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Retrofitting of a High-Rise Residential Building for Energy Efficiency with OTTV as an Assessment Tool

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ABSTRACT

Buildings account for nearly 50% of the total energy consumption. The use of air-conditioning is one of the major influencers to the high energy consumption in buildings. To tackle this high energy consumption, buildings are required to be more energy efficient. This study aimed to investigate the retrofitting of existing residential building for energy efficiency by using the Overall Thermal Transfer Value (OTTV) as an assessment tool. Various retrofitting measures were involved, including varying the colour of the opaque wall with different solar absorptivity, the U-value and shading coefficient of the Glazing system, and the type and projection of the external shading. The results showed that applying the retrofitting measures individually (i.e., using light colour with low solar absorptivity, replacing the glazing system to have lower shading coefficient and U-value, and the installation of external shading systems with low shading coefficient) can decrease the OTTV by 26% to 33.4%. However, combining these measures managed to decrease the OTTV by up to 75.6% (i.e., the OTTV decreased from 82.87 W/m² to 20.19 W/m²). This can improve the building energy efficiency as it contributes to less cooling load for the air-conditioned buildings, while it provides a better indoor environment in non-air-conditioned buildings.

1. Introduction

Malaysia has recently maintained high levels of economic growth, which led to a considerable increase in the country's energy consumption. For instance, the total energy consumption has increased from 26,167ktoe in 1997 to 62,489ktoe in 2017 [1]. Furthermore, the final energy consumption for the residential and commercial sector increased from 3,072ktoe in 1997 to 7,796ktoe in 2017. The domestic electricity in Malaysia increased rapidly due to enhancements in the living standards [2]. About 42% of the total electricity consumption in commercial buildings and 30%

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in residential buildings occurred due to air conditioners. The number of room air conditioners was 253,399 units in 1991, while it increased to 726,540 units in 2005 and 956,155 units in 2010. The energy sector is a major contributor to the high gas emissions [3], which is linked with climate change and global warming. As a large part of the energy consumption in buildings is associated with building's cooling, there is a high need to improve the energy efficiency in buildings to reduce building's energy consumption.

Energy efficiency is one of the six main criteria that were included in the Green Building Index (GBI) for evaluating the environmental design and performance of buildings in Malaysia [4]. These criteria include Energy Efficiency, Indoor Environment Quality, Sustainable Site Planning & Management, Materials & Resources, Water Efficiency, and Innovation. The GBI aims to assist the building sector to adhere to sustainable development. The assessed building can receive a maximum of 100 points in the GBI. Out of them, 23 points are achieved by evaluating the energy efficiency in buildings, which addresses the envelope thermal performance (13 points), renewable energy (5points), lighting and control (2 points), internet connectivity (1 point), and the maintenance (2 points). The thermal performance of the envelope is assessed by the Overall Thermal Transfer Value (OTTV) and the roof U-value.

The concept of OTTV was first introduced by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) [5], which is defined as the average cooling load gained in a building due to the choice of its envelope (excluding the roof) based on the outside conditions (weather) and a typical inside condition in an office building [6]. It was, then, adopted and developed in other countries such as Hong Kong, Singapore, Thailand, and Malaysia. The OTTV index assessment is utilized to control energy use in the building envelope, which aims to minimize the energy consumption of air-conditioning by reducing heat through the building envelope and, accordingly, improving the energy efficiency of the building. In other words, OTTV is a tool used to measure the thermal efficiency in the building envelope of the air-conditioned building. Even though the OTTV was developed for air-conditioned buildings, it is still considered a useful indicator for the thermal performance of non-air-conditioned buildings [7]. It offers a simple method to estimate the heat gain in buildings due to solar radiation through windows and conduction through walls and windows [6].

In Hong Kong, a staggering 90% of the energy consumption is attributed to buildings' air-conditioning [8]. Therefore, OTTV is a must in Hong Kong in accordance with the energy efficiency regulations for new commercial and hotel buildings. This is to ensure that their buildings are energy efficient and in compliance with the building efficiency goals. In Singapore, the OTTV formulas for the building's envelope and roof were reviewed in early 2000 and updated to Envelope Thermal Transfer Value (ETTV) and Roof Thermal Transfer Value (RTTV). Besides, since these formulas were developed for air-conditioned buildings, and due to the different air-conditioning patterns in residential buildings, another formula was developed for residential buildings to evaluate their envelope's thermal performance and was named Residential Envelope Transmittance Value (RETV) [9].

In Malaysia, air-conditioning contributes to a substantial 60% of the energy consumption in office buildings. Therefore, it is a mandatory requirement that the OTTV should not exceed 50 W/m² for buildings with a total air-conditioned area of more than 1000m² [7]. This is an essential step so that awareness is raised and sustainable development is enhanced [7,10]. A building with an OTTV of 50 W/m² can receive one point under the GBI assessment. However, as the OTTV value goes below 50 W/m², more points can be given, which can reach a total of 10 points if the OTTV reached 30 W/m² or below, as can be seen in Table 1 [4].

Table 1
Received points based on OTTV value for the Green Building Index (GBI) [4]

	OTTV value	Detail points	Maximum points
Minimum performance requirements	OTTV ≤ 50 W/m^2 and Lightweight Roof U-value ≤ 0.4 W/m^2K OR Heavyweight Roof U-value ≤ 0.6 W/m^2K	1	1
Advanced performance requirements	OTTV ≤ 46 W/m^2, OR	1	9
	OTTV ≤ 42 W/m^2, OR	2	
	OTTV ≤ 38 W/m^2, OR	4	
	OTTV ≤ 34 W/m^2, OR	6	
	OTTV ≤ 30 W/m^2	9	

Yik and Wan [11] studied the appropriateness of OTTV as a measurement to regulate the envelope energy performance of air-conditioned buildings. The study was carried out in Hong Kong and the results showed that for 16 buildings that are situated in a sub-tropical climate region like Hong Kong, it is possible to achieve an acceptable correlation between OTTV and energy use for air-conditioning (with all other things being equal). This can happen only if we ignore heat transfer in buildings during the cold months. OTTV, which is calculated in this way, is a good reflection of the impact of the envelope performance on energy use for air-conditioning.

In Malaysia, a study of the OTTV for residential buildings was conducted by Saidur *et al.,* [10]. The study involved a survey for 100 residential building to collect the required information for OTTV calculating. The results showed that OTTV ranged between 35 and 65 W/m^2 with a mean value of 41.7 W/m^2. They mentioned that around 90% of the residential buildings had an OTTV range between 35 and 49 W/m^2. Based on the survey, the WWR was very low for the residential buildings and ranged between 0.01 and 0.18, which might be the main reason for the low calculated OTTV. The study investigated the effects of varying the influential parameters for OTTV calculation including WWR, SC, U-Value, and solar absorptivity. The results showed that SC, U-Value, and solar absorptivity had a great influence on the OTTV calculation.

Some researchers have utilized the OTTV to estimate the improvements that can be achieved in buildings thermal performance when applying some retrofitting measures. For instance, Ismail *et al.,* [12] conducted an assessment for the envelope of a 38-storey office tower, known as the 4G11 Tower, which is an iconic high-rise building in Putrajaya, Malaysia and regarded as the nation’s pride. Initially, the 4G11 Tower has an OTTV value of 77.43 W/m^2. The assessment intended to retrofit the building to be more energy-efficient without changing the physical appearance or the building’s facade. By varying three variables, namely U-Value, Shading Coefficient (SC), and WWR, the assessment managed to decrease the OTTV to 28.43 W/m^2. Kandar [13] studied the impact of a self-shaded strategy in high-rise buildings on minimizing the amount of OTTV. The results showed a reduction of 68.94 × WWR (Window to Wall ratio) for Malaysia. The impact of the self-shaded strategy can be more significant if the number of WWR increases. This is an effective approach in architectural design, which can have more flexible building’s facade designs, more energy-efficient, and greener building development.

In this work, the OTTV was used to evaluate the retrofitting of high-rise residential building to improve its envelope thermal performance for more energy efficiency. The retrofitting involved measures that can be applied without the need to introduce major renovation, including solar absorptivity of the colour for the opaque wall, U-value and shading coefficient of the Glazing system, and type and projection of the external shading. These measures were investigated separately and in combination to find out their influence in improving the OTTV value.

2. Methodology

2.1 Case Study Building

Mutiara Idaman 2 is a high-rise residential building located at Solok Tengku, Jelutong, Penang. It consists of four blocks of 16 and 21 floor and has a total of 690 units. It was built for medium-income families with a unit area up to 650 square feet. Local materials, such as cement bricks and plaster, were used for the building façade and was painted with two different colours (i.e., dark red colour for the lower floors and beige colour for the upper floors) as can be seen in Figure 1. The fenestration system has normal single glazing with a 100mm projection above and below the windows. Mutiara Idaman 2 is implemented elements of the post-modern architectural style characteristics, which were a common facade design during the period from 1990 to 2010, such as complicated shapes, triangular ends for the facades, and the pitched roof. This style was more concerned with the cultural identity influenced by the country’s historical background [14].

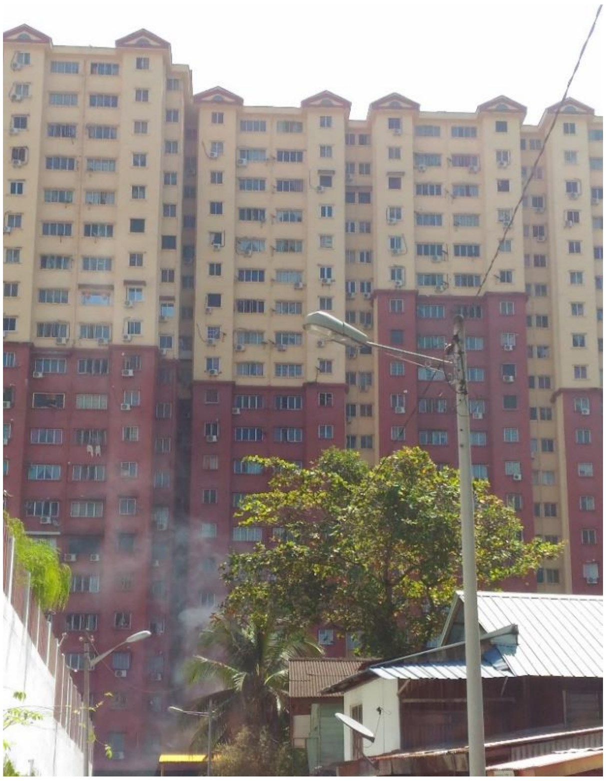

Fig. 1. Case study building; Mutiara Idaman 2

2.2 Principles of OTTV Calculation

The OTTV value indicates the average heat that is transferred into the building through its envelope, which consists of the opaque wall and the fenestration system (i.e., a glazing material, a shading device, and a combination of both). Therefore, the OTTV accounts for three main methods of heat transmits, namely heat conduction through opaque walls, heat conduction through fenestration system, and solar radiation through fenestration system [7,15]. Each of these components is calculated separately as can be seen in Table 2, while the sum of these three components produces the OTTV, as can be seen in Eq. (1).

Table 2
Main methods of heat transmission through building envelop and their calculations for OTTV

Heat transmission methods	Calculation for OTTV
Heat conduction through opaque walls,	15α (1 - WWR) Uw
Heat conduction through fenestration system	6 (WWR) Uf
Solar radiation through fenestration system	194 x OF x WWR x SC

$$OTTV_i = 15\alpha\,(1 - WWR)\,Uw + 6\,(WWR)\,Uf + (194 \times OF \times WWR \times SC) \quad (1)$$

where WWR is the Window-to-gross exterior wall area ratio for the orientation under consideration, α is the solar absorptivity of the opaque wall, Uw is the thermal transmittance of the opaque wall (W/m2 K), Uf is the thermal transmittance of fenestration system (W/m2 K), OF is the solar correction factor for the orientation of the fenestration under consideration, and SC is the shading coefficient of the fenestration system.

Since each orientation receives different incident solar radiation, the OTTV should be calculated for each orientation separately based on the OF value that can be obtained from Table 3.

Table 3
Solar correction factors for different orientations [7]

Orientation	North	Northeast	East	Southeast	South	Southeast	West	Northwest
OF	0.90	1.09	0.23	0.13	0.92	0.90	0.94	0.90

Then, the total OTTV for the building can be calculated based on the following equation:

$$\mathrm{OTTV} = \frac{(A_1 \times OTTV_1) + (A_2 \times OTTV_2) + (A_3 \times OTTV_3) + \cdots + (A_i \times OTTV_i)}{A_1 + A_2 + A_3 + \ldots + A_i} \quad (2)$$

where A_1 is the gross exterior wall area for orientation 1 and $OTTV_1$ is the OTTV value for orientation 1, which is obtained from Eq. (1).

2.3 Proposed Retrofitting Measures

As mentioned earlier, the OTTV considers three types of heat gain into the buildings. The first type of heat gain is the heat conduction through opaque walls, which is influenced by the WWR, the U-value of the materials, and the solar absorptivity of the external surface. The second type of heat gain is the heat conduction through the fenestration system, which is influenced by the WWR and the U-value of the glazing type. The last type of heat gain is the solar radiation through the fenestration system, which is influenced by the WWR, the shading coefficient of the glazing type, and the type and projection of the external shading system. As this retrofitting is intended to not implement measures that can result in major renovations, the proposed retrofitting measures include the following

i. The colour of the opaque wall (i.e., solar absorptivity), Table 4.
ii. The glazing type (i.e., U-value and shading coefficient), Table 5.
iii. The type and projection of the external shading, Table 6.

These proposed retrofitting measures are evaluated separately and in combination to identify their influences on the OTTV compared to the original case.

Table 4
Solar absorptivity of the opaque wall with different paint colour [16]

Opaque wall paint	Absorptivity
Flat black paint	0.95
Dark grey paint	0.91
Dark brown paint	0.88
Medium light brown paint	0.8
Medium orange paint	0.58
Medium blue paint	0.51
Light green paint	0.47
Light grey paint	0.4
White gloss paint	0.25

Table 5
Different types of glazing for the retrofitting [17]

Glazing type		Thick	U-value	SHGC	SC
Single	Clear float	4	5.88	0.85	0.98
	Tented grey float	5	5.85	0.62	0.71
	Low-E reflective clear	6	4.12	0.59	0.69
	Low-E laminated	6.38	3.6	0.52	0.6
Double	Clear + clear (4-12-4)	20	2.73	0.74	0.86
	Clear + Low-E (4-12-4)	20	1.9	0.69	0.81
	Tented grey + clear (5-12-4)	21	2.73	0.5	0.58
	Tented grey + Low-E (5-12-4)	21	1.89	0.45	0.52

Table 6
Different types and projections of external shading devices for the retrofitting [7]

	Horizontal	Vertical	Egg-crate
Projection/ Window Height	0.3-0.4		0.4
	0.5-0.7		0.6
	0.8-1.2		0.8
	1.3-2		1.2
Projection/ Window Width		0.3-0.4	0.4
		0.5-0.7	0.6
		0.8-1.2	0.8
		1.3-2	1.2
Shading Coefficient	0.79	0.86	0.64
	0.71	0.81	0.56
	0.65	0.77	0.42
	0.61	0.74	0.38

3. Results and Discussion

The OTTV was calculated for the building with various retrofitting measures, which includes Opaque wall's paint colours, glazing types, and external shading device. The results are illustrated in Figure 2. As can be seen, the use of light colours reduces the OTTV due to the lower solar absorptivity, Figure 2(a). The reduction reached a maximum of 21.05 W/m² with the white colour compared to the originally used dark brown colour. The white colour has an average solar absorptivity of 0.25 compared to 0.88 for the dark brown colour. The use of the other light colours, such as light grey and light green decreased the OTTV by 16.04 W/m² and 13.70 W/m², respectively.

Furthermore, using different glazing types with lower U-value and lower SC resulted in decreased OTTV, Figure 2(b). The maximum achieved reduction in OTTV when using single glazing type was 20.73 W/m² with the low-E laminated type, while the reduction increased to 26.94 W/m² when using double grey low-E glazing with air fill. Moreover, Figure 2(c) demonstrates the OTTV for the different external shading devices. It is obviously seen that the use of horizontal shading devices was more effective than using vertical shading devices. The maximum reduction on OTTV reached 17.41 W/m² with the horizontal shading devices, while it was 11.61 W/m² with the vertical shading devices. However, the reduction increased to 27.68 W/m² when using Egg-crate shading devices.

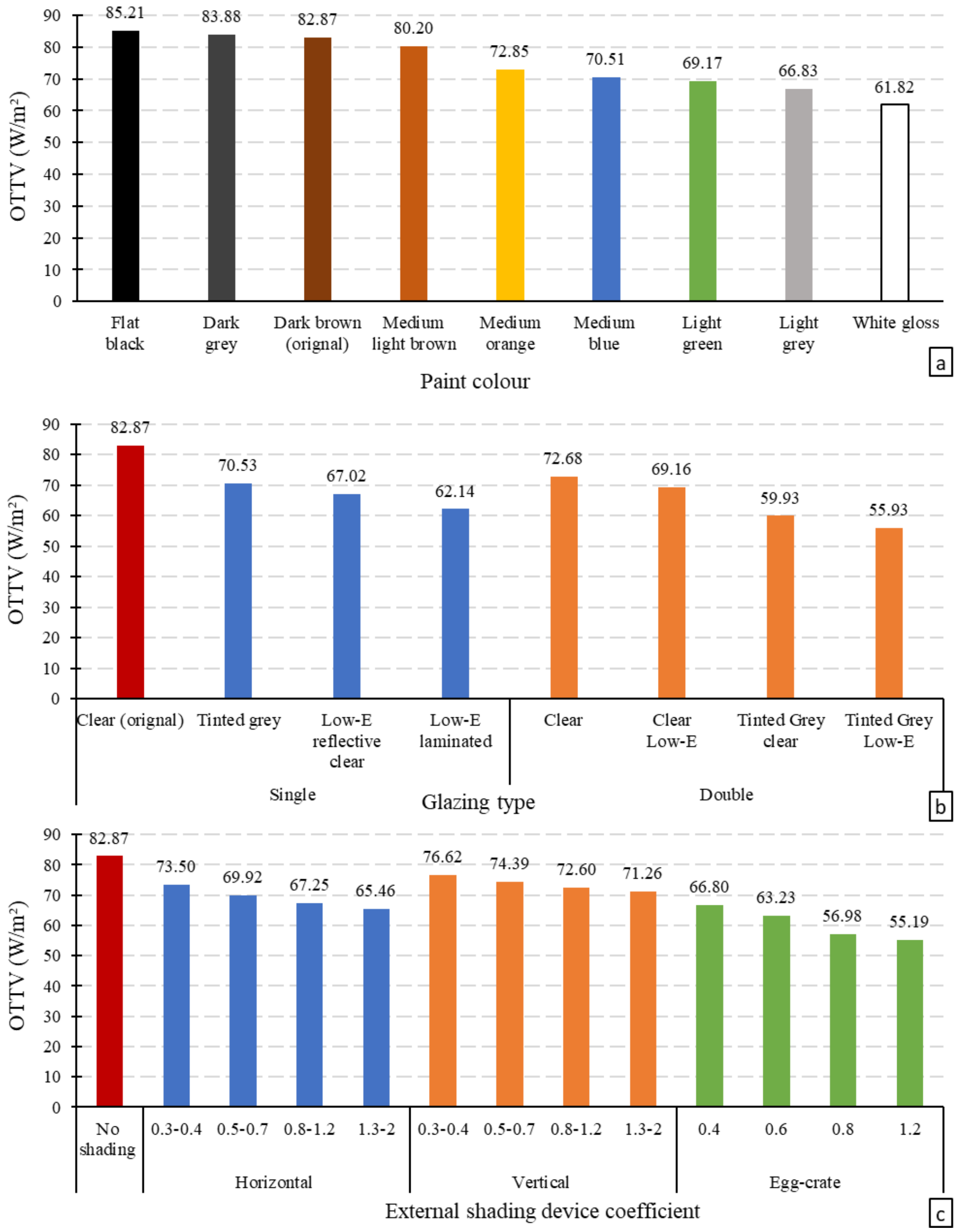

Fig. 2. The calculated OTTV using (a) Different paint colours (b) Different glazing types (c) Different external shading types and projections

The maximum reduction on OTTV ranged between 21.05 W/m² and 27.68 W/m² when applying the suggested retrofitting measures separately. However, combining their effects resulted in more reduction for the OTTV. For instance, by applying the white colour for the opaque walls, which decreased the OTTV to 61.82 W/m², in combination with different glazing types, the OTTV decreased further to the minimums of 41.09 W/m² and 34.88 W/m² for the single and the double-glazing types, respectively, which corresponds to total OTTV reductions of 41.78 W/m² and 47.99 W/m², respectively, compared to the original OTTV, Figure 3.

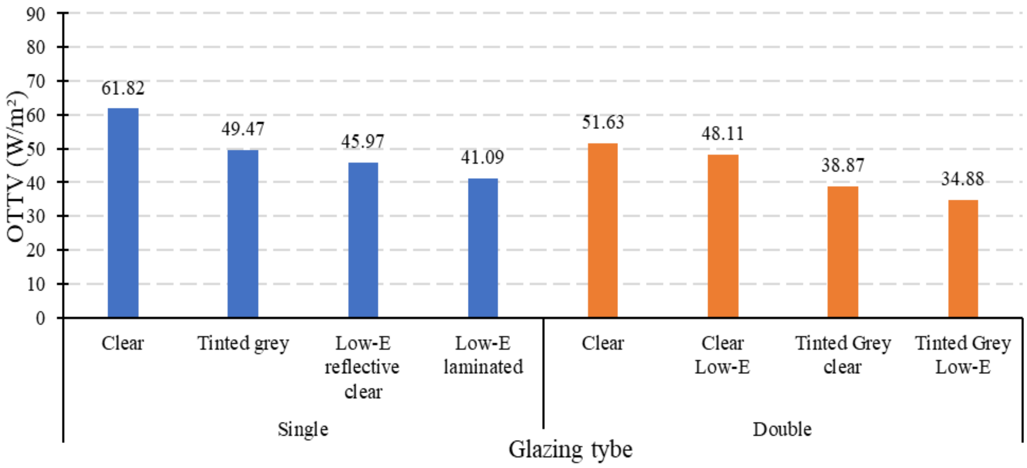

Fig. 3. Influence of the different types of glazing systems with the white coloured opaque walls

The lowest achieved OTTV based on the opaque wall colour and the glazing type was 34.88 W/m². This value can be further decreased to 25.64 W/m² and 20.19 W/m² by introducing horizontal and egg-crate shading devices, respectively, which increased the total OTTV reductions to 57.23 W/m² and 62.68 W/m², respectively, compared to the original OTTV, Figure 4.

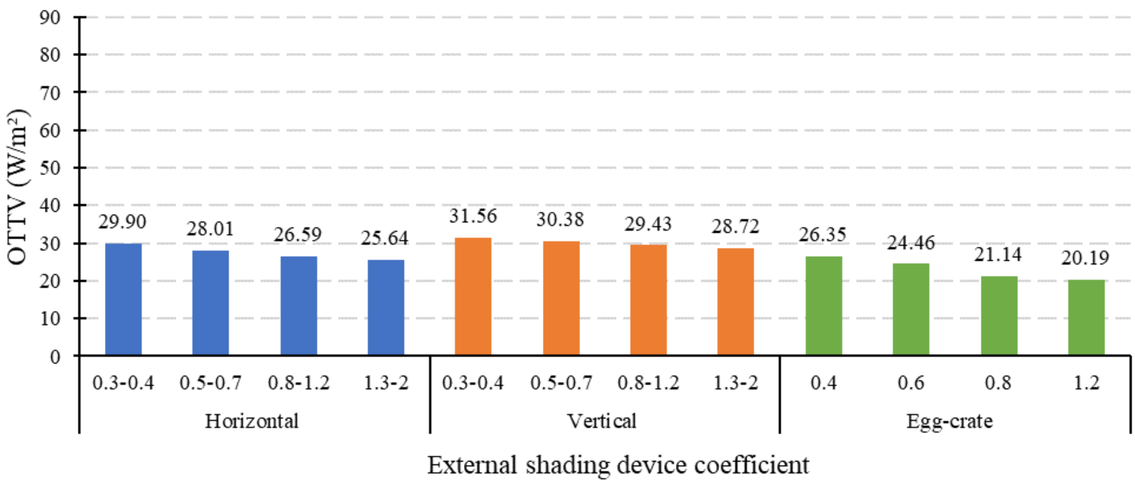

Fig. 4. Influence of different types and projections of the external shading devices when using the white coloured opaque walls and the double tinted-grey Low-E glazing system

It can be said that the retrofitting of the building with the proposed alternatives can decrease the OTTV by up to 75.6%, which means less heat gain to the indoor environment of the building. This can improve the building energy efficiency as it contributes to less cooling load for the air-conditioned buildings, while it provides a better indoor thermal environment for the non-air-conditioned buildings. The use of OTTV has made it easier to evaluate the proposed retrofitting measures to improve the building's energy efficiency and meet the energy security target in Malaysia [18].

4. Conclusion

This study investigated the use of the OTTV as a method to evaluate the retrofitting of an existing residential building to improve the building's energy efficiency. The proposed retrofitting measures, which are considered in the OTTV calculation and can be implemented for existing buildings are the opaque wall colour (i.e., the solar absorptivity), glazing type (i.e., U-value and shading coefficient), and the external shading type and projection. The following points can be concluded

i. The maximum achieved reduction on the OTTV was between 21.05 W/m^2 and 27.68 W/m^2 (i.e., 26% - 33.4%) when applying the suggested retrofitting measures separately (i.e., light colour with low solar absorptivity for the walls, glazing system with lower shading coefficient and U-value, and external shading systems with low shading coefficient).
ii. Combining the suggested retrofitting measures resulted in a further decrease in OTTV and the reduction reached a maximum of 62.68 W/m^2 (i.e., 75.6%).
iii. The OTTV make it possible to evaluate the proposed retrofitting measures in order to achieve the best or a targeted result.

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