ENERGY-EFFICIENT WINDOW RETROFIT FOR EXISTING HIGH-RISE RESIDENTIAL BUILDINGS WITH THE CONSIDERATION OF MUTUAL SHADING

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Upgrading the window glazing can help minimize the energy consumption through a reduction of solar heat gain in summer or indoor heat loss in winter. On the other hand, the mutual shading caused by surrounding high-rise buildings could affect the energy performance of the window glazing. In hot climate, mutual shading could further reduce the solar heat gain. In cold climate, overshadowing lowers the solar heat gain in winter resulting in greater demand for space heating. To explore the most energy-efficient window glazing for different climates, it is imperative to integrate mutual shading with window retrofit measures when evaluating the thermal performance of a building. This study applies a computer-based simulation program known as DesignBuilder to assess the building performance. The energy model is based on a typical high-rise residential building, and four common double energy-efficient glazing alternatives were employed in lieu of single clear glass. The results show that the optimum window retrofit solution vary with different climatic conditions and there are different choices for upgrading window glazing in the same building with and without the consideration of mutual shading due to the mutual shading effect on the energy use.

Keywords: energy efficiency, retrofit, energy analysis, mutual shading, building simulation

INTRODUCTION

Hong Kong is famous for its high population density and it is filled with close high-rise buildings. The street canyon with packed tall buildings is a typical urban feature in this region (Chen *et al*., 2012; Ng, 2009). Similarly, over 40% of existing dwellings are high-rise buildings in megacities of Mainland China due to the rapidly increasing urban population (Ekblad and Werne, 2015; Hui, 2013; Li *et al*., 2011). Shanghai is a typical megacity in China and its population density is the highest one in Mainland China. Existing high-rise housings account for about 44% of the total residential blocks in Shanghai (Yang *et al*., 2010). High-rise residential building is becoming much denser due to the limited available land (Pan, Zhao, Chen, Liang and Sun, 2008). The highest population density in Beijing is over 25,000 persons/km2 which occurs in some districts and the average population density is more than 20,000 persons/km2 in its urban areas, and high-rise buildings made up around 78% of existing buildings in urban areas ("High-rise Buildings of Beijing," 2016).

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The mutual shading effect due to surrounding high-rise buildings helps reduce up to 14% cooling demand in Hong Kong (Lam, 2000a). If shading effects from nearby buildings are neglected, the energy use of the control building would be over-predicted in this region (Lam, 2000b). The mutual impact among proximal buildings should be considered into the building energy analysis because the energy demand in a building without surrounding shading is underestimated by up to 23.1% during summer period and overvalued by 44.8% in winter compared to the same building considering the mutual shading from its neighbouring buildings in the United States (Pisello *et al*., 2012). The nearby obstructions strongly affect the energy consumption for cooling and heating (Pisello *et al*., 2014). Energy savings achieved through retrofit measures with the consideration of mutual shading is higher than reductions observed for stand-alone buildings (Xu, Taylor and Pisello, 2014). Although mutual influence is helpful to reduce energy use for cooling in summer, it still can increase the heating demand in winter due to the less solar heat gain. It can increase the heating demand by 30% in a typical building located in a real urban context with adjoining high-rise buildings in Japan (KAWAI *et al*., 2014). It is a key parameter to assess the real building performance in a real building environment because the difference of energy consumption in a building with and without surrounding buildings is up to 10%.

However, most previous studies focus on the mutual shading effect or building retrofit respectively. Little literature took the mutual shading effect into the energy-efficient building refurbishment. Most of them ignored the effect of overshadowing of surrounding buildings while they selected building retrofit solutions to save energy in existing buildings. But inter-building effect among nearby high-rise buildings is an important factor to affect the building energy consumption and it can offset or enhance the energy performance of a certain retrofit measure in different climates. Therefore, this study is to identify the mutual shading effect on the window retrofit solutions based on previous studies related to individual mutual shading and window glazing upgrading of high-rise buildings. The purpose is to find the most energy-efficient window glazing for high-rise housing to reduce the annual energy consumption of cooling and heating in different climates.

The annual energy consumption of a 30-storey residential building is simulated in the DesignBuilder program with and without surrounding buildings in four types of climatic conditions including mild summer and cold winter, hot summer and warm winter, hot summer and cold winter, severe cold. Four common 6/13mm double window glazing with 13mm air filled are selected to substitute the existing window system to improve its thermal performance based on a stand-alone building and a building network in this study. They are listed out as generic tinted pane and internal generic clear pane(GTGC), glazing with exterior generic clear pane and interior low-e clear pane(GCLC), glazing with exterior low-e clear pane and interior low-e clear pane(LCLC)light, glazing with reflective tinted pane and interior low-e tinted pane(RTLT). Quantified energy saving caused by window glazing and the effect of mutual shading on building retrofit are presented in this research and suitable energy-efficient window glazing is recommended for different climates based on the mutual shading effect.

METHODOLOGY

Primary Study Procedure

The case study was first modelled and simulated without any window glazing upgrade to provide assessment of building thermal performance as the baseline of energy requirements in the typical building. Then, the possible energy-efficient window glazing for the building envelope retrofit was used to substitute the glazing system of the base model and a series of simulations were conducted to predict the energy consumption of the improved building.

The major research step is shown as following: the first step is to build up a baseline mode of the stand-alone case building in DesignBuilder; the second step is to identify the common proximity between buildings and make assumptions for such space based on literature review; the third step is to evaluate the thermal performance of the case building which applied different double glazing with and without mutual shading; the fourth step is to analyse the effect of the mutual shading on the energy reduction caused by window glazing alternatives ;the fifth step is to find the most energy-efficient and appropriate glazing system in a real building context in different climates.

Computer-based Simulation

DesignBuilder was used to predict the energy consumption in this study, which has a powerful database and complex models to evaluate the energy performance of buildings (Tronchin and Fabbri, 2008). It can provide abundant templates for various types of building parameters and it can help users select most appropriate parameters for energy analysis (Wasilowski and Reinhart, 2009). It is based on the simulation engine of the latest EnergyPlus. This simulation engine has become one of the state- of- the- art and most powerful energy analysis tool for professionals (Henninger, Witte and Crawley, 2004). Many previous studies have applied DesignBuilder to evaluate the thermal performance of buildings and they have proved its accuracy and adaptability (Fasi and Budaiwi, 2015; Radhi, 2010; Reinhart and Wienold, 2011).

Validation of the Base Model

After developing the base energy model, the validation procedure was carried out by following the ASHRAE Guideline 2002 and DOE 2008. The primary purpose of the validation is to reduce the difference between the simulated energy consumption and realistic building performance. The validation process is useful to identify the improper assumptions in the base energy model and adjust them to match the realistic indoor temperature set, operation schedule, and local weather conditions. The validation procedure contains an iterative process including simulation run (first step), calculation and comparison (second step) and fine tuning (third step) and then repeat the same process again until the discrepancies between the simulated results and real energy consumption was reduced to meet the requirements mentioned before.

Since the energy bills of this case building are confidential, this research adopts publically available sources for the validation of baseline model. Hong Kong Energy End-use Data and the public housing statistics are published annually that can reflect the energy consumption in public residential buildings. The average annual energy consumption per floor area can be extracted from the public data and it was used for validating the simulated energy consumption of the base model of the typical building. According to published energy use in public dwellings, the annual energy use for each floor area is appropriate 273kwh/m2 for space conditioning, domestic hot water, lighting and others that consumes about 21%, 19%, 7% and 53%, respectively (Cheung *et al*., 2005; EMSD, 2015; Bojic *et al*., 2001). For the simulated baseline model, the annual energy use per floor area is around 285kwh/m2. The predicted energy use in the baseline model is very close to published benchmark of energy consumption in public housing in Hong Kong. In terms of the simulation result, the energy distribution ratios are 25% for cooling demand, 17% for domestic hot water, 8% for lighting and 50% for other building loads, which is very close to the real situation in this type of building.

Description of a Case Building

A typical 30-storey high-rise residential building in Hong Kong was chosen for the energy simulation by using the DesignBuilder program. The same case is also applied to predict the mutual shading effect on building thermal performance in other climates. There is no insulation consideration in the reference building since most existing old high-rise buildings did not consider insulation when they were built in selected cities including Hong Kong, Beijing, Shanghai (Yang, Lam and Tsang, 2008; Yu, Yang and Tian, 2008). Its window-wall ratio is 30% and the window glazing is 6mm single clear glass with the aluminium frame without the thermal break. There is no shading device on the typical building. The major structure of wall is cement plaster, concrete block and cement plaster from the outer side to the inner side. The configuration of roof is complicated and there are seven layers in all. The outermost and innermost material is clay tile (10mm) and cement plaster (20mm). Meanwhile, the functional components include the polyurethane foam (50mm), bitumen sheet (1mm) and the reinforced concrete (150mm) from the top to the bottom layer. The cooling operation period of the case building is set from 1pm to 7am of next morning (Bojic *et al*., 2001; Bojic, Yik and Sat, 2002). To meet the indoor thermal comfort and reduce the energy use, the temperature set point of air conditioning is assumed as 24°C in selected cities (Cheung, Fuller and Luther, 2005).

There are several neighbouring high-rise buildings surrounding the typical building on its four directions. The aspect ratio (building height-to-width ratio between buildings, H/W) is a direct parameter to reflect the density of high-rise buildings and the thermal environment of the reference building. It has a close relationship with the mutual shading effect of nearby buildings. The aspect ratio (H/W) of the reference building is larger than 2.0 on each direction and this study assumes that the canyon H/W ration is 2.0 for the case building's thermal environment on four major orientations in order to simplify and simulate the mutual shading effect of adjacent buildings. The same H/W on different directions was a hypothetical situation but it is beneficial to model the outdoor thermal environment in a simplified way and it can help identify the mutual shading from the surroundings. After modelling the nearby space, the study focuses on the thermal performance of upgrading reference building with and without mutual shading in term of its energy consumption for heating and cooling.

RESULTS AND DISCUSSION

Mutual shading effect on thermal performance of window glazing in mild summer and cold winter climate. To describe the potential effect of mutual shading of nearby buildings on the energy-efficient window retrofit in cold climate, the annual energy demand for cooling and heating in a typical building located in Beijing was evaluated. The double glazing applied in this study has two layers of different type of glass including low-e glass, generic glass and reflective glass with a 13mm air filled in between two glass layers as described in table 1.

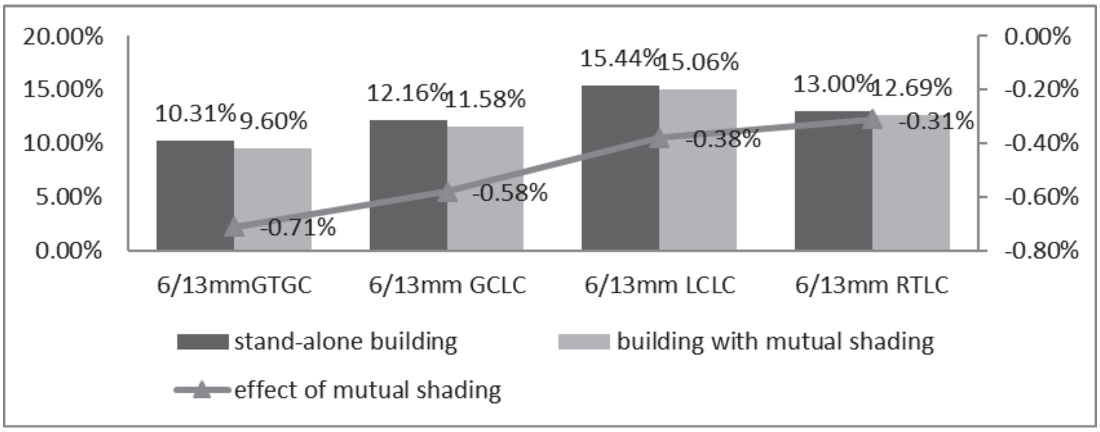
In cold climate such as Beijing, the overall cooling demand is less than its total heating demand. When considering the energy demand during summer and winter, energy analysis is observed from June to August for cooling and from November to March for heating. When the typical building is stand-alone, there is no nearby obstructions surrounding it and the mutual shading effect of adjoining buildings is not considered. In this outdoor thermal environment, the employed four types of double window glazing can reduce energy consumption by around10.31% (GTGC), 12.16% (GCLC), 15.44% (LCLC) and 13% (RTLT).

But if taking the mutual shading of the surrounding buildings into account, the total energy reduction caused by window glazing GTGC, GCLC, LCLC and RTLT are 9.6%, 11.58%, 15.06%, 12.69%, respectively. There is no significant difference of the overall energy consumption including heating and cooling in the case building with and without overshadowing from nearby buildings as shown in Figure 1. The effect of mutual shading on the building performance with different glazing is negative in the cold climate but the impact is less than 1%, therefore, it is reasonable to ignore such effect in this region when evaluate the effect of retrofitting measures on heating demand. Obviously, this overshadowing is beneficial to reduce the cooling demand in summer but such impact is not significant, therefore, it is reasonable to neglect this positive effect of overshadowing when evaluating the effect of window upgrading. In all, the mutual shading of nearby buildings can be ignored when analysing the thermal performance of building window retrofit solutions in the cold region.

Table 1: Thermal characteristics of 6/13mm double window glazing

Type	Name	External pane	Internal pane	U-value	SHGC
6/13mm double glazing with 13mm air filled	GTGC	6mm generic tint	6mm generic clear	2.66 W/m2•K	0.501
	GCLC	6mm generic clear	6mm Low-e clear	1.91 W/m2•K	0.568
	LCLC	6mm Low-e clear	6mm Low-e clear	1.35 W/m2•K	0.483
	RTLT	6mm reflective tint	6mm Low-e tint	1.69 W/m2•K	0.122

Figure 1: Energy reduction caused by different window glazing and mutual shading effect in mild summer and cold winter climate



Mutual Shading Effect on Thermal Performance of Window Glazing in Hot Climate

In hot climate such as Hong Kong, the dominated energy consumption originates from cooling demand throughout the whole year and there is no heating need in winter due to its warm climatic conditions. To assess the impact of mutual shading on the building thermal performance, the energy consumption in the stand-alone case building is the baseline and the changes caused by window glazing upgrading is given as percentage. The results are summarised in Figure 2. As seen in this figure, inter-building effect has a significant impact on the thermal performance of the typical building. When the energy analysis ignores the mutual shading of nearby buildings, upgrading existing window glazing can reduce only less than 10% of the total energy use no matter which double type of the window glass is chosen in the range of conventional ones. The most energy-efficient one is RTLC with external tinted reflective pane and internal tinted low-e pane, and it can help reduce energy use by 9.3% for a stand-alone building.

But if put the typical building in a building net-work, there will be some mutual shading which is beneficial to reduce the solar heat gain and lead to a bigger positive effect of window glazing on the energy saving. For instance, the energy-saving effect of LCLC glazing can be increased by around 7.5% while consider the inter-building effect. The mutual shading can lead to an increase of the building energy-efficiency and the most dramatic change is up to 7.84% as depicted in Figure 2. Inter-building effect plays in important role to present the thermal performance of window glazing and thus it is an important factor to predict the overall thermal performance of the applied window glazing. Based on this consideration of mutual shading, the best choice for the window retrofit would be changed compared to the stand-alone building. In this hot climate, the energy reductions caused by LCLC and RTLC are very close to each other while taking the inter-building effect into account. On the other hand, the tinted reflective glass may cause some light pollution and it can lead to the lighting demand. In addition, the low-e glass is expensive and thus it is not as practical as other conventional glass pane from the viewpoint of cost. Combining the energy reduction with other important factors, the best solution for window retrofit may be the GTGC glazing while considering the mutual shading which is completely different from the choice in a stand-alone building.

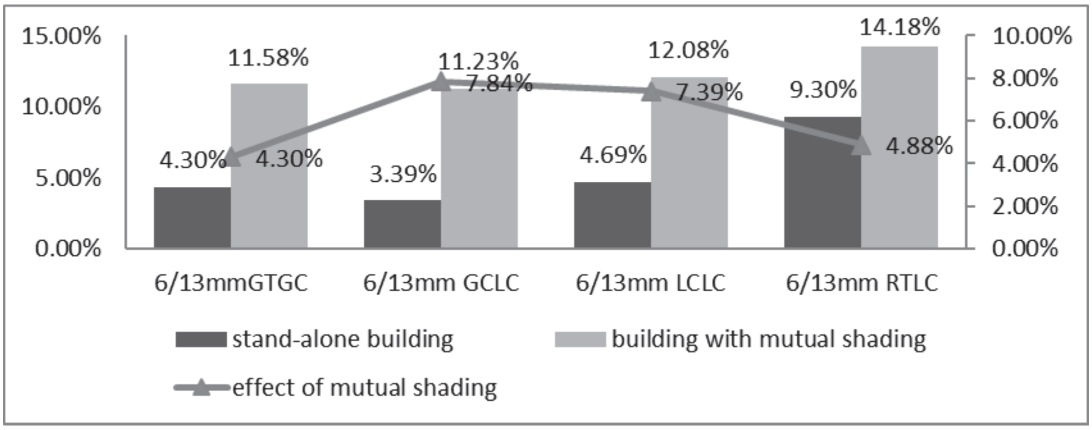


Figure 2: Energy reduction caused by different window glazing and mutual shading effect in hot summer and warm winter climate

Mutual Shading Effect on Thermal Performance of Window Glazing in Hot Summer and Cold Winter Climate

In hot summer and cold winter region such as Shanghai, the indoor environment requires heating in winter from December to February and cooling in summer from June to September. According to the traditional assessment of building thermal performance, the typical building is deemed as a stand-alone building without any mutual shading from its surroundings and the annual total energy consumption in such building is as shown in Figure 3. It is depicted that the biggest reduction is generated by RTLC and it is up to 14.23%, but the glazing GCLC has a lowest contribution to the energy reduction among the selected four types of glass in the stand-alone building.

However, if the case building is in a building context with the mutual shading, the effect of the double window glazing on the energy consumption will be changed as seen in Figure 3. The result shows that glazing GCLC has a better thermal performance with the consideration of mutual shading and it can reduce around 14.77% of the overall energy used that is close to the reduction caused by GTGC. Although they have similar thermal performance based on the consideration of mutual shading, it could be better to use GTGC for the window retrofit since low-e glass would lead to a higher cost. Meanwhile, the overshadowing is beneficial to improve the impact of LCLC on the building energy consumption and thus the energy saving generated by LCLC was increased by 16.8%. Compared to the most energy-efficient glazing RTLC in this region, there is no significant difference for the energy reduction between them since the disparity is around 2% in a building network. This means that LCLC and RTLC have similar effect on the energy consumption in a building environment with overshadowing, thus it is reasonable to choose any one of them for the building window retrofit. But if ignoring the mutual shading, this difference could increase to 4% and it is impossible to choose LCLC for the improvement of window glazing system.

Regarding the different types of glazing, mutual shading has different impact as seen in Figure 3 but these effects are positive and significant in this climate. The most significant one is to increase the energy reduction by 6.97% and the lowest one is around 4.58%. This positive effect is beneficial to enhance the building energy efficiency and it is necessary to take it into account when evaluate the thermal performance of the building window retrofit measures.

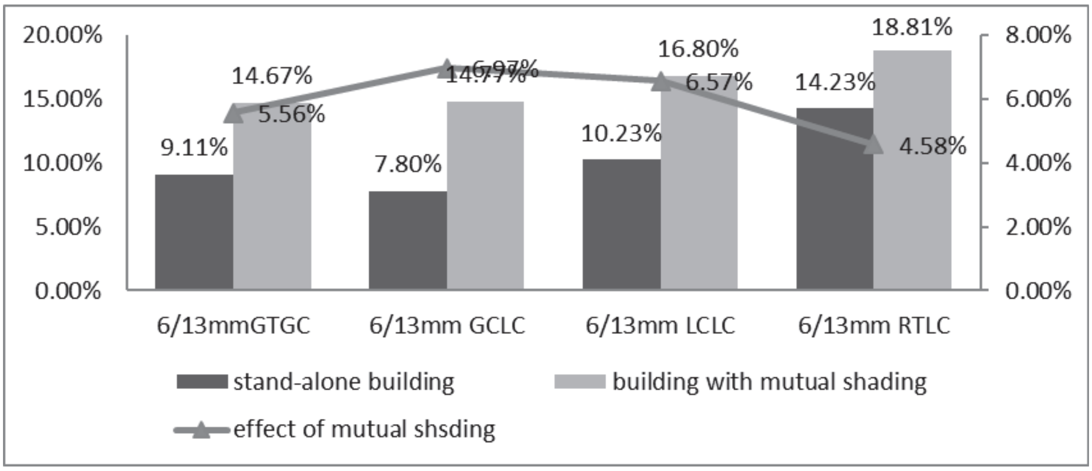


Figure 3: Energy reduction caused by different window glazing and mutual shading effect in hot summer and cold winter climate

Mutual Shading Effect on Thermal Performance of Window Glazing in Severe Cold Climate

In severe cold region such as Harbin, the cold winter lasts for 6 months from October to April but the summer is short and mild without cooling demand. The predominated energy use is caused by heating demand in this climate. To identify the effect of mutual shading on the energy consumption, there are two groups of energy reduction generated by different types of double glazing in the stand-alone building and the same building in a real urban context, as shown in Figure 4. Both with and without mutual shading, the glazing LCLC has the best thermal performance in this region but it can produce more than 20% energy saving in the stand-alone case building. The significant energy reduction is beneficial to improve the building thermal performance and it is rational to choose this glass to replace the existing one.

Obviously, the inter-building effect has a negative effect on the thermal performance of window glazing in this severe cold region. No matter what type the glazing is, the consideration of mutual shading easily weakens its energy performance. This means that the ability of the double glazing to reduce energy consumption in a real building environment is not as good as that in a theoretical urban context without any nearby obstruction in this region. If taking the mutual shading into account, the energy reduction generated by glazing GCLC is very close to that of glazing LCLC as we seen in Figure 3. There are different impacts of mutual shading on window glazing performance that ranges from -2.85% to -7.58%. This significant negative effect of mutual shading cannot be neglected when evaluating the building performance during the process of building window retrofit.

It will be practical and reliable to combine the inter-building effect with the thermal properties of possible glazing alternatives while selecting the most energy-efficient window retrofit measure in such specific climate. It may be practical to use GCLC instead of LCLC when considering the mutual shading effect since the low-e glass is very expensive. But if ignoring the urban context of the case building, there is no double that the LCLC is the best choice due to its much bigger energy reduction. Particularly, any of existing buildings is a real building which is definitely in a real building environment and it is essential to consider the mutual shading from its neighbouring buildings into the energy performance prediction when evaluating energy savings caused window retrofit solutions.

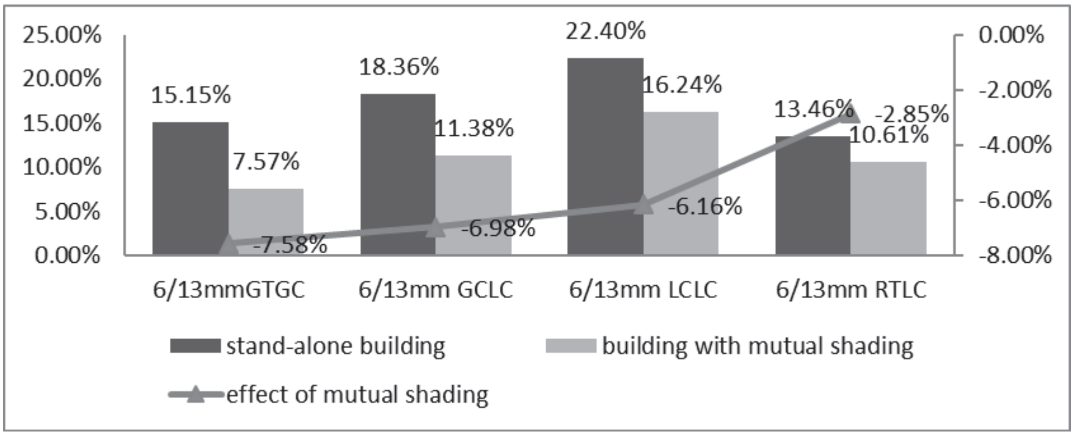


Figure 4: Energy reduction caused by different window glazing and mutual shading effect in severe cold climate

CONCLUSIONS

The findings of this study indicate that mutual shading from neighbouring buildings has a significant impact on the annual heating and cooling demand of a high-rise building. In cold winter and mild summer climate, it almost has no effect on the energy savings produced by the selected double glazing. Apparently, it is unnecessary to take mutual shading into account while evaluating the thermal performance of window retrofit measures in this zone. In hot summer and warm winter climate, the mutual shading is beneficial to reduce the solar heat gain through windows and thus the overall energy reduction caused by the energy-efficient window glazing in a building with mutual shading is far more than that in the same stand-alone building without nearby obstructions. Based on such enhancement, it is convinced that upgrading window glazing can help existing buildings save much energy in hot region. In the hot summer and cold winter region, the effect of mutual shading is close to that in hot summer and warm winter. The overshadowing plays an important role in the assessment process of window thermal performance and it can increase the energy reduction generated by double glazing by up to 6.97%. This significant positive effect provides more choices for decision-maker to select more appropriate window glazing. In severe cold zone, mutual shading has a negative effect on the building energy consumption and the energy saving would be decreased by 7.58% while putting the case building into a real urban context with overshadowing. Double glazing cannot lead to a dramatic energy reduction in severe cold region if deeming a building as a real case located in a real building environment with the mutual shading of neighbouring buildings. Therefore, it is worth evaluating the mutual effect on the building thermal performance while predicting the energy-efficiency of window retrofit measures. It is better to combine the mutual shading effect with the assessment of building thermal performance into making policies or recommendations of building retrofit. From the viewpoint of decision-maker, retrofit designers and other stakeholders, it is highly recommended that choosing energy-efficient building retrofit solutions would better consider the effect of mutual shading of the surrounding obstructions on the target building other than deem a building as an isolated on when evaluating the energy savings produced by retrofit measures in order to guide a practical retrofit direction, make some real energy-efficient designs, promote effective energy-saving methods and so forth.

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