Simulation Assisted Design Exploration to Evaluate View and Energy Performance of Window Shading

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Abstract

One of the most effective passive cooling strategies for buildings in a hot and dry climate is to use suitable shading devices. Dense shading is more effective in reducing the energy required for cooling, but it reduces visibility through openings.

This paper explores the influence of more than 300 fixed shading systems on view to outside and energy consumption of a typical south-facing office building in Tehran, Iran. The shading devices vary in depth, number, angle, and thickness in three types of horizontal, vertical and egg-crate.

Among the optimised shading devices, the horizontal shadings were the most frequent and on the contrary, no egg-crate shadings were found. The results showed that when the view to the outside is considered equally important as the energy consumption, the horizontal shadings are most suited. However, where the view to the outside has priority to energy consumption, vertical shadings are the best choice. The smaller the width and number of louvres, the higher the chance to reach the optimal performance. The research objectives were found not sensitive to the louvres' thickness and angle.

Introduction

Windows are regarded as one of the most critical building components in determining the overall energy demand in buildings (Pellegrino et al., 2017). They also play an essential role in providing a view to outside (Aries et al., 2010). In the design phase, contradictions often occur between maximizing the view to outside and minimizing energy consumption; the first one usually makes larger windows or fewer shadings a priority, but the second, gives priority to small windows or dense shadings.

This paper investigates the relationship between the two conflicting objectives: energy consumption and view to outside by applying energy analysis as well as view assessment of different shading devices on a south-facing office room.

The impact of several shading systems on energy consumption has been widely studied by several researchers in different locations and climates such as Bellia et. al (2013) or Evola et. al (2017). View to the outside is one of the significant qualities that most windows provide to occupants in the indoor environment. It also contributes significantly to the property value so in many cases large glazed facades are designed to take full advantage of it. Despite the importance of view to outside in reducing occupational stress and improving user performance, it is often neglected in the design process.

There have been very few studies that investigated the window design on energy consumption and view to outside simultaneously (Hellinga and Hordijk, 2014; Kim and Kim, 2010; Pilechiha et al., 2020, Valitabar et al., 2018).

This paper focuses on the design of shading devices that ensures energy performance with minimum sacrifice of the view to outside. The methodology developed in this paper can be used by designers or other operators to choose the most suitable solution among all possible shading devices and ensure its efficiency.

It utilizes computational and parametric tools to evaluate and optimize shading devices for energy and quality views. Grasshopper (Grasshoper3d, s.d.) and Rhinoceros (Rhinoceros3d, s.d.) as popular design environments for architects are used to explore design alternatives. One of the advantages of research modelling inside Grasshopper is the potential to benefit from several other developments in the Grasshopper community like Octopus and Galapagos to find the best trade-offs between the objectives, producing a set of possible optimum solutions that ideally reach from one extreme trade-off to the other (Vierlinger and Hofmann, 2013).

Methodology

General architectural design is a sort of linear workflow. Firstly, architects in the early stage of design, complete design schemes depend on their subjective experiences. Next, they study its performance through building simulations and afterwards modify the schemes based on the acquired feedback. Since the design and feedback process are independent in the linear workflow, modellers acquire final schemes through the following process: design-criticism-change-criticism-change.

This repetitious process can result in low optimization efficiency and make it hard to understand an optimal design scheme. On the contrary, the round-trip workflow proposed in this paper, can take care of the time lag problem between the design and simulation feedback and lead to a high-performance building optimization approach.

In this approach, initially, the base model of design should be built in Rhinoceros, then the design parameters of shading systems as all possible solutions should be determined in Grasshopper as the first stage. They the objective functions of energy consumption and view to outdoor will be defined in Grasshopper using Honeybee (EnergyPlus) and Ladybug respectively. In the third stage, to perform multi-objective optimisation, employing Octopus is recommended. This application is responsible to explore in design solutions and guess with high probability the optimum ones. Finally, in the fourth stage, the design team could choose the final solution among the best shadings found in this round-trip process. Hence, with such a workflow, architects can complete multi-objective shading scheme optimization and get an optimal scheme under complicated design conditions (Figure 1).

To study the feasibility of the proposed parametric optimization approach in shading design, a south-faced office room was chosen for the case study.

Stage 1: Parametric Modelling

The simulation was performed for three types of shading devices for a south-facing office room in Tehran, with fixed window dimensions which are subject to high solar exposure for most of the day, throughout the year. The room had an area of 29.52 m^2 and a Window to Wall Ratio (WWR) of 35% which was selected based on a previous study of Mahdavinejad et al. (2012) which investigated the optimal WWR for the office buildings in the same local context.

A model was created using the Rhinoceros, and to have a higher control on the design parameters, the model was modified in Grasshopper. The investigated space was located in the middle-size office building with office modules aligned on two facades, separated by a central corridor, with staircase and service spaces at both ends of the building (Figure 2). Its interior room dimensions were 3.6 m x 8.2 m x 2.8 m based on Reinhart reference office modified in Reinhart et al. (2013). Interior walls were assumed adiabatic allowing the research to concentrate on the thermal impact of various shading types and parameters.

The modelled window had double glazing without low-E coating with visible transmittance of 65%, Solar Heat Gain Coefficient (SHGC) of 28% and U-value of 1.6 W/m^2k. The window location was considered between 0.76 m and 2.28 m above the floor based on Reinhart et al. (2006) recommendation to supply proper view to outside. Different types of fixed shading devices including horizontal, vertical and egg-crate shadings were modelled to investigate their impacts on the energy performance and view to outdoors (Figure 3). These shadings are semi-specular external blinds with diffuse reflectance of 40% and a specular component of 12%.

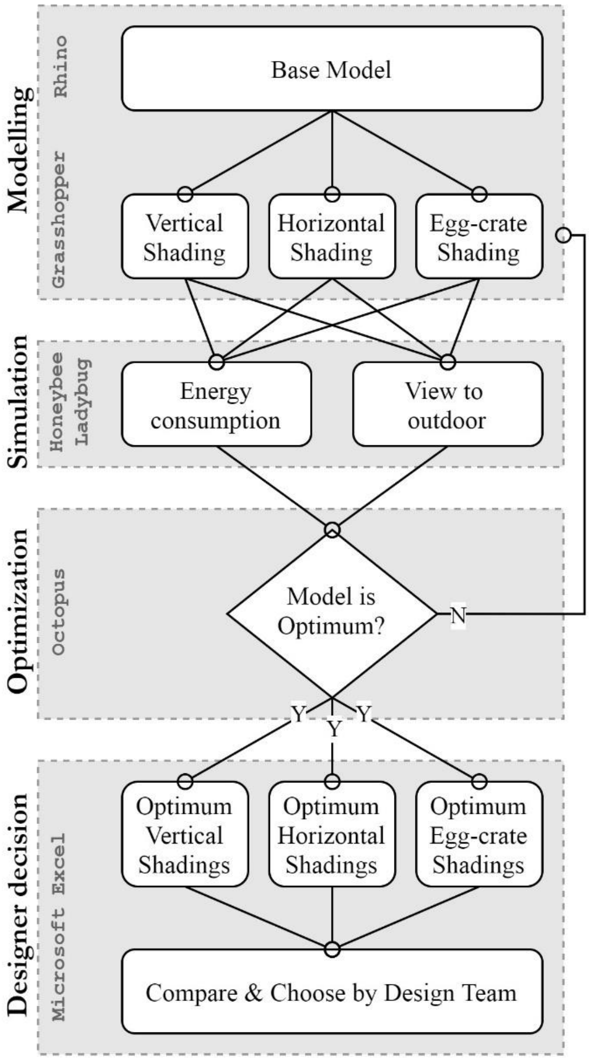

Figure 1- proposed research workflow

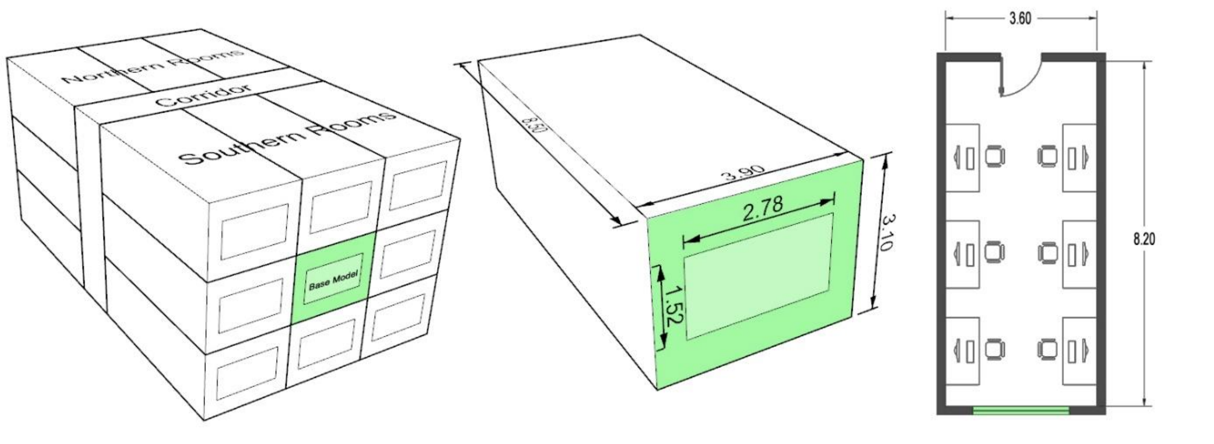

Figure 2- External dimensions of the base model and multiple rooms stacked together to form the building facade. The unit is the meter.

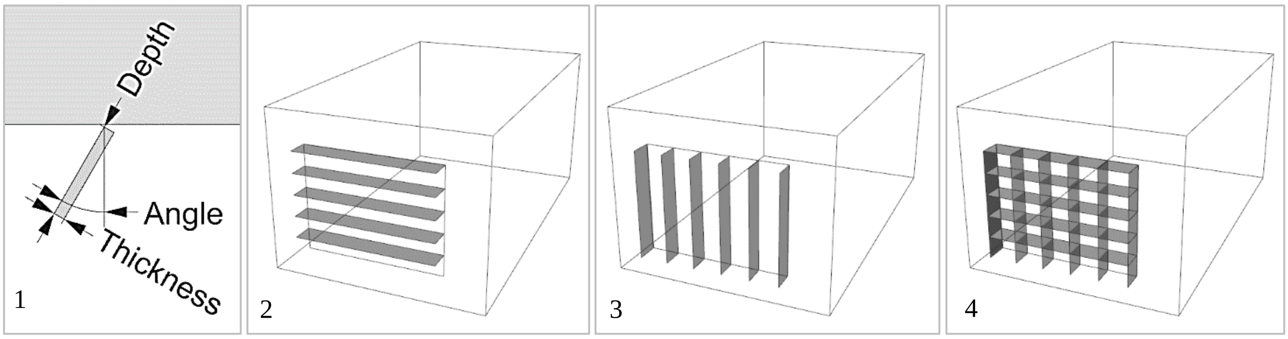

Figure 3- Shading devices. 1: Shading parameters, 2: Horizontal shading, 3: Vertical shading, 4: Egg-crate shading.

For each of these shading devices, the impact of changing the shading angle, depth, number, and thickness was studied. The ranges for different parameters of the shading devices that were examined are shown in Table 1. More than one thousand possible genomes for each type of fixed shadings were generated parametrically in Grasshopper.

Table 1- Shading parameters in three shading devices.

Shading parameters	**unit**	**Range**	**increment**
Number	-	2 to 8	1
Depth	meter	0.1 to 0.5	0.1
Thickness	millimetre	2.5 to 12.5	2.5
Angle	degree	0 to 50	10

Stage 2/1: View Simulation

There are few options available to Grasshopper users to undertake a view analysis: 2D and 3D Isovist and also Ladybug view analysis. An Isovist is the volume of space visible from a given point in the area. Grasshopper has a fundamental Isovist component which generates 2-dimensional Isovists but a 3D Isovist should be used to get a more spatial understanding of a view. Ladybug is a part of Ladybug Tools, the collection of free computer applications that support the environmental design and performs a detailed analysis of climate data to produce customized, interactive visualizations for environmentally-informed design.

In this research, for view evaluations from a façade, Ladybug's View Analysis component is chosen because it is perfectly coordinated with Honeybee as energy simulator. The component will allow running the analysis using either view type or points. There are four view types for pre-generated view analysis: "Horizontal Radial" which is the percentage of the 360 horizontal view band visible from each test point. This type is used to study horizontal views from interior spaces to the outdoors. "Horizontal 60-degree cone of vision" which is the percentage of the 360 horizontal view band bounded on top and bottom by a 30 degree offset from the horizontal (derived from the human cone of vision). This type is used to study views from interior spaces to the outdoors. "Spherical" which is the percentage of the sphere surrounding each of the test points that are not blocked by context geometry. "Skyview" which is the percentage of the sky that is visible from the input geometry.

To investigate view to outside, the spherical view is studied for each model. It is the percentage of the sphere surrounding the seated person in the room that are not blocked by room faces or shading systems. The horizontal view types are not able to assess the vertical and egg-crate shading devices completely so spherical view type is a better choice for studies like this and was selected here. This analysis is conducted from a centred viewpoint that represents a seated person (height = 1.2 m) facing the window. The idea of the component is the same as 3D Isovist which is defined in Benedikt (1979) as the set of all points visible from a given vantage point in space and concerning an environment.

Stage 2/2: Energy simulation

Energy analysis was carried out using Honeybee in Ladybug Tools which is an interface of validated energy simulation engines such as EnergyPlus (EnergyPlus, s.d.) and OpenStudio (OpenStudio, s.d.).

All energy simulation fixed parameters except local ones such as EPW file and occupancy schedule were adopted from Reinhart reference office room, Reinhart et al. (2013). The weather files used in this research was Mehrabad International Airport with the latitude of 35.683 and longitude of 51.317, located in elevation of 1190.0 meters. The occupied period for the office room was considered as 8 AM to 6 PM for all weekdays except Thursdays and Fridays (Local holidays). The peak occupant load was 7.38 m^2/occupant from 9 AM to 12 Am and also 1 PM to 3 PM. The heating and cooling setpoints were 20 °C and 26 °C respectively and were applied during the occupied hours. Setback temperatures were 15 °C and 30 °C and were applied during the unoccupied period. No external shading was considered for the base model. The electric lighting control was considered auto-dimming with the switch off occupancy sensor. Lighting power was 100 watts. Lighting setpoint was 300 lux. Minimum electric dimming level was 20%. Standby power was 3 watts. The switch-off delay time was 5 minutes. Peak plug loads was 8W/m^2 (One monitor and laptop per occupant present). All the material properties were considered based on ASHRAE 90.1 recommendations for climate zone 3B (Table 2). The infiltration rate was 0.5 ac/h. The HVAC system was considered a packaged rooftop VAV unit with reheat.

Table 2- Details of material properties used in the model

		Material	Reflectance	U value (W/m²K)	Tvis*	SHGC**
Glazing		Dbl glz	-	1.6	65%	28%
Walls	Interior	Lambertian diffuser	50%	adiabatic	-	-
	Exterior		50%	0.365	-	-
Ceiling			80%	adiabatic	-	-
Floor			20%	adiabatic	-	-
Ground			20%	-	-	-

*Visible Transmittance
**Solar Heat Gain Coefficient

Energy consumption in this research is the sum of three parts: normalized cooling, heating and electrical lighting loads. To considering the impact of daylighting control strategy in lighting electrical energy consumption, integrated daylight and energy simulation in Honeybee is adopted. So for each shading systems, annual daylighting is simulated using Daysim to update the lighting schedule adopted in electrical energy simulation in EnergyPlus.

Stage 3: Optimisation

Multi-objective optimization differs from a single objective, as finding the optimum solutions are no longer so simple due to the profoundly complicated nature of concurrently satisfying several goals, which are usually opposing to each other. Therefore, it is required to discover a set of circumstances that define the optimal solutions and create the Pareto frontier. All points within this set which are also called non-dominated or feasible solutions, are logically valid and result in various values of the objectives. Generally, in most applications including building design, only one best solution is required by decision-makers. The criteria to select the final point from the non-dominated points differs for each application.

Multi-objective optimization algorithm attempts to generate solutions that are as close to the Pareto optimal front with a possible uniform distribution. When the non-dominated solutions are identified, decision-makers require to choose from this set a final resolution according to the particular problem and personal preferences.

The multi-objective optimization plug-in used is Octopus that enables the application of evolutionary design principles in Grasshopper. It permits the investigation of several objectives at once, generating a wide range of optimized alternatives between the extremes of each objective.

In the process of optimizing view to outside and energy consumption, conflicting parameters are interactive with each other and the optimizer is trying to find the logical balance in between. The strategy of HypE (Bader et al., 2011), reduction/mutation is chosen. This approach is about how a Pareto non-dominated front should be truncated to fit the archive size when it is too large.

Results (stage 4)

Base model

The unshaded facade was assumed as the base model in this study to evaluate the effects of each shading device on energy consumption and view performance. The base model had a significantly poor energy performance due to the unshaded glazing in southern facades. The EUI (sum of normalized annual heating, cooling and electrical lighting loads) reached to 173.24 kWh/m² in a year. Such building is rated C in Iran's energy consumption labelling scheme (label C belongs to the buildings with EUI between 150 and 225 kWh/m²). Energy consumption in audited office buildings in Tehran is between 126 to 157 kWh/m² according to Bagheri et al. (2013). In the base model, view analysis showed that the average view was about 2.8%. This amount is the maximum percentage of the sphere surrounding the user position that is not blocked by room or shading geometry (Table 3).

Horizontal shadings

91 unique models of horizontal shading combinations were simulated. Figure 4 illustrates all horizontal studied models comparing to the base model. The best optimum found models are on the Pareto Frontier line.

Naturally, adding louvres leads to a reduction in view to the outside so all of the simulated models had less chance than the base model in this objective. However, interestingly about 49% of models consumed more energy than the base model in a year. This is perhaps due to higher energy use for space conditioning in the colder months and demonstrates the vital role of optimization in sustainable architectural design.

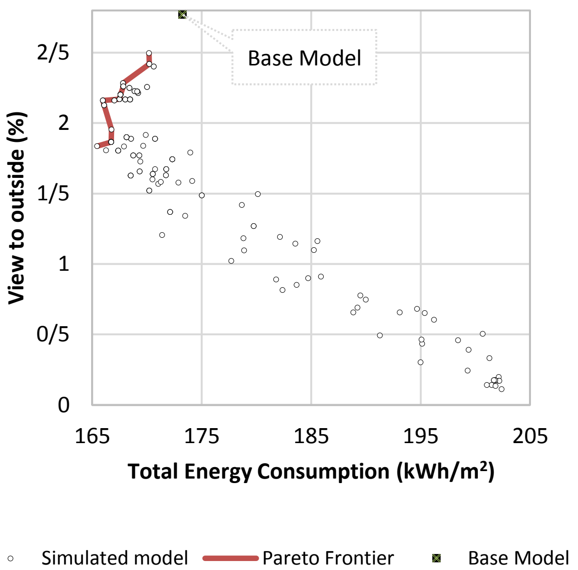

Figure 4- Horizontal shading simulation result.

Table 3 shows the optimized parameters and objectives of the best horizontal shadings and also the base model. The depth of optimized shadings was either 10 cm (for 63% of the cases) or 20 cm (for 37% of the cases), and no model was found with more depth. Most of the optimized models had four louvres, and just one model with more than four louvres was found. High rotation angles harmed view and energy, and 73% of optimized models have an angle between 0 and 10 degrees. 63% of optimized models have a thickness of 5 mm. Although some models with more thickness found no model existed with a thickness of 2.5 mm.

Table 3- parameters and objectives of the base model vs. optimized horizontal shadings

Model	Parameters				Objectives			
					Energy consumption			
	Depth	Number	Angle	Thickness	Cooling	Heating	Lighting	Ave View
	m	-	D	mm	kWh/m²			%
BM	-	-	-	-	83.4	55.8	12.1	2.8
H1	0.1	7	0	5	67.5	62.9	13.1	1.8
H2	0.2	4	0	7.5	68.7	63.0	13.1	1.9
H3	0.2	3	10	5	69.0	62.7	13.1	1.9
H4	0.1	4	20	10	69.0	62.6	13.0	2.1
H5	0.1	4	20	5	69.0	62.4	12.6	2.2
H6	0.1	4	30	7.5	68.8	63.1	13.7	2.2
H7	0.1	4	10	5	72.30	60.7	12.7	2.2
H8	0.2	2	10	5	72.9	60.5	12.6	2.3
H9	0.2	2	00	7.5	73.9	59.7	12.3	2.3
H10	0.1	2	10	5	78.0	58.1	12.2	2.4
H11	0.1	2	0	5	78.3	57.8	12.1	2.5

Among the optimized horizontal shadings, the H1 model had the least energy consumption (about 4% less) and the most decrease in the view (about 34% less) compared to the base model. In this model. On the contrary, most energy consumption was in H11 (about 2% less) while the lowest decrease in the view (about 10%) occurred compared to the base model. If the weight of both research objectives were considered the same, H6 with 3% and 22% reduction in EUI and view respectively, could be selected as the best solution.

Vertical shadings

Figure 5 shows the 97 unique models of simulated vertical shadings comparing to the base model results. The best optimum found models are on the Pareto Frontier line. Similar to the horizontal shadings, adding louvres led to view reduction but interestingly, again about 58% of the models consumed more energy than the base model in a year.

This shows that, if the parameters are selected randomly, the chance of reducing the energy consumption compared to the unshaded model is less than 50%.

Table 4 shows the optimized parameters and objectives of the best vertical shadings. 85% of optimized shading depth was 10 cm, and there was just one case with a depth of 20 cm. The results indicate that the lower depth of the

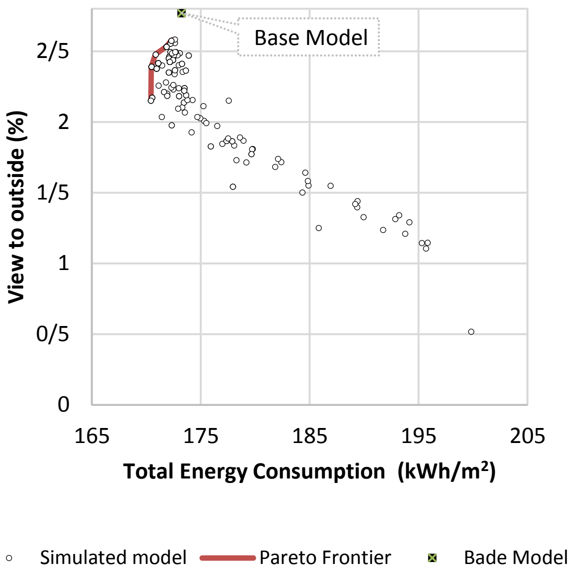

Figure 5- Vertical shading simulation result

vertical louvres would result in a better balance between energy consumption and visibility. Similar to horizontal shadings, most of the optimized models had four louvres, and only a few models were found with two and three louvres. Therefore, choosing four louvres would provide more freedom to architectural designers to select among other design parameters. High rotation angles harmed the trade-off between view and energy, and the choices were limited to 0 and 10 degrees. 66% of the optimized models had a thickness of 10 mm. Although a few models with less thickness were found, no model with a thickness of and 7.5 nor 12.5 mm was identified.

Among these shadings, the V1 model had the most energy consumption (almost equal) and the lowest decrease (about 7%) in the view compared to the base model. On the contrary, the most moderate energy consumed in V6 (about 2% less) while the most decrease occurred (about 22%) in the view. If the weight of both research objectives is considered the same, V3 with 9% and 1% decrease respectively in view and energy, will be the best results.

Table 4- parameters and objectives of optimized vertical shadings

Model	Parameters				Objectives			
					Energy consumption			
	Depth	Number	Angle	Thickness	Cooling	Heating	Lighting	Ave View
	m	-	D	mm	kWh/m²			%
BM	-	-	-	-	83.4	55.8	12.0	2.8
V1	0.1	2	0	2.5	81.0	57.5	12.2	2.6
V2	0.1	2	0	5	80.8	57.6	12.0	2.6
V3	0.1	3	0	10	79.3	58.7	12.0	2.5
V4	0.1	4	0	10	76.8	59.9	12.2	2.5
V5	0.1	4	10	10	75.3	60.3	12.9	2.4
V6	0.2	4	10	10	71.7	63.9	12.9	2.2

Egg-crate shadings

115 unique models were simulated to find the optimized egg-crate louvres. Figure 6 illustrates all these models compared to the base model results. The best optimum found models are on the Pareto Frontier line. Similar to other shadings, adding louvres led to a reduction in view objective. So, all of the simulated models had less chance

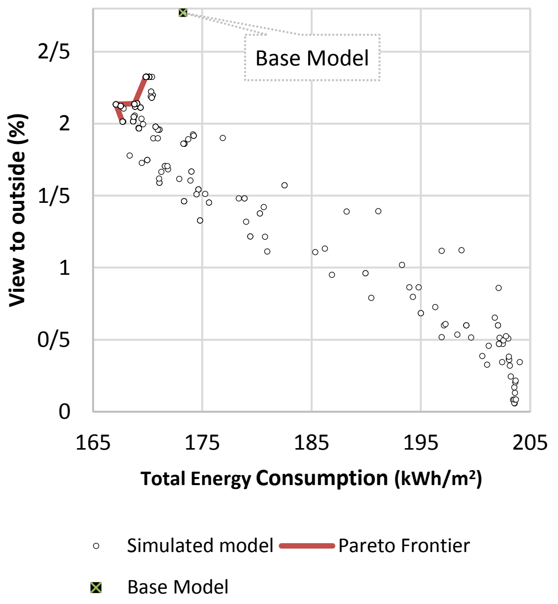

Figure 6- Egg-crate shading simulation result

rather than the base model. About 64% of models consumed more energy than the base model annually.

Table 5 shows the optimized parameters and objectives of the best egg-crate shadings. 80% of optimized shading had a depth of 10 cm, and there was just one case with a depth of 20 cm. Study of these models indicated that when the depth of the egg-crate louvres was lower, the balance between energy and visibility was better. Most of the optimized models had two egg-crate louvres, and some shadings were with three and four.

Although all found optimized models had just one unique louvre angle, a variety of choices was found for the thickness of louvres. Among egg-crate shadings, there was no significant difference in total energy consumptions rather than the base model (just 2-3%) but the reduction in view to the outside is considerable (16% for E5 and 27% for E1).

Table 5 parameters and objectives of base model vs. optimized Egg-crate shadings

	Parameters				Objectives			
					Energy consumption			
Model	Depth	Number	Angle	Thickness	Cooling	Heating	Lighting	Ave View
	m	-	D	mm	kWh/m²			%
BM	-	-	-	-	83.4	55.8	12.1	2.8
E1	0.2	2	0	5	70.4	62.8	12.5	2.0
E2	0.1	4	0	2.5	69.8	63.0	12.3	2.1
E3	0.1	3	0	5	73.3	61.1	12.5	2.1
E4	0.1	2	0	5	76.4	59.3	12.2	2.3
E5	0.1	2	0	12.5	76.3	59.4	12.9	2.3

Discussion

In this part, the found optimized horizontal, vertical and egg-crate shadings will be compared with each other along with the base model.

Figure 7 demonstrates only optimized models of horizontal, vertical and egg-crate shadings together. The best egg-crate models had weaker performance than other shading devices so although their average energy consumption and view to the outside were respectively 3% and 21% less than the base model, they are not recommended.

Figure 7 also shows that among three types of shading devices, the majority of the solution on the final Pareto

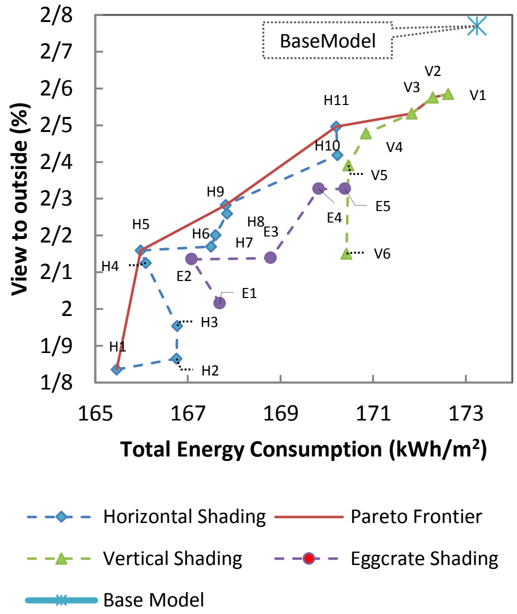

Figure 7- Total optimized shading simulation result

frontier is horizontal louvres. Just in case of giving more weight to the view, the vertical louvres have better performance than horizontal.

Parameters distribution of best shadings devices is shown in Figure 8 in the brown colour. Most of the louvres had 10 cm depth, and just one case was found with the depth of 20 cm. No louvres were found with more depth. For the number of louvres, designers can choose among 2, 3, 4 and 7. Selecting two louvres would allow one to have more options in selecting other parameters value (Table 6).

The smaller the angle of the louvres, the more likely to achieve the optimal result, except just one louvre with 20 degrees rotation, other louvres are not rotated. Four of seven louvres had 5 mm thickness, and there is just one choice for the thickness of 2.5, 7.5 and 10 mm but no one with 12.5 mm thickness.

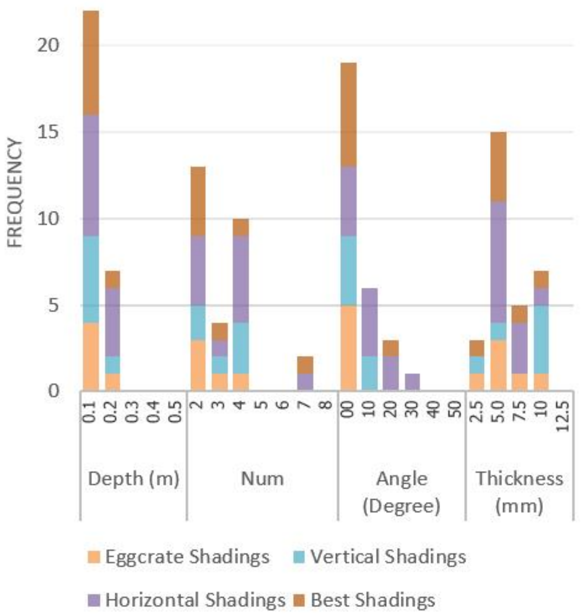

Figure 8- Parameters Distribution in Optimized Models

Conclusion

In this research, the impacts of shading devices on view to outside along with the energy consumption was investigated. Windows play a vital role in providing a view to outside in buildings and also have a significant impact on energy consumption. Although shading devices are necessary for façade design to reduce energy use in buildings in the hot and arid climate, it could have negative impacts on the visibility of occupants to outside. This issue is neglected in design or research studies most of the time.

This research aimed to present a framework for optimizing shading devices in the early stage of design for an office building in Tehran. The results and also the framework could be used by designers, investors or policymakers to apply in other projects of studies. In this regards, three types of vertical, horizontal and egg-crate shading devices were investigated by Ladybug tools.

Among the three types of shading devices, the horizontal shadings had the most abundance. Four out of seven best-optimized shadings found were horizontal. On the contrary, egg-crate shadings do not have any representation among the best-optimized shadings.

The results showed that as long as designers or decision-makers consider the weight of view less or the same as energy consumption, the best-optimized shading devices are horizontal. Otherwise, in the projects which view to the outside have priority than energy objective, vertical shadings are the best choices.

The lower the number of parameters in width and number of louvres, the higher the chance to reach the optimal shading. For the best trade-off between total energy consumption and view to outside, two to four louvres with the depth of 10 or 20 cm are recommended. Also, no rotation angle is preferred. The research objectives are not sensitive to the louvres thickness and variety of choices are applicable. For view objectives, although recently some indices are introduced there are no simulation tools to assess the view performance. Therefore, this research just investigated the 3D spherical view around the cantered seated occupant. The authors are developing Horsefly application which would help to overcome this limitation. It is recommended that further research is needed to investigate other related objectives such as daylight performance or visual and thermal comfort. Moreover, the impacts of window size and location could be also considered.

Table 6- parameters and objectives of the base model vs. final optimized shadings

	Parameters				Objectives			
					Energy consumption			
Model	**Depth**	**Number**	**Angle**	**Thickness**	**Cooling**	**Heating**	**Lighting**	**Ave View**
	m		**D**	**mm**	**kWh/m²**			**%**
BM	-	-	-	-	83.4	55.8	12.1	2.8
V1	0.1	2	0	2.5	81.1	57.5	12.1	2.6
V2	0.1	2	0	5	80.8	57.6	11.9	2.6
V3	0.1	3	0	10	79.3	58.7	11.9	2.5
H11	0.1	2	0	5	78.3	57.8	12.1	2.5
H9	0.2	2	0	7.5	73.9	59.7	12.3	2.3
H5	0.1	4	20	5	69.0	62.4	12.6	2.1
H1	0.1	7	0	5	67.5	62.9	13.1	1.8

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