Building and Environment 86 (2015) 141–150

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

# Implementation of green building specification credits for better thermal conditions in naturally ventilated school buildings

Kuo-Tsang Huang [a], Wen-Pin Huang [b], Tzu-Ping Lin [c], Ruey-Lung Hwang [d], *

[a] Department of Bioenvironmental Systems Engineering, National Taiwan University, Taiwan
[b] Department of Architecture, Feng Chia University, Taiwan
[c] Department of Architecture, National Cheng Kung University, Taiwan
[d] Department of Architecture, National United University, Taiwan

A R T I C L E I N F O

*Article history:*
Received 13 September 2014
Received in revised form
21 December 2014
Accepted 6 January 2015
Available online 13 January 2015

*Keywords:*
Passive design
Green building
Naturally ventilated buildings
Overheating risk
Work performance

A B S T R A C T

Most campus buildings in public education in Taiwan are naturally ventilated. Since it is hot and humid in summer, these free-running classrooms are vulnerable to overheating, which may impair the students' learning ability. We studied a Diamond-certified green building campus to determine the effectiveness of the strategies adopted to prevent overheating by quantifying the in-room thermal comfort via long-term in situ monitoring of temperatures. The passive planning and design means used in the case are presented in detail, and the resulting synthesis effect in terms of the relation of indoor thermal comfort to student learning performance is also discussed. The maximum percentage of dissatisfaction in classrooms is 15–22% less than that in the outdoor condition, and the severity of overheating is 12.5%–18.5% of that of the outdoors. The average learning performance is around 1.3% higher than in the outdoor condition. The green building certification system (EEWH) practiced in Taiwan evaluates various aspects regarding thermal comfort enhancement, the studied naturally ventilated school building demonstrates that by complying to these EEWH credits the indoor thermal quality can successfully be ensured.



## 1. Introduction

Since Taiwan's green building certification system was launched in 1999, school administrators have begun to pay closer attention to sustainable approaches in campus planning and construction. A sustainable school building is a building that consumes less energy, water, and resources and produces less waste than a conventional one. Such a building can also improve the indoor environment. As the classroom is where students spend more than half of each day, it is imperative to ensure that the indoor conditions are suitable for the students to learn. Previous studies [1–3] have shown that indoor environmental conditions can strongly affect student performance. In fact, the influence of the indoor environment on academic performance may be greater than that on adult productivity in an office [4]. Several studies of children's thermal perception in English schools by Teli et al. [5–7] also found that children have a higher sensitivity towards feeling warm than adults. A classroom occupied by 25–35 students has a far denser population density than a typical office. The unique characteristics of the classroom magnify the necessity of building a healthy and comfortable green school.

An on-site investigation by Issa et al. [8] revealed that teachers and students in a green school building are more satisfied with the quality of the classroom environment and have less absenteeism, and students tend to have higher student learning performance than those in conventional schools. Barrett et al. [9] studied 34 classrooms also revealed that the impact of environmental factors alone account for 25% on the learning progression of students. Moreover, green educational facilities are usually highly visible venues for practicing sustainable design and construction principles because they provide a precious learning opportunity for educating faculty, administrators, students, and neighbor communities about the importance of building an environmentally friendly building [10].

Taiwan's green building certification system for campus buildings was implemented in 2003. As of December 2013, a total of 337 newly-built school buildings had been certified as green buildings. Fig. 1 shows the number of green school buildings certified each year. In the past decade, the green school movement has grown

* Corresponding author. Tel.: +886 37 381635; fax: +886 37 381643.
*E-mail addresses:* rueylung@nuu.edu.tw, rlhwang6202@gmail.com (R.-L. Hwang).

http://dx.doi.org/10.1016/j.buildenv.2015.01.006

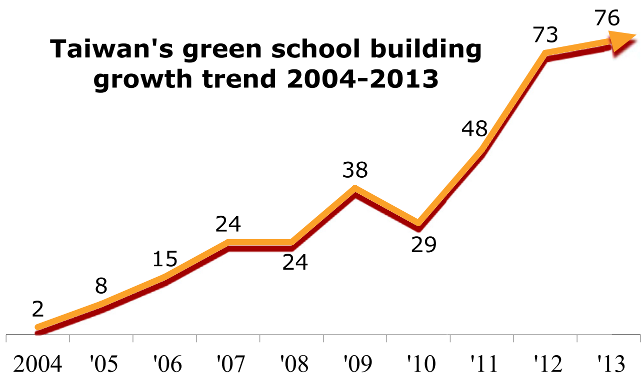


**Fig. 1.** Growing numbers of school buildings certified as green buildings during 2004–2013.

fast, from a few model buildings to a large-scale mainstream focus. The green building certification system in Taiwan, abbreviated as the EEWH system, comprises four major categories of building evaluation [11]: ecology, energy saving, waste reduction, and health. The EEWH system was expanded in 2004 to cover nine major indicators of building performance under the aforementioned categories, namely, biodiversity, greenery, water-soil content, energy savings, $CO_2$ emissions reduction, construction waste reduction, indoor environment quality, water resources, and garbage/sewage improvement. The EEWH certifies green buildings into five distinct levels: certified, bronze, silver, gold, and diamond.

In Taiwan, primary and junior schools usually do not have mechanical air conditioning apparatus in the past for the reason of energy saving. Natural ventilation is one of the viable options in alleviating summer overheating problem without the use of energy. A well designed building envelope with adequate microclimatic site planning can help facilitating cross ventilation and reducing interior heat gain, resulting in improving indoor thermal conditions of a naturally ventilated classroom. Paul and Taylor [12] compared a naturally ventilated green campus building with traditional one and confirmed that thermal comfort influences overall satisfaction with the workplace environment. Due to climate change, summer air temperatures are projected to rise in the near future, so naturally-ventilated classrooms in hot and humid climate regions may become severely overheated during the warmer months. In the past two decades, increasing amounts of attention have been focused on the issue of students' thermal comfort. Numerous significant studies have focused on this issue in hot and humid regions, such as Kwok [13] for Hawaii, Araujo and Araujo [14] for Brazil, Wong and Khoo [15] for Singapore, Ahmad and Ibrahim [16] for Malaysia, Hwang et al. [17] for Taiwan, and Zhang et al. [18] for the subtropical region of China. Obviously, it is possible to resolve the summer overheating problem by simply installing air-conditioning systems to maintain indoor thermal comfort. In the past decade, as the economy has grown, this approach has become the prevailing strategy for dealing with summer overheating in the classroom. However, this strategy conflicts with the goal of reducing the greenhouse gas emissions of buildings and is counter to the essence of sustainability. Even worse is that such a strategy will eventually lead to perceptions of air-conditioned environments as the norm, and plans to implement passive building design principles in many school architectural design practices may disappear completely.

Unlike air-conditioned buildings, where occupants' satisfaction depends simply on a single indoor environment indicator [19], naturally-ventilated buildings in the EEWH system are evaluated according to multiple indicators involving aspects of micro-climate, building envelope, and the occupants themselves. As an architect is managed to design a naturally ventilated building in complying with high certificated green building via EEWH system, he would prior consider the passive design strategies, by which would also lead to better indoor thermal environment. The indoor thermal condition, about which physical environments of a free floating space is majorly concerned, is deemed as a combination/synthesis outcome of these passive design effort. In order to describe how Taiwan's EEWH system is implemented to regulate and achieve indoor thermal comfort in practice, a Diamond-certified green building school was studied. This paper details the various design strategies implemented in the building to earn specific credits related to indoor thermal comfort improvement in achieving better thermal conditions in its naturally-ventilated classrooms. The purpose of this research is to evaluate the effectiveness of Taiwan's EEWH system in ensuring thermal comfort in naturally-ventilated classrooms.

## 2. Design concept and climatic characteristics

The study subject is a naturally-ventilated elementary school located in Taichung, central Taiwan. The school underwent a thorough renovation project from 2007 to 2011 to make its school campus and buildings sustainable. In the planning phase of the project, the planning team, led by the school principal and the architect, aimed to create a campus that would be regarded as a model example of sustainable design and practices, not only for its students and faculty, but also for communities both local and island-wide. As such, passive design techniques and thinking dominated the whole design process. The project team adopted Taiwan's green building certification and rating system as guidelines and criteria, which led to the success of this sustainable school. It is the highest-rated Diamond-certified green school in central Taiwan, according to the Architecture and Building Research Institute, Ministry of Interior, Taiwan (see Fig. 2). The school meets standards for eco-environment, energy and water use, indoor environment quality, and other significant factors. Consistent with the purpose of this study, only strategies implemented in the school aiming to minimize the potential for overheating during warm periods are mentioned and discussed in section 3.

Since the outdoor climate affects the amount of heat flux transferring into buildings, the indoor thermal condition of a building with natural ventilation is closely related to the outdoor climate. Without the aid of a mechanical cooling system, the indoor thermal condition of a free-running building is mainly determined or regulated by its


**Fig. 2.** The green building designation for the case study.

building orientation and the thermal efficiency of the building envelopes. In general, the Taichung region (24° 08′ N, 120° 40′ E) is hot and humid in summer but mild and humid in winter. The annual fluctuation of temperatures is shown in Fig. 3. In summer, the maximum and minimum temperatures are 35.1 °C and 22.6 °C, while in winter, they are 29.3 °C and 9.1 °C. Throughout the year, the monthly average relative humidity ranges from 65% to 79%. Maximum daily mean outdoor wind speed varies from 4.8 to 8.6 m/s. The prevailing wind directions during summer and winter are SW and NE, respectively.

## 3. Strategies adopted in the design

### 3.1. Credits relating to enhance thermal comfort

The indoor thermal comfort condition of a building is the product of interactions between the external climate, building shell, and internal space, as well as occupant adaptation to a specific thermal comfort range. The influential factors can be categorized into three aspects [20]: (1) environmental factors, including external climatic conditions and microclimatic profile; (2) building related factors, including building shape, building form, and the properties of the building materials and its envelope; and (3) occupant-related factors, including internal heat gain and occupant behavior. Credits related to the above three categories in the EEWH certification system are as follows and are illustrated in Fig. 4:

- Microclimate-related credits: site greenery and water-soil content.
- Building-related credits: availability of natural ventilation, availability of daylight, avoidance of solar heat gains, and enhancement of roof insulation.
- Occupant-related credits: efficiency of lighting system and facilities to increase air speed.

The following sections describe the various passive means adopted in the design of a school in Taichung in order to earn thermal comfort related credits.

### 3.2. Microclimate-related credits and strategies

Indices for the environmental microclimate in the EEWH certification system are the greenery indicator and the water-soil content indicator.

- Greenery

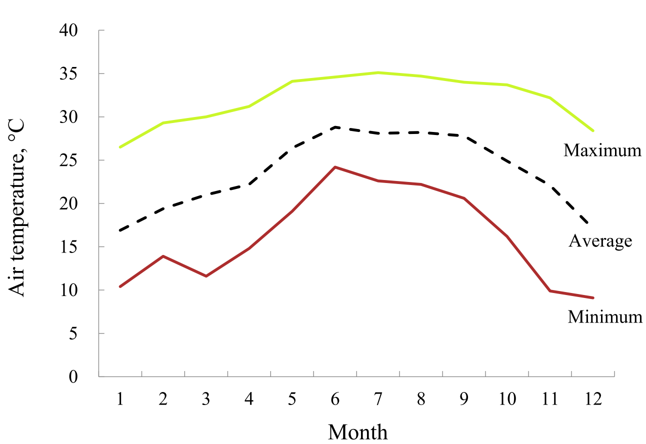


**Fig. 3.** The annual variation of maximum, minimum, and average air temperatures in Taichung.

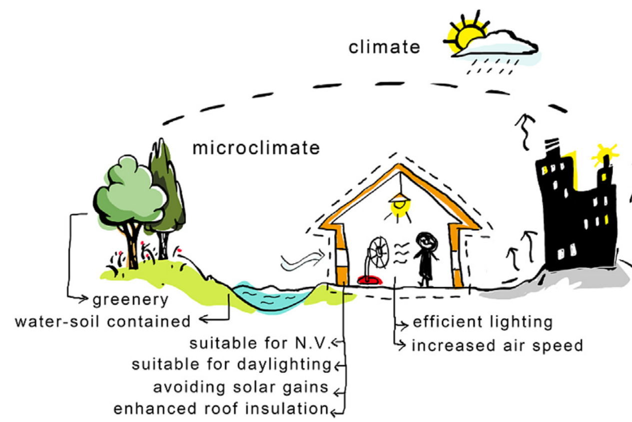


**Fig. 4.** Credits in the EEWH system related to indoor thermal comfort.

The amount of quantified carbon sequestration of plants during a 40-year life span is the basis of evaluation in the greenery indicator. Since the amount of carbon sequestration is proportional to the amount of leaves a certain plant possesses, planting large evergreen trees earns more credits in the greenery index assessment. When greenery is planted, especially big trees, the amount of moisture in the air is increased, and the air temperature is decreased by evapotranspiration of the greenery, which provides a more comfortable environment [21]. Fig. 5(a) shows the greenery condition of the campus of the school in Taichung. Most of the outdoor spaces, except for the playground, car park, and pedestrian walkways, are planted with grass, bushes, or trees. Furthermore, more than half of the rooftop area of the school buildings is planted with drought-resistant grass. The credit earned surpassed the criterion for greenery index certification by a factor of 1.3.

- Water-soil content

The water-soil content index aims to certify the potential of a site to retain rainwater. A site that retains water has a greater potential for decreasing the air temperature by evaporation of the water contained in the soil than one which does not retain water. According to on-site research conducted in Taiwan [22,23], ground surfaces planted with grass or paved with permeable materials are capable of substantially alleviating high outdoor temperatures and increasing outdoor thermal comfort. Strategies related to water-soil content adopted on the Taichung campus included preserving vast areas of green fields, building permeable rain water drainage ditches connected to a rainwater permeable retention pond, and permeable interlocking brick paving in all pedestrian ways and the car park. The credit earned surpassed the criterion for water-soil content index certification by a factor of 2.7.

### 3.3. Building-related credits and strategies

Indices related to the building itself include the indoor environment index and the energy saving index. The indoor environment index evaluates the indoor ventilation and daylight requirements, and the energy saving index evaluates the solar shading and the insulation requirements of walls and roofs.

- Availability of natural ventilation

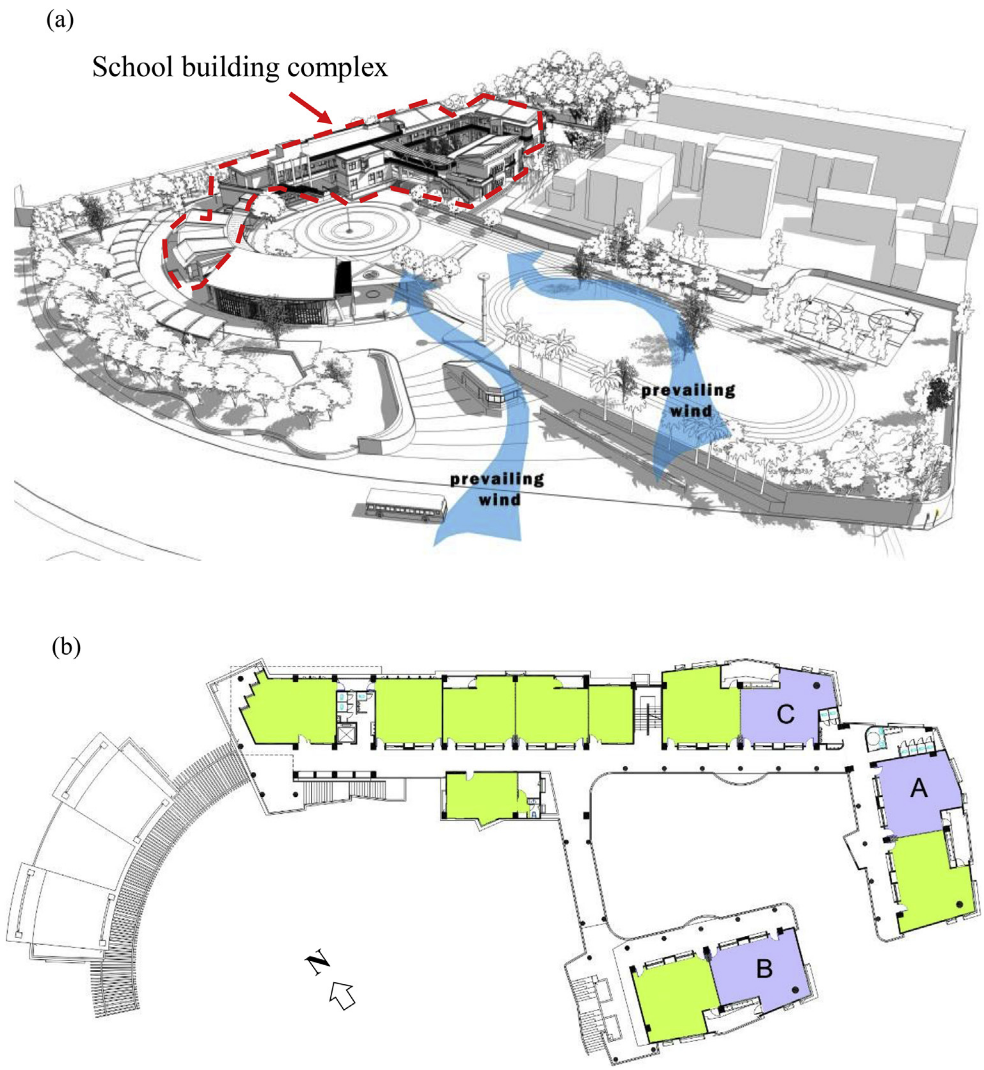


**Fig. 5.** (a) Arial view of the whole campus shows the layout of greenery and the buildings allocated according to local prevailing winds. (b) Location of the measured classrooms on the 2nd floor plan. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Before planning and designing a particular site, it is crucial to understand local wind conditions. Fig. 6 depicts the arrangement of the campus buildings according to local prevailing wind conditions to create ideal indoor comfort conditions. In summer, the thermal comfort of a free-running classroom is primarily maintained by sufficient internal air movement, preferably by utilizing light wind. To facilitate effective cross ventilation in summer, the campus buildings are spread out. The distance of the cross-ventilation path between two opposite windows also complies with the EEWH guideline that the path of the wind across the room should be less than five times the height of the space for all classrooms.

Sufficient wind-driven cross ventilation, developed by appropriate sizing and allocating of fenestrations with adequate indoor wind velocity, is able to remove heat resulting from internal heat gain, conduction of heat gain, and heat storage. It is crucial to maintaining thermal comfort during hours of occupation. However, for times when there is no wind, the building also employs buoyancy-driven stack ventilation. In this regard, the ceiling of the top story classroom is lifted and single-sloped windward to the local prevailing wind to increase the area of the cross-section for cross ventilation and also facilitate buoyancy ventilation. The design of the sloped roof and the raised ceiling raises the neutral pressure level as high as possible, allowing most of the induced cool, fresh air to flow through the majority breathing zone. The school earned natural ventilation credits in the EEWH system by means of adopting the above-mentioned passive strategies for facilitating indoor thermal comfort and air quality.

- Avoiding solar heat gains from windows

One of the disadvantages of a spread-out building plan is that more of the external surfaces of the buildings are exposed to solar radiation and outside air temperatures, which could possibly cause indoor overheating in warm months. To prevent this problem, detached shades or attached overhangs/fins are needed to block the solar radiation. Previous researchers have noted that solar radiation and the thermal properties of the window glazing severely influence the thermal comfort of occupants near a building's glazed perimeter zones [24–26].

Taiwan's building energy regulation requires that campus buildings comply with Averaged Window Solar Gain (*AWSG*) criteria, the purpose of which is to limit the solar heat gain from

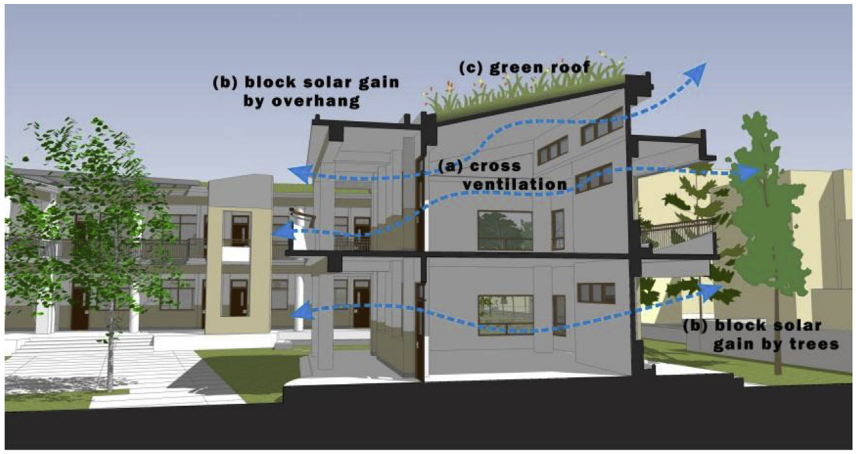


**Fig. 6.** The school building adopted passive strategies for increasing natural ventilation, blocking window solar gain, and enhancing rooftop insulation with a green roof to maintain indoor thermal comfort. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

fenestrations into the interior. The calculation of *AWSG* is as follows:

$$AWSG = \frac{\sum_i IH_i \times K_i \times \eta_i \times fv_i \times A_i}{\sum_i A_i} \tag{1}$$

where *IH* is solar insolation hours, $\eta$ is solar transmittance of glazing (1.0 for a school building), *K* is the reduction coefficient of exterior shading, *fv* is ventilation correction coefficient of fenestration types, and *A* is the area of fenestration.

Liang et al. [27] revealed that the *AWSG* index has a significant effect on controlling and improving the degree of thermal comfort for naturally-ventilated classrooms. On the Taichung campus, effective exterior shades are installed on side windows of the classrooms to block direct sunlight. A 4.0-m wide corridor is located on one side of the classroom, and balconies and horizontal overhangs line the other side. The corridors of the classrooms are located on the side facing the courtyard. The *AWSG* of a green school building in central Taiwan is required to be lower than the criteria threshold of 160 kWh/m$^2$a. The *AWSG* of the studied school building is 125 (kWh/m$^2$a), which is 22% lower than the criteria threshold. The calculated *AWSG* in this case is 22% lower than the threshold. Moreover, a row of trees planted parallel to the classrooms also provides sufficient shade. In terms of furniture arrangement, the students' desks are positioned on the corridor side in deep shade to provide shelter from the sun, whereas spaces for activities are left on the other side, which has less shade. Credits for avoiding window solar gain were earned by adopting the aforementioned strategies to prevent thermal discomfort caused by solar radiation, which could lower learning performance.

- Enhancing rooftop insulation with a green roof

The rooftop is the primary source of internal heat gain in summer, especially for spaces on the top floor. Ideal indoor thermal conditions rely on rational insulation design. According to Taiwan's building regulations, the thermal conductance (U value) of a roof slab must be lower than 1.0 W/m$^2$K. The school in this study utilizes a green roof to improve the insulation of the roof slab. The resulting U value of the roof is as low as 0.78 W/m$^2$ K. This low value earned the school credit for enhancing roof insulation. The greenery layer of the rooftop, which can be regarded as an extra layer of insulation, can reflect solar radiation. The equivalent albedo of an extensive green roof is around 0.70–0.85, which is far higher than that of a bare roof (albedo 0.10–0.20). A green roof can reflect solar radiation more efficiently than most conventional roof constructions, drastically decreasing thermal conduction into the interior space and helping to enhance indoor thermal comfort [28]. Huang and Hwang [29] evaluated the potential of the green roof for improving the indoor thermal comfort of naturally-ventilated classrooms in Taiwan and concluded that a green roof can reduce the frequency of indoor discomfort by 8.3% and alleviate the severity of overheating by 13.6%.

- Availability of daylight

In terms of utilizing daylight, the visible transmittance of glazing used on windows is generally higher than 0.6. In addition, the distance away from the window of any specific position in a space should not be greater than triple the ceiling height to maximize the availability of daylight. This design was followed by the school in Taichung, and the school was awarded the daylight availability credit. It increases the opportunity of utilizing diffuse daylight to minimize the demand for artificial lighting, which accordingly reduces the lighting heat gain and consequently alleviates the occurrence of overheating in summer. In addition, a previous study also showed that utilizing daylight instead of artificial lighting improves learning efficiency [30].

### 3.4. Occupant related credits and strategies

The energy saving indicator in the EEWH system also regulates the amount of internal heat gains. For example, the number of lighting fixtures is restricted and the use of ventilation fans to improve human thermal comfort is encouraged in order to minimize the use of air conditioning systems.

- Energy saving design of lighting installations

In classrooms, artificial lighting is the primary source of internal heat gain. Lighting heat gain can be reduced to improve the classroom's thermal comfort by adopting highly efficient lighting fixtures and by encouraging the utilization of daylight without sacrificing the quality of illumination. In this case, the lighting power density (LPD) of the classroom is 11.5 W/m$^2$, which is far below the upper limit of 15.0 W/m$^2$. High performance T5 lighting tubes with high reflective lighting fixtures are used. Even at this level of LPD, the illumination level on table surfaces is higher than the required value, which is > 350 lx for general classrooms [31]. The hybrid use of highly efficient lighting and daylight is credited with lighting energy saving scores and also indirectly reduces the internal heat gain, thereby preventing overheating in summer.

- Increasing air speed

The indoor thermal condition is also determined by the environmental control equipment that is available to the occupants and can alleviate the impact of the outdoor climate [32]. In this case, these available environmental controls include the aforementioned operable windows, lighting switch controls, and also electric overhead fans. Each classroom is equipped with 6 ceiling fans to increase air speed so as to improve thermal comfort. Previous research [33,34] has indicated that even in classrooms or residential spaces equipped with heating, ventilating, and air-conditioning (HVAC) systems, fans are the most frequent prior use apparatus among the thermal regulating equipment in Taiwan.

## 4. Evaluation of the thermal conditions in the case study school

### 4.1. Adaptive model and overheating criteria

Before an overheating risk analysis of the classroom can be conducted, it is necessary to identify an appropriate thermal adaptive model. Hwang and Shih [35] evaluated several internationally-recognized thermal adaptive models based on a database established by long-term investigations conducted in both naturally-ventilated and hybrid-ventilated school classrooms in Taiwan [17,36,37]. They found that the acceptable upper temperature limit for students in Taiwan is closer to the value predicted by the adaptive model proposed in CEN Standard EN 15251 than to that proposed in ASHRAE Standard 55. In view of this, the adaptive model proposed by CEN Standard EN 15251 is used herein to evaluate indoor overheating risk.

The neutral temperature of thermal comfort ($T_c$) in relation to outdoor climate is formulated as (equations (2) and (3)), in which $T_{rm}$ denotes seven-day outdoor running mean dry-bulb temperature, $T_{-1}$ is the daily average temperature one day before, $T_{-2}$ is the daily average temperature two days before, and so on.

$$T_c = 0.33 \times T_{rm} + 18.8 \tag{2}$$

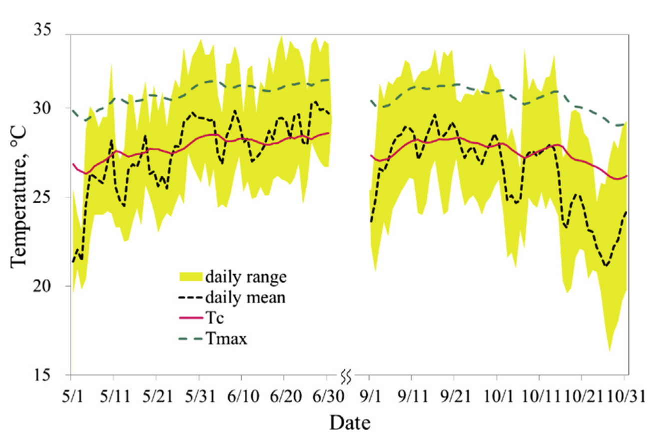


**Fig. 7.** Daily range and mean outside temperature, as well as $T_c$ and $T_{max}$ for Category II during the monitoring periods.

$$T_{rm} = (T_{-1} + 0.8 \times T_{-2} + 0.6 \times T_{-3} + 0.5 \times T_{-4} + 0.4 \times T_{-5} + 0.3 \times T_{-6} + 0.2 \times T_{-7})/3.8 \tag{3}$$

School classrooms fall in Category II of CEN Standard EN 15251. For Category II, the maximum allowable temperature ($T_{max}$) in a naturally-ventilated building in summer is given linearly by:

$$T_{max} = 0.33 \times T_{rm} + 12.8 \tag{4}$$

The amount by which the operative temperature ($T_{op}$) in the classroom exceeds $T_{max}$ is given by:

$$\Delta T = T_{op} - T_{max} \tag{5}$$

Fig. 7 shows the maximum, minimum, and daily mean outside temperatures during the monitoring period superimposed on the adaptive thermal comfort neutrality ($T_c$) and the maximum allowable temperature ($T_{max}$) defined in Category II.

### 4.2. Indoor temperature measurement

Three classrooms (A, B, and C classrooms), all located on the top floor (the second floor) and facing different directions, were chosen for evaluation of indoor overheating risk, as shown in Fig. 5(b). Overheating time is judged by the indoor air temperature measured at the center of the student occupation zone. Although the adaptive model suggests that operative temperature be used for assessment, we deemed the value of air temperature measured to be much the same as the operative temperature because the observed discrepancies between indoor air temperature and the globe temperature were almost less than 1 K, which is considered small enough to be neglected and it was confirmed by additional intermittent measurements paralleled the long-term continuous measurements. In the intermittent measurements, we took measures of air temperature ($T_a$), globe temperature ($T_g$) and air velocity ($v$) in the three investigated classrooms from early September to the next year's January every seven or eight days each month, a total of 113 measurements were obtained with $T_a$ ranged between 14.0 and 32.9 °C, which roughly covers the entire range of the $T_a$ measured during the long-term continuous monitoring period. The reason for taking intermittent measurement was because the conspicuous instruments of aerometer and globe temperature meter which may interfere with the class activity when they are deployed around student's sitting area for long-term measurement. The measured $T_a$, $T_g$ and $v$ were substituted into equation (6) to calculate the mean radiant temperature ($T_{mrt}$). Then, the operative temperature ($T_{op}$) was determined as the weighted average of $T_a$

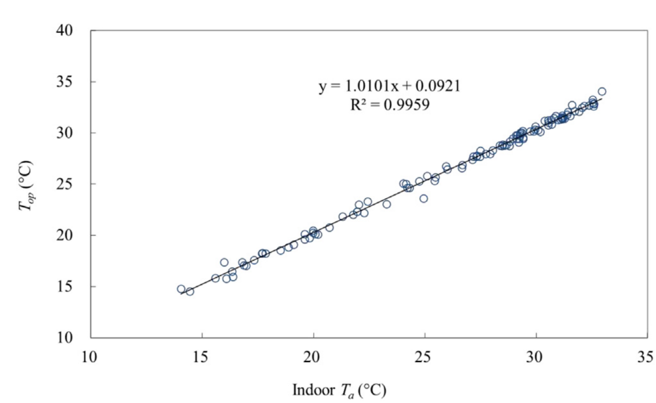


**Fig. 8.** Relationship of indoor $T_{op}$ and $T_a$ from *in-situ* intermittent measurements.

and $T_{mrt}$, as shown in equation (7). As the weighting factor $A$ is determined by air velocity suggested in ASHRAE standard 55-2010, according to *in-situ* measured values of indoor air velocity around the students were between 0.6 and 1.0 m/s due to the use of ceiling fans, 0.7 is given to $A$ for estimating $T_{op}$. Fig. 8 shows the results of measurements. The slope of the fitted line of $T_a$ against $T_{op}$ was very close to 1.0, which certifies our assumption of deeming indoor $T_a$ as $T_{op}$.

$$T_{mrt} = T_g + 0.237v^{0.5}(T_g - T_a) \tag{6}$$

$$T_{op} = A \cdot T_a + (1 - A) \cdot T_{mrt} \tag{7}$$

In the long-tern continuous measurements, $T_a$ was measured with the ESCORT iLog temperature recorder, which has a manufacturer-specified accuracy of $\pm$0.25 K. The temperature recorders for measuring the outdoor air temperature were hung approximate 2.5 m above the floor of the outdoor corridor next to the classrooms to avoid direct sun exposure.

Since the school summer vacation is during the months of July and August, the measurements were taken in May, June, September, and October, when the weather is hot. The total number of school hours during these months is 624. Elementary schools in Taiwan are in session from 8:00 to 12:00 on Wednesdays and from 8:00 to 16:00 on other weekdays. Temperatures at all hours, whether they were class hours or not, were recorded, but only the data recorded during the class hours were used for analysis. The measurements were taken at 1 Hz but averaged and recorded every 5 min Fig. 9 reveals the difference between measured temperature and thermal comfort neutral temperature ($T_{op}$−$T_c$) during the hours of occupation of the three classrooms. Values of the difference of $T_{op}$−$T_c$ greater than 3 K was considered overheating, the overheating percentage in the classrooms A, B, and C were 7.2%, 7.2%, and 5.0%, respectively.

### 4.3. Occurrence of overheating

As suggested in Refs. [38,39], three criteria should be used for classifying the risk of overheating:

- Criterion 1 - Hours of Exceedance ($H_e$): The number of hours the room operative temperature exceeds the maximum acceptable operative temperature ($T_{max}$) by 1 K or more must not exceed 3% of the total hours of occupation or 40 h, whichever is the smaller, during the summer months.
- Criterion 2 - Weighted Exceedance ($W_e$): The sum of the weighted exceedance for each degree K above $T_{max}$ (1 K, 2 K and 3 K) is $\leq$ 10.0, where $W_e = \Sigma H_{e(1,2,3)}{}^{*}(\Delta T)^2{}_{(1,2,3)}$ and $\Delta T = (T_{op} - T_{max})$, rounded to a whole number.
- Criterion 3 - Upper Limit Temperature ($T_{upp}$): The measured operative temperature should not exceed the $T_{max}$ by 4 K or more at any time.

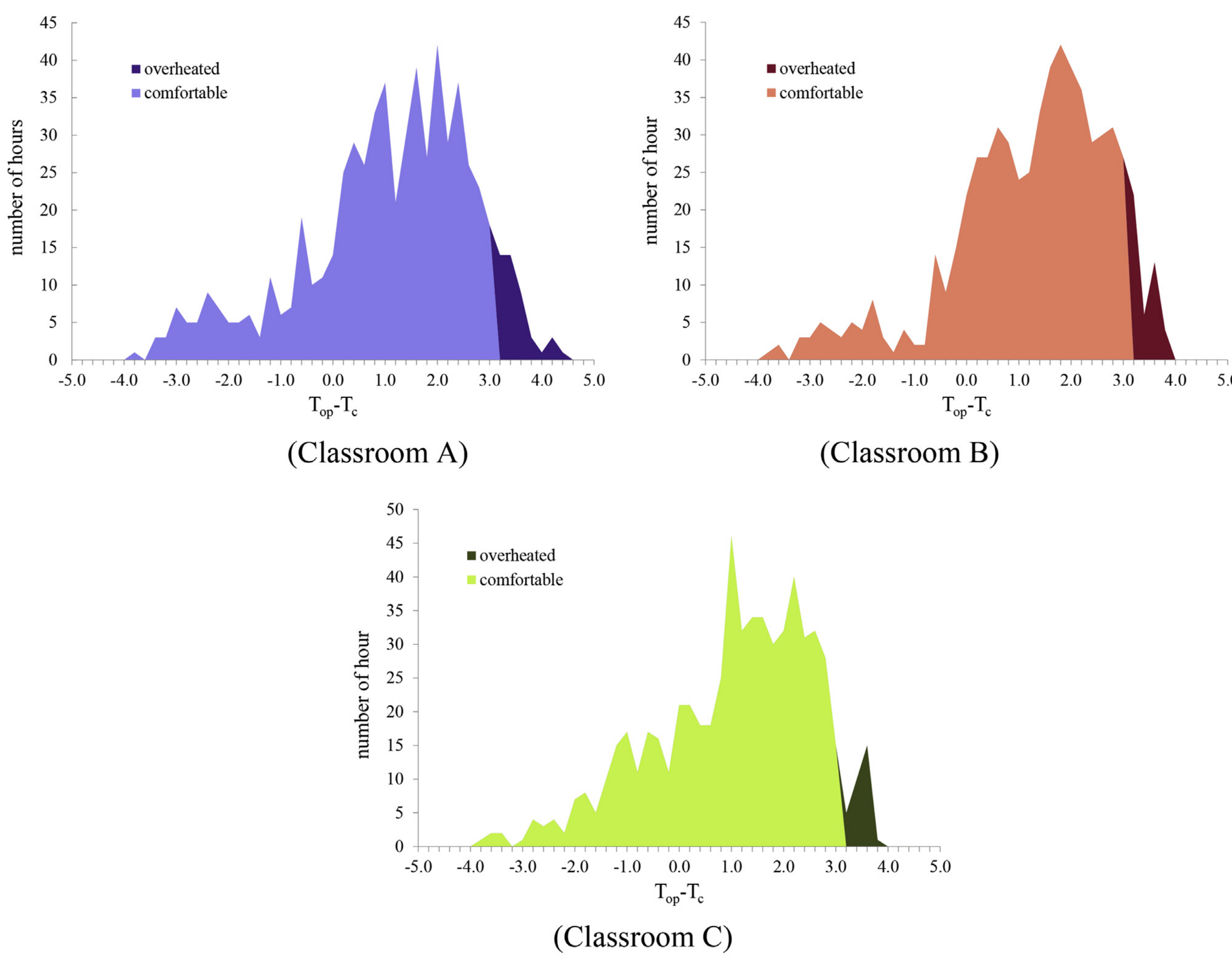


**Fig. 9.** Distribution of ($T_{op}$-$T_c$) of the three classrooms during hours of occupation.

According to the guidelines, if any two of the three criteria are not met, then the classroom is deemed to be overheated. The first criterion for this study is that the frequency of ($T_{op}$−$T_{max}$) ≧ 1 K is tested against less than 3% of hours of occupation, which in this study is equivalent to 19 h.

Table 1 presents the results of hours of exceedance ($H_e$), weighted exceedance ($W_e$), and the number of hours the temperature exceeds the upper limit temperature ($T_{upp}$) of the three classrooms under investigation, as well as the outdoor conditions during the experiment period. The outdoor column in the table is a pseudo reference assessed from the measurements obtained from the outdoor temperature sensors deployed at corridors for giving comparisons for indoor thermal environment as it would the same conditions with outdoors. The $H_e$ of the three classrooms all met the criterion, which was less than 19 h; conversely, the $H_e$ of the outdoor thermal condition during the same period was 84 h. From the measured results, we observed that the value of $W_e$ outdoors was 306, which was much higher than the 10-h criterion limit when assessed with criterion 2. In contrast, two of the three classrooms met the requirement of $W_e \leq 10$. Although the calculated value of $W_e$ in classroom A was 11, or slightly over the limit, it is considered only moderately overheated. It does no harm to conclude that the passive design strategies succeeded in maintaining indoor thermal comfort. Moreover, neither the classrooms nor the outdoor climate exceeded the requirement in criterion 3. Synthesized from the above analysis, the various passive means adopted in the campus buildings leave no risk of indoor overheating.

### 4.4. Percentage of dissatisfaction from overheating

The European Standard EN 15251 suggests that occupant discomfort is related to the difference between the actual operative temperature ($T_{op}$) in the room and the comfort temperature ($T_c$) as defined by equation (2). The potential proportion of occupants that would perceive heat discomfort, or the percentage of dissatisfaction of heat ($PD_H$), can be calculated with equation (8).

$$PD_H = \frac{\exp[0.4734 \times (T_{op} - T_c) - 2.607]}{1 + \exp[0.4734 \times (T_{op} - T_c) - 2.607]} \quad (8)$$

For each hour of occupation over the entire monitoring period, the value of ($T_{op}$−$T_c$) was evaluated, and the proportion of occupants feeling discomfort was estimated by using equation (8). The results of the distribution of hourly $PD_H$ both for outdoors and classrooms during the whole monitoring period are box plotted in Fig. 10. The outdoor air in the figure is a pseudo reference as describe earlier for comparison reason. As expected, the various passive means used in this case lowered the maximum value of in-room $PD_H$. The maximum values of $PD_H$ for classrooms A, B and C were 37%, 31%, and 30% respectively, far lower than that of the outdoors, 52%. In comparison with the mean value of $PD_H$, the values of classrooms A, B, C and the outdoors are 12.4%, 13.1%, 12.1%, and 16.3% accordingly.

**Table 1**
Values of $H_e$, $W_e$ and $T_{upp}$ of classrooms and the outdoor climate.

| Criteria | Without building shells (outdoors) | Classroom A | Classroom B | Classroom C |
|---|---|---|---|---|
| Criterion 1:$H_e \leqq 19$ | 84 | 4 | 0 | 0 |
| Criterion 2:$W_e \leqq 10$ | 306 | 11 | 8 | 6 |
| Criterion 3:$T_{upp} = 0$ | 0 | 0 | 0 | 0 |
| At the risk of overheating? | Yes | No | No | No |

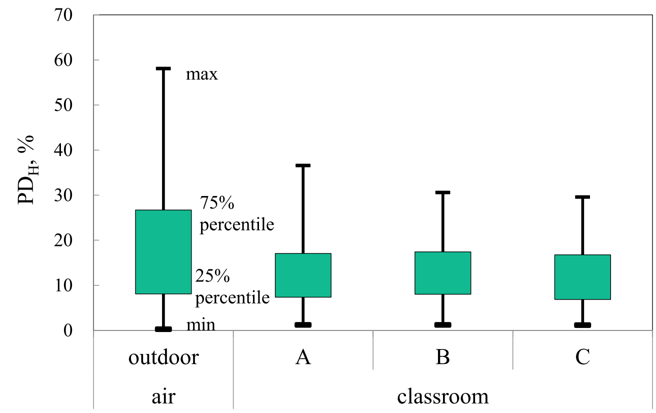


**Fig. 10.** Box plots for the $PD_H$ over the whole period of the survey.

In order to further understand the effects of the various means adopted to alleviate overheating risks, an index ($S_{PD}$) representing the overheating severity is used. The definition of $S_{PD}$ is a summation of the product of weighting factor *wf*, which is a function of $PD_H$, and the time during which the actual $T_{op}$ exceeds the $T_{max}$. It can be calculated with equations (9) and (10). The values of $S_{PD}$ are provided in Table 2. In comparison with the outdoor conditions, the values of $S_{PD}$ in the classrooms decreased to 12.5%–18.5% to that of the outdoors, again confirming the effectiveness of the passive design.

$$S_{PD} = \sum wf \cdot time \quad \text{for } T_{op} > T_{max} \quad (9)$$

$$wf = \frac{PD_{H,act}}{PD_{H,limit}} \quad (10)$$

where $PD_{H,act}$ is the $PD_H$ corresponding to the actual operative temperature; $PD_{H,limit}$ is the $PD_H$ corresponding to the $T_{max}$. The estimated $PD_{H,limit}$ is 23.4% in this study.

### 4.5. Impact on student performance

Constant indoor overheating imposes a threat of reduced productivity and reduced learning ability. To evaluate the effects of temperature exposure on academic performance, the hourly measured temperatures obtained in each classroom and outdoors were substituted into an empirical model suggested by Seppanen et al. [40] to convert indoor temperature ($T_a$) into a relative performance percentage index (*RP*) for characterizing the academic performance. The model is a normalized task weighted performance curve against temperatures, which was developed from numerous studies of various task types including report work, complex task, visual task, vigilance task, and also learning. The formula is a dose–response cubic equation as shown in equation (11), which is applicable for an indoor air temperature range of 15–35 °C. According to the model, maximum performance is

**Table 2**
The values of $S_{PD}$ of the classrooms and the outdoor environment during the monitoring period.

| | Without building shells (outdoors) | Classroom A | Classroom B | Classroom C |
|---|---|---|---|---|
| $S_{PD}$ | 281 | 52 | 50 | 35 |
| Percentage of the outdoor environment | – | 18.5% | 17.8% | 12.5% |

reached at an indoor temperature of 21.8 °C, whereas productivity/performance is reduced by 11.7% when the indoor temperature rises to the maximum of the $T_{max}$ (31.7 °C) during the whole monitoring period.

$$RP = 0.1647524 \times T_a - 0.0058274 \times T_a^2 + 0.0000623 \times T_a^3 - 0.4685328 \quad (11)$$

The measured temperature profiles are input into equation (11) for determining hourly relative performance indices ($RP$s) in both indoor and outdoor environments. Fig. 11 shows the box plots for the predicted performance distribution outdoors and in each classroom. Again, the outdoor air column is a pseudo reference as describe in section 4.3. The resulting average performances are listed in Table 3. The difference between the mean student performance among the three classrooms and the outdoor condition is moderate, despite considerable differences in the occurrence of overheating and the percentage of dissatisfaction with overheating. It is worth mention that less than 25% of the hours of occupation observed in all three classrooms were below 90% in terms of academic performance, but this was not the case in the outdoor condition. As referencing to Wargocki's study focusing on children's learning [4], reducing temperatures by 1 °C will improve student's performance by 2–4%. The increment in the performance by a unit degree drop in temperature is larger than the model proposed by Seppanen et al. [40], which is 1.7%. Thus, one should be noted that the results derived in this study may be more conservative than they actually are. Moreover, this model do not considered the occupant's adaptive behavior effect on the learning performance, further study on this field in the context of local climate is needed.

## 5. Conclusion

This work is a preliminary attempt to integrate overheating risk assessment and student learning performance with the EEWH system for post-occupant evaluation. We explain the various passive means adopted in the surveyed school to earn the highest level of green building certification (Diamond level) in Taiwan's EEWH system and present our investigation of the capabilities of these strategies to prevent overheating in classrooms. The investigation was based on the EEWH certification system framework, which examines such aspects as eco environment, energy saving, waste reduction, and health categories. In the last category, issues of thermal comfort and student learning performance were evaluated. As physical quantities of each evaluation aspects in EEWH system

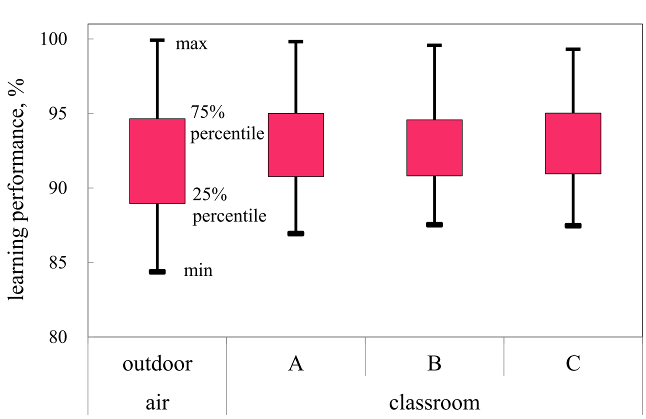


**Fig. 11.** Box plots for the learning performance during the whole period of the survey.

**Table 3**
Summary of resulting average performances.

| | Without building shells (outdoors) | Classroom A | Classroom B | Classroom C |
|---|---|---|---|---|
| $RP$ | 91.8% | 93.0% | 92.8% | 93.1% |

are difficult to take measures directly, it's hard to quantify certain index in EEWH causes such thermal comfort effect to what extent. However, indoor $T_{op}$ is the main figure-of-merit for a natural ventilated space in perspective of adaptive thermal comfort. Thus, long-term measurement of $T_{op}$ was conducted in assessing indoor overheating problem.

Passive strategies adopted in the school campus planning and design were assessed for their effectiveness in achieving indoor thermal comfort and preventing the risk of overheating. Notable findings and suggestions are as follows:

1. A Diamond certificated natural ventilated school building evaluated with EEWH system was surveyed. The results demonstrated that under the combination effect of various aspects of passive design features implemented in complying with EEWH system, indoor thermal environment could also be sufficiently ensured as compared to outdoor conditions.
2. Three classrooms under study didn't have overheating problem while the outdoors conditions during the same period did. The average percentage of dissatisfaction of heat ($PD_H$) for classrooms was 12.5%, which is 23.2% lower than the outdoor conditions. In perspective of long-term overheating severity ($S_{PD}$), three classrooms demonstrated 12.5–18.5% to that of the outdoors conditions.
3. Students' average academic performances in the three classrooms remained above 92%, indicating that the classrooms were not under the influence of severe overheating.
4. The evaluation aspects in EEWH system comprises the following passive design/planning strategies and are demonstrated in the studied naturally ventilated green school:

- Facilitate natural ventilation by properly sizing and allocating the fenestration positions as well as the geometry of the space cross-section.
- Install exterior sun shades for window openings or create deep corridors or balconies near the rooms to providing sufficient shade.
- Increase the insulation on the rooftop with extensive vegetation, preferably drought-resistant grass.
- Utilize daylight by carefully applying the width-height geometry ratio of the space to ensure maximum availability of daylight.
- Properly allocate the layout of the buildings according to local prevailing winds to maximize cross ventilation.
- Plant trees parallel to the building perimeter such that they cast shadows on building surfaces to reduce heat gain and enhance environmental microclimate conditions.
- Use energy saving artificial lighting designs to reduce internal heat gains in maximizing the effectiveness of natural ventilation.
- Slightly increase the in-room air velocity by using overhead fans to alleviate the heating perception of the occupants.

Although thermal effectiveness of each above aspects cannot be proven alone, $T_a$ or $T_{op}$ is regard as an indicator to synthetically describe the overall thermal performance. Considering the behavior of occupants was not monitored and discussed due to time constraints, with the limitation of this study, as regards to what extent the thermal comfort perception and learning performance are affected by occupant's adaptive behavior are unidentified, further research on this field is needed.

## Acknowledgment

The authors are thankful to the financial support from Ministry of Science and Technology, Taiwan in grant under the Project Number: NSC-102-2221-E-239-028.

## References

[1] Ito K, Murakami S. Cost-effectiveness analysis of Improved indoor temperature and ventilation conditions in school buildings. J Asian Archit Build Eng 2010;9:523–9.
[2] Mendell MJ, Heath GA. Do indoor pollutants and thermal conditions in schools influence student performance? a critical review of the literature. Indoor Air 2005;15:27–52.
[3] Wargocki P, Wyon DP. The effects of moderately raised classroom temperatures and classroom ventilation rate on the performance of schoolwork by children (RP-1257). HVAC&R Res 2007;13:193–220.
[4] Wargocki P, Wyon DP. Providing better thermal and air quality conditions in school classrooms would be cost-effective. Build Environ 2013;59:581–9.
[5] Teli D, Jentsch MF, James PAB. The role of a building's thermal properties on pupils' thermal comfort in junior school classrooms as determined in field studies. Build Environ 2014;82:640–54.
[6] Teli D, James PAB, Jentsch MF. Thermal comfort in naturally ventilated primary school classrooms. Build Res Inf 2013;41:301–16.
[7] Teli D, Jentsch MF, James PAB. Naturally ventilated classrooms: an assessment of existing comfort models for predicting the thermal sensation and preference of primary school children. Energy Build 2012;53:166–82.
[8] Issa MH, Rankin JH, Attalla M, Christian AJ. Absenteeism, performance and occupant satisfaction with the indoor environment of green Toronto schools. Indoor Built Environ 2011;20:511–23.
[9] Barrett P, Zhang Y, Moffat J, Kobbacy K. A holistic, multi-level analysis identifying the impact of classroom design on pupils' learning. Build Environ 2013;59:678–89.
[10] Barratt Hacking E, Scott W, Lee E. Evidence of impact of sustainable schools. London, UK: Department for Children, Schools and Families; 2010.
[11] ABRI. EEWH green building evaluation system of Taiwan. Taipei, Taiwan: Architecture and Building Research Institute (ABRI), Ministry of the Interior, Taiwan; 2012.
[12] Paul WL, Taylor PA. A comparison of occupant comfort and satisfaction between a green building and a conventional building. Build Environ 2008;43:1858–70.
[13] Kwok AG. Thermal comfort in tropical classrooms. ASHRAE Trans 1988;104:1031–50.
[14] Araujo VMD, Araujo EHS. The applicability of ISO 7730 for the assessment of the thermal conditions of users of the buildings in Natal-Brazil. Proc Indoor Air 1999;99:148–53. Edinburgh, UK.
[15] Wong NH, Khoo SS. Thermal comfort in classrooms in the tropics. Energy Build 2003;35:337–51.
[16] Ahmad SS, Ibrahim N. A study on thermal comfort in classrooms in Malaysia. In: PLEA 2003 passive and low energy architecture proceedings. Santiago, Chile; 2003. p. 9–12.
[17] Hwang R-L, Lin T-P, Chen C-P, Kuo N-J. Investigating the adaptive model of thermal comfort for naturally ventilated school buildings in Taiwan. Int J Biometeorol 2009;53:189–200.
[18] Zhang G, Zheng C, Yang W, Zhang Q, Moschandreas DJ. Thermal comfort investigation of naturally ventilated classrooms in a subtropical region. Indoor Built Environ 2007;16:148–58.
[19] Liang H-H, Chen C-P, Hwang R-L, Shih W-M, Lo S-C, Liao H-Y. Satisfaction of occupants toward indoor environment quality of certified green office buildings in Taiwan. Build Environ 2014;72:232–42.
[20] Teli Despoina, Jentsch Mark F, James Patrick AB, Bahaj AS. Overheating risk evaluation of school classrooms. Linköping, Sweden: World Renewable Energy Congress; 2011. p. 1821–8.
[21] Ng E, Chen L, Wang Y, Yuan C. A study on the cooling effects of greening in a high-density city: an experience from Hong Kong. Build Environ 2012;47:256–71.
[22] Lin T-P, Ho Y-F, Huang Y-S. Seasonal effect of pavement on outdoor thermal environments in subtropical Taiwan. Build Environ 2007;42:4124–31.
[23] Lin T-P, de Dear R, Hwang R-L. Effect of thermal adaptation on seasonal outdoor thermal comfort. Int J Climatol 2011;31:302–12.
[24] Sengupta J, Chapman KS, Keshavarz A. Window performance for human thermal comfort. ASHRAE Trans 2005;111:254–75.
[25] Chan MY, Mak CW. Thermal comfort levels in a room with solar radiation. Indoor Built Environ 2008;17:516–24.
[26] Hwang R-L, Shu S-Y. Building envelope regulations on thermal comfort in glass facade buildings and energy-saving potential for PMV-based comfort control. Build Environ 2011;46:824–34.
[27] Liang H-H, Lin T-P, Hwang R-L. Linking occupants' thermal perception and building thermal performance in naturally ventilated school buildings. Appl Energy 2012;94:355–63.
[28] Niachou A, Papakonstantinou K, Santamouris M, Tsangrassoulis A, Mihalakakou G. Analysis of the green roof thermal properties and investigation of its energy performance. Energy Build 2001;33:719–29.
[29] Huang K-T, Hwang R-L. Thermal comfort and energy saving potential of a roof-vegetated classroom in hot and humid climate. In: CLIMA2013, 11th REHVA world congress & 8th international conference on IAQVEC. Prague, Czech Republic; 2013.
[30] Heschong L. Daylighting and human performance. Ashrae J 2002;44:65–7.
[31] Ministry of Education. Manual of lighting energy efficiency improvement in school (in chinese). Taipei: Ministry of Education, Taiwan; 2004.
[32] Raja LA, Nicol JF, McCartney KJ, Humphreys MA. Thermal comfort: use of controls in naturally ventilated buildings. Energy Build 2001;33:235–44.
[33] Hwang R-L, Cheng M-J, Lin T-P, Ho M-C. Thermal perceptions, general adaptation methods and occupant's idea about the trade-off between thermal comfort and energy saving in hot-humid regions. Build Environ 2009;44:1128–34.
[34] Chen C-P, Hwang R-L, Shih W-M. Effect of fee-for-service air-conditioning management in balancing thermal comfort and energy usage. Int J Biometeorol 2014:1–10.
[35] Hwang R-L, Shih W-M. Applicability of different adaptive thermal comfort models in Taiwan. Heat Vent Air-Cond (HV&AC) 2014;44(1):23–7.
[36] Shih W-M, Chang S-Y, Hwang R-L, Chen C-P. The thermal perception of students and adaptive use of environmental controls in a hybrid-ventilated classroom. In: HB2012–10th international conference on healthy buildings. Brisbane, Australia; 2012.
[37] Hwang R-L, Lin T-P, Kuo N-J. Field experiments on thermal comfort in campus classrooms in Taiwan. Energy Build 2006;38:53–62.
[38] Montazami A, Nicol F. Overheating in schools: comparing existing and new guidelines. Build Res Inf 2013;41:317–29.
[39] Education Funding Agency. EFA PSBP-natural ventilation strategy. London: Cundall Johnston & Partners LLP; 2012.
[40] Seppänen O, Fisk WJ, Lei Q. Effect of temperature on task performance in office environment. Lawrence Berkeley National Laboratory; 2006. LBNL report 60946.