The Impact of Tropical Classroom Facade Design Alternatives on Daylight Levels and Cooling Energy Consumption

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ABSTRACT

In educational buildings the use of daylight may not only improve students' learning performance but can also reduce electric lighting energy consumption. However, in tropical climates allowing daylight in to rooms can also create a potential overheating risk and increased cooling energy requirements in order to achieve thermal comfort. In this study an actual educational building located in Thailand was investigated using the DesignBuilder modelling package. Daylight levels in several classrooms were measured in order to check the validity of DesignBuilder predictions. A series of classroom façade design alternatives were then investigated by modelling them and analyzing their influence on visual and thermal comfort and cooling energy requirements in each classroom. The aim of the study was to suggest optimized design solutions that created good daylight levels in classrooms but without excessive cooling energy requirements. Some of the different facade designs were found to perform adequately in terms of light levels but poorly in terms of cooling energy usage. Parametric studies such as this one can inform the solution concept and facilitate decision making for designers at the preliminary stages of a design. This paper suggests some facade solutions that could be applied generally to classroom design in tropical regions to achieve a good compromise between daylight access and thermal comfort.

INTRODUCTION

Many studies, such as Altomonte (2009), have confirmed the positive effect of natural light on human visual quality and psychological well-being. There is some evidence, for example Halliday (2008) and Lee et al. (2012), of the advantage of daylight to student learning performance. Results from Theodorson (2009) appear to support this idea by suggesting that good views of the outside world are associated with an improvement in student performance. Although the National Research Council (2006) pointed out that the evidence was too limited, it concluded that a classroom without a window can create stress in students. Windows in façades which directly provide daylighting are, therefore, necessary and desirable in classrooms.

Research background

The provision of natural light to rooms in hot-humid climates leads to two major issues - thermal discomfort and visual quality. Correct façade design is one of the significant solutions to optimizing daylight use in buildings. This research aims to investigate the influential parameters of façade design and to recommend some design guidelines. In this paper the influence of window area and overhang depth on classroom illuminance levels, thermal comfort and cooling energy consumption were examined.

Literature review and research questions

For both human and visual comfort, several façade design strategies have been investigated by researchers – for example, Aksamija (2013). There strategies include glazing type, window size, window orientation and window shading. In terms of thermal performance, Perez and Capeluto (2009) stated that glazing type, window size and orientation have very high impacts while window shading has a high impact on energy consumption. Zurigat et al. (2003) also presented some relevant results. Compared to other strategies, shading devices seem to have low impact on cooling load. However, cooling load could be reduced by up to 11% when shading devices were applied. Window shade consequently was recommened to be an additonal strategy to lessen cooling load. Concerning other factors, Catalina and Iordache (2012) argued that window size does not have a major influence on operative temperature. In daylighting research some studies were found to be useful for facilitating design decisions but, generally, most studies focused on one specific daylighting aspect. There is a lack of literature that attempts to integrate façade parameters, daylighting and thermal issues. When considered separately, it is obvious that for glazing type and window size then the higher the light transmittance and the larger the window area then the higher the prevailing daylight levels. Similarly, less window shading helps more natural light into the room. However, those strategies are probably not proper solutions. Their expected negative outcomes may consist of excessively high light levels and direct sunlight can bring about visual discomfort or disability glare. Because of glare and disturbrance the USA's National Research Council (2006) pointed out that natural light can cause negative effects on student performance, particularly when direct sunlight enters the classroom. Boubekri and Boyer (1992) partly disagreed by claiming that unless directly facing a window, occupants were rarely influenced by direct sun or glare. The significance of shading devices for daylighting which was affirmed by Dubois (2001), who implied that just changing occupants' position and vision may not be the right solution. The optimization of those façade design parameters for improving and controlling light levels is still an important question. A southwest facing façade, as one of the orientaions which is largely dominated by low sun altitudes, was chosen in this study for assessing the impact of window size and shading. Overhangs were initialy studied not only because of their simplicity but also because overhang investigations by Dubois (2001) suggested that they were probably suitable for horizontal visual tasks as they provided sufficient illuminance. At this stage other influential factors, such as glazing type, and other potential components, such as light shelves, were not included in this study. In addition, lighting control systems may, as suggested by Perez and Capeluto (2009), have a high impact but are required to be combined with other façade parameters.

Research methodology

As an example of typical classrooms in Thailand, some classrooms in the Faculty of Architecture, Mahasarakham University were investigated using the DesignBuilder software. Twelve façade variations of window areas and overhang were applied to the representative classroom model, which was oriented to the southwest. Window area parameters consisted of (i) no window, (ii) existing window and (iii) glazed wall with percentages of glazing varying as: 0%, 31.5% and 100% (fully glazed wall). The parameters of overhang depth were (i) no overhang, (ii) existing overhang with a 2.1 metre depth, (iii) existing overhang with 4 metre depth and (iv) 7 metre depth overhang with percentage depth varied as: 0%, 30%, 57% and 100% (7 m depth), repectively. In addition, the two opposite fully glazed cases were included in order to examine the influence of the façade in the opposite sides of the room. The study focused on predictions of total cooling load (kW), Fanger PMV comfort scores, average maximum illuminance and daylighting distribution. These parameters were simulated hourly during the building's working hours for weekdays. Two other indicators were considered: the illuminance ratio (highest to lowest illuminance ratio in room) and the percentage of classroom positions where illuminance levels met a stated standard. Cantin and Dubois (2011) recommended the Useful Daylight Illuminance (UDI) as a practical indicator. The UK's Department for Education and Employment (1999) recommended classroom light levels of 300-500 lux, and an upper threshold of UDI of 2,000 lux was chosen. CIBSE (1994) recommended 1:10 as an illuminance ratio between the task and more remote lighter surfaces, but Cantin and Dubois (2011) pointed out that this appears too strict. They suggested instead the ratios of 1:20 and 1:50 as acceptable and tolerance ratios. In this paper these three ratios will be applied as recommened, acceptable and tolerable limits. Apart from simulation modelling, the case study school was also surveyed. The daylight level measurements and occupants' satisfaction survey were completed for validating the prediction and studying actual problems.

PROBLEM MORNITORING OF THE CASE STUDY

Supansomboon and Sharples (2013) reported results of the survey, which was done during June 2011. The satisfaction survey and the measurement are concordant in terms of insufficient illuminace levels. The participants raised a variety of problems regarding variations in light levels which can decrease their effectiveness in all visual tasks. The measurements also showed that the differences in maximum and minimum illuminance and luminance values were considerably higher than design recommendations. One of the crucial causes was the influence of direct sunlight enerting the room. In addition, it was also found that, although the majority of classroom users agreed with the advantage of applying natural light, their actual behavior appeared to rarely use daylight. This was due to the fact that the natural light is generally fluctuating and the existing shading devices are not only inadequate for preventing direct sunlight but also difficult to operate. These results reveal that the exsiting classroom façade might not be suitable for daylighting. Adjustment of the façade appears to be necessary to solve fluctuation of the daylight and optimise the different visual task requirements.

DAYLIGHT LEVELS

Daylight level distributions for sidelighting generally display a common pattern. The illuminance is maximum in the area next to the window and then reduces dramatically with distance from the window into the rear area. For the case study, when illumination levels were collected during the period of summer solstice, on average, this pattern was observed. However, the average illuminances did not meet the recommended standard of 300-500 lux for all measured positions. When measurement positions were considered separately, the daylight levels of the mid position and the furthest position had no significant change during working hours - the average illuminances were approximately 150 and 50 lux respectively. Conversely, illuminance levels in the position next to the window did vary with time. Illuminance levels were, on average, about 250 lux in the morning and increased to a peak value of about 350 lux at 2.00 pm and then reduced until the end of working hours. The minimum illuminance was about 120 lux. The results suggest that the daylight levels are insufficient at all working times.

Validation of illuminance predictions

The sky was classified to be partly couldy sky but the percentage of cloud in the sky varied. When the measurements and predictions were compared, it was found that none of sky conditions provided in the DesignBuilder lighting module had exactly the same pattern as occurred during the measurements. However, two sky conditions were accepted that could represent minimum and maximum illuminances. In term of patterm similarity, the sunny clear sky condition is the condition that matches the peak illuminance at approximately at 2.00 pm. The illuminances at the mid and the furthest positions from the window were, on average, close to the measurement values. The lowest illuminances were predicted for the overcast sky. At the position next to the window, the value was near the average illuminance of the measurements.

Influence of time and season

The predictions for the exiting façade model under a sunny clear sky are shown in Figure 1, and suggest that illuminance ratios are normally acceptable in the morning, excluding 27th of April and 22nd of December. In the afternoon, the ratios increase to be tolerable in general but beyond tolerable limits for 27th April, and the 22nd of December, March and September. Excessively high illuminance ratios occured on 22nd of December, March and September, and this can be assumed to be due to the influence of direct sun ingress. In terms of illuminance distribution, there were more than 50% of classroom positions where the illuminance levels did not meet the recommendations. The majority of the positions experienced less than 300 lux. Interestingly, the cases where illuminance levels mostly met the recommentations were the times when the sun's influence was most evident. It can be concluded that the classroom with the existing façade might require additional illumination in general. The direct sun may cause excessively high illuminance levels and unbearable illuminance ratios in the area next to the window at some specific times in the afternoon but it can also bring about useful amounts of daylight in the rest of the room. However, it was noted that applying the sunny clear sky conditions gave predictitions that appeared to overestimate daylight levels, particularly at the position beside the window.

Comparison of illumination levels in different façade types

For overcast sky predictions, most daylight levels did not meet the recommendations. However, it is obvious from Figure 2 (b) that the greater the overhang depth then the lower the daylight levels. For illuminance ratios shown in Figure 2 (a), the classroom with the existing window had excessively high illuminance ratios for all overhang depths, while the ratios for all cases in both fully glazed wall cases were lower than the tolerance scale. The optimization cases appear to have the most satisfactory ratios. It was also found that the ratios were all acceptable once the opposite wall of the window had been modified to be fully gazed. Moreover, some of the ratios in this group met the recommendations.

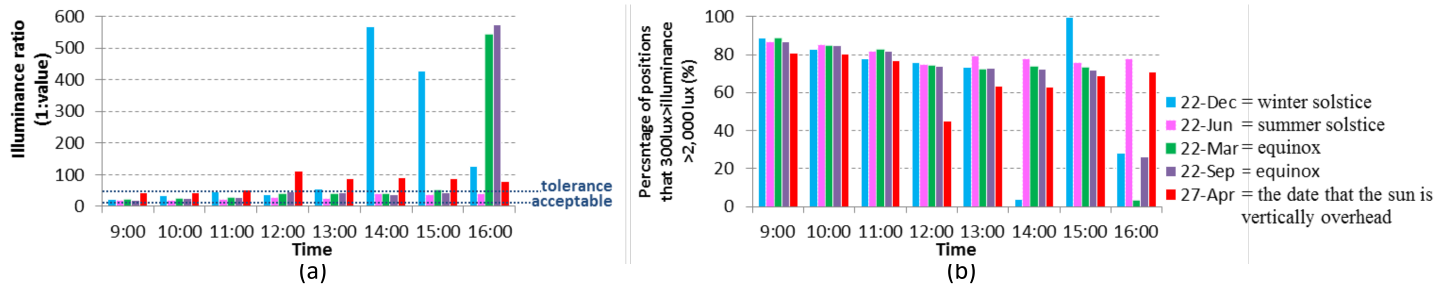

Figure 1 Variation of illuminance predictions of base case during working hour for a sunny clear sky (a) ratios of maximum to minimum illuminance and (b) percentage of room position to all while illuminance does not meet the recommendations

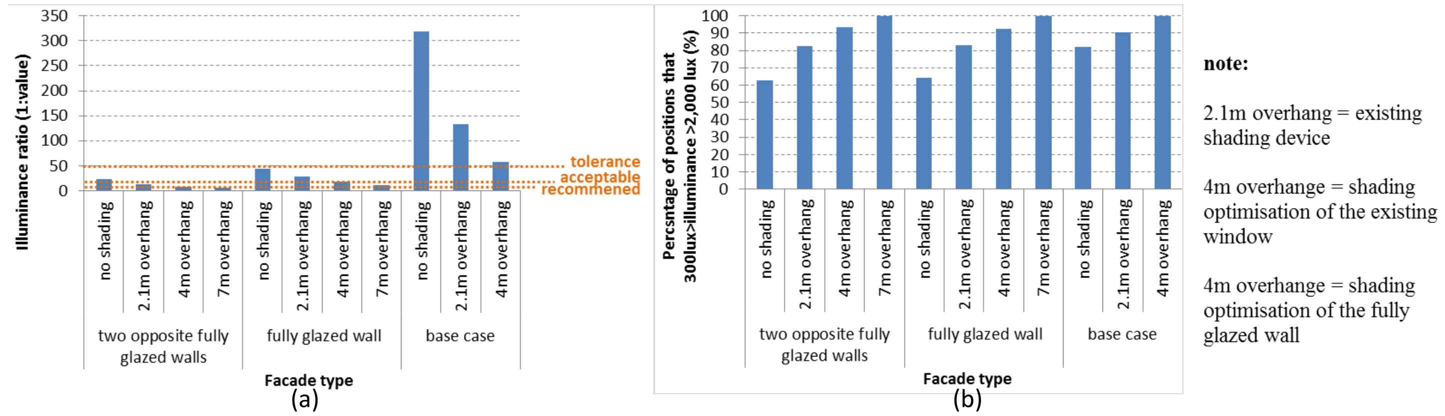

Figure 2 Comparison of illuminance predictions of 11 façade types for overcast sky (a) ratios of maximum to minimum illuminance and (b) percentage of room position at which illuminance levels did not meet the recommendations

INTERACTION OF LIGHTING LEVELS AND THERMAL DATA

For this interaction study, the relationship of overhang depth and window area will be presented for each indicator. The predictions at the winter solstice and the date when the sun is vertically overhead were selected, representing the coldest and warmest weather of a whole year. Generally, the predictions of total cooling load at the winter solstice were approximately equal to that on average for the year (Figures 3 (c) and 4(c)). For the warmest period, the cooling load was about 7-8 kW higher than average.

Overhang depth

All values for illuminance, PMV score and cooling energy requirement decreased as the depth of overhang increased (shown in Figure 3). The decreasing rate is high for in the case of the winter solstice while it is almost constant when the sun is vertically overhead. Without overhangs the illuminance levels and Fanger PMV scores seem too high for the fully glazed window types. Although the optimised depths of overhang may provide less cooling load and better comfort conditions, daylight levels never reach the recommended standard. The ranges of overhang depth that meet the requirements are 0-45% of 7m overhang for the existing window cases and 30-80% of full overhang for fully glazed wall cases.

Window type

Three types of window, consisting of existing window, one fully glazed wall and two opposite fully glazed walls, were studied. The highest differences between the existing window and fully glazed cases were approximately 1,300 lux for illuminance, 0.4 for Fanger PMV and 2 kW for cooling load. When one fully glazed wall and two opposite fulling glazed walls were compared, there was no significant difference of daylight levels but there were differences up to about 0.5 for Fanger PMV and 1 kW for the cooling load (see Figure 3). The cases of two opposite fully glazed walls also did not meet the neutral scale of the PMV model.

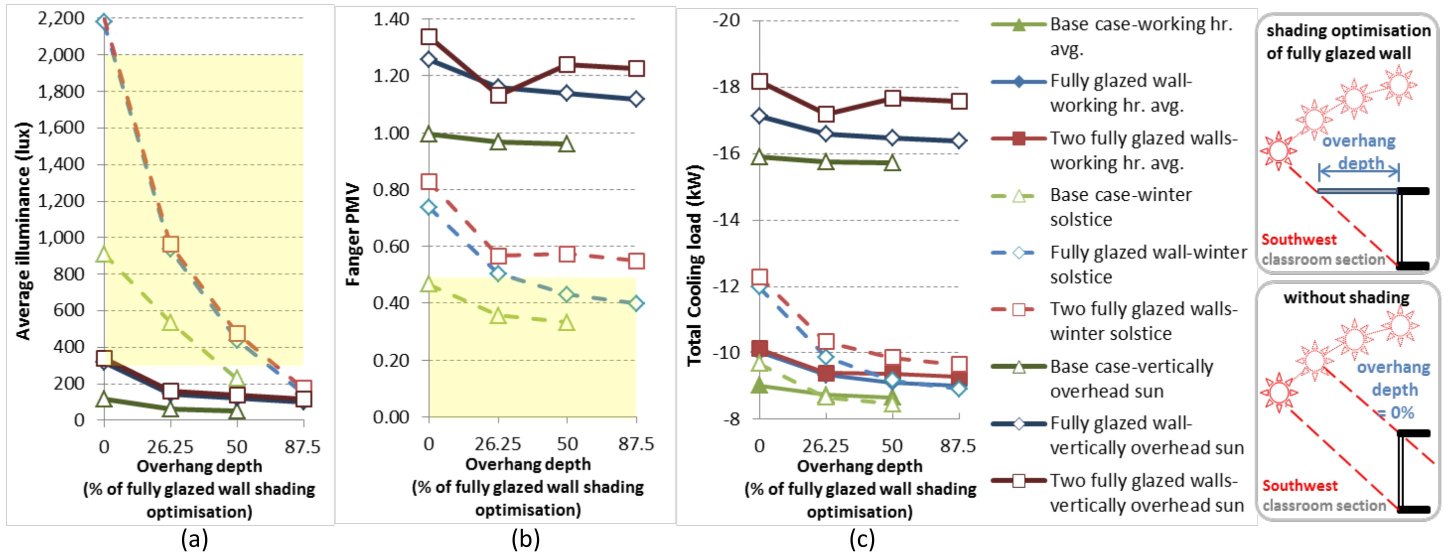

Figure 3 Decreases of illuminance, Fanger PMV and cooling load by overhang depth (a) Average of maximum illuminance, (b) Average Fanger PMV when air conditioning was operated and (c) Average of hourly total cooling load when air conditioning was operated in working hours during week days.

Window area

According to Figure 4, illuminance, Fanger PMV and cooling load all increase when the window area increases. The cases without an overhang have the largest rate of increase. The greater the overhang depth, the smaller the increase. Solar radiation affects the classroom in a negative way when the sun is directly overhead. Not only were the Fanger PMV and cooling load values considerably higher, but the illuminances levels were also inadequate in all cases. However, at the winter solstice four useful cases were found with both daylight levels and thermal comfort in the recommended ranges. The ranges of window areas that meet the requirements are 10-35% for the no shading cases, more than 18% for the existing overhang cases and more than 60% for the 4 metre-depth overhang cases.

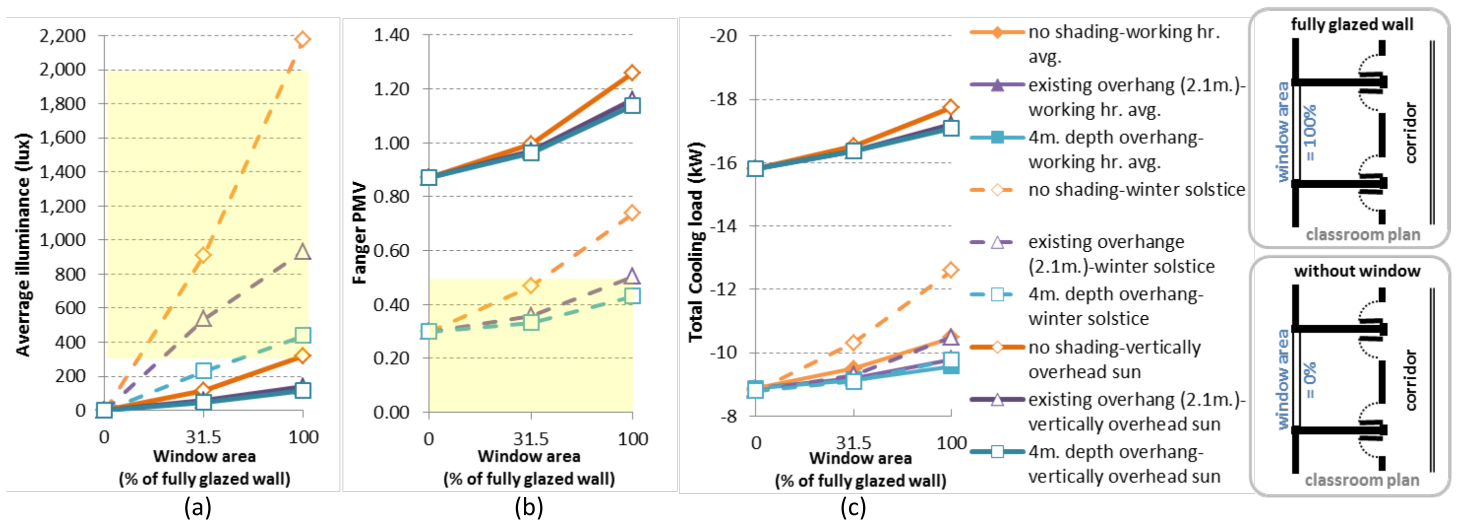

Figure 4 Increases of illuminance, Fanger PMV and cooling load by window area (a) Average of maximum illuminance, (b) Average Fanger PMV when air conditioning was operated and (c) Average of hourly total cooling load when air conditioning was operated in working hour during weekday.

DISCUSSION AND CONCLUSION

In general, it was found that daylight levels in the classroom were mostly not high enough even though the window area and overhang depth were improved. This problem arose from less daylight level being transmitted in to the room and its poor distribution around the room. It is probable that other innovative solutions could increase daylight levels and improve distribution.

The problems can be different if the façade is affected by a low sun altitude, such as at the winter solstice. Agreeing with previous research and the preliminary survey, direct sunlight possibly caused visual dissatisfaction in the classroom. The influence of the direct sun resulted in excessively high daylight levels in the area next to the window and overwhelming illuminance ratio values. This is due to insufficient shading devices for the southwest orientation in the afternoon. It appears that the window shading needs to be improved. On the other hand, when the thermal aspect was combined, the fully glazed wall without an overhang appeared to have excessively high illuminance levels and slightly warm discomfort voting, although high amounts of cooling energy were consumed. The optimal case of an overhang which can completely shade for direct sunlight was not suitable for daylighting. Interestingly, benefits from the direct sun were also found. Apart from the intense illuminance which affected the area next to the window, the low angle of the sun also influenced illuminance levls in the rest of the room. It is possible that this advantage is brought about by reflections of the transmitted solar beams. As a further solution, diffusing the direct solar beam might benefit unaffected areas – for example, using reflection techniques such as lightshelves. It appears that the impact of changing window area, compared to changing overhang depth, was more significant for daylight levels rather than thermal conditions. Their influences also were dependent on each other. In terms of illuminance ratio, the impact of overhang depth will be reduced if a large window is used. Similarly, the impact of window area will be high if there is no shading. It appears that the combination of full glazing on the opposite wall did not have much effect on daylight levels and, instead, resulted in higher heat transfer. However, the results show that this additional window provided more pleasant illuminance ratios. This strategy is, therefore, still useful for reducing variations in daylight distribution.

Generally, the 30-50% overhang depth and window areas more than 60% of toatal wall area are recommended. These ranges can be expanded when both parameters were specified - for example, a recommended overhang depth can be 0-50% for the existing window and 30-80% for the fully glazed wall. Unexpectedly, the existing façade, which was proved not to be practical, is also in the range. It reveals that those recommendations might be overestimates as they used the maximum average illuminance values. Consequently, the ranges will be examined and refined in the next stage of study.

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