Healthy Low Energy Redesigns for Schools in Delhi

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Indoor air quality and thermal comfort of existing naturally ventilated classrooms in the Indian capital territory, Delhi, is substandard. This should be improved while trying to prevent the increase in energy demand. The research question focused on solution options to answer these contradictory requirements.

Introduction

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, see **Figure 1**.

Since children's lungs are still developing, they are more vulnerable to air pollution than adults. Continuous exposure to polluted air can disrupt lung develop-ment {CPCB, 2008}, leading to reduced lung function and even chronic respiratory diseases {Kumar, 2008}. Currently, as an extreme measure, the Indian government has to resort to shutting down schools on hazardous days, i.e., days when the particulate matter ($PM_{2.5}$) hits hazardous levels (>300 µg/m³). This is no long-term solution for the over 600 000 Indian schools. Even a small step to improve indoor air quality in these schools can have a major impact on the lives of millions of children.

Sustainable improvement

India also has a growing energy problem due to the rapid population growth and being an emerging economy {Wang, 2016}, with demand transcending supply. In order for India to reach its economic and social targets, the energy infrastructure is potentially India's main challenge {Tripathi, 2016}. The energy usage (already 5% of the world's energy) continues to grow in an unsustainable manner, being based primarily on fossil fuels. This, consequently, also contributes to outdoor air pollution {Wang, 2016}.

These circumstances make it abundantly clear that it is important to sustainably improve the indoor climate (IC) in existing, naturally ventilated classrooms in places like Delhi in order to restrain the energy demand. Beyond environmental concerns, the extra energy and investment costs can also become a giant burden for such schools. Even so, sustainably improving the health in governmental schools is both socially and economically valuable in the long term. It can stimulate teachers to improve education and can provide better social opportunities for economically disadvantaged families {Garg, 2006}. Subsequently, the sustainable schools will set a socio-economic example for the energy reformation and the market-oriented economy {Swaminathan, 2016}.

First step

This study was set to develop generic, sustainable, indoor climate improvement packages for a typical, naturally ventilated classroom in Delhi. Solutions easily available in local market, passive, and of "plug and play" type were preferred. However, entirely relying on passive solutions may not suitably address the risks of exposure to particulate matter. To design these packages an inventory of the current condition was necessary. Therefore, a field study was deemed necessary.

The final packages were designed and evaluated based on IAQ, thermal comfort, energy use, and (financial) feasibility. We presume 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 – or even less demanding – in other regions.

School visits

Between 10 September and 11 October 2017, five schools in and around Delhi were visited. In total, 15 teachers were surveyed regarding their perception of the classrooms' indoor environmental quality (IEQ), covering thermal comfort, air movement, humidity, air quality, noise, and lighting. Additionally, indoor air temperature (T_{in}), outdoor air temperature (T_{out}), relative humidity (RH), surface temperature, indoor air velocity, carbon dioxide (CO_2) concentration, and $PM_{2.5}$ concentration in the classrooms were measured (see **Figure 2)**.

The survey showed that roughly 11/15 of the teachers were at least slightly warm at time of measuring, though still 12/15 were satisfied with the thermal conditions. Most teachers expressed some dissatisfaction regarding the thermal condition during peak summer and winter periods. Even though the study fell during monsoon, 8/15 were satisfied with humidity conditions. Additionally, 12/15 did not experience dissatisfaction with the IAQ. Seemingly, teachers had a hard time judging the IAQ, being only able to associate it with coarse dust and 'fresh' outdoor air.

Depending on the classroom and occupancy, the mean indoor CO_2 concentrations per classroom were between 50 and 300 ppm above outdoor CO_2 concentration, when doors and windows were opened, and fans were

Figure 1. Example of naturally ventilated classroom.

Figure 2. Two hours measurement in reference classroom.

running. These conditions correspond to ACH rates of roughly 17 to 24 [1/h]. This fluctuation is related to the opening sizes, solar shading, fans, and cross ventilation. The high ACH rates results in high $PM_{2.5}$ infiltration rate and an indoor to outdoor ratio of roughly 1, as can be seen in **Figure 3.**

The thermal conditions in the classrooms differed with their orientation, exposure to outdoor conditions, and occupancy. T_{in} was roughly deviating 1°C from T_{out}. The classrooms tend to be 0.5°C cooler compared to the hallway, at least during the morning session. The mean radiant surface temperature varied 0.5°C from the T_{in}, depending on the surface construction and orientation. This indicated that T_{in} was little affected by the radiant temperatures.

Development of numerical model

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 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). For example, the model assumes a constant natural ventilation rate, while in reality, the wind pressures around the building and occupancy patterns were fluctuating, affecting the indoor climate. We compared the modelled CO_2 concentration towards a measurement and concluded that the model was able to spot the same peak.

The National Building Code of India (NBC, 2016), in combination with IEQ standard (ISHRAE, 2016), led to the IEQ performance goals for this research. Thermal comfort was evaluated based on 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),

which is in line with the air quality guidelines as given by the World Health Organisation (WHO, 2005). Thence, the threshold value for CO_2 is 750 ppm above the ambient concentration and the daily average $PM_{2.5}$ threshold is <25 μg/m³.

Indoor climate simulation results

In winter, the outdoor temperatures drop towards 12°C. As the schools are unequipped with any heating, the windows are kept closed to keep warm. Still the uninsulated façade causes high heat losses and cold infiltrating air, leading to under heating hours with indoor temperatures towards 15°C. Additionally, the lack of fresh air results in CO_2 exceeding hours. Still, the outdoor hazardous pollutants keep infiltrating into the indoor environment (above 100 μg/m³).

In mid-season, the windows are opened, and the fans are off. The natural ACH rate seems just sufficient to keep the CO_2 concentration within the limit. Though, the smallest decrease in ventilation leads to CO_2 exceedance hours.

Delhi has two hot seasons, the dry summer and the rainy monsoon. During both seasons, the windows are fully open and fans are running. Especially during summer, T_{op} is frequently above the neutral temperature. Classrooms on the top floor are particularly hot due to the additional rooftop solar load. The indoor CO_2 concentration is always below the threshold due to high natural ventilation rates. Furthermore, the outdoor $PM_{2.5}$ concentration is usually below 100 μg/m³.

Table 1 shows the indoor climate and energy performance for one school year.

Improvement packages

These nested problems may not be resolved by any single intervention. For example, to reduce the CO_2 exceedance hours, ventilation rate should be increased in winter.
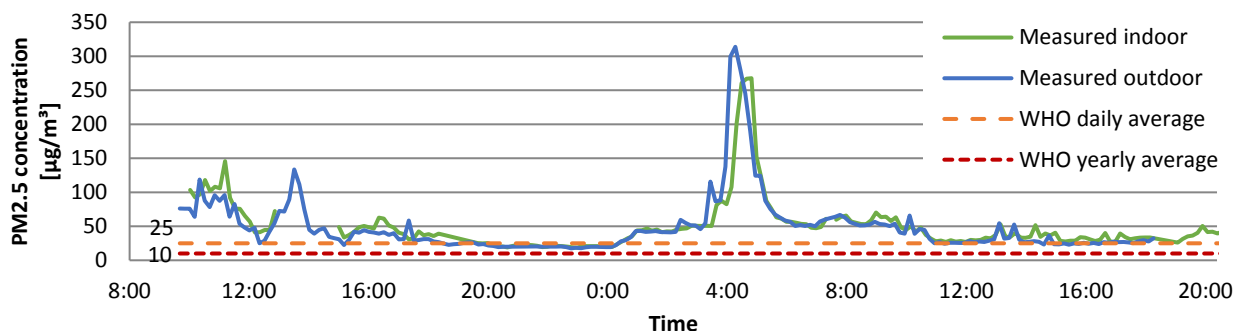

Figure 3. Example of measured indoor and outdoor concentrations of fine particulate matter $PM_{2.5}$ compared to WHO guidelines, at school 1 on 11/07/2017-12/07/2017.
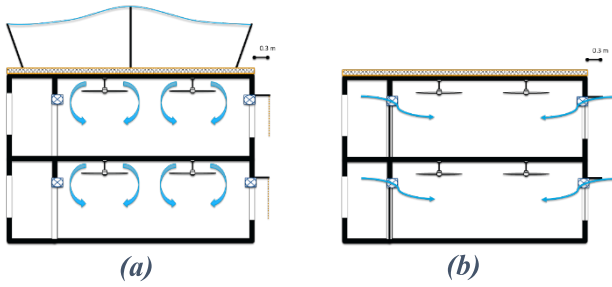
Figure 4. Schematic representation of package 1, with retrofitted single glazing, roof insulation, integrated window purifying ventilators, bamboo window shading, and summer canopy. (a) in summer (b) in winter.
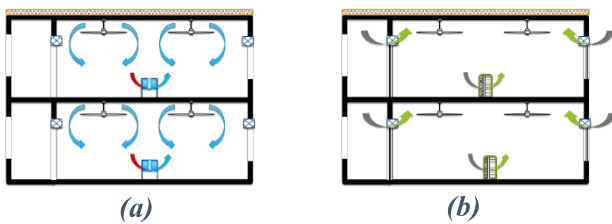

Figure 5. Schematic representation of package 2, with fully operable double-glazed windows, roof insulation, integrated window purifying ventilators, and modular electrostatic precipitator/evaporative cooling. (a) in summer (b) in winter.
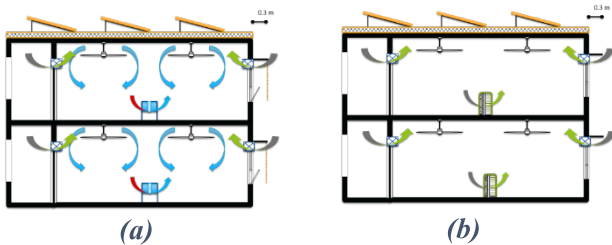

Figure 6. Schematic representation of package 3, with partly operable double-glazed windows, roof insulation, bamboo window shading, integrated window purifying ventilators, modular electrostatic precipitator/ evaporative cooling, and solar PV. (a) in summer (b) in winter.
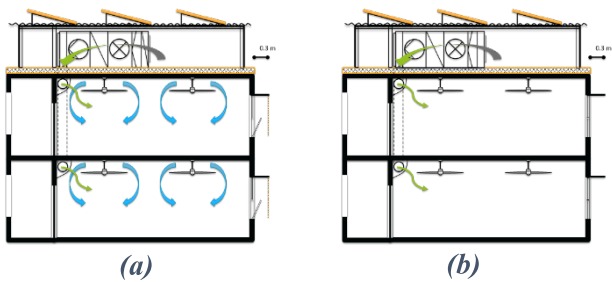

Figure 7. Schematic representation of package 4, with partly operable double-glazed windows, roof insulation, air handling unit with three stage air filtering and cooling coil, and solar PV. (a) in summer (b) in winter.

However, this would also increase the under-heating hours. Instead of adding heating capacity, heat recovery ventilation can be a better option. Additionally, in winter the solar load contributes to heating up the space.

Also, while blocking pollutants from entering the classrooms, sufficient fresh air is required. As active filtering showed to be necessary it is of great interest to create overpressure in the rooms to reduce infiltration.

Besides the necessity of active filtering, it appeared that active cooling is needed to eliminate overheating hours. To this end, evaporative cooling would be more energy efficient than mechanical cooling.

The unilateral interventions were assembled into 4 packages, varying in level of technology, control, and sustainability. Each package may easily be scaled up. Package 1 (**Figure 4**) represents the most low-end decentralised solution by retrofitting window panes and the least amount of active technologies. Package 2 and 3, respectively **Figure 5** and **Figure 6**, are more high-end solution due to the costly application of electrostatic precipitators. The biggest difference is the use of photovoltaics in package 3. Finally, package 4 (**Figure 7**) is the only centralised solution with 3 stage filtered air handling unit.

The package performances are tested concerning the indoor climate, energy, investment costs, and operating costs. All packages are designed such that there is always an ACH rate of at least 7 [1/h] to restrain the indoor CO_2 concentration. The $PM_{2.5}$ exposure (**Figure 8**) is reduced by installing more filtering capacities. Regarding the thermal comfort (**Figure 9**) it is clear that active cooling is necessary to eliminate the overheating hours. Though the increased ventilation capacity in winter causes extra under heating hours.

Table 1. Simulation results of the base case, over one school year (1890 occupancy hours).

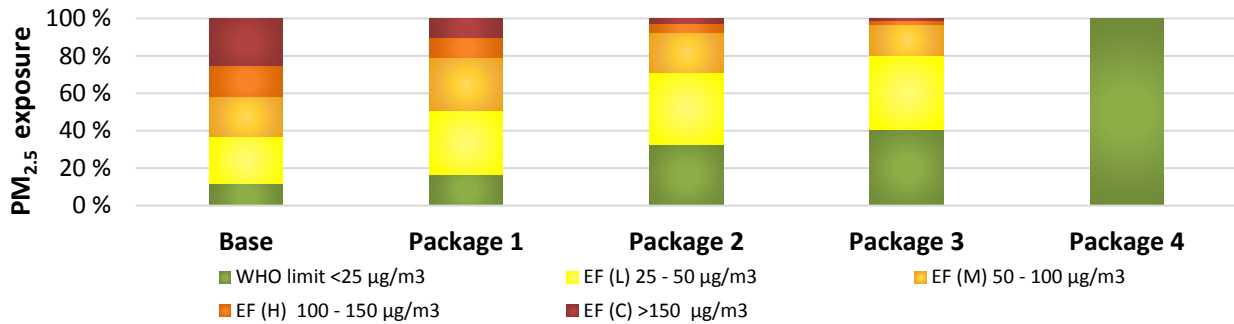| Criteria	Base case
Under heating hours [h]	75
Overheating hours [h]	330
CO_2 exceedance hours [h]	250
Annual average CO_2 concentration [ppm]	830
$PM_{2.5}$ exceedance hours [h]	225
Annual average $PM_{2.5}$ concentration [μg/m³]	115
Electricity use [kWh]	685

Figure 8. Annual mean indoor PM$_{2.5}$ exposure categorized in exceedance factor (EF) hours - Low (L), Moderate (M), High (H), and Critical (C) - and hours underneath daily WHO limit, over in total 1890 occupancy hours.
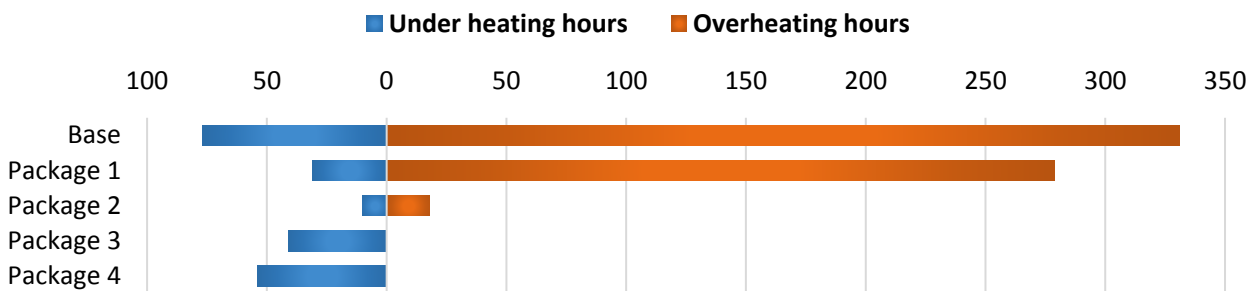

Figure 9. Thermal performance of the different packages in the classroom at the ground floor, expressed in under- and overheating hours outside the 80% satisfaction range of the ATC model with a total amount of occupancy hours = 1890 h.

Subsequently, the packages were ranked via a decision matrix (**Table 2**). The financially most feasible solution, package 1, has the least effect on the indoor climate. Additionally, package 4 scores the best on healthy indoor climate in respect to PM$_{2.5}$. Though financially, it is most infeasible and unsustainable on the longer term due to the high cooling demand. Package 2 scores points on all criteria and therefore scores best overall, whereas package 3 and 4 actually lose points due to an increase in under heating hours. However, on the longer term package 3 is more sustainable and financially feasible.

Table 2. Decision matrix to rate 4 different solution packages (more ★'s = better performance; more €'s = more expensive).

Criteria	Package 1	Package 2	Package 3	Package 4
Under heating hours	★	★★★	–	–
Overheating hours	★	★★★	★★★★	★★★★
CO$_2$ exposure	★★	★★	★★	★★
PM$_{2.5}$ exposure	–	★★	★★	★★★
Electricity use	★★	★★	★★★	–
Investment costs	€	€€€	€€€€	€€€
Total cost of ownership	€	€€€€	€€	€€€

Conclusion

Via fieldwork and simulations, it is concluded that naturally ventilated schools in Delhi mostly experience high PM$_{2.5}$ concentration, extreme overheating and slightly under heating. Both active air filtering and cooling seem required. As the occupants are used to an open façade (open doors and windows), sealing the classrooms is unacceptable. Instead the openness is decreased by applying partly operable windows and creating an overpressure during hazardous days.

The packages assessment showed that package 3 as decentralised solution potentially is the most effective, sustainably and financially, generic solution to create a healthier indoor climate in such schools. The high investment cost might be attenuated by implementing the package in phases. Though, in order to reach the target to reduce the PM$_{2.5}$ exposure towards the WHO limit, a multiple stage filtering seems necessary. Additionally, it is interesting to integrate a heat recovery into the ventilation system to eliminate the under-heating hours. It might even function as cold recovery to reduce the cooling demand. ■