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Evaluating the performance of shading devices and glazing types to promote energy efficiency of residential buildings

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Abstract

This study presents a novel residential envelope transmittance value (RETV) performance-based approach for determining the suitable external shading devices and glazing types to improve energy efficiency in residential buildings. The approach is applied to two residential buildings types, namely, point block and slab block, for any given orientation in an entire year. In this approach, a RETV equation for residential buildings was first developed. Employing this equation, we demonstrated how the design of shading devices and the selection of glazing type impact the cooling load of high-rise residential buildings. Comparing results from the model simulations, the half egg-crate louver was found to be the most suitable shading device for residential buildings facing the north and south orientations, whereas a horizontal projection with 30° downward tilt was appropriate for facade facing the east and west orientations to reduce cooling load. In addition, simulations also indicated low-E single clear glazing to be a suitable glazing since it results in relatively economical short payback periods.

Keywords

shading device,
glazing,
residential buildings,
residential envelope transmittance value,
energy performance

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1 Introduction

With the raising pressure in societal and governmental pursuit to reduce carbon footprint, engineers, government bodies, and academics alike have been working closely together in a concerted effort to meet the call. Many avenues have been explored and many more are being discovered with each passing day. Among them, ensuring efficient energy use in buildings, both commercial and residential, is one key area of focus. Energy consumption in buildings is particularly high in developed countries, thus there is a great potential for energy savings in these sectors (Chwieduk 2003). While some have looked at energy savings in buildings from an architectural perspective (Numan et al. 1999; Wan and Yik 2004), others have studied thermal performance of envelope designs to minimize heat gains in buildings (Yu et al. 2009).

Efforts to encourage the wide use of renewable energy technologies in residential districts are often hampered by building managers being reluctance to replace existing expensive but energy-inefficient equipment. The other alternative of boosting energy efficiency in buildings is still the best and easiest way to reduce carbon emissions (Ashina and Nakata 2008). It is known that in the near future, to realize big carbon emission, employing ways to enhance energy efficiency is imperative. In residential buildings, seemingly small energy-efficiency improvements, such as installing the right choice of glazing and the use of external shading devices, can lead to big energy savings.

When shading devices are applied in combination with the appropriate glass type they can modify the thermal effect of windows to a great extent (Tzempelikos et al. 2010 Gratia and Herde 2007). Adjustable and retractable shading devices can be used to fulfil the changing requirements, but fixed external devices exert their effect in a predetermined fashion, depending on the interplay between their geometrical configuration, orientation, and the diurnal and annual patterns of the sun movement. To adjust this effect to the

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List of symbols

A	total building envelope area (m^2)
A_e	exposed area of window (m^2)
A_s	area of the space or a group of spaces (m^2)
BCA	Building and Construction Authority
c	load factor
COP	coefficient of performance of the chiller at design point
CF	solar correction factor for fenestration
D	number of 18.3℃-based degree-days in a year (℃·days)
E_c	annual cooling energy consumption (MWh)
ETTV	envelope thermal transfer value(W/m^2)
RETV	residential envelope transmittance value (W/m^2)
$G = A_e/A$	fraction of area exposed to direct solar radiation to total building envelope area
I_d	diffused radiation (W/m^2)
I_D	direct radiation (W/m^2)
I_T	total radiation (W/m^2)
LIT	lighting power intensity (W/m^2)
n	correction factor for part-load performance of chiller
OTTV	overall thermal transfer value (W/m^2)
Q_d	design space cooling load (W)
$Q_{wall,cond}$	heat conduction through the walls (W)
$Q_{win,cond}$	heat conduction through the windows (W)
$Q_{win,rad}$	solar radiation through the windows (W)
$SC_{1,effective}$	effective shading coefficient of external shading device
SC_2	shading coefficient of fenestration
SF	solar factor for vertical window (W/m^2)
T_c	temperature setpoint (℃)
TD_{eq}	equivalent temperature different for opaque walls (℃)
Δt	design indoor-outdoor temperature difference (K)
ΔT	temperature difference of outdoor and indoor condition for window (K)
U_f	overall thermal transmittance coefficient for the fenestration ($W/(m^2{\cdot}K)$)
U_w	overall thermal transmittance coefficient of the wall ($W/(m^2{\cdot}K)$)
WWR	window to wall ratio
α	day diversity factor of building's operation
β	week diversity factor of building's operation
γ	correlation factor for average space cooling load

Subscripts

D	December
J	June
M	March
S	September

functional requirement, it is necessary to take into account all these considerations when designing the details of shading devices. The performance of shading devices installed on windows at various orientations have been carried out in several studies (Gratia and Herde 2007; Moeseke et al. 2007). One study considered the impact of shading design and control on building cooling and lighting demand with various configurations of shading device fitted for the overheated period under consideration (Tzempelikos and Athienitis 2007). Another study detailing energy simulations performed during early building design stage made appropriate recommendations on the facade, glazings, shading devices, lighting control options, and natural ventilation to be employed in order to realise energy-efficient buildings (Tzempelikos et al. 2007).

The residential envelope transmittance value (RETV) is a measure of the average external heat gain into a building, normalized over all hours of the year and averaged over the whole envelope area of the building. RETV is a product from a study commissioned by Building Construction Authority (BCA) in 2007 to expand the envelope thermal transfer value (ETTV) concept to residential buildings. The main purpose of establishing RETV is to measure the envelope thermal performance standard for residential buildings which mainly have their air-conditioners being turned on at night, differentiating it from ETTV which applies to buildings that primarily operate the air-conditioners during the day (BCA 2008a). Examining the RETV formulation has brought about a deeper understanding on the strong influence of the external shading devices and glazing types in determining the overall thermal performance of the envelope of a building. Identifying these factors is essential to improving the efficacy of the energy used by decreasing the effective shading coefficient.

In order to minimize the RETV, studies on external shading devices is necessary to fully understand the unique properties of each design before they are extensively used in residential buildings to reduce the amount of solar radiation entering into the buildings (Tzempelikos and Athienitis 2007). Similarly, knowledge of the individual properties of a glazing type is essential to maximize the effectiveness in reducing heat gain and cooling load (Stegou-Sagia et al. 2007). Other key factors include the type of glazing used, buildings' orientation, and the external shading devices built, all of which have significant influence on the cooling and dehumidifying load of the air-conditioning system. Effective design of shading device installed in the right building orientations and judicious selection of glazing types are key approaches in reaping appreciable energy savings (Bojić and Yik 2007).

How does the building shading device design and glazing type of one residential building compared with another in terms of minimising external heat load? What are the important design parameters that significantly impact residential building energy efficiency? Can there be a simple methodology for analysing potential energy-saving strategies arising from the use of shading device and glazing for residential buildings? The present work intends to address these issues for residential buildings in climates requiring air conditioning. Therefore, the specific objectives of this work are: (i) to study the impact of a single parameter change on the annual space cooling load of a building; (ii) to carry out performance evaluations of selective external shading devices on two types of residential buildings; (iii) to compare the performance of four different glazing types in terms of shading coefficients, U-values of glazing and visible transmittances and investigate their impact on building energy; and (iv) to identify optimum design features in external shading devices and appropriate glazing type for high-rise residential buildings.

2 Methodology

2.1 Envelope thermal transfer value (ETTV)

ETTV is a measure of the average heat gain into a building through its envelopes. It was refined from the original OTTV (overall thermal transfer value) equation, which did not accurately account for the relative components of heat gain. Chou and Lee (1988) and Chou and Chang (1996) first mooted the idea of developing a more accurate building index that takes into account three heat gain components through the building envelope, namely, heat conduction through opaque walls, heat conduction through windows, and solar radiation through windows. Thus, the ETTV equation takes into consideration three key components that contribute significantly to the heat gain through the building envelope.

The ETTV correlation is particularly suited to buildings experiencing tropical climates where outdoor-indoor temperature difference and diurnal variations of temperature are relatively small. The ETTV formula is thus presented as

$$\begin{aligned}\mathrm{ETTV} = {} & \mathrm{TD}_{\mathrm{eq}}(1-\mathrm{WWR})U_{\mathrm{w}} + \Delta T(\mathrm{WWR})U_{\mathrm{f}} \\ & + \mathrm{SF}(\mathrm{WWR})(\mathrm{CF})(\mathrm{SC})\end{aligned} \tag{1}$$

where $\mathrm{TD}_{\mathrm{eq}}$ is equivalent temperature difference (℃), ΔT is the temperature difference (℃), SF is the solar factor (W/m^2), WWR is window-to-wall ratio, U_{w} is the thermal transmittance of opaque wall (W/(m^2·K)), U_{f} is the thermal transmittance of fenestration (W/(m^2·K)), CF is the solar correction factor for fenestration, and SC is the shading coefficients of fenestration. The coefficients $\mathrm{TD}_{\mathrm{eq}}$, ΔT, and SF vary according to the weather of the locality of interest. These coefficients are determined using computer simulations using the particular local weather file. Coefficients for each particular heat gain component can be obtained using the following three equations as proposed by Chou and Chang (1996).

$$\mathrm{TD}_{\mathrm{eq}}(1-\mathrm{WWR})(U_{\mathrm{w}}) = \frac{\sum\limits_{1\ \mathrm{year}} Q_{\mathrm{wall,\ cond}}}{\text{annual operating hours} \times A} \tag{2}$$

$$\Delta T(\mathrm{WWR})(U_{\mathrm{f}}) = \frac{\sum\limits_{1\ \mathrm{year}} Q_{\mathrm{win,\ cond}}}{\text{annual operating hours} \times A} \tag{3}$$

$$\mathrm{SF}(\mathrm{WWR})(\mathrm{SC}) = \frac{\sum\limits_{1\ \mathrm{year}} Q_{\mathrm{win,\ rad}}}{\text{annual operating hours} \times A} \tag{4}$$

Equations (2), (3) and (4) account for the heat conduction through the walls, the heat conduction through the windows, and the solar radiation through the windows, respectively. Using Singapore's weather data consolidated for a particular year, the three coefficients can be derived from performing several multi-parametric simulations on two residential building types.

2.2 Annual cooling energy consumption (E_{c})

The annual cooling energy consumption, E_{c}, is defined as the annual electrical energy consumption of the air-conditioning system. This includes chillers, cooling towers, AHUs (air handling units), and other miscellaneous pumping equipment. The annual cooling energy can be estimated using the modified degree-day method for cooling formulated earlier by Chou et al. (1986). The present method of estimating energy, invoking the ETTV, is by way of estimating the cooling degree days for the specific location. The resulting equation for E_c can be expressed as

$$E_{\mathrm{c}} = \frac{(c)(Q_{\mathrm{d}})(24)(D)(\alpha)(\beta)}{\Delta t(\mathrm{COP})^{n}} \tag{5}$$

Work by Chou and Chang (1993) has led to a simplification of the modified cooling degree-day equation (Eq. (6)); resulting in the key development of a new expression incorporating the ETTV. The simplified cooling energy-estimating equation is thus written as

$$E_{\mathrm{c}} = \frac{\gamma(\mathrm{ETTV})A(24)(D)(\alpha)(\beta)}{\Delta t(\mathrm{COP})^{n}} \tag{6}$$

where α and β are diversity factors of the operating hours in a day and the operating days in a week, respectively. Thus,

$$\alpha = \frac{\text{operating hours of a building in a day}}{24} \tag{7}$$

and

$$\beta = \frac{\text{operating days of a building in a week}}{7} \tag{8}$$

The cooling degree-day is defined as the difference between the daily mean outdoor temperature and reference temperature and is expressed as

$$D = \sum_{i=1}^{n}(T_{\mathrm{m}} - T_{\mathrm{ref}}) \tag{9}$$

Equation (5) can also be re-cast in the following form:

$$n = \frac{\ln\left[\dfrac{24 \cdot D \cdot \alpha \cdot \beta}{\Delta t \cdot E_{\mathrm{c}}/(cQ_{\mathrm{d}})}\right]}{\ln(\mathrm{COP})} \tag{10}$$

Equation (10) is further re-arranged to obtain the values of n (the part load factor of the cooling plant) and Δt (design indoor-outdoor temperature difference) from the multi-parametric simulation data by making use of the approximate linear relationship between the two values. The resultant expression is given as

$$\ln\left(\frac{E_{\mathrm{c}}}{cQ_{\mathrm{d}}}\right) = -n\ln(\mathrm{COP}) + \ln\left(\frac{24D\alpha\beta}{\Delta t}\right) \tag{11}$$

Equation (11) demonstrates linearity and the values of n and Δt can then be directly extracted from the gradient and y-intercept, respectively. In determining the cooling load of the building, the correlation factor, γ, is defined as the ratio of the annual cooling load to envelope heat gains, thus,

$$\gamma = \frac{(c)(Q_{\mathrm{d}})}{Q_{\mathrm{env}}} = \frac{\text{total cooling load}}{(\mathrm{ETTV})(A)} = \frac{(c)(Q_{\mathrm{d}})}{(\mathrm{ETTV})(A)} \tag{12}$$

where the total cooling load $= Q_{\mathrm{env}} + Q_{\mathrm{int}} + Q_{\mathrm{misc}}$ and Q_{env} is the average cooling load due to envelope heat gains (W); Q_{int} is the average internal load due to occupants, lights, and equipment (W); and Q_{misc} is the average miscellaneous load due to infiltration, roof and ground heat gains (W). Both Q_{env} and Q_{misc} are affected by changes in weather as well as building operation schedules. Therefore, Q_{int}, which can be easily calculated, is chosen as an independent variable. Thus, Eq. (12) is rearranged as

$$\gamma = \left[B + \frac{(1+M)Q_{\mathrm{int}}}{(\mathrm{ETTV})(A)}\right] \tag{13}$$

where B is the cooling load due to envelope gains/(ETTV·A) and M is given by $Q_{\mathrm{misc}}/Q_{\mathrm{int}}$.

Chou and Chang (1993) further observed that the ratio M shares a linear relation with (ETTV)(A)/Q_{int} in Eq. (13). Therefore, M, in terms of (ETTV)(A)/Q_{int}, is expressed as

$$M = \frac{Q_{\mathrm{misc}}}{Q_{\mathrm{int}}} = a \cdot \frac{(\mathrm{ETTV})(A)}{Q_{\mathrm{int}}} + b \tag{14}$$

Finally, using Eqs. (13) and (14), Chou and Chang (1993) expressed γ as a linear function of Q_{int}/(ETTV·A), given by

$$\gamma = (B+a) + (1+b)\left(\frac{Q_{\mathrm{int}}}{(\mathrm{ETTV})(A)}\right) \tag{15}$$

where B is the cooling load due to envelope heat gains/(ETTV·A) and, a and b are constants.

The value of average internal load, Q_{int}, is required to enable the calculation of γ using Eq. (15). In order to estimate Q_{int}, we employed the cooling load factor (CLF) method specified in the ASHRAE Handbook of Fundamentals (ASHARE 2005). Q_{int} is the sum of three components, namely, Q_{occ} (average cooling load due to heat gain from occupants), Q_{light} (average cooling load due to heat gain from lights), and Q_{equip} (average cooling load due to heat gain from equipment).

2.3 Simulation program

In this paper, eQUEST was employed to estimate the annual energy consumptions and space cooling loads of air-conditioned high-rise residential buildings. Different permutations of glazing type, external shading devices and building orientations will be considered in the simulations. Analyses were performed to evaluate the best design in terms of energy efficiency and cost effectiveness.

eQUEST is a building energy analysis tool that allows users to perform detailed comparative analysis of building designs and technologies. Its simulation engine is derived from DOE-2 simulation program which has been fully validated (DOE-2E 1981) and is an ASHRAE qualified (Diamond and Hunn 1981) computer program that predicts the hourly energy use and energy cost of a building when information such as the hourly weather information, building model descriptions and its heating ventilation and air conditioning (HVAC) equipment and utility rate structure are provided. DOE-2 has undergone rigorous validations with test data from actual building operations (Lam et al. 2008).

eQUEST calculates hour-by-hour building energy consumption over an entire year (8760 hours) using hourly weather data for the location under consideration. Input to the program consists of a detailed description of the building being analyzed, including hourly scheduling of occupants, lighting, equipment, and thermostat settings. It provides very accurate simulation of such building features as shading, fenestration, interior building mass, envelope building mass, and the dynamic response of differing heating and air conditioning system types and controls (James 2003). In short, eQUEST is a building energy analysis tool which produces high quality results by integrating a building creation wizard, an energy efficiency measure wizard and a graphical results display module with an enhanced DOE-2 simulation program (Crawley 2008). eQUEST was adopted to produce the ETTV (residential buildings) — E_c correlation in order to study energy performance of residential buildings in Singapore. It is worth noting that while eQUEST does not have more sophisticated features found in advanced software like EnergyPlus which includes innovative simulation capabilities such as time steps of less than an hour, modular systems and plant integrated with heat balance-based zone simulation, multi-zone air flow in-built thermal comfort settings, its energy predicting capability is suffice for the present work.

2.4 Simulation parameters

To obtain the residential ETTV coefficients and energy estimation correlations, energy performance simulations with local climatic data were conducted. The weather file is a compilation of typical climatic data ranging from dry-bulb and wet-bulb temperatures, wind velocities, cloudiness and hourly values of direct and diffuse radiation for all building operating hours of the year.

The window-to-wall ratio (WWR) of buildings represents the ratio of the fenestration area to the total wall facade. The building characteristics are presented in Table 1. These values covered some of the common combinations of building

Table 1 Characteristics of model building used in simulations

Building descriptions	
Building type	20-storey high rise residential building
Building area	12 560 m^2
Area per floor	628 m^2
Floor to floor height	3.05 m
Orientation	North
External walls	115 mm thickness brickwall with 25 mm thickness plaster on both sides; U_w = 4.348 W/(m^2·K)
Interior walls	100 mm thickness precast wall; R = 0.197 (m^2·K)/W
Floor slabs	200 mm concrete floors; Total R = 0.275 (m^2·K)/W
Wall solar absorptance	0.45
Window and lighting	
Window-to-wall ratio	0.30
Shading coefficient	0.8
Glass conductance	5.83 W/(m^2·K) (single clear glazing)
Window setback	0.0
Lighting power	4.306 W/m^2
Infiltration	0.6 air changes per hour when windows are open
System	
HVAC	DX coils (no heating); split system single zone DX
Cooling setpoint	22℃
Chiller COP	2.5
Economizer	None
Number of people per apartment	4
Outdoor air	1.981 cmh/m^2 (11.7 cfm/person)
Base design parameters	
U_f	5.8 W/(m^2·K)
U_w	4.4 W/(m^2·K)
SC	0.8
T_c	22℃
WWR	30%
LIT	4.306 W/m^2
COP	2.5

construction materials and glass types used in the construction of residential buildings in Singapore. The shading coefficient (SC) can be defined as the ratio of the solar heat gain through fenestration under standard conditions to the solar gain through a single pane of a reference double strength sheet glass under the same conditions (Carmody et al. 2007).

2.5 Point and slab block descriptions

The reference generic buildings used for computer simulations are 20-storey point block and slab block, modelled after actual residential buildings in Singapore. The floor plan of a generic point block building is presented in Fig. 1. The reference case building of a point block is of symmetrical cross section and its four facades face the north, south, east, and west orientations. It has a floor-to-floor height of 3.05 m. One storey houses four apartments, each with 144 m^2 or 1552 ft^2 of space. In each apartment, up to two bedrooms can be air conditioned. This provides a measure of diversity with regard to air-conditioned space within each household. The bigger bedroom occupies a space of 36 m^2 while the smaller bedroom occupies 16 m^2.

The floor plan of a generic slab block building is presented in Fig. 2. The reference building of a slab block has a rectangular floor plan, generally with individual apartments along the length of the block. The reference building is oriented in the east-west direction. Like the point block, each storey comprises four apartments, each with 144 m^2 or 1552 ft^2 of space. The generic makeup within each apartment is the same as the point block. There are two air-conditioned bedrooms, with the bigger bedroom occupying a space of 36 m^2 while the smaller bedroom occupies 16 m^2. A common non-air conditioned corridor runs the length of the block. The corridor is 1.8 m wide and acts as an overhang to the facade of the floor below it. Residential slab blocks usually have such common corridors that provide some form of shading to one facade of the building. The floor plan is identical for each of the building's 20 storeys.

2.6 External shading device

External shading devices have been extensively implemented in regions where solar radiation is prominent in influencing the cooling load of a building. An optimal design of an external shading device will reduce solar heat gained and subsequently, resulting in lower space cooling load. An in-depth knowledge on the physical characteristics of shading devices is essential before any form of implementation as different building orientations require different types of shading devices for effective shading. The primary reason lies being, in a day, different facets of a building will emit sunlight at different angles. Figure 3 shows the typical user requirements for external shading devices.

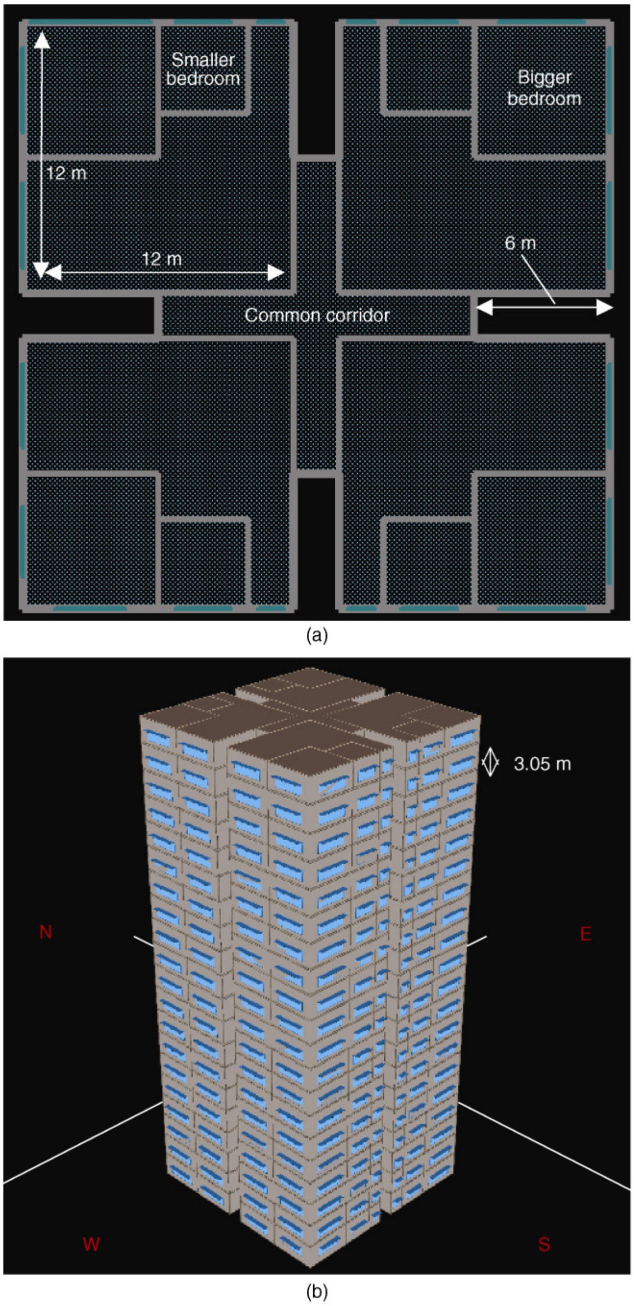


Fig. 1 (a) Two-dimensional geometry of a generic point block building; and (b) three-dimensional geometry of a generic point block building. The point block building is of symmetrical cross section. It has a floor-to-floor height of 3.05 m. One storey houses four apartments, each with 144 m^2 or 1552 ft^2 of space

According to Wong and Agustinus (2003), fenestration can contribute to 22% of energy consumption in residential buildings. In addition, uncontrolled fenestration heat gain causes overheating, thereby causing poor thermal

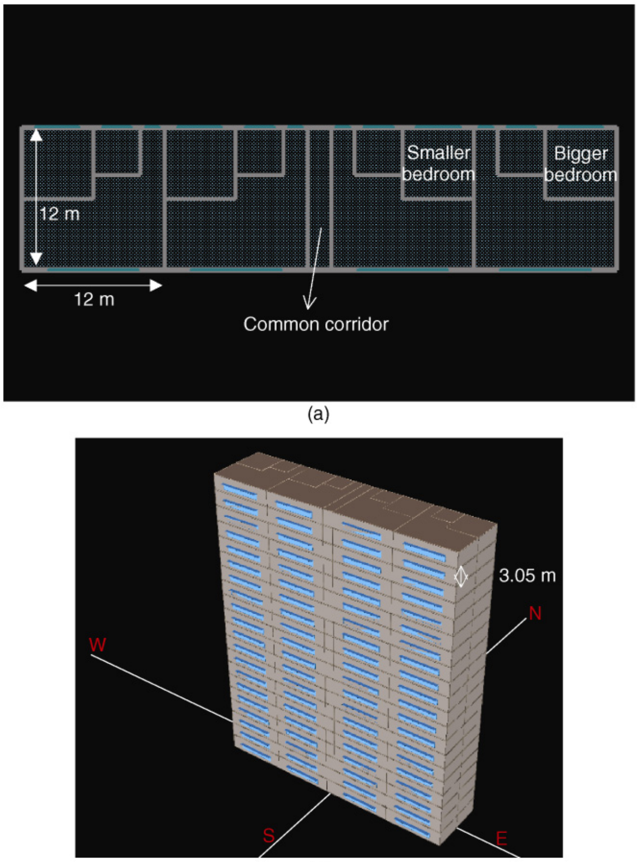


Fig. 2 (a) Two-dimensional geometry of a generic slab block building; and (b) three-dimensional geometry of a generic slab block building. The slab block has a rectangular floor plan, generally with individual apartments along the length of the block. Each storey comprises four apartments, each with 144 m^2 or 1552 ft^2 of space, and the floor-to-floor height is 3.05 m

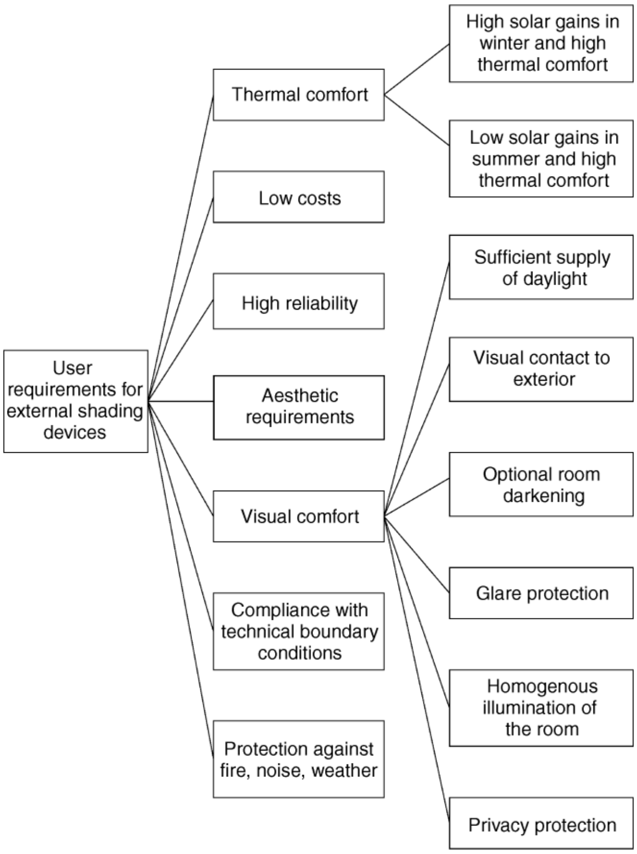


Fig. 3 Typical user requirements for external shading devices (adapted from Tilman et al. 2001)

performance. With proper external shading devices, large reduction of cooling load may allow the capacity of cooling equipment to be reduced by a similar amount. Among the external shading devices commercially available, some of the commonly encountered shading device (Wulfinghoff 1999) include: (i) horizontal projection; (ii) vertical projection; (iii) balconies; (iv) eaves and overhangs; (v) continuous vertical louvers; (vi) awnings; (vii) egg-crate louvers; (viii) half-egg crate louvers; and (ix) horizontal projection with vertical louvers.

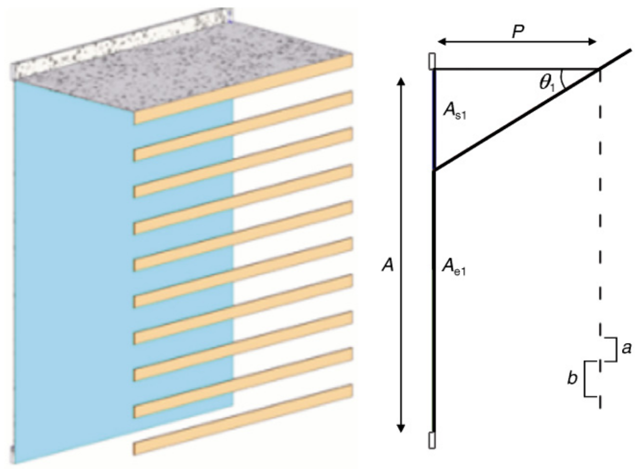
In calculation of the shading coefficient of any shading device, the most important component is the determination of "G" factor, which is the fraction of area exposed to direct solar radiation at any time. Formulation of equations to physically represent the G-factor of the half egg-crate louvers, continuous vertical louvers and vertical sunscreen with horizontal projection are shown in Fig. 4. With reference to the Code of Envelop Thermal Performance for Buildings by BCA, the effective shading coefficient of external shading device is mathematically obtained by

$$SC_{1,\text{effective}}=\frac{\Sigma_{\mathrm{M}}(G\times I_{\mathrm{D}}+I_{\mathrm{d}})+\Sigma_{\mathrm{J}}(G\times I_{\mathrm{D}}+I_{\mathrm{d}})+\Sigma_{\mathrm{S}}(G\times I_{\mathrm{D}}+I_{\mathrm{d}})+\Sigma_{\mathrm{D}}(G\times I_{\mathrm{D}}+I_{\mathrm{d}})}{\Sigma_{\mathrm{M}}I_{\mathrm{T}}+\Sigma_{\mathrm{J}}I_{\mathrm{T}}+\Sigma_{\mathrm{S}}I_{\mathrm{T}}+\Sigma_{\mathrm{D}}I_{\mathrm{T}}} \tag{16}$$

2.7 Window glazing

Besides the design of the external shading devices installed, the type of glazing used impacts the cooling load of an air-conditioned building. Different glazing will have different properties that determine the amount of solar radiation emitted into internal space as well as amount of heat being conducted away. In relation to the climate in Singapore, the following glazing types, as shown in Table 2, will be considered in the simulations as they are more pertinent to be used in buildings which predominantly demands cooling load instead of heating due to climatic conditions.

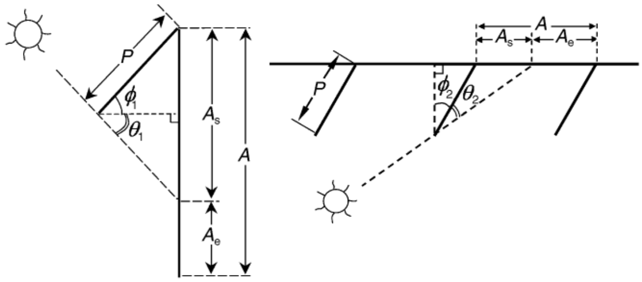
In ensuring a holistic understanding on the influence of external shading device on cooling load, it is imperative to calculate the shading coefficient. Shading coefficient of the



Effective $G = \frac{A_e}{A} = \frac{A_{e1}\left(\frac{a}{b}\right)}{A} = \frac{[A-(P\tan\theta_1)]\left(\frac{a}{b}\right)}{A} = (1-R_1\tan\theta_1)\left(\frac{a}{b}\right)$

where $R_1 = \frac{P}{A}$

(a)



Continuous horizontal projection (left hand figure): $G_1 = 1 - R_1(\cos\phi_1 \tan\theta_1 - \sin\phi_1)$ where $R_1 = P/A$ and ϕ_1 is the projection angle of horizontal projections with respect to horizontal plane.

Half of vertical fins (right hand figure): $G_2 = 1 - R_2 \mid \tan\theta_2 \mid$ where $R_2 = P/A$.

Egg-crate shading is made up of horizontal and vertical components for which the horizontal component may be sloped. Since G_1 and G_2 are independent of each other, the combined effect of the two components, which represents the G-factor for egg-crate shading can be expressed as follows: Effective $G_3 = G_1 \times G_2$

(b)

Fig. 4 (a) Vertical sunscreen with horizontal projection with derivation of effective G; and (b) half egg-crate louver with derivation of effective G (adapted from BCA 2008b)

fenestration system is defined as the ratio of solar heat gain through the fenestration system having combination of glazing and shading device to the solar heat gain through an un-shaded 3 mm clear glass (BCA 2008b). This ratio is a unique characteristic of each type of fenestration system and is represented by the following equation:

$$\mathrm{SC}_2 = \frac{\text{solar heat gain of any glass and shading device}}{\text{solar heat gain through a 3 mm unshaded clear glass}} \tag{17}$$

When both shading device and glazing are installed, the shading coefficient of any fenestration system can be obtained by multiplying the shading coefficient of the glass and the shading coefficient of the external shading device as follows:

$$\mathrm{SC} = \mathrm{SC}_{1,\text{effective}} \times \mathrm{SC}_2 \tag{18}$$

2.8 Calculation of simple payback period

Payback period is the time taken for the total initial investment of a product to be recovered by the accumulated savings. A simple calculation of payback period for any shading devices or glazing types can be assessed by employing Eq. (19). In this paper, we will conduct a simple exercise to calculate payback period for the selection of glazing type based on prices provided by a local manufacturer. Unfortunately, we were unable to obtain prices for all the shading devices expect for that of half egg-crate louver.

Based on the latest utility cost pricing, the energy cost has been taken at 0.2454 SGP$/kWh. The yearly maintenance was conservatively assumed to be 4% of the initial investment. The total energy cost savings and total maintenance costs are reduced to their present value using the present worth factor at assumed interest rates of 6%. In economics, money has a time value and a given amount of money will be worth less in the future than it is today. Thus, the relation between present and future cash flows is embodied in the discount rate (Kreider et al. 1989).

$$\text{payback period} = \frac{\text{initial investment \& maintenance costs}}{\text{expected returns per year}} \tag{19}$$

3 Results and discussion

3.1 Establishing the ETTV for residential buildings (RETV)

In determining the coefficients for the residential ETTV equation or RETV, the envelope loads were generated in order to determine the coefficients at a cooling setpoint of 24℃. The values of $\mathrm{TD}_{\mathrm{eq}}$, Δt and SF for each of the two types of residential building were evaluated by using Eqs. (2), (3) and (4) and the coefficients calculated for each building and tabulated as shown in Table 3. To facilitate the submission of residential RETV to BCA and to standardise the RETV equation, we propose an averaging of the two sets of coefficients. The proposed residential ETTV or RETV

Table 2 Glazing types and properties (Meng Heng Glass Pte Ltd 2009)

Glazing type	*U*-Value (W/(m²·K))	Shading coefficient (SC)	Solar heat gain coefficient (SHGC)	Visible transmittance (VT)	Glazing cost (S$/m²)
Single clear glazing (6 mm) [6 mm metrolite™ clear annealed glass]	5.70	0.96	0.83	0.89	$ 14
Low-E single clear glazing (6 mm) [6 mm metrolite™ sunergy clear low-E annealed glass]	4.20	0.70	0.61	0.68	$ 57
Double clear glazing (18mm) [6 mm metrolite™ clear annealed glass + 6 mm A/S + 6 mm metrolite™ clear annealed glass]	2.90	0.85	0.74	0.79	$ 70
Low-E double clear glazing (18 mm) [6 mm metrolite™ sunergy clear low-E annealed glass #2 + 6 mm A/S + 6 mm metrolite™ clear annealed glass]	2.80	0.59	0.51	0.61	$ 127

Table 3 $\mathrm{TD}_{\mathrm{eq}}$, Δt, and SF for various residential building types

Building type	$\mathrm{TD}_{\mathrm{eq}}$ (℃)	Δt (℃)	SF
Point block	3.31	1.21	56.12
Slab block	3.56	1.32	61.05

equation is thus:

$$\mathrm{RETV} = \underbrace{3.4(1-\mathrm{WWR})U_{\mathrm{w}}}_{\text{heat conduction}_{\text{wall}}} + \underbrace{1.3(\mathrm{WWR})U_{\mathrm{f}}}_{\text{heat conduction}_{\text{glass}}} + \underbrace{58.6(\mathrm{WWR})(\mathrm{CF})(\mathrm{SC})}_{\text{solar radiation/heat retention}_{\text{glass}}} \quad (20)$$

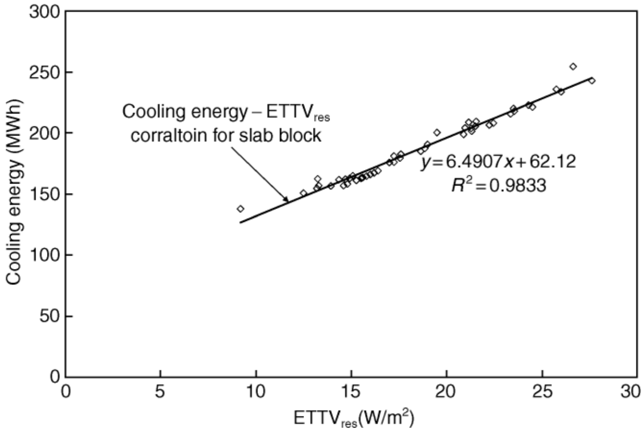


Fig. 5 Graph of cooling load versus RETV for residential slab block

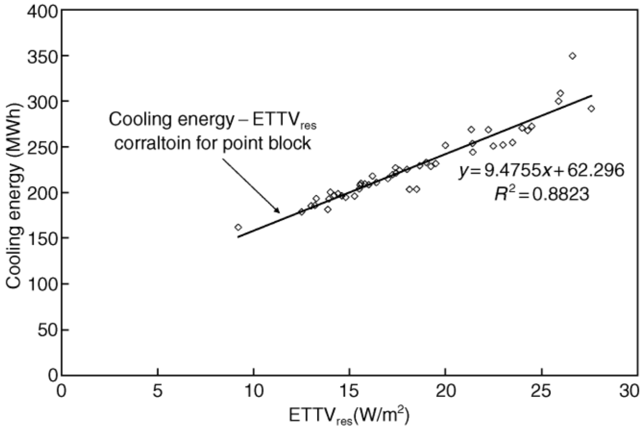


Fig. 6 Graph of cooling load versus RETV for residential point block

3.2 Relationship between RETV and cooling energy

To investigate the differences in annual cooling energy E_c when RETV fluctuates, a set comprising 100 parametric simulation runs for each building was performed. Results were generated and illustrated in plots of E_c against RETV. Interestingly, E_c demonstrated a strong linear correlation with RETV. Therefore, RETV, by itself could be a stand-alone parameter for appreciating the energy consumption pattern in buildings linked to envelope heat gains.

It is now appropriate to discuss the potential energy-savings based on the equations displayed in Figs. 5 and 6. At about the mid-point RETV range of 20 W/m², it is readily observed that for slab block, a unit decrease in RETV resulted in 3.5% decrease in annual cooling energy. Correspondingly, for point block, a unit decrease in RETV gave rise to 4% decrease in annual cooling energy. In addition, the following approaches may be adopted to reduce, in varying degree, the RETV: (i) reducing glass shading coefficient; (ii) reducing wall absorptance; (iii) increasing wall resistance; (iv) reducing *U*-value of fenestration; (v) applying appropriate wall cladding; (vi) implement external shading devices; (vii) applying solar film; and (viii) employing self shading in building design.

In some of the above approaches such as in wall and glazing resistance and cladding, materials are major players contributing to significant beneficial effects. Architectural aspects that exploit the judicious employment of shading devices and natural elements of the location and designing to take advantage of self shading and orientation of the building are of equal importance in helping to reduce heat transmission through the building envelope. It is clear at this stage that the use of shading devices and glass glazing impacts RETV and, hence, the cooling load energy in buildings.

The RETV criterion can be subtly revised as buildings become more energy efficient, measured by their energy index (W/(m^2·year)) at the design and post occupancy stage.

3.3 Impact of key parameters on cooling load

In this parametric analytical exercise, the degree of influence of several key building parameters on cooling load of high-rise residential buildings is determined. Numerous simulations were performed by varying one parameter at a time either by increasing or decreasing the value from the base design while keeping the other parameters fixed. This simulation mode enabled the degree of influence of each parameter on space cooling load to be determined. The knowledge of the parameters' influence serves as an important guide in enhancing the energy efficiency of residential buildings at the preliminary design stage.

Taking slab block residential building as a reference model, Table 4 shows the average percentage change in energy required to meet space cooling load when different parameters were varied. The ranking of parameters in increasing degree of influence is as follows: (1) coefficient of performance (COP); (2) shading coefficient (SC); (3) window to wall ratio (WWR); (4) setpoint temperature (T_c); (5) light intensity ration (LIT); (6) heat transfer coefficient for wall (U_w); and (7) heat transfer coefficient for window (U_f). From a theoretical perspective, it is prudent to invest in energy-efficient chillers yielding high COP. Energy simulations conducted by varying the COP from 2.5 to 4.5 have shown a significant decrease in space cooling load by about 72% and an average decrease of 34% in annual utility expenditure. Better performance of chillers is thus seen as a key solution in decreasing energy consumption. However, for existing residential buildings, retrofitting new chillers may be a costly exercise and hence an expensive option.

The second most influential parameter is the effective shading coefficient of the fenestration system in the building. Reducing SC from 0.8 to 0.2 will result in an average decrease of 15% in space cooling load due to a significant reduction of heat gained from external solar radiation. Maintaining a small window-to-wall ratio is also seen as a viable method to reduce space cooling load and is ranked third in the list. Other influential parameters down the list of order include setpoint temperature; light intensity ration; heat transfer coefficient for wall; and heat transfer coefficient for window. External shading device and window glazing affects the effective shading coefficient of the fenestration system in the building, it is expected that they will significantly impact the cooling load and hence energy efficiency of the building. Therefore, it is worthwhile to study their performance and how they can promote better energy efficiency of residential buildings.

3.4 Performance of external shading devices

In determining the correlation between the performance of external shading device and cooling load of a high-rise residential building of both the slab block and point block, simulations were performed to assess the performance of the four basic types of external shading device commonly used in buildings, namely, horizontal projections, vertical fins, egg-crate louvers, and half egg-crate louvers. Simulation results were obtained and comparative analysis was carried out to evaluate the effectiveness of the respective external shading device with respect to building orientations and building type.

Tables 5 to 7 show the performance of these devices in both the point block and slab block of differing orientations. Several key observations were deduced. Firstly, there was minimal difference in space cooling load between slab block facing south and north as well as east and west. These disparities amounted to about 1% difference or less and they are primarily due to the unique design of slab block which has window areas about the same size on both the

Table 4 Average percentage change of space cooling load as key parameter changes (positive percentage indicates an increment while negative percentage indicates a reduction)

Parameters	Range of parameter change	Average percentage change in energy required to meet space cooling load (%)	Average percentage change in annual utility charges (%)
WWR	0.3 to 0.7	12.8	8.3
LIT (W/m^2)	4 to 20	5.2	21.8
U_f (W/(m^2·K))	5.8 to 2.0	0.31	0.19
U_w (W/(m^2·K))	4.4 to 2.8	−3.44	−2.07
T_c (℃)	22 to 25	−12.26	−7.01
SC	0.8 to 0.2	−14.64	−8.37
COP	2.5 to 4.5	−72.373	−33.98

Table 5 Performance of external shading devices for slab block facing different orientations

	Type of shading device	Reduction in space cooling load (%)	Reduction in annual utility (%)	Annual savings ($)
Slab block (south facing)	Horizontal projection	19.5	10.3	14 700
	Vertical projection	3.6	2.3	3 100
	Egg-crate louver	24.4	12.7	17 800
	Half egg-crate louver	22.5	11.7	16 600
Slab block (north facing)	Half egg-crate louver	22.0	11.5	16 300

Table 6 Performance of external shading devices for slab block of west facing and east facing

	Type of shading device	Reduction in space cooling load (%)	Reduction in annual utility (%)	Annual savings ($)
Slab block (west facing)	Horizontal projection	14.0	7.9	12 100
	Vertical projection	2.8	1.6	2 700
	Egg-crate louver	17.4	9.6	14 600
	Half egg-crate louver	15.7	8.7	13 400
Slab block (east facing)	Half egg-crate louver	16.9	9.4	14 300

Table 7 Performance of external shading devices for point block

	Type of shading device	Reduction in space cooling load (%)	Reduction in annual utility (%)	Annual savings ($)
Point block (south facing)	Horizontal projection	16.6	8.9	13 700
	Vertical projection	4.6	2.6	4 300
	Egg-crate louver	22.5	11.8	17 700
	Half egg-crate louver	19.9	10.6	16 000
Point block (north facing)	Half egg-crate louver	19.7	10.5	15 800

Table 8 Performance of external shading devices with 30° tilt for point block of south facing and west facing

	Type of shading device	Reduction in space cooling load (%)	Reduction in annual utility (%)	Annual savings ($)
Slab block (south facing)	Horizontal projection (30° tilt)	23.7	12.3	17 300
	Half egg-crate louver (30° tilt)	26.5	13.6	18 900
Slab block (west facing)	Horizontal projection (30° tilt)	21.2	11.6	17 300
	Half egg-crate louver (30° tilt)	23.0	12.5	18 400

front and back of each apartment. Secondly, on the basis of performance, the more desirable external shading device would be the egg-crate louvers for slab block facing south as well as west. On the basis of cost effectiveness involving the construction materials, half-egg crate louver would present a positive option for south facing slab block, whereas horizontal projection is a favourable option for west facing slab block. With a marginal reduction of 2% – 3.5% in performance, it is a good compromise to reduce material costs in exchange for better views and external aesthetics purpose.

Understanding the sun path is a critical factor in improving the design of sun shading devices. Evidently, based on the sun's trajectory, the perpendicular horizontal projection may not be an effective design for the slab block of east-west facing. Energy performance simulations have indicated a better alternative—horizontal projection slanted downward at about 30° below the horizontal. As shown in Table 8, this design enhances the performance by about 6% – 7% as it is more effective in blocking off solar radiation coming at low angle when the sun rises or sets.

From a building architectural standpoint, it would be best to avoid having any fenestration system in the east-west direction as these facades receive the most solar radiation in a day. In comparison to a residential slab block facing in south-north direction, an east-west facing block demands 9.2% more in cooling load to maintain similar thermal comfort of occupants.

3.5 Performance of glazing types

By entering the glazing properties into the model, simulations were performed on several glazing types with varying orientations. The methodology employed in the simulations follows a methodical approach of substituting the glazing type one after another in each building at different orientations.

Simulation results portrayed in Tables 9 and 10, pointed low-E single clear glazing to be an appropriate option due to its relatively shorter payback period in the range of 7 to 9 years. This is followed by the low-E double clear glazing while double clear glazing has the longest payback period spanning 26 to 33 years. Based on the glazing properties obtained from a local glazing supplier based in Singapore, the energy performance of double clear glazing was not as effective as low-E single clear glazing though it cost approximately 19% more. Despite this fact, double clear glazing is selected for applications in situations where there is a need to improve noise attenuation as it is able to filter medium to high frequency range of noises.

Even though the model presents quantitative results of glazing performance, they cannot be taken as the absolute performance indicator. It is worth noting that the payback period is often based on building design and it does not take into account the arising cost reduction due to bulk purchases which may significantly trim the cost prices of glazing. For such bulk-purchase scenario, reduced payback period ensues. In addition, reducing the size of windows can potentially reduce the payback period for the glazing as well. Therefore, there are numerous factors that need to be considered that will potentially affect the eventual return-on-investment time.

3.6 Cumulative effect of external shading and glazing enhancement

Besides evaluating the performance of each design (external shading and glazing type) per se, simulations were also conducted to study the energy performance of buildings incorporating external shading device together with glazing enhancement. Buildings were modelled with half egg-crate louvers on each window and space cooling loads were measured with different glass types.

The cumulative effect of shading device and glazing type on the residential building cooling load is depicted in Tables 11 and 12. It is evidential that the energy performance

Table 9 Glazing performance for slab block

Glazing type	Reduction in space cooling load (%)	Reduction in annual utility (%)	Annual savings ($)	Payback period (years)
Slab block (south facing)				
Low-E single clear glazing	8.9	4.9	7 400	9.2
Double clear glazing	3.0	1.7	2 600	33.4
Low-E double clear glazing	12.9	6.9	10 300	17.3
Slab block (west facing)				
Low-E single clear glazing	10.9	6.2	9 700	7.0
Double clear glazing	3.6	2.1	3 400	26.0
Low-E double clear glazing	16.0	8.9	13 600	13.0

Table 10 Glazing performance for point block

Glazing type	Reduction in space cooling load (%)	Reduction in annual utility (%)	Annual savings ($)	Payback period (years)
Point block (south facing)				
Low-E single clear glazing	9.9	5.5	8 700	7.8
Double clear glazing	3.2	1.8	3 000	29.4
Low-E double clear glazing	14.6	7.9	12 300	14.5
Point block (west facing)				
Low-E single clear glazing	11.8	6.7	10 500	5.8
Double clear glazing	3.9	2.2	3 500	24.8
Low-E double clear glazing	17.5	10.0	15 700	10.4

Table 11 Glazing performance for slab block incorporating half egg-crate louvers

Glazing type	Reduction in space cooling load (%)	Reduction in annual utility (%)	Annual savings ($)	Payback period (years)
Slab block (south facing)				
Low-E single clear glazing	29.4	14.9	20 500	3.3
Double clear glazing	25.4	13.1	18 300	4.8
Low-E double clear glazing	32.5	16.3	22 200	8.0
Slab block (west facing)				
Low-E single clear glazing	24.5	13.2	19 400	3.5
Double clear glazing	19.0	10.4	15 700	5.6
Low-E double clear glazing	28.7	15.2	22 000	8.1

Table 12 Glazing performance for point block incorporating half egg-crate louvers

Glazing type	Reduction in space cooling load (%)	Reduction in annual utility (%)	Annual savings ($)	Payback period (years)
Point block (south facing)				
Low-E single clear glazing	27.3	14.1	20 700	3.2
Double clear glazing	23.0	12.1	18 000	4.9
Low-E double clear glazing	31.1	15.8	22 900	7.8
Point block (west facing)				
Low-E single clear glazing	22.5	12.1	17 800	4.1
Double clear glazing	16.7	9.2	13 700	6.3
Low-E double clear glazing	27.1	14.3	20 700	8.9

of a building can be appreciably improved by integrating external shading device and appropriate glazing. Consequently, the payback periods have been drastically shaved with increased annual savings. Thus, external shading devices should be the main design feature in the building before further energy efficient enhancement via incorporating glazing should be considered. The presence of shading devices exerts greater influence on cooling load reduction compared to the type of glazing employed. Hence, it is concluded that buildings without the external shading devices incur 12.7% to 22.4% higher in cooling load, translating to higher operating cost of about S$8,400 to S$15,700 annually, as compared to a building with half egg-crate louvers and with everything else remaining the same. The potential savings with the installation of external shading devices are indeed significant and should be seriously considered as a first option in trimming building cooling load.

4 Conclusions

Using computer simulations, two types of residential buildings were modelled and parametric runs were performed. An ETTV equation for residential buildings was formulated. We have shown that the RETV correlates well with the energy consumption of a large scale residential building. A set of simple energy and load estimating equations were developed using computer simulation and local climatic data.

Employing the RETV—E_c correlations, evaluations on the performance of selective external shading devices on point block and slab block were carried out. Simplified expressions to calculate shading coefficient of external shading devices were established and presented. In addition, comparative analysis were carried out to analyze the design of several external shading devices and compute their impacts in changing the energy consumptions for slab block having different orientations. Results showed half egg-crate louver as the most suitable design for building facing the north and south orientations, whereas horizontal projection with 30° downward tilt is best for east and west orientations considering the energy efficiency it offers and the overall cost effectiveness.

Conducting a comparative analysis on four different glazing types with different shading coefficients, *U*-values and visible transmittances, we have shown low-E single clear glazing to be the most suitable glazing for direct application as part of the fenestration system. Lastly, we demonstrated that the most effective fenestration system should incorporate both external shading device as well as good window glazing. The presence of an appropriate external shading device coupled with a judicious selection of the right glazing has the potential to reduce the cooling load of residential buildings by up to 30%.

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