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EFFECTS OF SHADING ON THE ENERGY CONSUMPTION OF HIGH-RISE OFFICE BUILDINGS IN HONG KONG

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ABSTRACT

This paper aims to investigate the effects of shading from the building itself and nearby buildings on the energy consumption of high-rise office buildings in Hong Kong. The paper first analyzes the typical shading effects on energy use in Hong Kong by investigating four typical office buildings with different building typologies and surroundings. The paper then chooses one typical building for further parametric study. Energy consumption regression models are established under different height, building interval and orientation conditions. The findings reveal that the shading effects show a great influence on energy consumption of high-rise buildings and cannot be neglected.

INTRODUCTION

Hong Kong is a high-density subtropical metropolis with a large proportion of high-rise buildings (Yu, Pan et al. 2015, Pan, Qin et al. 2017). The shading effects from nearby buildings in Hong Kong are more significant than in other regions. Shading can decrease the visual light transmission and heat gain from sunlight which can leed to the change of the overall energy consumption.

However, based on the site survey and interviews with building energy designers, the shading effects were seldom considered in the assessment of building energy performance in Hong Kong. Also, it has been a controversial issue whether shading has large effect on energy consumption in previous research due to the different climates and policies on building construction.

Previous research debated on the shading effects from nearby buildings on energy use. In Hong Kong, Lam (2000) analyzed the shading effects from nearby buildings by two steps. One was the investigation of 120 commercial buildings in seven main business districts to gain an appreciation of the degree of shading from adjacent buildings. It could be found that the degree of shading at the local peak design condition (i.e. 15:00 July) ranged from 25 to 31%. The other step was to establish a general office building model using DOE-2 to analyze the building cooling load oversizing. The results showed that the total building cooling load was overestimated by about 2%. The impacts on the total building energy budget were not significant. However, Li and Wong (2007) held an opposite view. They modeled a general commercial building in Hong Kong using energy simulation tool EnergyPlus. It was found that the shading effects due to nearby buildings affect around 7% of total building energy use when daylighting designs were used. Chan (2012) explored the shading effects between different residential flat types. Adjacent shading effect was found to have a substantial impact on the thermal performance of residential buildings. He and Ng (2017) studied the mutual shading effect on energy performance by considering various window glazing materials. A typical 30-storey high-rise residential building with and without shading was established in four different climates. Their results showed that the effect of mutual shading on the building performance with different glazing was less than 1% in the cold climate but had maximum 8% total energy decrease with low-e clear window glazing in hot climate such as in Hong Kong. Worldwide, Dou and Xiao (2010) used an actual building in Qing Dao, China as the reference building and proposed several senarios to evaluate the shading effects from nearby buildings by using energy simulation tool DEST. Their results indicated that the building inter-block had more influence on heating load and almost had no influence on cooling load. In the same building interval, the block in the southeast had the minimum impact on building energy load than in other orientation. Fang and Liu (2012) investigated the shading effects using an actual office building in Shen Zhen and found that shading from nearby buildings could affect around 10% of total building cooling load. Pisello, Taylor et al. (2012) examined the inter-building effects of a realistic block of twenty single-family homes subject to different climates. The results revealed that by considering shading effects the energy requirement modeling inaccuracies of up to 42% in summer (in Miami, FL) and up to 22% in winter (in Minneapolis, MN).

Shading effects from building itself are related to building typologies. Different typologies with different shading overhangs and fins or internal shading will lead to different energy consumptions. Tzempelikos and Athienitis (2007) investigated shading device with lighting control on cooling demand. It was shown that for 20% transmittance, simultaneous control of a shading device and a controllable lighting system on a south-facing façade could lead to minimization of energy demand for lighting and cooling, and maximization of daylight utilization. Comparing with the base case without shading, shading control (20% average transmittance over the facade) accounts for 50% decrease in annual cooling energy demand. Hachem, Athienitis et al. (2011) studied the solar potential of seven geometries (square, rectangle, trapezoid, L, U, H and T shapes) of two-story single family housing units located in mid-latitude climate. The results indicated that shading facades with in-self shading geometries and their relative dimensions are the major parameters affecting solar incident and transmitted radiation.

Previous research showed that in Hong Kong, daylighting control was not widely used. Lam (2000) investigated 120 commercial buildings and found that none adopted daylighting technology. Li and Tsang (2008) also reported on their site survey that in Hong Kong daylighting strategies were not commonly incorporated in office buildings. Zhou, Yan et al. (2015) evaluated 15 office buildings in Beijing and Hong Kong and found that outdoor illuminance levels had little impact on lighting energy use due to the lack of automatic daylighting controls. In recent years, daylighting control has been recognised as a useful energy saving strategy and an increasing number of new constructions in Hong Kong are equipped with daylighting control systems (Li and Wong 2007). To reach a more comprehensive and acceptable results of the shading effects on energy consumption, daylighting and visual comfort are considered in this paper.

All in sum, previous research mostly used hypothesis model as research objects which may not reflect the real situations and be practical. Previous research did not explore the interaction between the main shading factors (such as building orientation, building interval) and total energy consumption for high-rise buildings.

This paper thus aims to investigate the effects of shading from the building itself and nearby buildings on the energy consumption of high-rise office buildings in Hong Kong. This paper addresses the shading effects in real situations and explores the interaction between energy reduction and shading factors.

METHODOLOGY

Research object

Four real-life office buildings with their surroundings were selected as the research objects in Part 1 of this research. Part 2 uses one real-life office building and one hypothesis adjacent building for further parametric research.

The shading from surroundings can be the adjacent buildings or trees. However, in the high density urban environment of Hong Kong, trees' shading effects are relatively less significant, and therefore are not considered herein.

Scope of shading

Shading includes self-shading and mutual shading. Self-shading depends on building's typology, such as building layout, overhang, fins and internal shading control. Mutual shading means the shading from nearby buildings. This paper considers the complex shading conditions covering building's typology and mutual shading in Part 1 and shading parametric index (building interval, building height, building orientation) in Part 2.

Procedure

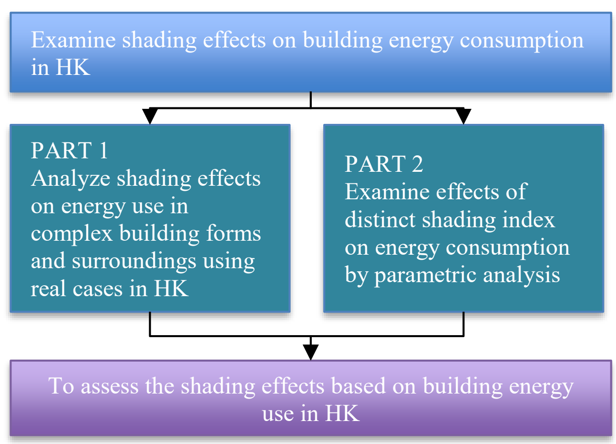

Figure 1 Procedures of analyzing the shading effects on energy consumption

Figure 1 displays the procedures of analyzing the shading effects on energy consumption. The paper has two case studies to explore the shading effects on energy consumption. Shading effects are complex since they can be influenced by several factors, such as glazing area, glazing material, building height and so on. To investigate the shading effects on energy consumption in

Hong Kong in detail, it is necessary to analyze real-life buildings with actual complex surroundings.

Therefore, firstly, the paper investigates one hundred of high-rise office buildings in Hong Kong identified by using GIS tool Google-Earth. From the investigation, the geometries for high-rise office buildings were found to be totally different from one to another. This study selects four typical real-estate high-rise office buildings with different building typologies (1 trapezoid, 1 hexagon, 1 rectangle, 1 trapezoid) as research objects. Then two scenarios were conducted to analyze the shading effects on energy consumption for each building. One is the energy model without shading which is regarded as base case. The other is the energy model considering shading effects from itself and nearby buildings. The simulation results compared with two scenarios indicate the importance of shading effects on energy consumption.

Secondly, the paper chooses one typical rectangular building for further analysis. This part aims to investigate the impact of shading parameters on energy consumption. One typical building with one adjacent building is selected as the research object. Building height, building interval and building orientation are considered to be three shading parameters. Using the scenario analysis method, energy consumption reduction prediction regression models for shading effects were established under different height, building interval and orientation conditions. The results display the interaction between shading index and the reduction of energy performance for high-rise office buildings.

PART I: ANALYSIS OF SHADING EFFECTS ON ENERGY USE IN REAL BUILDINGS

Model establishment

After investigating one hundred of high-rise office buildings in Hong Kong, four typical realistic buildings were selected to be object buildings. Typical buildings are all office buildings and their heights varied from 123m to 160m. The basic information of the four buildings was obtained from the Electrical and Mechanical Services Department (EMSD) of the HKSAR Government (listed in Table 1). All the four buildings use distinct window glazing materials. The energy models of all the buildings were built using simulation tool EnergyPlus. The geometry models were built by using simulation tool DesignBuilder. The weather file of the whole year used in the energy simulation is provided by Energy Plus weather database (CHN_Hong.Kong.SAR.450070_CityUHK.epw).

Building forms and surroundings are displayed in Figure 2. From Figure 2, the buildings circled by yellow rectangles represent the typical buildings from building number B1 to B4. The buildings' typologies are totally different among the four buildings. Typology of B1 is trapezoid. B2 is hexagon shape. The shape of B3 is irregular rectangle while the shape of B4 is octagon.

The collected information (Figure 2) shows that the shading effects from both adjacent buildings and itself are significant. B4 has less shading effects from mutual buildings compared with others. Because there is only one high surrounding building near the object building. The height of B1 is much higher than its surrounding buildings but the distance between them are too close, leading to critical shading problem. However, B2 and B3 suffer from more serious shading problems. Buildings near B2 and B3 are either too close or too high with large floor area.

Table 1 Basic information of four buildings

BUILDING NAME	**B1**	**B2**	**B3**	**B4**
Building height (above ground)	160m	123m	154m	147m
Lifts number	7	9	9	9
Summer indoor set temperature ℃	23	24	23	23
Winter indoor set temperature ℃	21	21	21	21
WWR (N)	0.81	0.75	0.8	0.8
WWR (S)	0.5	0.75	0.8	0.8
WWR (W)	0.85	0.75	0.1	0.8
WWR (E)	0.85	0.75	0.3	0.8
Opaque wall U-value (W/m2 K)	1.9	1.9	2.5	3
Roof U-value (W/m2 K)	0.56	0.42	0.46	0.39
Partition U-value (W/m2 K)	2.1	1.7	1.8	2

Floor U-value (W/m2 K)	1.2	1.2	1.2	1.2
Window (SC)	0.81	0.54	0.46	0.6
Window (Tvis)	79	39	49	61
Window U-value (W/m2.K)	3.1	2.8	2.7	2.1
Window (SHGC)	0.705	0.470	0.400	0.522
Window type	Double glazed unitized curtain wall	Unitized system Curtain Wall with 32mm grey tinted heat strengthened insulating glass, color anodized aluminum windows	Blue-green reflective glass and American Granite complimented by trims, suspended canopies, fluorocarbon coated aluminum	Low-e double-glazed thermally-insulated panels set in anodized aluminum frames
AC Schedule	Mon to Fri: 0830-1930 Sat: 0830-1400	Mon to Fri: 0800-1900 Sat: 0800-1900	Mon to Fri: 0800-1900 Sat: 0800-1400	Mon to Fri: 0800-1900 Sat: 0800-1400
Air-conditioning	VAV	VAV	VAV	VAV
COP	2.9	2.9	2.67	4
Heat rejection method	air-cooled	air-cooled	air-cooled	water-cooled

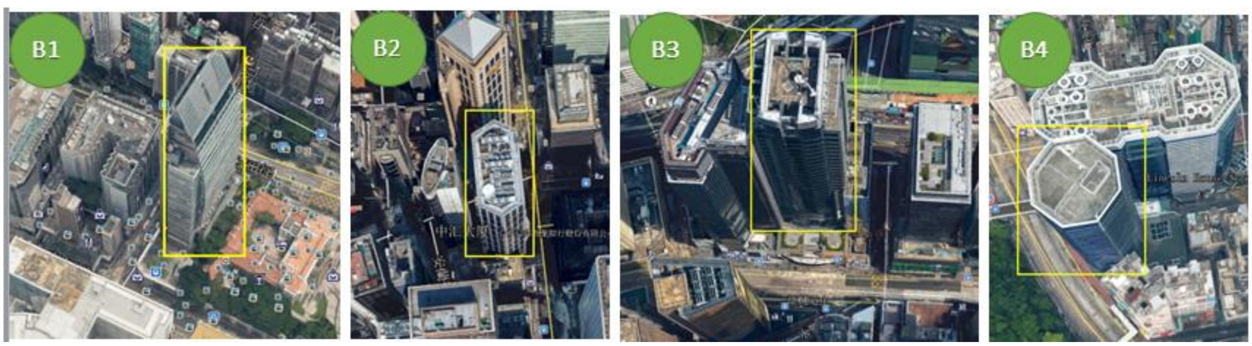

Figure 2 Building forms and surroundings

Results

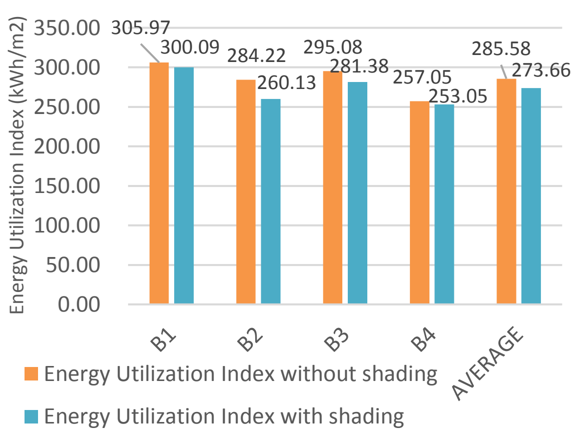

Figure 3 Energy Utilization Index comparison with/without shading effects

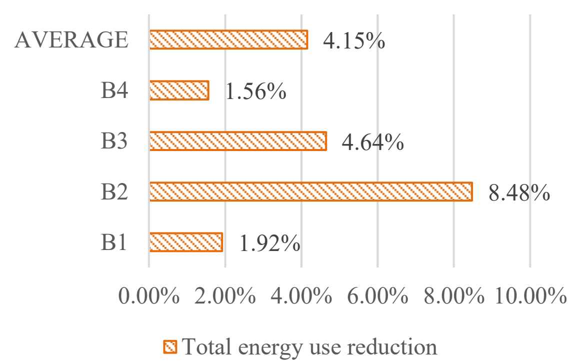

Figure 4 Total energy consumption reduction comparison

Since the energy bills for Hong Kong office buildings are confidential, the research validated the energy use results through website and published papers. The results in Figure 3 show that the total building energy consumption without shading was simulated to be 305.97, 284.22, 295.08, 257.05, 285.58 kWh/m^2 for B1, B2, B3 and B4 respectively. The whole year energy use is in agreement with that reported in previous studies, e.g. 259.2 kWh/m^2/year by Philip and Chow (2007), 233 kWh/m^2/year to 368 kWh/m^2 by Lam, Wan et al. (2008), 74 kWh/m^2/year to 529 kWh/m^2/year by Jing, Wang et al. (2017). From Figure 4, the results show that the total energy consumption with shading effects of B1, B2, B3, B4 can be decreased by 1.92%, 8.48%, 4.64%, 1.56%, 4.15% respectively compared with those without shading effects. The average energy use decrease is 4.15%.

The difference of the total energy consumption over the whole year among the four buildings is attributed to complex reasons. For example, the variation of HVAC systems, the envelope materials, the shape, the surroundings.

The energy decrease of B1 is not obvious because B1 is much higher than the surrounding buildings and the shading area are relatively lower. B4 only have one high building near the base building. Even the nearby building is high and close to B4, the total energy consumption reduction with shading effects is only 1.56%, minimum among the four buildings. B2 is surrounded with some higher buildings and the distance between B2 and adjacent buildings is less than 10m which contribute to high shading impacts (8.48% energy use decrease). From the results, the shading effects show a great influence on energy consumption and cannot be neglected in Hong Kong.

PART II: ANALYSIS OF EFFECTS OF DISTINCT SHADING INDEX ON ENERGY CONSUMPTION

According to the results of Part 1 research, in Hong Kong, the shading effects are one important factor which must be considered during energy use calculation in design stage. The shading effects from nearby buildings are caused by multiple factors, including the distance between two buildings, the height, layout and orientation of the nearby building. Part 2 research aims to analyze the impact of independent shading parameters on energy consumption. Building B3 is selected as the typical building to do the parametric study on energy consumption. This is because B3 has the typical core rectangular shape that lifts, lobby and equipment rooms are located in the middle of the total area and the rest are office rooms. This case does not consider the layout influence since the layout is complex and totally different by different buildings. In this case, the layout of the nearby building is identified to be B3's layout.

To demonstrate the shading parameters in a more intuitive and simplified way, this part of study only focuses on one object building and one adjacent building. Scenario analysis approach is utilized to analyze the impact of the shading factors on energy consumption. In total eight scenarios are established. These scenarios are based on the different building orientations (N, S, E, W, N-E, N-W, S-E, S-W). N, E, S, W mean the adjacent building is located on the North, East, South, West of the object building respectively. N-E means the adjacent building is on the Northeast of the object building. So as the N-W, S-E, S-W. Building interval (x_i) means the distance between object building and its adjacent building. h represents the object building height (154m). y_i means the height of adjacent building (m). z means the reduction of yearly average total energy consumption (%).

The location of the adjacent building is near the object building or across the street. According to Hong Kong Planning Standards and Guidelines (2017), the recommended minimum carriageway widths in accordance with the Transport Planning and Design Manual are among 6.75m and 14.6m. The central reserve has two options: 1.8m and 2.3m. These mean that the street widths are longer than 8.55m (6.75m+1.8m). According to Buildings Ordinance and Regulations (2011) in Hong Kong, the desirable width of industrial area and area of mixed usage is 6m for one-way and 10.5m for two-way. Moreover, Ng (2009) used 20m and 30m as the two typical street widths to analyze the sound propagation in street canyons in Hong Kong. Chen, Ng et al. (2012) summarized that tall buildings of 40-60 storeys with 15-25m narrow streets have been the norm in Hong Kong.

Thus, in this paper, building interval is considered to be varied ranging from 10m to 35m at 5m intervals for each simulation model. Daylighting control systems are utilized in these models. Figure 5 shows the sketches for the independent variables. Table 2 displays the independent variables' range. Each orientation, 25 energy models with different x_i and y_i are established. In total 200 simulation models are established in this study.

Table 2 Independent variables' range

INDEPENDENT VARIABLES	VALUE	UNIT
Building interval (x_i)	10, 15, 20, 25, 30	m
Building height (y_i)	0.25h, 0.5h, 0.75h, h, 1.5h	m

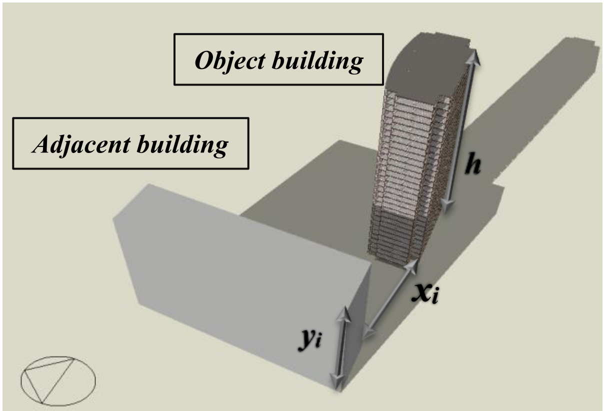

Figure 5 Sketches for the independent variables (x_i, y_i)

Results

Regression models were established under eight orientations in Eq. (1), where z is a linear function of x and a quadratic function of y. Table 3 shows the R^2 and P value of the regression model. It can be seen that the R^2 ranges from 0.8898 to 0.9939, which means x, y and z fit the regression model well.

$$z = \begin{cases} 0.4181 - 0.0234x + 1.7282y - 0.7017y^2, \; North \\ 0.2629 - 0.0193x + 1.3848y - 0.5206y^2, \; South \\ -0.1651 - 0.0387x + 6.2899 - 2.3385y^2, \; West \\ 0.2243 - 0.0231x + 1.6538y - 0.4978y^2, \; East \\ 0.3083 - 0.0179x + 0.8464y - 0.283y^2, \; Northeast \\ 1.0571 - 0.0744x + 3.8038y - 1.4429y^2, \; Northwest \\ 0.1702 - 0.0109x + 0.7703y - 0.2789y^2, \; Southeast \\ 0.2509 - 0.0182x + 1.3679y - 0.5069y^2, \; Southwest \end{cases} \quad (1)$$

Table 3 R-square value and P value under eight orientations

ORIENTATION	R-SQUARE VALUE	P-VALUE
North	0.9267	$<10^{-11}$
South	0.9428	$<10^{-12}$
West	0.9939	$<10^{-22}$
East	0.9694	$<10^{-15}$
Northeast	0.7644	$<10^{-6}$
Northwest	0.9382	$<10^{-12}$
Southeast	0.8898	$<10^{-9}$
Southwest	0.9473	$<10^{-12}$

Figure 7 displays the relationship among the building interval, building height and energy use reduction under eight building orientations. The energy use reduction of all the scenarios is not as obvious as that in real cases. Because the scenario only chooses one nearby building to investigate. But in real case, the object building may be surrounded with two or more buildings with different height and orientation.

From Figure 7, it can be easily found that low x with high y will lead to high z. That means that low building interval between two buildings and high height of adjacent building can save energy. Another finding is that with one adjacent building, the reasonable shading impact is below 2% on total energy consumption in the other six orientations besides west and Northwest orientation. However, the adjacent building on the west orientation has the maximum shading impact on energy consumption than other orientations in general. Therefore, shading control or devices installed on the west side will be an efficient way to reduce energy.

Verification

A set of 30 testing data (x=10, 15, 20, 25 and 30m, y=1.25h for each orientation) are used to validate the regression model. The results show that the absolute error of the regression model is no bigger than ±0.34% and the total accuracy rate is 97.5% with an acceptable error threshold of ±0.25%. Significant correlation ($p < 10^{-37}$) is found between true z-value and predicted z-value with a Pearson's correlation coefficient of 0.9943 (R^2=0.9886). Figure 6 shows the comparison between the true data and corresponding predicted z-values from the regression model.

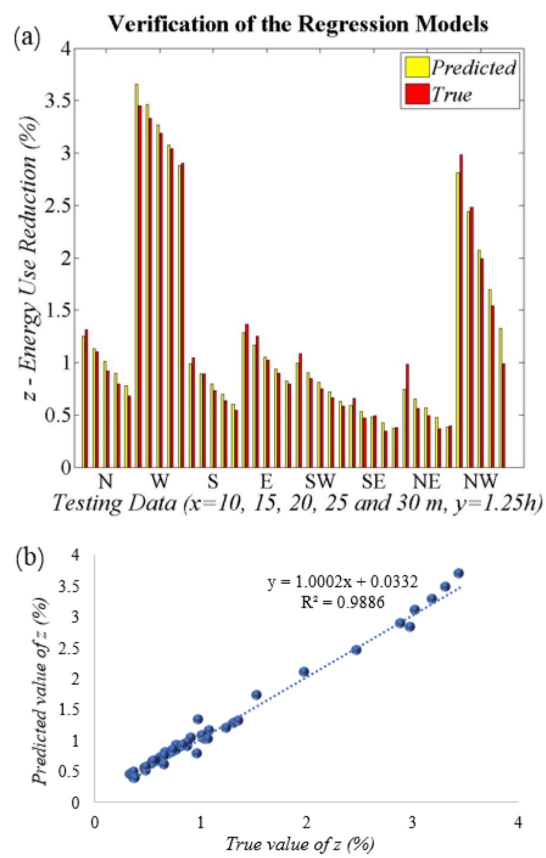

Figure 6 Verification of the regression models

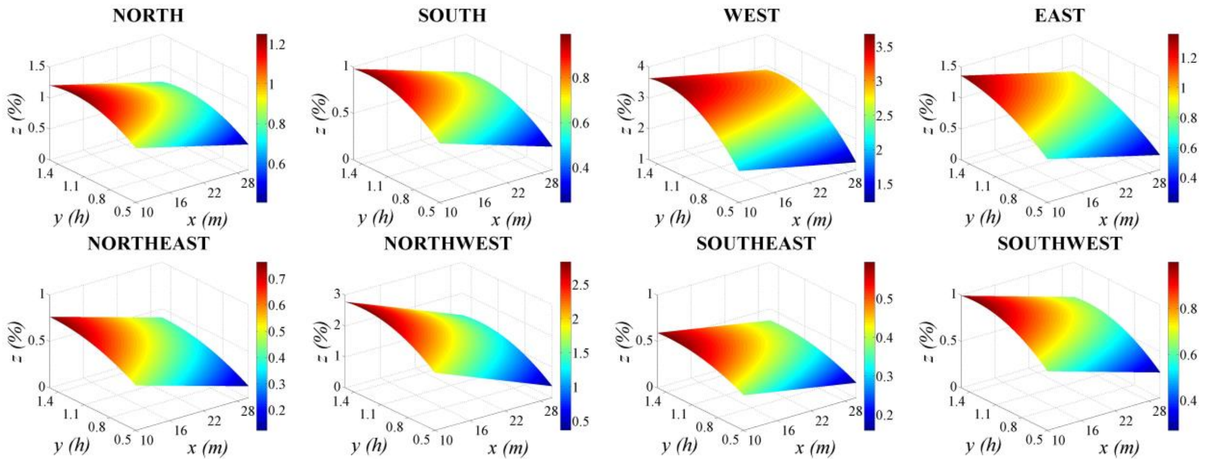

Figure 7 Sketches of regression models under eight orientations

Discussion

Eq. (1) and Figure 7 demonstrate how and to what extent building energy consumption is affected by building interval, building height and building orientation. A multi-orientation quantitative regression model with high performance has been obtained in this study.

A few interesting observations are achieved through the regression model analyzes.

1) The building interval cannot be too far. If the x is too big, i.e. if the "adjacent" building is very far away from the object building, there can be no shading effects. the shading effects cannot be stimulated as well due to the sun angles and building height.

2) Besides shading effects, the sunlight reflection and thermal radiation of the nearby building is another factor affecting the overall energy consumption. It can be noted that for a given object building, there may exist a critical height "h_0" for its nearby building. If the nearby building's height is below a specific value ($<h_0$), the energy consumption will decrease as the increase of building interval and decrease of building height. The reduction of energy consumption will reach maximum when nearby building's height is h_0. Because when the height is less than or equal to h_0, the effect of shading will be greater than the effect of thermal radiation from nearby buildings. When the height outweighs h_0, the curve of reduction of energy consumption will slow decline. Because the shading effects are already "saturated", thermal radiation increases according to the increase of building height.

CONCLUSIONS

Based on the analysis of four typical real-life office buildings in Hong Kong, the total energy consumption can be decreased by shading effects from itself and nearby buildings, from 2.86% to 8.48%. The average energy consumption decrease was averaged 4.15%. These findings reveal that shading is an important factor affecting total energy consumptions and should not be neglected in building energy simulation. Different typologies and different surroundings will lead to different shading effects. It means that the shading effects must be considered case by case.

Regression models were established under eight orientations, where total yearly energy use reduction is a linear function of building interval and a quadratic function of adjacent building's height. Among eight orientation scenarios, the nearby building on the west orientation of the object building has the maximum shading impact on energy consumption than other orientations generally. It can be noted that for a given object building, there may exist a critical height "h_0" for its adjacent building. When the adjacent building reaches a height of h_0, it will cause a "saturated" shading effect on the object building, which means even if the height of the adjacent building is higher than h_0, the energy reduction is not going to further increase. In fact, when increasing the height of the adjacent building starting from h_0, the energy reduction slightly decreases. This can be due to the sunlight reflection and thermal radiation of the nearby building.

The research reported in this paper is preliminary, and future research will analyze shading effects of multiple buildings on energy consumption of the object building.

The findings should aid building energy design decision making for new construction.

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