HEALTHY LOW ENERGY REDESIGNS FOR SCHOOLS IN DELHI: INVENTORY OF THE CURRENT CONDITIONS

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SUMMARY

India's capital, New Delhi, struggles with high outdoor air pollution and extreme temperatures during summer and winter. Together they are liable to adversely affect health and learning of children in classrooms without mechanical ventilation and cooling. This work targets to provide a guideline on how to sustainably improve the indoor climate quality in such classrooms with a weighing of the measures against investment cost and energy needs. The current conditions in classrooms of 5 schools located in the National Capital Territory of Delhi were analysed. Major parts of these schools were completely reliant on natural ventilation. Thus indoor to outdoor $PM_{2.5}$ concentration ratio remained close to 1. During summer, indoor temperature rises up to 40 °C. During winter, indoor CO_2 concentration can exceed 1150 ppm. Using monitored conditions as input, a TRNSYS base model was created for the classrooms. This model functions as a test environment for proposed interventions towards improving indoor climate quality. The proposed solutions target CO_2 level $\leq$ 1150 ppm, $PM_{2.5} \leq 25\mu g/m^3$ and temperatures within 80% acceptability range of the Indian adaptive thermal comfort model.

Keywords: Particulate matter, thermal comfort, classrooms, passive cooling, building performance simulation

1 INTRODUCTION

Classroom indoor environmental quality (IEQ) has a close relation with absenteeism, health, and learning performances. For example, a lack of 'fresh' air supply negatively affects the learning performance (Shaughnessy et al., 2006, de Gids, 2006, Wargocky at al., 2007, Bakó-Biró, 2008). New Delhi, India's capital city, is burdened with highly polluted outdoor air and an extreme climate. These conditions can adversely affect health and learning of children in classrooms without mechanical ventilation and cooling.

Since their lungs are still developing, children are more vulnerable than adults to air pollution. Continuous exposure to polluted air can disrupt lung development (CPCB, 2008), leading to reduced lung function and even chronic respiratory diseases. While government shuts down schools on days with high air pollution, this is not a long-term solution for the over 600 000 Indian schools (MHRD, 2018). Even a small step to improve indoor air quality (IAQ) in these schools can have a major impact on the life of millions of children.

The objective of the current study is to provide well-defined guidelines for sustainably improving IAQ and thermal comfort in naturally ventilated classrooms in India. In the guidelines, the effectiveness of different interventions are weighted against their energy demand and required investment. The focal point was kept on the schools of the National Capital Territory of Delhi. The current work discusses the field measurements, corresponding base case simulation, and preliminary strategies based on the measurements and simulations.

2 METHODS

2.1 Overview

To design suitable improvement guidelines for naturally ventilated schools in India, a good inventory of the current condition is necessary. Due to the limited research on IEQ in Indian schools an on-field study was deemed necessary. Since Delhi area suffers from the worst air quality challenges in India and being the capital city, it is well connected to the rest of the world, these studies focused on evaluating school conditions in Delhi. We hypothesize that solutions developed for Delhi conditions could be extrapolated to other regions of India by taking into account climatic differences for indoor thermal conditions while IAQ concerns would remain similar in different regions.

2.2 Field work

Between 10 September and 11 October 2017, end of monsoon season, five schools in and around Delhi have been visited. During those visits, the school building characteristics were analysed, usage profile was inventoried, and short and long term indoor measurements were performed in 10 different classrooms. At three out of five schools teachers were surveyed regarding their perception of the classrooms' IEQ through subjective questionnaire covering thermal perception, thermal satisfaction, air movement, humidity, air quality, noise, and lighting. Feedback was obtained from 15 respondents. The measured parameters were indoor air temperature (T_{in}), outdoor air temperature (T_{out}), relative humidity (RH), surface temperature, indoor air velocity, carbon dioxide (CO_2) concentration, and particulate matter $PM_{2.5}$ concentration. The indoor air velocities were measured at window and door openings and in the middle of the classroom by a Hot Wire Anemometer. The T (+/- 0.4-0.6°C) , RH (+/- 2-3%), and CO_2 (+/- 50 ppm) and $PM_{2.5}$ concentrations were measured with both a manual hand devices (Rave and AZ7755), Eltek sensors, ClarityAir monitor, and particle counter Dylos DC1700.

2.3 Numerical Model

The numerical model needs to function as a test environment to roughly estimate the performance of the proposed interventions. Therefore, the numerical model is designed with a relatively low resolution, as this already gives sufficient information to evaluate the necessary interventions to achieve a healthier and more comfortable IEQ (Djunaedy, 2012). The field measurement results, together with the corresponding inventory led to the boundary settings for the base model. The model is executed in TRNSYS 18 using the building model Type 56.

The National Building Code of India (NBC, 2016) in combination with IEQ standard (ISHRAE, 2016), led to the IEQ performance goals for this research. The thermal comfort was evaluated using the simulated operative temperatures and the adaptive thermal comfort (ATC) model for mixed mode and naturally ventilated buildings. The IAQ was evaluated based on ISHRAE standards Class C (ISHRAE, 2016). The threshold value for CO2 in Class C is 750 ppm above the ambient concentration. Note, the ISHRAE standard for fine particles $PM_{2.5}$ is related to the air quality guidelines as given by the World Health Organisation (WHO, 2005), which advise a daily average of <10 $\mu g/m^3$ and a yearly average of <25 $\mu g/m^3$. Since the ISHRAE standard does not clarify if they have provided daily or annual average exposure values, it is assumed to be daily average threshold. This value is given to be <25 $\mu g/m^3$ for Class C. In addition, the Exceedance Factor (EF) as defined by Central Pollution Control Board (CPCB) has been used to subdivide the pollution level into four categories:

- Low pollution (L)   EF < 0.5
- Moderate pollution (M)   0.5 > EF < 1.0
- High pollution (H)   1.0 > EF < 1.5
- Critical pollution (C)   EF > 1.5

EF is the observed annual mean of respective pollutant, which is approximately 100 μg/m^3 for PM$_{2.5}$ in Delhi. The solutions would be assessed by means of over and under heating hours, CO$_2$ exceedance hours, pollution level categories L, M, H, and C, increased energy demand, and corresponding investment costs.

2.4 Boundary conditions

The boundary conditions within the TRNSYS model were primarily based on the data from field measurements. For example the CO$_2$ measurements were used to assess the ventilation and infiltration rate. The outdoor CO$_2$ concentration are assumed to be fixed at 450 ppm. Additionally the following occupancy profiles are used: on schooldays the classrooms are occupied from 08:00 to 17:00 with a lunch break from 12:00 to 13:00, the fans are activated whilst the operative temperature (T$_{op}$) exceeds 25°C, and window shutters are closed whilst T$_{op}$ drops below 21°C. However, the shutters are opened again whilst the sun radiation exceeds 1200 kJ/h.m^2.

2.5 Sensitivity analysis

In order to evaluate the reliability of the base model and the performance assessment a sensitivity analysis is iteratively executed. During this analysis several parameters and set points are changed within the model as shown in Table 1, while exploring the effect on the performance indicators.

Table 1. Sensitivity analysis variables

Building model parameters		Set points	
Construction thickness	+/- 25%	Fans operative temperature switch point	+/- 2 °C
Solar absorbance	- 33%		
Ventilation	+/- 25%	Windows operative temperature switch point	+/- 2 °C
Occupancy	+/- 25%		
Air velocity	+/- 50%	Windows solar radiation switch point	+/- 200 kJ/h.m2

3 RESULTS

3.1 Field Measurement results

At the time of measuring the outdoor temperature varied from 31°C to 35°C during occupancy hours. The corresponding subjective data on the classroom' IEQ showed that the roughly 70% of the teachers was at least slightly warm, though still 80% of all was satisfied with the thermal conditions. Most teachers expressed some dissatisfaction regarding the thermal condition in hot summer and cold winter. Even though the study fell during monsoon, 53% was satisfied with humidity conditions. Additionally, 80% does not experience dissatisfaction with the IAQ. It seemed that the teacher were having a hard time judging the IAQ conditions, while they were only able to associated it with coarse dust and 'fresh' outdoor air. Also, 80% was satisfied with the lighting conditions, while only 60% was satisfied with the acoustical conditions, while they suffer from sound disturbance (mostly traffic noise)

During occupancy hours the difference in indoor and outdoor CO$_2$ concentration was approximately 100 ppm, in case of open doors and windows, running fans, and an occupancy rate of roughly 40 people. Simultaneously, the indoor PM$_{2.5}$ concentrations indoors approached the outdoor concentration. Therefore, the indoor to outdoor ratio of PM$_{2.5}$ is assumed to be roughly 1, as can be seen in Figure 1.
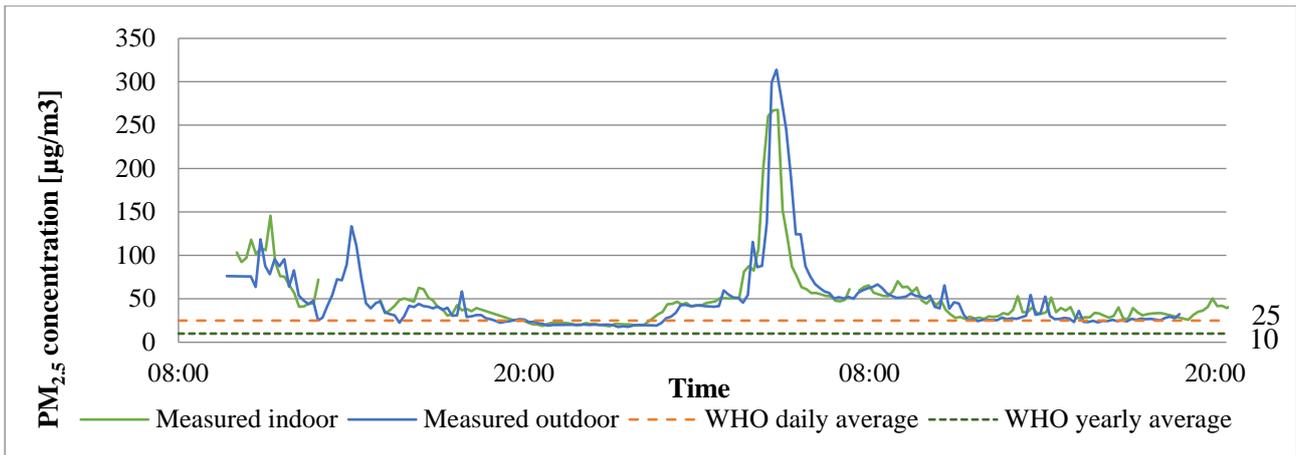
Figure 1.Measured indoor and outdoor concentrations of fine particulate matter PM$_{2.5}$ at school 1 class A, compared to WHO guidelines

The classrooms tend to be 1°C cooler compared to the hallway temperature, at least during the morning session. During the 'long' term measurement at school it seems that after the hottest time of the day, the classroom temperate is exceeding the hallway temperature as seen in Figure 2. However, the outdoor temperature is continuously lower compared to both the hallway and classroom temperatures. This likely due to the high occupant density in the classrooms.
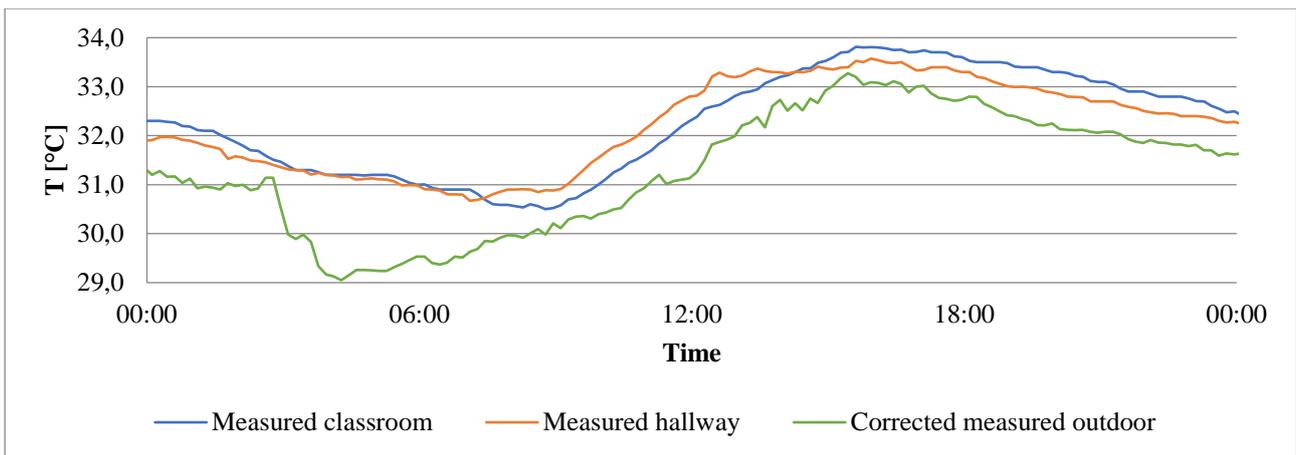

Figure 2.Measured classroom, hallway, and outdoor air temperature at school 1 class A

3.2 Modelling results

The TRNSYS base model behaves in line with the field measurements, though absolute agreement is not completely achieved. In addition the model responses in line with physical expectations when exposed to the sensitivity analysis. As expected the ground floor classroom stays cooler during summer and warmer during winter, compared to the first floor classroom, while they have similar CO_2 profiles. Figure 3 shows that the base model is able to catch the right peak.

The TRNSYS base model is most sensitive for the assumed ventilation rates. Mainly, this is occurring during winter time when the ventilation rate is assumed to be relatively low. An increase in air exchange rates (ACH) reduces the amount of CO_2 exceedance hours. Additionally, a small change in ventilation rates also reasonably affects the under heating hours. Indirectly, changing the air velocity parameters also changes the ventilation rates. Therefore, the velocity parameter is also rather sensitive. Finally, a drop in occupancy rate or a change in occupancy behaviour (opening windows and turning on fans) notably affect the CO_2 exceedance hours and the under heating hours.
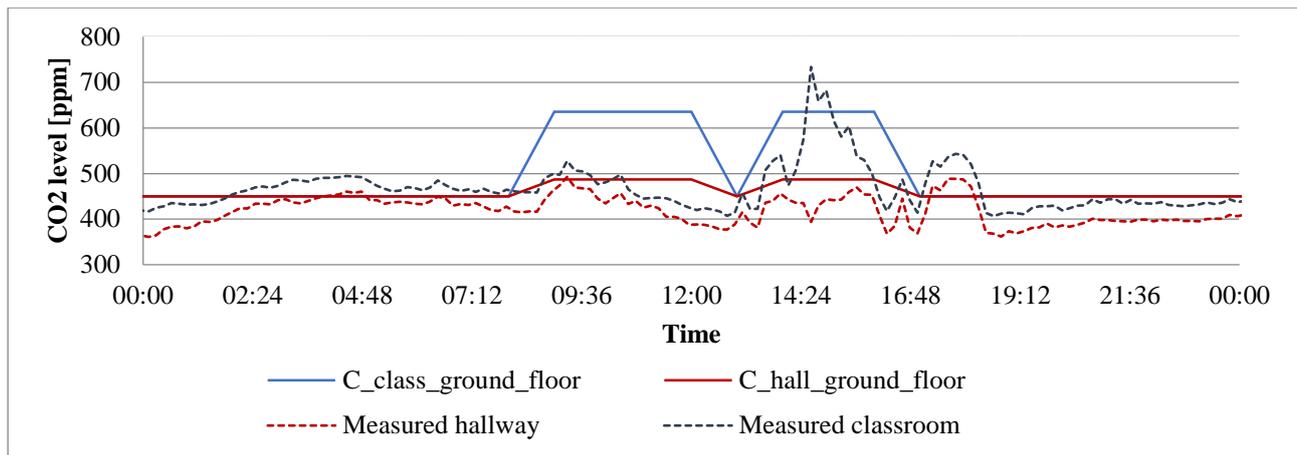
Figure 3.Measured CO_2 concentration in classroom and hallway, at school 1 class A, versus modelled CO_2 concentration at the ground floor. Note: measured classroom was only occupied during afternoon.

4 DISCUSSION

Major part of the schools were completely reliant on natural ventilation, resulting in an indoor to outdoor $PM_{2.5}$ concentration ratio of 1. Due to the openness of the classroom and the fans as a driving force, high ACH rates are reached, causing the CO_2 concentration to be rather low. The subjective data showed that the teachers were warm, although thermally satisfied. At the point of measuring the indoor temperature was around 32°C while the outdoor temperature was around 33°C. This corresponds with the Indian ATC model for naturally ventilated buildings.

The base model shows that during summer, indoor temperature might peak up to 40°C. During winter, the indoor temperature might easily drop below 20°C. The bottom classroom visibly encounters less solar load. Simultaneously, it loses less heat during winter. Regarding the air quality, the CO_2 in summer and monsoon always stays under 1150 ppm, in winter this is expected to exceed 1150 ppm. The TRNSYS base model is able to ordinal distinguish the design solution as required. Though there still remain some unknowns in order to better estimate the occupancy and use of fans and windows. Furthermore, the model neglects the actual fluctuating ventilation and infiltration rate which might be relevant in the future for more detailed evaluation of the design solution. In order to better validate the model, more and longer measurements are necessary, preferably 2 weeks per season. Such extensive measures could not be conducted due to bureaucratic red-tape and time issues.

In the upcoming project phase the intervention will be tested step by step, in order from passive to active within the TRNSYS base case. The design strategies consists of 5 steps: reduce entering pollution, reduce heat load, actively purify air, actively cool room, and produce solar electricity. This functions as a guideline to compose the final design packages. The final packages will be assessed based on the investment costs and IEQ performances.

5 CONCLUSIONS AND FUTURE WORK

As the outdoor fine particles are easily infiltrating into the classrooms the biggest health risk is occurring during hazardous winter time. Additionally, during the hot summer the ATC model shows quite some overheating hours while during winter there are little under heating hours (80% acceptance limit). While reducing the infiltrating air pollution the risk of CO_2 exceedance hours is increasing. Additionally, the thermal load on the classroom is expected to increase. This is likely to be demonstrated by the TNRSYS model as it functions as a capable test environment to indicate the worst case scenario.

Next step is to use the base model to test various suitable interventions, combining passive solution with active solutions in the most energy efficient way. Within the proposed solutions, the CO_2 level is to be

kept under 1150 ppm, $PM_{2.5}$ below 25µg/m^3 and the ATC within the 80% acceptability range. Solutions easily available in local market and of "plug and play" type are preferred. However, entirely relying on passive solutions cannot suitably address the risks of exposure to particulate matter.

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