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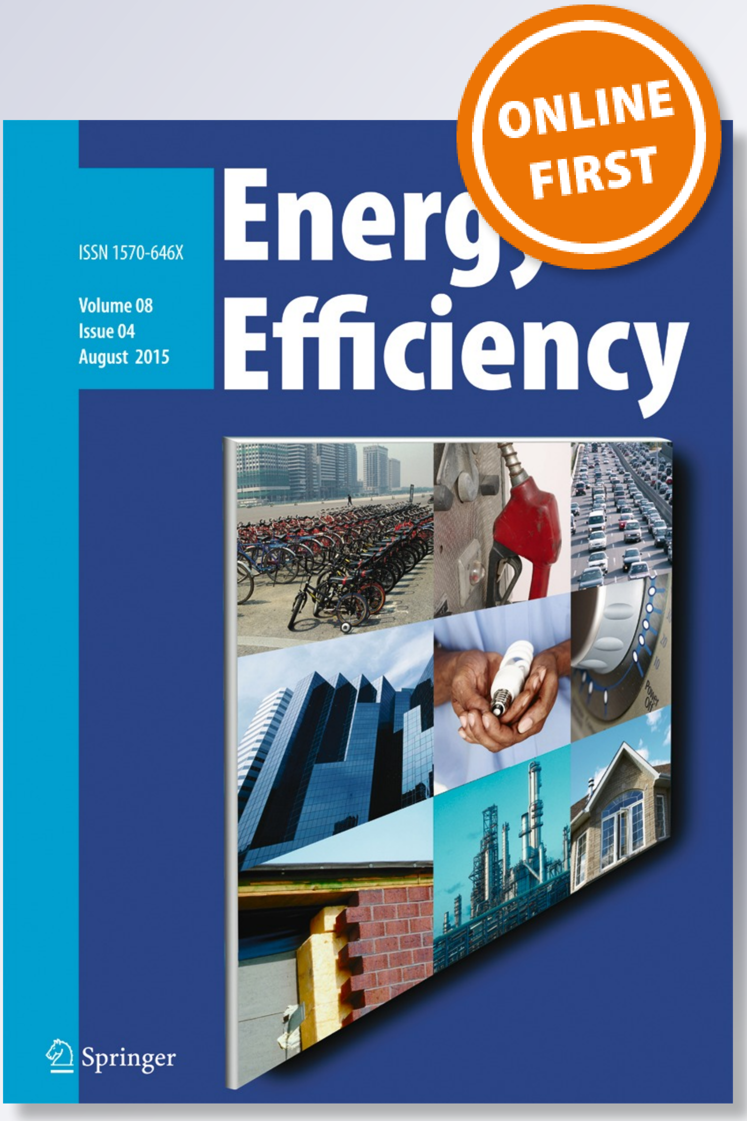

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ORIGINAL ARTICLE

ShadingPlus—a fast simulation tool for building shading analysis

Yunyang Ye · Peng Xu · Huajing Sha · Peng Yue · Hua Zhang

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Abstract Shading system plays a significant role in reducing building energy demand. To analyse the performance of a shading system, traditional method is either conducting experimental tests for solar heat gain coefficient (SHGC) or through detailed energy simulation for energy saving during specific period. But no simulation tool is able to accomplish the two objectives at the same time, and the latter is always too detailed and cumbersome with traditional simulation tools. To help architects analyse the shading system in a more comprehensive and simple way, a fast simulation programme—ShadingPlus—is proposed and developed in this work. With EnergyPlus as its core simulation engine, ShadingPlus applies an optimal methodology to calculate SHGC. Moreover, annual energy saving calculation is also available with ShadingPlus which reflects shading system in a more realistic way. It is expected that the analysis for shading system can be greatly simplified using this tool. Case studies are also given to illustrate the way ShadingPlus works.

Keywords Shading · Solar heat gain coefficient · Energy saving · Building simulation

Y. Ye · P. Xu (✉) · H. Sha
School of Mechanical and Energy Engineering, Tongji University, Shanghai, China
e-mail: xupengessay@gmail.com

P. Yue · H. Zhang
Shanghai Research Institute of Building Science, Shanghai, China

Introduction

Building industry consumes more than 30 % of the total energy worldwide (IEA 2009). An efficient way to alleviate global warming and improve environmental sustainability is to enhance building energy efficiency. However, a current trend in building industry is to use glass curtain wall instead of traditional window as better aesthetics and visual effect can be achieved. This greatly increases the risk of energy waste especially in hot and warm areas with large cooling loads. To allow the use of glass curtain wall without causing energy waste, the use of shading devices is extremely important. Evidences have shown that a proper shading device can both reduce energy demand and improve visual comfort (Hammad and Abu-Hijleh 2010; Shen and Tzempelikos 2012).

In the past, lots of studies have been devoted to this topic. These studies can be categorised as either design-oriented or operation-oriented. Operation-oriented studies include the adjustment of external louvres (Datta 2001; Hammad and Abu-Hijleh 2010); Design-oriented studies include a parametric study of external blind regarding its location, size and colour (Gratia and Herde 2007) .

To analyse the performance of a shading system, different methods have been proposed. One method is using simplified mathematic models to calculate certain performance indices, such as solar heat gain coefficient (SHGC) and shading coefficient (SC) (Cascone et al. 2011; Cheng et al. 2007; Athientis and Tzempelikos 2002). This method, although simple, is targeted at shading system with simple configurations.

Table 1 SHGC measurement condition

Variable	Value
Outdoor temperature	32 °C
Indoor temperature	24 °C
Wind velocity	2.75 m/s
Wind direction	Windward
Solar direct radiation	783 W/m^2
Solar incident angle	≤5°
Sky temperature	32 °C
Sky emissivity	1.00

As SHGC and SC are the most common performance indexes for shading devices (ASHRAE 2009), the National Fenestration Rating Council (NFRC) has compiled a guideline for measuring SHGC in lab environment (NFRC 201-2010 E0A1). Lawrence Berkeley National Laboratory has also developed a suit of facility named as mobile window thermal test (MoWiTT) to measure window and shading performance on site (LBNL 2011). However, evaluating shading performance using a single index measured in a specific condition is not sufficient. It is not able to reflect its performance in real dynamic weather conditions.

An emerging analysis method is to use dynamic simulation models and solve them with a computer. A programme for this purpose is EnergyPlus (Crawley et al. 2001). Using EnergyPlus, shading performance can be easily estimated for any period with good accuracy given a weather file with good quality. However, this approach suffers from too detailed user input, which is unnecessary for a shading system analysis. For example, designer is required to describe the building geometry in detail in which the shading system is used, and many parameters have to be set. Furthermore, EnergyPlus does not provide the functionality of calculating SHGC and SC for shading device, which is important for the designers.

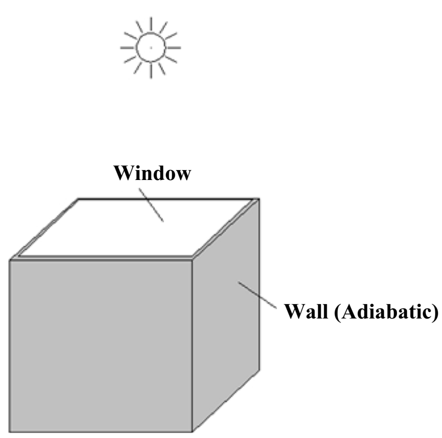

Fig. 1 Building model for SHGC calculation

In this study, a new calculation tool, ShadingPlus, for shading analysis purpose is developed. It is based on the computer simulation methodology and uses EnergyPlus as its core simulation engine. However, the modelling effort is greatly reduced to simplify the analysis procedure. The user interface is designed and developed also to facilitate the analysis procedure. In addition to the results provided by EnergyPlus, SHGC and SC are also calculated and displayed in ShadingPlus. In this regard, ShadingPlus is an improvement based on EnergyPlus for shading system performance analysis.

Description of ShadingPlus

Methodology to SHGC calculation

In ShadingPlus, SHGC and energy saving rate (energy saving in the paper is cooling load saving) are the two evaluation indexes for shading performance. SHGC is short for solar heat gain coefficient. It is an internationally recognised index for window glass and shading device performance evaluation. Solar heat gain means the heat gained by a space due to direct solar irradiance incident on the fenestration. SHGC is obtained through dividing solar heat gain by direct solar irradiance (ASHRAE 2009). Actually, SHGC is angle- and wavelength-dependent. It is defined by Eq. (1)(ASHRAE 2009).

$$\mathrm{SHGC}(\theta,\lambda) = T(\theta,\lambda) + N\alpha(\theta,\lambda) \quad (1)$$

where T is the solar transmittance, α is the solar absorptance and N is the inward flowing fraction of the absorbed radiation. θ is solar incidence angle (angle between 0~90°), and λ means wave length. For convenience, SHGC widely used for engineering application is often the one when θ is 0. Another index of SC is derived from SHGC. It means the ratio between the SHGC of a specific device and the standard white glass is 0.87. It is obvious that SHGC is very hard to calculate by hand. Many tools based on computer have been developed to calculate SHGC. The most famous one is WINDOW developed

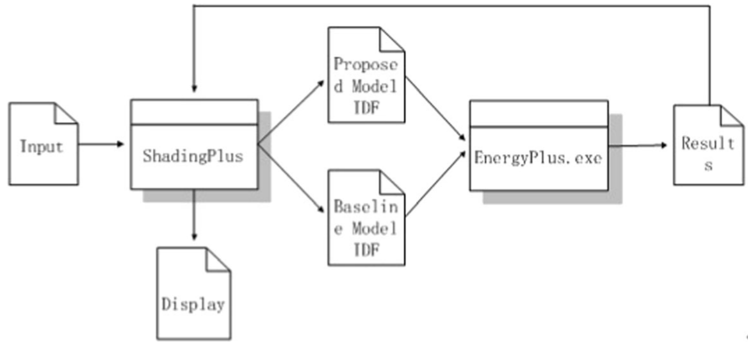

Fig. 2 Working mechanism of ShadingPlus

by Lawrence Berkeley National Laboratory (LBNL). Its algorithm is based on Eq. (1) which is only able to calculate multi-panel glazing window and shading device including venetian blind and roller shading which are parallel to window glass (Finlayson et al. 1993).

Another method to obtain SHGC is real-time experimental. NFRC has stipulated the measuring condition as shown in Table 1 (NFRC 201-2010 E0A1). In order to test SHGC, a testing platform which is able to model the experimental condition has to be built. Obviously, it is very costly, and numerous errors may occur during real-time test. Numerical modelling is a good way to replace real-time test to save time and energy. EnergyPlus is a popular whole building simulation tool developed by LBNL, and its simulated results are accepted through comparing with the results from experiments. It is able to model buildings with user-specified geometry, envelope performance and building system.

Table 2 ShadingPlus user input

Input categories	Details
Building information	Location, room size, visible reflectivity of ceiling and wall and floor
Glass and shading material	Material properties such as solar transmittance, conductivity and thickness
Shading control schedule	Ending date and time and control rule within the period
HVAC control schedule	Ending date and time and control rule within the period
Window information	Window orientation, size and construction
Shading system	Shading type, control strategy and dimension
Lighting system	Power intensity, daylighting setpoint, glare and control strategy
Report	Baseline set, report frequency

The test condition defined by NFRC can be modelled in EnergyPlus through a building specific model and changing a few variables in the weather file. As shown in Fig. 1, a test building model which is a simple cube and meets all the limitations specified in NFRC documentation is established in EnergyPlus to calculate solar heat gain. In order to keep solar incidence angle within 5°, we made the following settings in EnergyPlus:

- Latitude of building location is set to be 0°.
- Window is on the top roof.
- Simulation period is 12:00–13:00 on 23 September.

There is another problem: EnergyPlus is only able to report *window heat gain* instead of *solar heat gain*. These two variables have strong relation but are not

Table 3 The control strategies of movable shading devices

Movable shading devices	Control strategies
Venetian blind	1. According to schedule 2. Perpendicular to direct sunlight all the time 3. Fixed angle
Roll shade	1. According to schedule 2. According to indoor temperature 3. According to preventing indoor glare
Spring-arm awning	1. According to the set value of expanding ratio
Rotate-arm awning	1. According to the set value of included angle between blind and window
Drop-arm awning	1. According to the set value (included angle and length)
Folding awning	1. According to the set value (Expending or retracting)

Table 4 The thermal properties of the shading materials

Solar transmittance	0.2
Solar reflectance	0.7
Transmittance of visible light	0.2
Reflectivity of visible light	0.7
Thermal conductivity (W/(m·K))	0.06

the same. In order to be more accurate, *window heat gain* has to be converted into *solar heat gain. Window heat gain* means the heat flow through the window to the room (EnergyPlus Input Output Reference). But *solar heat gain* means heat flow to the room which is only induced by solar irradiation.

In allusion to the problems mentioned above, ISO 15099 (Thermal Performance of Windows, Doors and Shading Devices-Detailed Calculations, 2003) provides a method as Eq. (2):

$$\tau_s = \frac{q_{int} - q_{int}(I_S = 0)}{I_S} \tag{2}$$

τ_s is total solar energy transmittance, meaning the portion of radiant solar energy incident on the projected area of a fenestration product or component that becomes heat gain in the internal conditioned space, and it presents quite a similar meaning of T as mentioned above; q_{int} is the net density of heat flow rate through the window or door system to the internal environment for the specified conditions, and its unit is W/m^2; $q_{int}(I_S=0)$ is the net density of heat flow rate through the window or door system to the internal environment for the specified conditions, but without incident solar irradiation, and its unit is W/m^2; I_S is incident solar irradiation, and its unit is W/m^2.

It can be assumed that τ_s has the same meaning with SHGC. q_{int} has the same meaning with *window heat gain* which can be reported directly by EnergyPlus. So SHGC and SC can be obtained through the following equations.

$$SHGC = \frac{\text{window heat gain} - \text{window heat gain}(I_S = 0)}{I_S} \tag{3}$$

$$SC = \frac{\text{SHGC}}{0.87} \tag{4}$$

For ShadingPlus input, the user just needs to give detailed information about window and shading device, and then an intermediate data format (IDF) file which

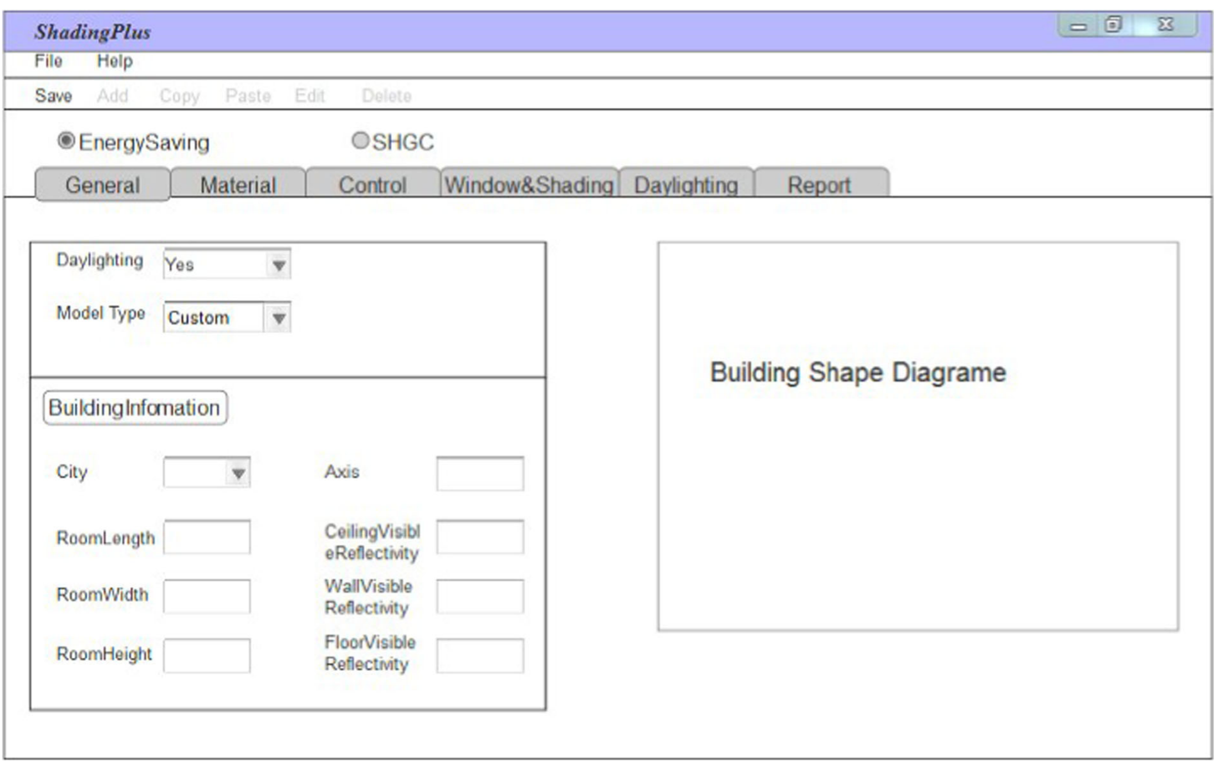

Fig. 3 ShadingPlus Interface 1

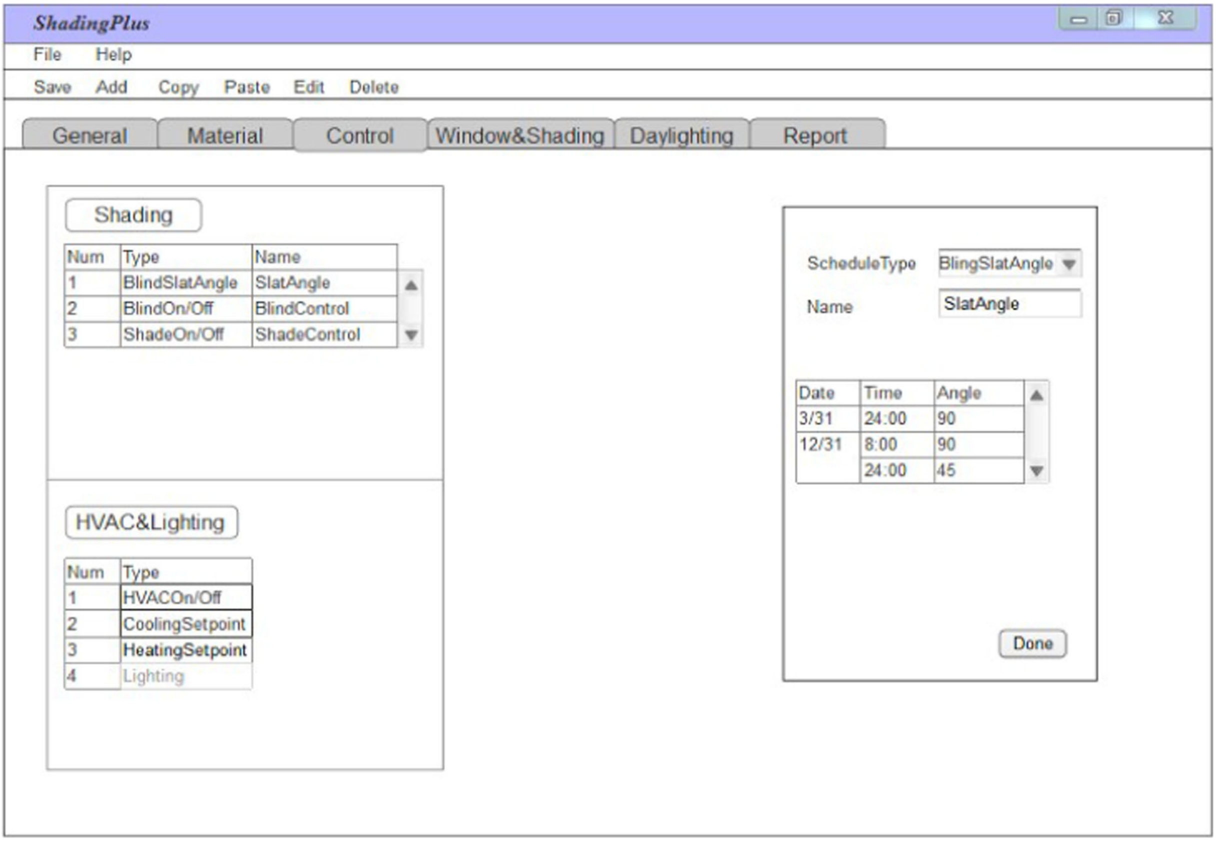

Fig. 4 ShadingPlus Interface 2

describes a text building model is built in the behind. It should be noticed that two weather files are needed for SHGC calculation: one with normal direct solar irradiation and the other with no direct solar irradiation. EnergyPlus.exe is then called twice to run the simulation, and useful variables are reported and processed by ShadingPlus.

Methodology to energy saving rate calculation

Energy saving rate is another evaluation index for shading system. Energy saving is defined through comparing the energy consumed by building with and without shading device. So two models are built within ShadingPlus which are called design model and baseline model. Both of the design simulation file and baseline model file are in IDF format which is readable for EnergyPlus engine. As shown in Fig. 2, ShadingPlus mainly contains the two modules: both design and baseline simulation files in an IDF file. A user interface component which reads the user inputs compiles both design simulation file and baseline simulation file in IDF format. EnergyPlus is then called to run both simulation files. Finally, the simulation results are processed and displayed. The EnergyPlus engine, which sits behind the user interface, simulates the system performance and then sends the results back to user interface. (Table 2).

Compared with EnergyPlus, the input parameters are largely simplified and categorised according to user habits. Finally, shading related output variables are selected for further processing and then displayed.

User inputs

In ShadingPlus, the user inputs required is greatly simplified. Temperature set point and air-conditioning period need to be specified by the user, but the user does not need to set cooling/heating load and coefficient of performance (COP) of the cooling/heating supply equipment.

For shading system, both fixed shading devices and movable shading devices are included. Current fixed shading devices included in the tool are as follows: overhang, fin, comprehensive shade, damper shade,

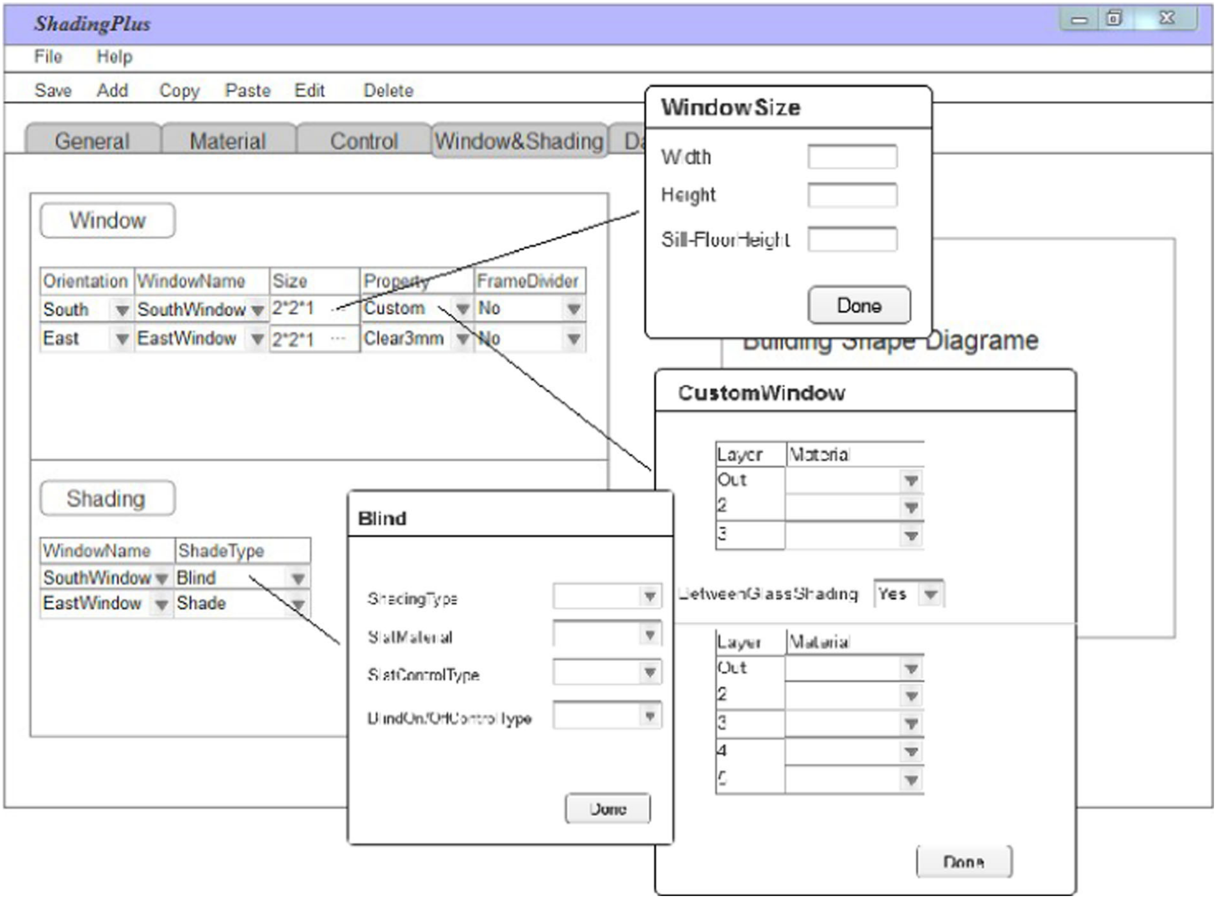

Fig. 5 ShadingPlus Interface 3

horizontal flap shade and vertical flap shade. For each type of fixed shading device, both location and dimension data are needed from the user to determine its position. Current movable shading devices included in the tool are venetian blind, roll shade, spring-arm awning, rotate-arm awning, drop-arm awning and folding awning.

For the first two movable shading devices, three control strategies are available, and for the other devices, each one has only one strategy (The details of control strategies are shown in Table 3). In ShadingPlus, all types of awning are developed on the basis of Shading:Building:Detailed in EnergyPlus. Shading transmittance is changeable but limited control strate-

Table 5 SHGC validation for window glass

Glass type	SHGC (ShadingPlus)	SHGC (Window)	SHGC (WIS)
3mmWhiteGlass	0.859	0.860	0.866
3mmBrown	0.740	0.733	0.721
3mmGray	0.727	0.708	0.720
Low-E	0.649	0.659	0.707
3mmWhiteGlass+12 mm A+3mmWhiteGlass (*A* means air gap)	0.763	0.763	0.773
3mmWhiteGlass+ aluminium alloy frame	0.708	0.682	0.679

Table 6 SHGC validation for exterior blind

Slat angle	SHGC (ShadingPlus)	SHGC (Window)	SHGC (WIS)
30°	0.167	0.156	0.159
45°	0.265	0.248	0.315
60°	0.464	0.458	0.506
90°	0.871	0.885	0.885

Table 7 SHGC validation for between-glass blind

Slat angle	SHGC (ShadingPlus)	SHGC (Window)	SHGC (WIS)
30°	0.287	0.244	0.214
45°	0.350	0.328	0.342
60°	0.467	0.484	0.491
90°	0.695	0.764	0.773

gies are available for them. The awnings can only be controlled through scheduling its position or open ratio. Lighting system set is optional according to case situation.

User interface

Figures 3, 4 and 5 demonstrate part of interface windows. Figure 3 presents the initial window in which general building information should be set, and a sketch of building shape will be shown in right part of the window. For control schedule setting, the rule is similar to that of EnergyPlus but is more straightforward. The fourth tab (Window & Shading) is for window and shading setting as shown in Fig. 5. The visualised tab interface is very simple and contains little information. For fields which need detailed information, user can get a sub-tab with more parameters by double clicking it. All the thermal properties of the shading materials can be found in the sub-tab, and we have added many shading materials in the database. Also, the thermal properties of the shading materials can be modified, and new shading materials can be added (Table 4).

Output

ShadingPlus is convenient for determining the suitable shading system in the initial design stage. Six fixed shading systems and six movable shading systems are now available for ShadingPlus. Only heating, ventilation, and air conditioning (HVAC) and light energy consumption are calculated, because they are directly influenced by shading. SHGC and annual energy saving rate are the main evaluation indicators for shading device performance. The former is obtained through modelling experimental condition. With its unique calculation methodology, it is able to calculate the SHGC both for window glass and shading device. The latter is achieved through comparison of energy consumption of user-specified baseline and design building models. Besides, dynamic results of window heat gain and building load are also available for report at given frequency. Shading device has significant influence on daylighting application and therefore changes lighting energy. ShadingPlus supports shading strategies analysis with or without automatic artificial lighting system. Indoor glare and illuminance of particular position are also available.

Table 8 SHGC validation for interior blind

Slat angle	SHGC (ShadingPlus)	SHGC (Window)	SHGC (WIS)
30°	0.311	0.348	0.337
45°	0.412	0.447	0.467
60°	0.565	0.602	0.608
90°	0.855	0.855	0.860

Case study

Case study 1: SHGC

To validate the accuracy of ShadingPlus in calculating SHGC, the calculation result is compared with that from WINDOW, a tool developed by LBNL and widely accepted by researchers and engineers to calculate SHGC of window and shading devices and Window Information System (WIS). The distance between the shade and the window is the default in EnergyPlus.

In this study, six types of window glasses and blinds of different slat angles are simulated with ShadingPlus, WINDOW 6, and WIS, and the results are shown in Tables 5, 6, 7 and 8. The thermal properties of the shading materials are listed in Table 4. The three kinds of blinds are the same thermal properties. As shown, SHGC calculated by ShadingPlus is very close to WINDOW 6 and WIS, but there is still small deviation between them, usually below 10 %. As these three tools use different calculation algorithm, deviation is reasonable. In Tables 6 and 7, slat angle is the angle of louvre, and the angle is between 0~90°.

Case study 2: energy saving rate

To illustrate how ShadingPlus works, several case studies of venetian blind are given below. Since shading

Table 9 Venetian blind case study summary

Case	Invariable	Variable
1. Shading position	South, slat angle: 45°, blind with high reflectivity slats	Exterior shading, between-glass shading, interior shading
2. Shading orientation	Exterior shading, slat angle: 45°, blind with high reflectivity slats	South, east, west, north
3. Slat angle	Exterior shading, south, blind with high reflectivity slats	15°,30°, 45°, 60°,75°,90°
4. Blind material	Exterior shading, south, blat angle: 45°	Blind with high, medium and low reflectivity slats
Other information	Location: Shanghai, China Room size: 3*3*3 m Window to wall ratio: 25 % Window glass: 3 mm white glass (for between-glass shading option, both glasses are 3 mm white glass) Glare view point: centre of the room Glare view direction: south	

system is used mainly to reduce cooling load, the analysis focuses on the energy performance in summer cooling season. During the analysis, it is assumed that HVAC system is on from 8:00 to 18:00 each day. It is only in working position, and the room is occupied when HVAC system is on. During the analysis, the energy saving percentage is calculated by dividing the saved energy by the baseline energy. The baseline model is the same as the proposed model except that the shading is removed.

Venetian blinds are extensively used for shading purpose due to their ability to reflect and transmit daylight efficiently into buildings as well as to ensure privacy when needed (Tzempelikos 2008). In this study, venetian blinds of different types, orientations, slat angles and slat materials are simulated to study the impact of design parameter on energy and daylighting performance. The cases studied are shown in Table 9.

The simulation results are shown in Figs. 6, 7, 8, 9, 10 and 11 below (The 0° slat angle is fully closed). Figs. 6, 7, 8 and 9 show the impact of shading position, shading orientation, slat angle and blind material on energy performance, Fig. 10 shows the impact of slat angle on daylighting performance, and Fig. 11 shows the daylighting performance with or without blinds. These results are very obvious even without simulation. They are done just to show how ShandingPlus works. ShadingPlus has much more functions for various shading analysis.

Case study 3: energy saving rate

In case study 2, we can get some information on how ShadingPlus works, but energy saving rate calculated by the software needs to be verified by experiment. In case study 3, I have made the comparison between calculated and experimental results.

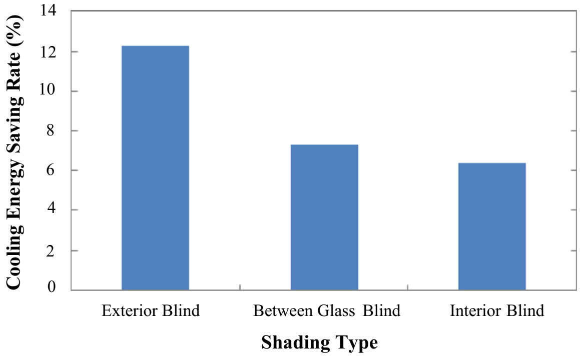

Fig. 6 Influence of shading type on cooling energy

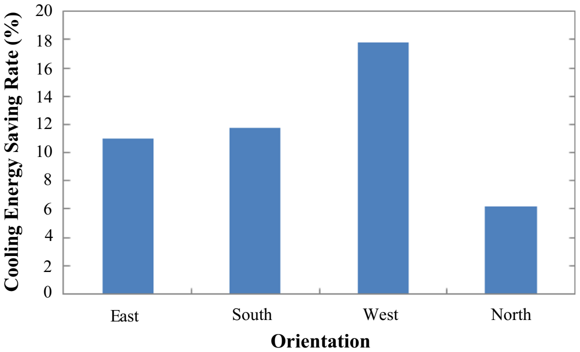

Fig. 7 Influence of blind orientation on cooling energy

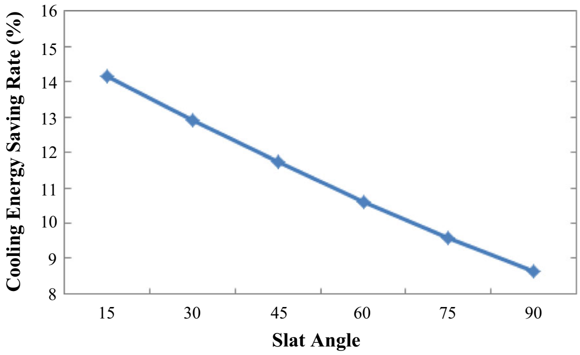

Fig. 8 Influence of slat angle on cooling energy

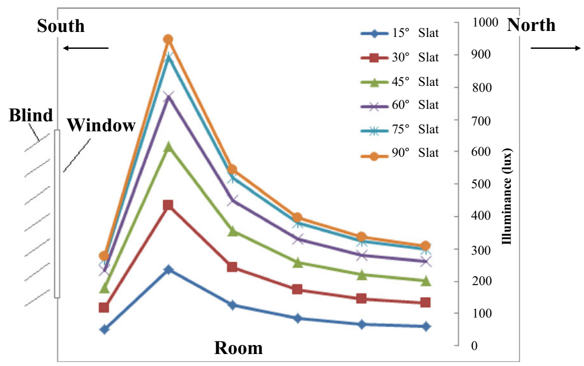

Fig. 10 Indoor luminance distribution as a function of blind slat angle

The experimental platform has been established in Shanghai. The platform consists of two identical rooms equipped with AHU, which can perform comparative experiment of energy consumption. The experiments are carried out in three working conditions (external, internal and no shading systems) during the period when the outdoor environment parameters are similar. When the air-conditioners operate at the same temperature, the hourly cooling capacity will be tested, and the cumulative cooling capacity of each working condition from 9 a.m. to 2 p.m. will be calculated. And, the condition with no shadings is regarded as standard condition.

The result of comparison is listed in Table 10.

Through Table 10, we can know that ShadingPlus can get the relative precise answer, and the results gotten by calculation and experiment are similar. The difference is caused by the environment parameters. The environment parameters taken into calculating are the data of design day, but these in the experiment are the actual value when the experiment has been done.

Discussion

ShadingPlus can tackle the calculation of SHGC and energy saving rate well. Through comparing with the results of simulation by other software and experiment, we can make a conclusion that ShadingPlus not only has convenient operation but also can get the accurate results in SHGC and energy saving rate.

Conclusion

ShadingPlus is a fast simulation programme for shading analysis based on EnergyPlus. This tool is developed especially for initial design optimization. It is written in Visual Basic 6.0. It reserves the advantages of EnergyPlus in shading simulation and also has its own feature. The input parameters aimed at shading simulation are selected from EnergyPlus, and forms are changed, which largely simplifies the procedure for

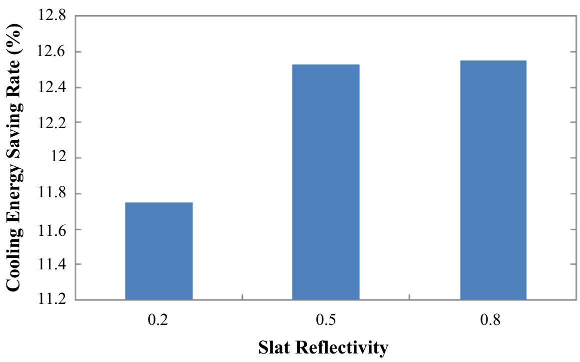

Fig. 9 Influence of slat reflectivity on cooling energy

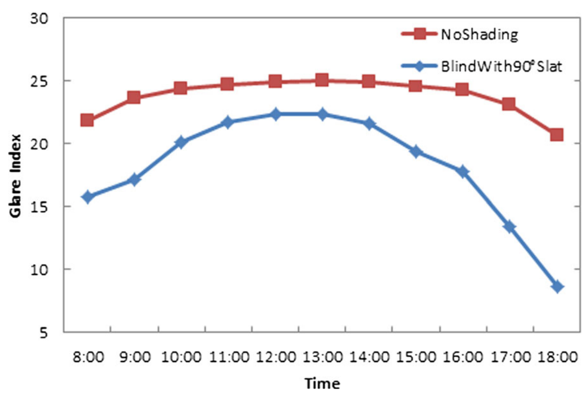

Fig. 11 Glare index variations for room with and without blind in south orientation

Table 10 The energy saving rate gotten by calculation and experiment

	ShadingPlus	Experiment
External blind (%)	22.3	23.6
Internal blind (%)	18.1	20.2

shading simulation compared with EnergyPlus. Besides, ShadingPlus also developed a module for calculating SHGC and SC for both window glass and shading device which is impossible in Energyplus. It combines the two widely used evaluation methods and largely reduces workload for shading analysis compared with traditional way. However, ShadingPlus cannot consider the effect of different materials, colour and slat angles on the overheating that occurs on the interspace between channel and screen, and we will add this function when we optimise ShadingPlus.

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