Forming a Unitary Envelope Thermal Performance Index for Office Buildings in Taiwan

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Abstract

It is a crucial method to mitigate greenhouse gas emission and save building energy by complying the formulated regulations on buildings' envelope efficiency design. The existing Taiwanese building technical regulation provides three evaluation alternatives to comply with while developing a building envelope design scheme. Each evaluation alternative uses different index to direct a building's envelope energy efficiency design. However, it exhibits inconsistencies among these alternative methods including the use of different building design and climatic parameters, which would result in counterintuitive contradictions in some certain evaluation cases. To solve this phenomenon, this study attempts to integrate the three evaluation methods and propose a new index to regulate the building envelope's energy efficiency design.

Introduction

The Taiwanese government has released an annual energy consumption performance index to assess the thermal performance of building envelopes in 1995. The method has provided a maximum allowable annual sensible cooling load for the perimeter of a building. The sensible cooling load in the perimeter of a proposed building, over a whole year, must be lower than the benchmark value designated for the climates of different regions. This method allows for a trade-off between some design factors, such as window openings and external walls, to preserve some design flexibility. Taiwan's currently in-force building performance index is called ENVLOAD (Ministry of the Interior of Taiwan, 2011), which is calculated using Equations 1-5.

$$ENVLOAD = -20370 + 2.010 \cdot IG + 0.033L \cdot CDH + 1.079 \sum_i M_i \cdot SF_i \quad (1)$$

$$IG = 13.5(a_0 + a_1 \cdot T_u + a_2 \cdot T_u^2) \quad (2)$$

$$T_u = \frac{13.5}{L} \quad (3)$$

$$L = \frac{\sum_i (U_{w,i} A_{w,i}) + 0.5 \sum_i (U_{w,i} A'_{w,i})}{A_p} + \frac{\sum_i (U_{f,i} A_{f,i}) + 0.5 \sum_i (U_{f,i} A'_{f,i})}{A_p} + 1.011 \quad (4)$$

$$M = \frac{\sum_i (K_i \eta_i A_{f,i}) + 0.5 \sum_i (K_i \eta_i A'_{f,i})}{A_p} + \frac{0.035 [\sum_i (U_{w,i} A_{w,i}) + 0.5 \sum_i (U_{w,i} A'_{w,i})]}{A_p} \quad (5)$$

where, IG is the internal heat gain in W/m^2K ; L is the heat loss factor of building envelope in W/m^2K ; CDH is the annual total cooling degree-hours based on $23^\circ C$; M_i is the solar heat gain corrected factor of i orientation of the building envelope; SF_i is the annual total solar insolation of i orientation in Wh/m^2 ; T_u is the average room temperature increment in $^\circ C$; a_0 to a_2 are regression coefficients; U_w is the thermal transmittances of external walls in W/m^2K ; U_f is the thermal transmittances of external windows in W/m^2K ; K_i is the external sunshade shading coefficient of i orientation; A_w is the areas of the external walls for air-conditioned zones in m^2 ; A'_w is the areas of the external walls for non-air-conditioned zones in m^2 ; A_f is the areas of fenestrations for air-conditioned zones in m^2 ; A'_f is the areas of fenestrations for non-air-conditioned zones in m^2 ; A_p is the total floor area of the air-conditioned perimeter zone in m^2 .

In Equation 1, the ENVLOAD equation was developed based on numerous building cooling load simulation cases and was established using multiple regression technique. It includes three terms, i.e. the G , $L \cdot CDH$, and $M_i \cdot SF_i$ terms, the first term denotes to the annual internal heat loads from the occupants, lighting, and equipment; the second term stands for the heat insulation capabilities of a given building; and the third term accounts for the building's solar shading capabilities.

In the 1990s, after Taiwan began using ENVLOAD as the thermal performance index of envelopes, other than the simplified correction proposed by Wang and Lin (2015) and the natural ventilation correction coefficient proposed by Lai (2008), it has not been further subjected to review or correction. Some studies have extended the applications of ENVLOAD. For example, Hwang and Hsu (2011) used a visitor center as an example to explore the influence of ENVLOAD on air conditioning energy consumption and indoor thermal comfort. Chen and Lin (2017) established a method to predict the maximum air conditioning load using the ENVLOAD indicator. Shih et al. (2018) combined building energy simulation techniques through an uncertainty analysis to prove that both ENVLOAD and the overall thermal transfer value

(OTTV), both envelope thermal performance indices commonly used in Southeast Asian countries, can be converted into each other. Hwang et al. (2018) suggested that OTTV can be used to replace ENVLOAD; they analyzed a correction for the OTTV calculation formula and generated a benchmark value in response to future climate warming.

However, the evaluation equations of ENVLOAD are too numerous and there are too many variable combinations, leading to a complicated calculation and a cumbersome use of look-up tables. The equations are thus inconvenient to use in practice. Therefore, another aim of this study is to formulate and specify a new index equation for the thermal performance of a building envelope that can account for the accuracy of the prediction, while simultaneously being succinct and convenient to use.

Methods

Definition of the performance metric

In order to eliminate problems caused by the derivation of meteorological parameters (CDH and SF), one of the solutions is to change the current passing standard (the requirement that the annual sensible cooling load for the perimeter of a proposed building be lower than a certain benchmark value) to a new requirement (that the ratio of annual sensible cooling loads for perimeter zones between a proposed building and a specific baseline building, called the performance rating (PR), be lower than a certain value). In this paper, the performance rating is the main basis for developing the envelope performance index. The performance rating for each side of a proposed building's envelope is defined as:

$$PR = 100 \times \left(\frac{L_p}{L_b} - 1 \right) \quad (6)$$

where, L_p refers to the annual sensible cooling load per square meter of envelope area in the perimeter of a proposed building; and L_b refers to the annual sensible cooling load per square meter of floor area in the perimeter of a baseline building.

The seasonal sensible cooling load per square meter of floor and envelope area in the perimeter is expressed in Equation 7. SC is the product of the glazing shading coefficient and the external sunshade shading coefficient, i.e., $SC = 0.87\eta$. SF is the solar radiation incident on the south-facing external wall during the cooling season. CF is the correction factor for the solar radiation azimuth, which is defined as the ratio of all-season solar radiation incident in any orientation to the solar radiation incident from the south. The WWR , U_w , U_f , and η are varied simultaneously to generate a sufficient number of proposed building cases; the L_p of these cases is obtained by performing energy consumption simulations. The numerical values of $\sum(T_e - T_i)$, $\sum(T_o - T_i)$, $\sum SF_o$, and $\sum IG$ in Equation 7 can be obtained using regression analysis. In the above terms, the T_e denotes equivalent temperature, T_i is the indoor temperature, T_o is the outdoor ambient temperature.

The sensible cooling load per square meter of external wall area in the perimeter of a baseline building is the numerical value of the sensible cooling load obtained by substituting $WWR=0.31$, $U_w=0.857 \text{ W/m}^2\text{K}$, $U_f=3.24 \text{ W/m}^2\text{K}$, $K=1$, $\eta=0.25$, as well as the average CF corresponding to the proposed building's orientation at azimuths of 90° , 180° , and 270° , into Equation 7.

$$L_p = (1 - WWR)U_w \sum (T_e - T_i) + WWR \cdot U_f \sum (T_o - T_i) + SC \cdot CF \cdot WWR \sum SF_o + \sum IG \quad (7)$$

In fact, the average value of the 4 CF s obtained from the rotation 0° , 90° , 180° , and 270° is almost equal to the average values at all orientations. As for the baseline buildings in any climate, since the WWR , U_w , U_f , K , η , and CF substituted into Equation 7 are constant, meaning that L_b is also a constant value, only the constant L_b value will differ with different climates. Therefore, the PR defined in Equation 6 can be expressed as:

$$PR = \left[\frac{100 \sum (T_e - T_i)}{L_b} \right] (1 - WWR) \cdot U_w + \left[\frac{100 \sum (T_o - T_i)}{L_b} \right] \cdot WWR \cdot TD \cdot U_f + \left(\frac{100 \sum SF}{L_b} \right) \cdot WWR \cdot SC \cdot CF + 100 \left(\frac{\sum IG}{L_b} - 1 \right) \quad (8)$$

In the same way, the numerical values of $100 \sum (T_e - T_i)/L_b$, $100 \sum (T_o - T_i)/L_b$, $100 \sum SF/L_b$, and $100(\sum IG/L_b - 1)$ in Equation 8 can be obtained by regression analysis as long as there are sufficient PRs in the proposed buildings.

Building model

The required performance index equation is obtained in this paper by using EnergyPlus to conduct simulations on the energy consumption of an office building model. The typical office building model shown in Figure 1 is used. The typical building plan is divided into 4 air-conditioned perimeter zones, as well as other zones with inner-perimeter air-conditioned spaces and non-air-conditioned spaces, such as stairs, elevators, or restrooms. Perimeter zones refer to indoor spaces within a distance of 5 m from external walls, which are susceptible to the heat flow entering from the envelope. The 4 air-conditioned perimeter zones are spaces of interest and are analyzed in this paper. The other zones are not considered and outside the scope of the energy consumption simulations. The local meteorological data of a typical meteorological year (TMY3) has been used, assuming that the building is located in three climate regions in Taiwan represented by three cities: Taipei, Taichung, and Kaohsiung. The climatic and geographical properties are briefly summarized in Table 1.

As the focus of this study is to formulate and specify a new index equation for the thermal performance of a building envelope, the methodology is based on energy simulations conducted for a large number of different office building models, as well as multiple regression

analyses. Therefore, the parameters involved are the ambient temperature of the building's location, the intensity of the solar radiation, the orientation of envelope, the window to wall ratio (WWR), the wall's U-value (U_w), the glazing's U-value (U_f), the glazing's SHGC, and the external sunshade depth ratio. These 6 parameters are also the architectural design parameters used in the calculation of the ENVLOAD index.

Figure 1: Floor plan of the typical office building.

Table 1: Summary of the geographical data and the climate of the studied cities.

Locations	Coordinates	Annul HDD ₁₈ (K.hrs)	Annual CDD ₁₈ (K.hrs)	Annual global horizontal solar radiation (kW/m ²)
Taipei	N25.0, E121.5	194	2139	6641.9
Taichung	N24.1, E120.7	134	2344	8572.9
Kaohsiung	N22.6, E120.3	25	2768	7914.5

In order to obtain a sufficient number of building models, this paper uses Latin hypercube sampling from a uniform distribution to generate 1,000 simulated samples with different combinations of envelope thermal performances. Table 2 shows the range of variation for these input variables. Other variables, such as the internal load and the air conditioning operative controls, are not included in the modelling process to facilitate observations of the unique effects of the passive thermal performance design on the annual sensible cooling load. The air-conditioning system was set to only operate on working days from May 1st to September 30th during the main cooling season; the operation time period is 07:00-19:00. Referring to the ASHRAE 62.1 Standard (2004), the fresh air exchange rate is provisioned to be 8.5 L/s per person. The density of occupants is 0.15 person/m², the lighting density is 11.8 W/m², and the density of the office equipment heat generation is 12.5 W/m². The occupant, lighting, and equipment usage schedule are ascertained according to ASHRAE 90.1 Standard (2013). Since there are no

provisions for the performance of a baseline building envelope in Taiwan, this paper directly adopts the relevant provisions of a baseline building envelope performance from ASHRAE Standard 90.1 appendix G; these provisions are listed in Table 2. The indoor thermostat control is a dry-bulb temperature control and is set at 24°C constant during the hot season.

Results and Discussions

Simulation results

In order to illustrate the uncertainty triggered by the architectural design parameters, variations in the seasonal sensible cooling loads per square meter of perimeter zone of all proposed building cases obtained from the EnergyPlus simulation, for all the three cities, are presented using histograms and statistical values. Figure 2 has shown the range of possible seasonal sensible cooling loads and the probability of each interval in the three cities. For the seasonal sensible cooling loads, the Taipei range is between 86 kWh/m² and 182 kWh/m², the Taichung range is between 87 kWh/m² and 200 kWh/m², and the Kaohsiung range is from 91 kWh/m² to 189 kWh/m². Obviously, Taipei has the lowest seasonal sensible cooling loads and the largest loads occurred in Taichung. The mean seasonal sensible cooling loads for Taipei, Taichung, and Kaohsiung are 112 kWh/m², 118 kWh/m², and 122 kWh/m², respectively.

Table 2: The input variables, variation ranges, and the baseline values of the building model.

Input variables	Ranges	Baseline values
Orientation (degree)	0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°	The baseline building performance shall be generated by simulating the building with its actual orientation and again after rotating the entire building 90, 180, and 270 degrees, then averaging the results.
Width of the perimeter zones	10-50 (m)	Same as the proposed building design.
Window-to-wall ratio	0.1-0.9	0.310
U-value of the exterior wall	0.5-5.0 (W/m ² K)	0.857 (W/m ² K)
U-value of the fenestration	1.0-5.5 (W/m ² ·K)	3.240 (W/m ² K)
SHGC of the fenestration	0.1-0.85	0.25
Depth ratio of the exterior shading	0.0-2.0	no shading projections

The most commonly-seen seasonal sensible cooling load interval in Taipei, Taichung, and Kaohsiung are 110 kWh/m², 110 kWh/m², and 115 kWh/m², respectively. Moreover, the difference between the minimum and maximum seasonal sensible cooling loads is also different among the three cities; they are 96 kWh/m², 113 kWh/m², and 98 kWh/m² for Taipei, Taichung, and Kaohsiung,

respectively. The ratio of uncertainty can be defined by observing the standard deviations, which are 13 kWh/m², 17 kWh/m², and 16 kWh/m², respectively.

The results presented in Figure 2 mean that the design parameters have a considerable influence on the variation of the seasonal sensible heat-cooling load. Therefore, the architect should confirm at the early design stage that the proposed building can provide a sufficient seasonal sensible heat-cooling load. By accounting for the local mandatory energy indices, architects can understand the possible range of seasonal sensible heat-cooling loads, because many of the energy indices have linear relationships with the seasonal sensible cooling load. Figure 3 is a scatter plot of the simulated annual sensible cooling load against ENVLOAD for the 3 cities, as obtained from the simulations on all the proposed building cases at 24 °C. In the plot, the linear regressions of L_p and ENVLOAD are also shown.

Figure 2: Variation of L_p for all cases in the three cities.

Figure 3: Scatter plots of L_p against ENVLOADs in the three cities.

Using the results of these simulations, the L_p equations for the three cities can respectively be obtained through regression analysis as:

Taipei:

$$L_p = 6.3(1 - WWR)U_w + 2.7 WWR \cdot U_f + 75.7 WWR \cdot SC \cdot CF + 84.5 \quad R^2 = 0.946 \quad (9)$$

Taichung:

$$L_p = 7.5(1 - WWR)U_w + 2.1 WWR \cdot U_f + 102.9 WWR \cdot SC \cdot CF + 85.0 \quad R^2 = 0.975 \quad (10)$$

Kaohsiung:

$$L_p = 7.8(1 - WWR)U_w + 3.7 WWR \cdot U_f + 91.3 WWR \cdot SC \cdot CF + 88.2 \quad R^2 = 0.956 \quad (11)$$

Establishing of a unitary envelope thermal performance index

From the EnergyPlus simulation results of various proposed buildings corresponding to a baseline building, we discovered that the seasonal sensible cooling load per square meter for baseline buildings, L_b , is almost identical to the numerical values obtained by substituting the provisioned WWR, U_w , U_f , K , η , and CF into Equations 9-11, where L_b is 98.3 kWh/m² in Taipei, 101.8 kWh/m² in Taichung, and 105.6 kWh/m² in Kaohsiung. By observing Figure 4, there are consistent PR probability distribution curves in the 3 investigated climate regions. Once again, the regression analysis is applied to the PRs of all proposed building cases, and the resulting regression formula is shown in Equation 12.

$$PR = 7.1(1 - WWR)U_w + 2.8 WWR \cdot U_f + 88.2 WWR \cdot SC \cdot CF - 15.7 \quad R^2 = 0.956 \quad (12)$$

Figure 4: The probability distributions of PR of all the proposed cases in the three cities.

Sensitivity analysis

A sensitivity analysis is executed to ascertain the contribution of each input variable to the variation of the designated output of a building model. In this paper, the sensitivity index used is a standardized regression coefficient (SRC). A standardized regression coefficient is used to measure the linear influences of each input variable (x_j) on the output variable (y), and is calculated by Equation 13, where $\bar{x}_j$ and $\bar{y}$ are the averages of the input and output, respectively.

$$SRC_j = \frac{\beta_j \sqrt{\sum_{i=1}^N \frac{(x_{i,j} - \bar{x}_j)^2}{N-1}}}{\sqrt{\sum_{i=1}^N \frac{(y_i - \bar{y})^2}{N-1}}} \quad (13)$$

While complying with local mandatory regulations, conducting sensitivity analyses on design parameters can assist an architect to examine the sensitive design parameters, so as to achieve a building possessing higher energy performance. During the building process, design requirements for the minimum cooling load can be

obtained by selecting the upper limit of the design parameters with negative SRC and by selecting the lower limit of the design parameters with positive SRC. Moreover, the magnitude of the SRC absolute value represents the importance of the design parameter. Based on the simulation results, the results of the SRC are summarized in Table 3.

Table 3: SRC comparison between the dry-bulb based and the operative temperature based control method.

Variables	CF	WWR	U_w	U_f	η	K
SRC	0.23	0.49	0.24	0.11	0.52	0.37

The glazing shading coefficient (η) has the largest SRC value (0.52). This indicates that the glazing shading coefficient has the most influence on PR. The second and the third most influential are the window to wall ratio (WWR) and the external sunshade shading coefficient (K), followed by the external wall U_w value, the window to wall ratio (WWR) and the fenestration U_f value. Though the value of the SRC for U_f is lower, its influence still needs to be considered.

Conversion of the baseline values

As a result of climate regions having different *CDH* and *SF*, climate zoning requires different formulas and benchmark values, shown in Equations 9-11. Through the standardization of Equation 8, this paper has found a single formula that is applicable for the envelope performance index of all cities in Taiwan, i.e., Equation 12 can be used as the single envelope performance index in Taiwan. The logic that converts the benchmark ENVLOAD to the benchmark PR is explained below. Taking Taipei City as an example, the benchmark ENVLOAD is 90kWh/m²year. Based on the linear regressions of L_p and ENVLOAD in Figure 3, the corresponding $L_p=124.8\text{kWh/m}^2\text{year}$ can be obtained. For the baseline buildings in Taipei, $L_b=98.3\text{kWh/m}^2$ and $PR = 100 \cdot (124.8/98.12 - 1) = 27.0$. This numerical value is the PR benchmark value corresponding to the currently in-force ENVLOAD benchmark value for the Taipei region. Benchmark values for PR in Taichung and Kaohsiung are 16.8 and 21.9, respectively.

Equation 12 is used as a formula because it can eliminate problems caused by a one-calculation-formula for one-climate-zone for different climates. Furthermore, the relative standards used in PR are unlike the absolute standards used in ENVLOAD; its benefits can help Government construction management units to understand the stringent standards required for benchmark values in different climates. For example, if the standard values of ENVLOAD in the three regions are 80, 90, and 115 kWh/m²year, it is easy to misinterpret that there are stricter standards in Taipei, and that Kaohsiung has a more lenient standard. However, PR tells us that, actually, the currently in-force Taiwan standard is the most lenient for Taipei, because it has the highest value calculated using the same index formula. This indicates that, in a given proposed building, for Taichung or Kaohsiung climates, there must be more stringent requirements for external wall U_w as well as window U_f

and SC in order to pass the mandatory regulations. If the construction management unit wants to have consistent requirements throughout Taiwan, this can be achieved with a single PR throughout the whole country; however, this cannot be achieved by using a consistent ENVLOAD because its calculation directly involves the local climatic conditions. Another benefit of the PR is that it directly indicates the percentage of sensible cooling load allowed in the proposed building compared to the baseline building. According to current standards, Taipei allows a proposed building to be at more than 27.0%, whereas Taichung and Kaohsiung only allow 16.8% and 21.9%, respectively.

Conclusion

This study has expounded the problematic points of the currently in-force building envelope energy consumption index in Taiwan (ENVLOAD), including the cumbersomeness of the practical evaluation process and the presence of unequal benchmark values for each climate region. Therefore, this study proposed the development of a thermal performance evaluation index for new building envelopes based on the performance rating. The advantage in the proposed method relies on removing the meteorological parameters from the original ENVLOAD, while preserving the main envelope design factors that influence the thermal performance of a building. Simultaneously, it is simplified to a single formula for all of Taiwan, which can greatly reduce the complexity of the assessment. The newly proposed index includes all the six building and two meteorological parameters that are currently used in the three existing indices, including building orientation, window-to-wall ratio (WWR), U-value of the exterior walls, U-value of the window glazing, solar heat gain coefficient (SHGC) of the glazing, the exterior shading of the window, cooling degree hours, and annual solar insolation. At the same time, the existing ENVLOAD benchmark is converted and applied to the new index. This study has reached the following important conclusions:

1. This study develops a new building envelope thermal performance evaluation index through a performance-based rating system compared with a baseline building.
2. The study has shown that the stringency level of currently in-force ENVLOAD benchmarks is not uniform, being the most lenient for Taipei and the most stringent for Taichung among the examined cities. However, if PR is used as an evaluation index, the unfairness due to the non-uniform level of stringency for building envelope energy management, which is generated by climate induced variations in benchmarks, can be eliminated.
3. Through the sensitivity analysis in this study, the importance of various building envelopes designs to the cooling load is in the following order: η , WWR, external sunshade K, and external wall U_w .

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