Sensitivity analysis of envelope design on the summer thermal comfort of naturally ventilated classrooms in Taiwan

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Abstract. This paper uses Monte Carlo Analysis (MCA) for sensitivity analysis of the influence of sunlight shading and ventilation performance of classrooms in Taiwan on students' cumulative overheating risk and average learning efficiency. The parameters influencing the sunlight shading and ventilation performance of classrooms include window orientation, window opening rate, ventilation rate, and external shading depth. EnergyPlus and local TMY3 weather data are used to simulate the hourly thermal environment conditions of 400 sample classrooms in two climatic regions (Taipei and Kaohsiung). The sensitivity of design parameters to the thermal risk of naturally ventilated classrooms and students' learning efficiency is judged by using standardized regression coefficient, and the order of importance is window opening rate, ventilation rate, orientation, and external shading depth.

1. Introduction

Most high school and elementary school classrooms in Taiwan use natural ventilation. In the hot and humid climate of Taiwan, it is foreseeable that the air temperature in classrooms is often higher than 30°C during May-September in summer. The high temperature of classrooms results in thermal discomfort, which influences students' learning efficiency. While installing air conditioners in the school is an effective solution, the air conditioning costs will increase the school's electricity costs. In order to maximize the students' learning efficiency, while reducing electric costs, a good passive classroom design is necessary. The passive design of school building can be implemented by adjusting the classroom orientation, window area, sunlight shading depth, and ventilation area; when the least thermal is brought into the classroom, the natural ventilation of the classroom is maximized, thus, the use of air conditioning is reduced by increasing the natural ventilation time, and power consumption is reduced, in order to achieve the optimum balance point of low cost and high learning efficiency. The purpose of this paper is to use MCA to design the sunlight shading and ventilation performance of classrooms, which is used in the sensitivity analysis of students' overheating risk and learning efficiency.

2. Method and materials

2.1. Research Subjects

Figure 1 shows the common high school and elementary school buildings in Taiwan. The standard classroom on the second floor, which is 9.0 m wide, 8.1 m deep, and 3.0 m high, is selected as the simulation subject in this paper. Two outer walls are provided with two windows, respectively, and the outer wall facing the corridor, which is 2.0m deep, is provided with two doors. The classroom service time is 8:00-16:00. The simulation sites are Taipei City and Kaohsiung City, which represent the two climatic regions in the south and north of Taiwan. EnergyPlus and local TMY3 weather data are used to simulate the annual hourly thermal condition of the classroom.
Figure 1. Common high school and elementary school buildings and standard classrooms in Taiwan are taken as the research subject.

2.2. Design parameters and simulation samples

Ventilation can be increased by opening the windows to remove the heat from the room. According to the theory of the cooling-degree day method, the outside air temperature at which the air conditioning shall be switched on for the classroom is increased from $T_{bal}$ to $T_{max}$, as shown in figure 2[1]. $T_{bal}$ is the outside air temperature at which the air conditioning shall be switched on when the windows are closed. $T_{max}$ can be calculated by Eq. (1).

\[ T_{max} = T_i - \frac{Q_{int} + Q_{solar}}{K_{max}} + \rho C_p \dot{V} \]  

\[ K_{max} = \sum U_w A_w + \sum U_f A_f + \rho C_p \dot{V} \]  

where, $Q_{int}$ is the indoor heat gain of the generated heat of persons, illumination, and equipment in the classroom.

$Q_{solar}$ is the solar heat gain transmitted into the classroom through the windows, and is related to the window area, orientation, and external shading; $U_w$ and $U_f$ are the $U$ values of the outer walls and windows, respectively; $A_w$ and $A_f$ are the areas of the outer walls and windows, respectively; $\rho$ and $C_p$ are the density and specific heat of the air, respectively; $\dot{V}$ is the ventilation when the windows are opened, and is related to the orientation and ventilation area of the windows. In addition, most school buildings in Taiwan use 120mm RC walls as the exterior walls of classrooms, and the window glass is almost 6mm clear glass. This paper only analyses the sunlight shading and ventilation performance of classrooms, thus, the classroom orientation, window-wall ratio, external shading depth of non-corridor side windows, and the ventilation area ratio of windows are selected as the passive design parameters for classrooms.

This paper uses MCA for sensitivity analysis of passive design parameters for classrooms. First, 400 simulation samples are generated by random sampling of MCA. The 400 samples are derived from combining the 400 values randomly generated by the uniform random number generator from different variables according to the parameter setting ranges, as shown in Table 1. Afterwards, the sensitivity analysis of the design parameters on a naturally ventilated classroom regarding thermal risk and students' learning efficiency is discussed by standard regression coefficient. The standard regression coefficient is -1 to 1, which represent the forecast abilities of the independent variables and dependent variables, where a larger absolute value represents higher influence. The sign direction represents the positive or negative trend of influence, as calculated by Eq. (3).
3. Thermal risk and learning efficiency evaluation

According to the results of multiple tests in the classrooms of high schools and elementary schools, Liang et al. [2] built a thermal comfort model for high school and elementary school students in Taiwan, and found that the thermal sensation experienced by students in Taiwan is obviously different from the model recommended by ASHRAE 55 [3]. Therefore, this study uses the thermal adaptive model recommended by the article. The relation between the optimum comfortable temperature \( t_\text{n} \) and the monthly mean temperature of outside air \( t_\text{om} \), as recommended by the model, is expressed as Eq. (4). The relationship between the thermal dissatisfaction \( P_\text{hot} \) and the deviation of indoor operative temperature \( t_\text{op} \) from the optimum comfortable temperature, as resulted from overheating, is expressed as Eq. (5).

\[
t_\text{n} = 12.1 + 0.62 \times t_\text{om}
\]

\[
P_\text{hot} = \frac{\exp(0.6802\Delta t - 3.7690)}{1 + \exp(0.6802\Delta t - 3.7690)}
\]

\[
P_\text{cold} = \frac{\exp(-0.5768\Delta t - 4.4666)}{1 + \exp(-0.5768\Delta t - 4.4666)}
\]

\[
PPD = P_\text{hot} + P_\text{cold}
\]

\[
\Delta t = t_\text{op} - t_\text{n}
\]

\[
ISO 7730 [4] recommends a method for evaluating the severity of long-term indoor environment overheating. For each actual thermal condition exceeding the upper bound of thermal comfort, the method uses a weighting factor to quantize the severity of overheating. The weighting factor \( w_f \) is calculated as Eq. (9). The year-round cumulative severity of overheating of the classroom can be the index \( I_\text{hot} \) for evaluating the thermal risk of classrooms using different roof constructions, which is expressed as Eq. (11). The \( PPD_{\text{lim}} \) for school classrooms, as recommended by ISO 7730, is 15%, which corresponds to \( t_{\text{lim}}=t_\text{n}+2.4^\circ\text{C} \).

\[
I_\text{hot} = \sum w_f \Delta t
\]

\[
P_{\text{lim}} = 0.15
\]

\[
t_{\text{lim}} = t_\text{n} + 2.4^\circ\text{C}
\]
\[ w_{op} = 1 + \frac{|t_{op} - t_{lim}|}{|t_n - t_{lim}|} = 1 + \frac{t_{op} - t_n + 2.4}{2.4} \quad \text{for } t_{op} > t_{lim} \quad (9) \]

\[ w_{ppd} = 1 + \frac{PPD_{act}}{PPD_{lim}} = 1 + \frac{PPD_{act}}{0.15} \quad \text{for } PPD_{act} > PPD_{lim} \quad (10) \]

\[ I_{op} = \sum w_{op} \times t \quad \text{or } I_{ppd} = \sum w_{ppd} \times t \quad (11) \]

This paper uses the mean learning performance, as established by Wang et al. [5], to establish the relation between learning efficiency (RP) and air temperature (t), which is expressed as Eq. (12).

\[ RP = -0.062t^3 + 4.691t^2 - 115.898t + 1039.842 \quad (12) \]

3. Results and discussion

Figure 3 shows the possible ranges of the cumulative overheating risk and average learning efficiency, and the frequency of each interval of 400 sample classrooms, as generated by MCA in Taipei City in winter, summer, and the whole year, are shown in histograms. It is observed that the ranges of cumulative thermal risk and average learning efficiency vary with the considered classroom design parameter combination, and there are obvious differences between the minimum and maximum cumulative thermal risks, thus, it is obvious that the building parameters must be deliberated during the early design stage to reduce the thermal risk of classrooms. Figure 3 shows that the annual cumulative thermal risk of classrooms vary drastically with building parameters.

The overcool hours in winter are 150 to 400 hours, while the overheating hours are 500 to 1000 hours in summer, thus, the annual overcool/overheat hours are 750 to 1300 hours. The most familiar overcool/overheat hours in winter is 300-350 hours, while the ranges in summer are 800-1800 and 1200-3100 hours, respectively, and the annual ranges are 1100-2200 and 1900-3900 hours, respectively. The most familiar I_{op} ranges in winter, summer, and the whole year are 400-500, 1000-1100, and 1400-1500 hours, respectively, while the I_{ppd} ranges are 900-1000, 1600-1700, and 2800-2900 hours, respectively. For classrooms of the same design, the value of I_{ppd} is higher than I_{op}, as I_{op} uses linear weighting to calculate overheating hours, whereas, I_{ppd} uses exponential weighting to calculate overheating hours. In brief, in terms of thermal risk evaluation, the uncertainty of summer overheating risk is higher than the uncertainty of winter overcooling risk.

The average learning efficiency is 100-104% in winter, 92-99% in summer, and 96-101% in the whole year, thus, learning efficiency is higher in winter; Wang et al. [5] found that a neutrally cool environment is more favourable for learning.

According to the SRC analysis of cumulative thermal risk and average learning efficiency in summer by building parameters, the design direction for obtaining the minimum overheating risk and maximum learning efficiency can be known. Figure 4 shows the sensitivity of each building parameter to cumulative thermal risk and average learning efficiency in Taipei City and Kaohsiung City. The building parameter with a higher absolute SRC value has higher influence. Different thermal risk evaluation methods and learning efficiencies in the two climatic regions of Taipei and Kaohsiung will not result in significant difference in the order of importance regarding building parameters, which is window opening rate, ventilation rate, orientation, and rear shading depth.
Figure 3. Annual cumulative overheating risk and average learning efficiency distribution of all sample classrooms (a) overcool/overheat hours (b) $I_{op}$ (c) $I_{ppd}$ (d) learning efficiency.

Figure 4. Sensitivity of each building parameter to cumulative thermal risk and average learning efficiency in summer.

According to the results of sensitivity analysis, the design elements for naturally ventilated classrooms in a wet hot climate can be deduced, as follows:

Window opening rate: the windows play the foremost role in the thermal comfort of naturally ventilated classrooms. The classroom air change per hour can be increased by appropriately enlarging the window area; however, excessive windows will result in high solar heat gain, which is the primary cause of high thermal risk. Therefore, the effects of ventilation rate and solar heat gain must be simultaneously considered in the design of classroom windows, in order to obtain the balance point.

Ventilation rate: the natural ventilation rate is closely correlated with the thermal risk of a classroom. Generally, the larger the ventilation area, the higher the natural ventilation rate of the classroom, which is more favourable for eliminating the possible thermal risk. Therefore, fixed windows without the ventilation effect shall be avoided when designing the windows, and horizontal/vertical slider windows and pivoting windows are preferred, in order to obtain a higher ventilation rate.

Orientation: solar heat gain varies with orientation, thus, it is necessary to avoid orienting classroom windows for high solar heat gain, e.g. west and south. However, the local prevailing wind direction must be considered in the selection of window orientation, as windows on the windward side have larger...
received air volume. If the angular deviation between the window orientation and the windward side is too large, the air change rates will severely decrease.

External shading depth: there is a 2.0m deep corridor on one side of the classroom, and there is good external shading effect on the windows on the corridor side, thus, while the importance of external shading is relatively reduced, it does not mean the external shading of the non-corridor side windows is not important. When the window orientation conflicts with the solar heat gain and windward side, the external shading design can be used to help reduce the solar heat gain, thus, external shading becomes very important. Therefore, the designers shall make different solutions for different directions.

References
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