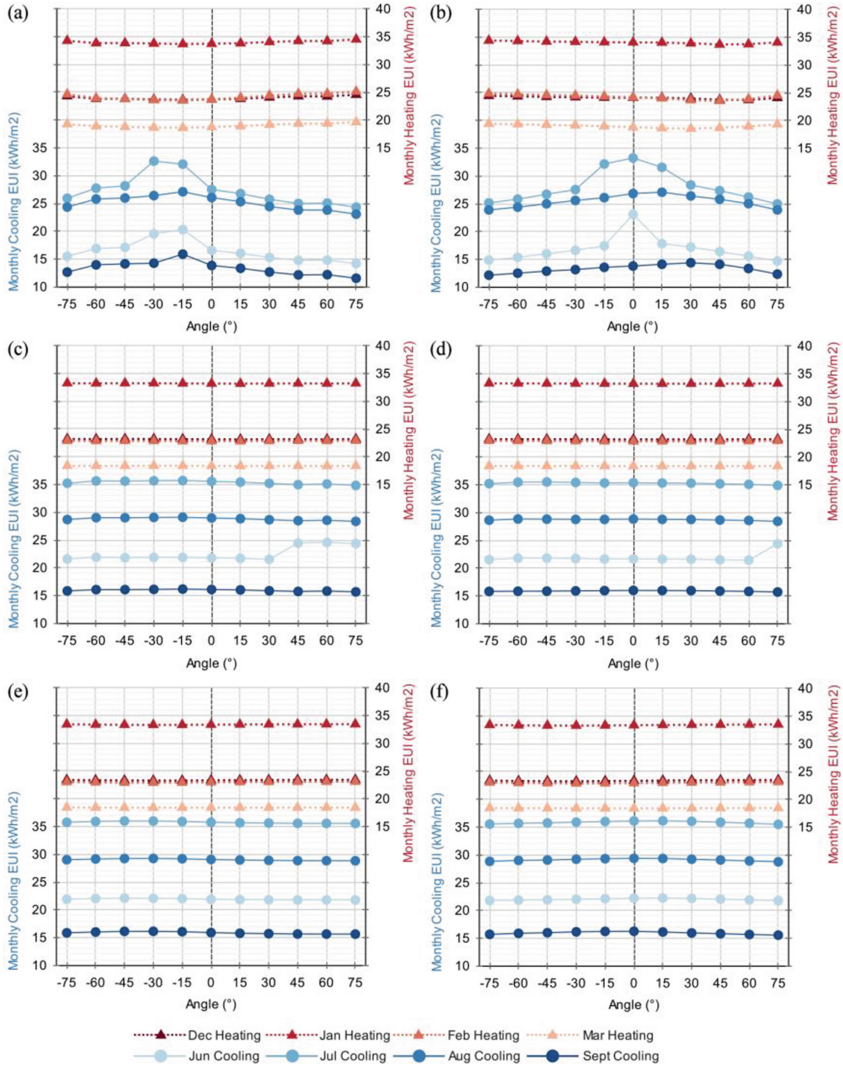


When the angle of the sunshade is not adjustable, considering both the heating demand in winter and cooling demand in summer, by comparing all the results of horizontal shading and vertical shading, the vertical sunshade with the angle set at 45° has better performance in both the heating EUI and cooling EUI.



**Fig. 7.** Correlation between horizontal and vertical shading panels' tilt angle and annual heating and cooling EUI in three orientations: **a** Horizontal shades. **b** Vertical shades.

Figure 8 provides correlation between shading panels' tilt angle with monthly energy consumption, including monthly heating EUI from December to March, and cooling EUI from June to September. Shading system in north and west have less impact on monthly energy consumption and can be designed with priority from the perspective of daylighting health. Shading in east has less effect on heating EUI and more effect on cooling EUI. For horizontal shading in east side, -45° to 0° are the angles that should be avoided, and the monthly cooling EUI is lower in the 45°–60° range. Similarly, for vertical shading in east side, -30° to 30° should be avoided and -60° and 60° are better choices.



**Fig. 8.** Correlation between horizontal and vertical shading panels’ tilt angle and monthly heating and cooling EUJ in three orientations: **a** Horizontal shades on east side. **b** Vertical shades on east side. **c** Horizontal shades on north side. **d** Vertical shades on north side. **e** Horizontal shades on west side. **f** Vertical shades on west side.

### 4 Conclusion

The results show that exterior shading systems play an important role in reducing building energy consumption and improving the indoor environment. Based on a “feed-forward” design idea, a large solution space is obtained by modeling and parametric iteratively optimization of the building shading. And the relationship between the shading effect with the depth, spacing and tilt angle of the shading panel in three different directions of

east, north and west was obtained by sensitivity analysis. This has a great significance for guiding architects in selecting design solutions. In specific cases, the results show that proper passive shading systems can reduce energy consumption by about 13% while thermal comfort is met. The parameterization of shading system design indicates the potential that can guide future building design.

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