THE IMPACT OF DYNAMIC FACADE TYPOLOGY ON DAYLIGHT AND ENERGY PERFORMANCE: COMPARING ROTATION AND FOLDING MOTION

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ABSTRACT

In recent years, architectural design with dynamic facade has been more widely introduced as a solution for building environmental issues. From the morphological point of view, this paper attempts to explore the performance otherness of different dynamic typologies during the optimisation of the design process. Take highrise office building in the tropical region as an example, The two common typologies of rotation and folding are compared and discussed by parameter simulation method with 36 cases in terms of scale, motion and transmittance to find the optimal trade-off between minimising energy demand for cooling and lighting and maximising daylight comfort.

The results of the study show that the energy demand for cooling and lighting can be reduced by 19%-24% through dynamic façade while folding typology has better performance in energy conservation in all the three orientations. For daylighting, the average daylight comfort area has an increase of 5%-14%, while the value of rotation typology is higher than folding typology. Furthermore, Motion has an influence on the daylight and energy performance except for energy demand of rotation typology. Differently, Transmittance is related to both performances except daylight of rotation typology. This study provides a performance-based approach to dynamic facade selection. A designer could make the decision not only from aesthetic considerations but also combine them to get higher performance.

Keywords: energy conservation, daylighting, dynamic façade

1. INTRODUCTION

1.1 Challenge

As global warming and people's demands of indoor space comfort continue to increase, office building energy consumption is increasing by years. In the tropical region, due to the use of Large glass curtain wall and excessive solar radiation intensity, the uneven distribution of indoor illuminance and the excessive indoor radiation are serious in high-rise office buildings. These external factors have led to the formation of current "refrigerator" buildings. As the demand for visual and thermal comfort continues to increase, the "refrigerator" building is intensifying, and the challenges of building energy consumption are even more severe. According to the Building Energy Benchmarking

Report of Singapore, the annual energy consumption office buildings reached 221 KWh/ m^2 . Face to these issues, the use of passive design strategies in the early stages of the design is a necessary method for architects to optimise the environmental issues and reduce energy consumption from on-site resources such as daylight. However, optimising by using daylight is challenging because occupant comfort and energy consumption sometimes conflict with each other. Especially diurnal sun movement gives a different hourly angle of incidence during the daytime that influences the indoor condition. Thus, it is necessary to provide an optimisation method to respond to environmental stimuli dynamically and balance different objectives.

1.2 Dynamic Façade

Façade, as a complex interface, has a capability that protective or regulatory element against severe fluctuations of the external climate. Recent studies show the significant effect of façade design on indoor visual quality [1],[2]. The investigation of the existing literature also revealed an expanding interest in the dynamic façade since significantly influencing the building performance, which considers the strategies and

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approaches [3]. Some researchers found that dynamic facade, which positions, or tilt angles can be adjusted according to the sun position, are more effective than static façade element in reducing heat gain as well as achieving enough daylighting [4]. Currently, Quantitative methods have widely been applied for analysing and evaluating dynamic facade's performance, including digital model simulation and parametric evaluation aimed to reduce energy consumption, improve thermal comfort and daylight performance. Mahmoud and Elghazi investigated daylight performance use two kinds of movement (translation and rotation) with the hexagonal pattern by parametric digital modelling [5], while Pesenti explored folding patterns, inspired by Japanese paper origami, to understand the potential of dynamic patterns' morphology for application in dynamic façade [6]. Similarly, Elzeyadi measured the actual performance of the prototypes in full-scale and compared six main typologies for energy saving and visual comfort [7]. Likewise, Panopoulos investigated the available smart facade to the existing office building in perspective of new material and technology.

The existing dynamic facade research mainly focuses on basic typologies such as translation, rotation and scaling. However, folding typology still lacks attention and targeted optimisation research. Moreover, in recent years, the folding typology in high-rise building practice has been more widely used, such as Al Bahar Towers and CJ in South Korea. Due to the complex form and the high initial cost, the folding typology should be measured by the architects in terms of aesthetics performance. Therefore, it is necessary to analyse the performance characteristics of the folding typology by quantitative comparison with several other typologies. The basic principles of rotation and folding are the same, based on the common motion axis moving in the same direction or symmetrically, so it is used as a contrasting typology for this study. Moreover, there are also few typologies of research that integrate multiple influences such as element size, angle, transmittance and movement while considering design optimisation, as well as evaluate the effect of orientation on the performance of dynamic facade and compare several dynamic movements in same building orientation.

1.3 Objective of this research

This research aims to employ a parameter optimisation method to explore the performance otherness of different dynamic typologies (folding and rotation) to improve daylight efficiency and energy conservation in the same orientation and then provide recommendations of optimization for three orientations. Specifically, typical high-rise office buildings in the tropical area are chosen as an example.

Two goals are specifically pursued in this research: 1) to implement an optimization process of office buildings with dynamic façade based on parameter simulation and multi-objective overall best. 2) to quantitatively evaluate and compare the potential improvements of daylight efficiency and energy conservation that different dynamic typologies could contribute, for typical office buildings with different orientations.

2. METHODOLOGY

2.1 Parameter office model

In this study, a typical office model was constructed with 8.4m*10m dimension and 3.6M high, which mean one open office room inside two columns in a 35M*35M high-rise tower standard layer (Fig.1). The model has a window-to-wall ratio (WWR) of 50% with 0.9m sill, and the opening has clear glazing with visible transmittance (VT) of 0.7 according to the requirement of Singapore. This office room as a reference. More specifically, the details of the internal surface properties and the characteristic of glazing materials are shown in Table 1 and Table 2.





The dynamic facade is an external layer of double façade type which acts as a shading screen coupled with a glazed interior layer, the distance in-between the two layers is 0.5m. This office space was chosen so that each of the systems could be consistently compared.

2.2 Dynamic Façade Parameters

Table 1. Description of internal surfaces properties of office model.

Component	Reflecta	nce	Specularity	Roughness
Wall	0.7		0.03	0.05
Floor	0.4		0.03	0.05
Ceiling	0.8		0.03	0.05
According to <	Certification Stand	lard for New Buildings	> requirement by Building	and Construction Authority
		(W/㎡ K)	coefficient	Transmittance
[Dbl_LoE(e2=0.1) 13 mm Air/6 mm]	: Clr 6 mm/	1.49	0.57	0.7

The façade has an array of the rectangular module as a general design pattern since this shape gives a good combination of edge and represent most kind of existing configuration of façade. The dynamic typologies are tested on these planar uniform identical modules. Also, after sensitivity analysis, three kind of design parameter variables are considered during the optimisation and comparison, including module size, motion, and transmittance, to find the optimal solution of each typology. The characteristics of variables are presented in Table 3, together with their variation range. Table 4 and Table 5 show the properties of the parameter. Changing each of them will affect all three performances. In total, 36 dynamic façade cases of each typology are evaluated and compared considering size, motion, transmittance, while the angle is only calculated during daylight and energy consumption simulation (Fig.2, Fig.3).

Variable	Abbreviation	Unit	Range	Disribution
Module Size	Ms	m	[0.2,0.4,0.6]	Discrete
Dynamic Motion	Dm	-	[0,1,2]	Discrete
Transmittance	Tr	%	[0%,25%,50%,75%]	Discrete
Motion Angle	Ma	•	[90,75,60,45,-45,-60,-75]	Discrete
Table 4. Charac Value	teristics of dynamic r Dynamic Motion	notion Description	Diagram	
0	Horizontal	action alone	horizontal axis	j. j.
1	Vertical	action alone	vertical axis	r P
_	Discourd	antine stress	dia anna di anta	d A

Table 5. De	Table 5. Description of dynamic façade transmittance material property				
	Diffuse Transmission	Diffuse Reflectance	Specular Reflection		
0.00	0.00	0.70	0.30		
0.25	0.25	0.50	0.05		

0.50	0.50	0.30	0.05
0.75	0.75	0.10	0.05





Fig. 3 36 dynamic facade cases

2.3 Climate data

Singapore, a typical major city in a tropical region, is selected as the location for the simulation. The weather conditions of Singapore (1.3°N) including the values of solar radiation and sky illuminance are taken from the ASHRAE International Weather for Energy Calculations (IWEC) Data (US Department of Energy, 2013).

2.4 Visual comfort calculation

Simulations for daylighting performance is planned to be studied for the base case without dynamic facade, the dynamic façade with rotation typology and the folding typology. Previous studies used LEED v4 daylighting as a design standard. The simulation process conducted in this paper complied with LEED v4 daylighting requirement in which the three illumination evaluation levels for the floor area were used: "Daylit," 'Partially daylit,' "Overlit'" areas. The "Daylit" area achieves illuminance levels between 300 lux and 2000 lux for the floor area; "Overlit" area achieves illuminance greater than 2000 lux for the floor area with potential glare; "Partially Daylit" area achieves illuminance below 300 lux for the floor area.

Daylighting system is set up for Singapore, with a climate-based sky condition. The simulation is planned to be performed for four days of the year, March 22, June 22, September 22 and December 22, at 8 hours of a day from 9:00 am to the end of 4:00 pm. The day is chosen according to the requirement of the Building and Construction Authority, Singapore. Test plane 0.7m above the floor.

2.5 Energy demand calculation

Energy consumption of high-rise building in the tropical area has three main aspects, that is, cooling energy, lighting energy demand, and equipment energy during the whole year. In this study, the average daily energy consumption per square meter will be calculated using EnergyPlus software.

2.6 Simulation setup

For the simulation, the 3D graphics software Rhinoceros and its plug-in Grasshopper were applied to control the geometric parameters. Plug-in Ladybug and honeybee were used to add physical properties of building and façade and connect to energy simulation software EnergyPlus, and daylight simulation program Radiance. The details of the EnergyPlus and Radiance parameters of calculation are given in Table 6, Table 7. The parameters were set according to a Radiance validation study by Reinhart and Walkenhorst. For EnergyPlus, the default settings for open office room were selected.

2.6.1 Construction

It is assumed the room is located on the middle floor of a high-rise tower. The thermal transmittance from the ceiling, floor, and interior wall are set to adiabatic. The external wall is defined according to ASHRAE 90.1-2010

Table 6 Setting	of Radiance simu	llation parameter	s			
Ambient Bounces	Ambient division	Ambient sampling	Ambient accuracy	Ambient resolution	Direct threshold	Direct sampling
5	1000	100	0.1	300	0	0
Tabel 7. Setting	of EnergyPlus sir	nulation paramet	ters			
Equipment Load Per Area	Infiltration Rate Per Area	Lighting Desnsity Per Area	Num of People Per Area	Ventilation Per Area	Ventilation Per Person	Cooling Set Point
7.6	0.0002	11.8	0.057	0.0003	0.002	24



Extwall Mass Climate zone 1A construction with a U value of 3.69 $W/{\ensuremath{\mathbb{M}}^2}\,$ K.

2.6.2 HVAC

The ideal load air system is selected as the HVAC system in EnergyPlus, which is most suitable in the early design stage considering it's the consistent issue in the procession of comparing shading device variables and reduce calculation time cost. The cooling set point is set to 24 °C.

2.6.3 Schedule

The office is open from 9:00 AM to 5:00 PM on weekdays and Lighting schedules for energy calculation results from the daylight simulation. An auto-dimming with occupancy sensor is assumed with the illuminance threshold set to 300 lx, which mean dim electric light until the total work plane illuminance reaches the minimum threshold.

3. RESULT

3.1 Design variables analysis

There totally have 8064 solutions for each typology in one orientation. Comparing seven angle's performances, the 1152 "Overall best" solutions is selected which mean the optimal angle for each of 36 cases in a specified time point. The calculation as follows

$$O_{best} = Min\left(\sqrt{\left(\left(\frac{(Ei-Emin)}{Emin}\right)^2 + \left(\frac{(Di-Dmax)}{Dmax}\right)^2\right)}\right)$$

(E= Total Energy demand, D= Four-day average value of area percentage (Daylight illuminance among 300-2000Lx), I= index of the case, the min=minimum value in the set, max= maximum value in the set.)

Then the performances of 36 cases for each typology are evaluated by calculated average energy consumption and daylight for four days.

Fig. 4 shows the characteristic of folding and rotation in each orientation. From Fig. 4, it can recognise that, with the change of parameters, the results of the percentage of "daylit" area show a periodic change with obvious peaks and troughs. For rotation typology, case 1 (0.2m-horizontal-opaque), case 13 (0.4m-horizontalopaque), case 25(0.6m-horizontal-opaque) represents the maximum value of the percentage of "daylit" area. That means motion with horizontal and opaque material usually have better performance among their group. Oppositely, case 5 (0.2m-vertical-opaque), case 17 (0.4m- vertical -opaque), case 29(0.6m- vertical -opaque) show the minimum, mean that motion with vertical is unlikely to improve the quality of the light environment compared with other two motions(horizontal and diagonal). While the daylight performance of Folding Typology shows a shifting". The peak value appears in case 2 (0.2-horizontal-25%), case 14 (0.4-horizontal-25%), case 26 (0.6-horizontal-25%), but the troughs are same with rotation typology. That means, for dynamic façade with folding typology, horizontal motion with 25% transmittance façade present higher daylight performance than other motion and transmittance.

According to Fig.5, rotation typology has an advantage than folding typology in terms of improving indoor daylighting performance in all the three orientations. However, folding typology shows lower energy consumption in the same condition.

Size, Motion, and Transmittance influence the performance of rotation and folding typologies. Through regression analysis, take west façade as an example, Table 8,9 shows that, for rotation typology, "Motion" is the significant element for daylight performance (horizontal > Vertical > Diagonal), while for folding



Fig. 5 Compare daylight performance and energy demand of 36 cases

Ta	ble 8-1	Coefficient	s* (Wes	t façade with rot	ation typo	logy)
		Unstand	lardized	Standardized		
Mod	del	Coefficients		Coefficients		
		В	Std. Error	Beta	t	Sig.
1	(Constant)	0.624	0.021		29.332	0.000
	Size	-0.012	0.034	-0.049	-0.344	0.733
	Motion	-0.026	0.007	-0.556	-3.912	0.000
-	Transmittance	0.029	0.020	0.209	1.471	0.151
a. D	ependent Variable:	Percentage of	"Daylight are	a" (among 300-2000	Lx) /hour	
Ta	ble 8-2	Coefficient	s* (Wes	t façade with rot a	ation typo	logy)
		Unstand	lardized	Standardized		
Mod	del	Coeffi	cients	Coefficients		
		В	Std. Error	Beta	t	Sig.
1	(Constant)	0.499	0.012		41.783	0.000
	Size	0.015	0.019	0.106	0.778	0.442
	Motion	0.000	0.004	-0.017	-0.125	0.902
		0.051	0.011	0.629	4.616	0.000
a. D Tal	Transmittance ependent Variable: ble 9-1	Total energy de	s* (Wes	t Façade with fol	ding typol	ogy)
a. D Tal	transmittance ependent Variable: ble 9-1	Total energy de Coefficient Unstand Coeffi	s* (Wes dardized cients	t Façade with fol Standardized Coefficients	ding typol	ogy)
a. D Tal Mod	Transmittance ependent Variable: ble 9-1 del	Total energy de Coefficient Unstand Coeffi B	emand (Kwh s* (Wes Jardized cients Std. Error	t Façade with fol Standardized Coefficients Beta	ding typol	ogy)
a. D Tal Moo	Transmittance ependent Variable: ble 9-1 del (Constant)	Total energy de Coefficient Unstanc Coeffi B 0.595	emand (Kwh s* (Wes dardized cients Std. Error 0.012	/ m· d) t Façade with fol Standardized Coefficients Beta	t 50.310	ogy) Sig. 0.000
a. D Tal Moo 1	Transmittance ependent Variable: ble 9-1 del (Constant) Size	Total energy de Coefficient Unstanc Coeffi B 0.595 -0.019	emand (Kwh s* (Wes dardized cients Std. Error 0.012 0.019	/ m· d) t Façade with fol Standardized Coefficients Beta -0.140	t 50.310 -1.029	ogy) Sig. 0.000 0.311
a. D Tal Moo 1	Transmittance ependent Variable: ble 9-1 del (Constant) Size Motion	Total energy de Coefficient Unstanc Coeffi B 0.595 -0.019 -0.012	emand (Kwh s* (Wes dardized cients Std. Error 0.012 0.019 0.004	t Façade with fol. Standardized Coefficients Beta -0.140 -0.445	t 50.310 -1.029 -3.261	ogy) Sig. 0.000 0.311 0.003
a. D Tal Moo 1	Transmittance ependent Variable: ble 9-1 del (Constant) Size Motion Transmittance	Total energy di Coefficient Unstance Coeffi B 0.595 -0.019 -0.012 0.035	s* (Wes dardized cients Std. Error 0.012 0.019 0.004 0.011	/ m· d) t Façade with fol Standardized Coefficients Beta -0.140 -0.445 0.432	t 50.310 -1.029 -3.261 3.169	Sig . 0.000 0.311 0.003 0.003
a. D Tal Moo 1	Transmittance ependent Variable: ble 9-1 del (Constant) Size Motion Transmittance ependent Variable:	Total energy de Coefficient Unstanc Coeffi B 0.595 -0.019 -0.012 0.035 Percentage of	s* (Wes lardized cients Std. Error 0.012 0.019 0.004 0.011 "Daylight are	/ m· a) t Façade with fol Standardized Coefficients Beta -0.140 -0.445 0.432 a" (among 300-2000	t 50.310 -1.029 -3.261 3.169 Lx) /hour	Sig . 0.000 0.311 0.003 0.003
a. D Tal Moo 1 a. D	Transmittance ependent Variable: ble 9-1 del (Constant) Size Motion Transmittance ependent Variable: ble 9-2	Total energy di Coefficient Unstanc Coeffi B 0.595 -0.019 -0.012 0.035 Percentage of Coefficient	emand (Kwh s* (Wes Jardized cients Std. Error 0.012 0.019 0.004 0.011 "Daylight are s* (Wes	/ m· a) t Façade with fol Standardized Coefficients Beta -0.140 -0.445 0.432 a" (among 300-2000 t façade with fold	t 50.310 -1.029 -3.261 3.169 Lx) /hour	<u>Sig</u> . 0.000 0.311 0.003 0.003
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Fig. 6 Design selection (west facade example)

typology, "Motion" "Transmittance" are common influence the result.

In terms of energy demand, "Transmittance" has more influential than any other variables for rotation typology. Differently, both "Motion" and "Transmittance" can contribute to energy performance.

3.2 Design selection

The characteristics of solutions for three orientations are analyzed and compared (Fig.6). Considering energy aspect, the minimum energy demand of the rotation and folding typology for west façade is 0.47 KWh/m² · d and 0.44 KWh/(m² · d) respectively, 19% and 24% less than the 0.58 KWh/(m² · d) value of the reference office room without dynamic façade. South and east orientation with dynamic façade have similar energy reduction. For west façade daylighting performance, the best design of rotation typology reaches to 66% percentage of the area ("Daylit" among 300lx-2000lx), and folding typology reaches to 61% while 14% and 5% more than the value of reference room (58%). For south façade, rotation typology is 63%, folding is 59%, which 13% and 7% more than the reference room (55%). For east façade, rotation typology is 64%, folding is 61%, which 12% and 7% more than the reference room (57%).

4. CONCLUSION

This study is a comparative research of dynamic façade to introduce the optimal façade based on a simulation-optimisation method to improve daylight and energy performance. These two typologies have their characteristics, rotation typology usually has higher daylight performance, but compared with folding typology, it does not have advantages in terms of energy conservation. Through providing a performance-based approach to dynamic facade selection, the designer could make the decision not only from aesthetic considerations but also combine them to get higher performance building design.

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