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Architectural Design Optimization for Energy Efficiency Using Mixed-mode System: Tracing the Challenges and Opportunities in a Warm-humid Climatic Context

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ARCHITECTURAL DESIGN OPTIMIZATION FOR ENERGY EFFICIENCY USING MIXED-MODE SYSTEM: TRACING THE CHALLENGES AND OPPORTUNITIES IN A WARM-HUMID CLIMATIC CONTEXT

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ABSTRACT

This paper is based on the experiences of designing an energy efficient building in the warm-humid climatic zone of India. The building is a part of a government project to promote awareness and use of energy efficient home appliances. From the stage of conception, therefore, it was designed as a demonstration project in order to integrate the knowledge dissemination objective with the performance of the building itself. This paper highlights the various challenges and opportunities that were part of the process of design, procurement (of building materials and components) and execution, towards making it an energy efficient building. It also presents in detail the thermal comfort analysis that was done to capture the adaptive model of thermal comfort for a mixed-mode strategy.

INTRODUCTION

The project under analysis is the upcoming Regional Energy Efficiency Centre (REEC) in Kolkata, India. It is one of the three REECs being established in different parts of the country by the Government of India in partnership with other organizations and institutions to focus on the three sectors for implementation of energy efficiency – buildings, small and medium industries (SMEs) and home appliances. The West Bengal Renewable Energy Development Agency (WBREDA) is a state-designated agency for the state of West Bengal and will be housing the REEC at Kolkata in their existing premises. The main objectives of the Centre, with a focus on energy efficient domestic appliances, are as follows:

- Enhance energy efficiency awareness and education among energy end-users
- Facilitate showcasing and demonstration of energy efficient products for public at large
- Promote development (incubation) of energy efficient technologies
- Encourage research and interdisciplinary collaboration on energy efficiency
- Catalyze the development and growth of energy efficiency market and business in the country.

REEC Kolkata is envisaged as a regional hub that will attract visitors from nearby states and regions along with other interested audience such as scientists, engineers, government officials, consumers, entrepreneurs, college and school-going students and enterprises dealing in the manufacture and sale of home appliances.

The building will be located in the Solar Energy Educational Park, on a land-fill site, in Science City situated near the renowned Birla Museum in Kolkata, one of the prime locations in the city. The architectural design firm working on the project is based within the city. Their initial response to the program and purpose that the Centre is going to serve was to propose to 'create a climate responsive structure to achieve energy efficiency through the ECBC guidelines'. Energy Conservation Building Code (ECBC) was launched in May 2007 by the Bureau of Energy Efficiency (BEE), Ministry of Power, Government of India. The Code specifies minimum requirements for the energy performance of various components of a building such as envelope, heating, ventilation, and air conditioning system, interior and exterior lighting system, service hot water, electrical power system and motors. It also lays down the standards for compliance through the Whole Building Performance Method using building energy simulation tools.

As part of the initial design exercise, the architect carried out a sun path analysis and proposed following measures as part of the building design:

1. Reduce solar heat gain by incorporating different external shading devices - a combination of horizontal and vertical shading devices on south and south-west facades and vertical shading devices on north and east
2. Hollow brick wall with insulation to reduce conductive heat gain from outside
3. High performance glazing to mitigate solar radiation

4. Multiple numbers of small openings with deep overhangs on south facade and relatively larger openings on the north

It is important to note here that the limitations of the site do not allow the flexibility of changing the orientation and profile of the building. At this stage, the project was introduced to us (the USAID ECO-III Project) to provide technical assistance towards making the proposed design more energy efficient using the Whole Building Performance method, and to help in procurement of building components, materials and services to realize the design in construction. The pages that follow outline the main barriers and challenges and the way they are being dealt with. The study is still in progress; this paper, therefore, covers the process in parts.

Building Description

The total built up area is $250m^2$, divided over three floors. The ground floor has the reception area and a hall for rotating demonstration of energy efficient home appliance and other related products along with display and information panels. The first floor has a similar hall which can either be used for exhibits or as a training/ presentation room for occasional lectures. The floor also has offices and a small conference room. The facility is assumed to be run by a staff of five, including one Centre in-charge, two assistants and two people as maintenance crew. The second floor has rest room facility, including a pantry, for the occasional visitor (of non-official and technical cadre) and an open terrace. The overall window-to-wall ratio is about 20%.

CHALLENGES AND BARRIERS

Climate and Client Brief

The foremost challenge we faced with the project was to propose a low-energy design while maintaining thermal comfort in response to the difficult climatic conditions. National Building Code of India (BIS, 2005) divides the country into five climatic zones based on ranges of mean monthly maximum temperature and mean monthly relative humidity. According to this classification, Kolkata falls within the Warm-Humid climatic zone. Mean monthly temperatures range from 19 °C to 30 °C and maximum temperatures can often exceed 40°C. During winter months of December and January, the lowest temperatures range between 10 °C - 14 °C. Day and night time temperature differential is not significant enough to aid night-time cooling. Annual average relative humidity is as high as 78%. This, coupled with summer high temperatures, is a very challenging climate to design for. High humidity also leads to ingress of moisture into the envelope, reducing its integrity envelope and creating conditions for mould growth. A slight compromise on the quality of material and construction workmanship can lead to high maintenance costs in the long run. Natural ventilation is one of the most important strategies to improve thermal comfort. However, the wind speed is less; about 50% of blowing wind is classified as 'Calm'. Solar radiation levels are high which means shading devices such as overhangs and fins are important strategies to improve the envelope.

Some of the other challenges were a result of the nature of the project and the client. As mentioned earlier, the project is a public undertaking. The initial brief from the client strongly stressed on avoiding air conditioning at all costs, because the general notion of a 'green' building is that of a building without any mechanical system for air-conditioning and relying entirely on passive strategies. In the process of interacting with the client, it became obvious that the idea of a 'green' or 'sustainable' building is to avoid air conditioning at all costs. Many of the existing public sector buildings in India are considerably old and were designed without any provisions for air conditioning, and were later retrofitted as and when needed. Well-designed buildings in passive mode became inefficient when air conditioning systems were haphazardly used. In many new constructions, such as this one, the brief does not include the provision of air conditioning. One of the challenges, therefore, was to convince the clients of the need for cooling, and dehumidification, especially in zones that have high occupancy levels, such as the demonstration and presentation halls where conditions would become unbearable during peak summer months. It had to be emphasized that between the two extremes of fully-conditioned spaces and fully-naturally ventilated space, there is an option of mixed-mode ventilation where '*the building "changes-over" between natural ventilation and air-conditioning on a seasonal or even daily basis'*. However, it is important to state here that the government is gradually making it mandatory for the new buildings to be energy efficient and has been taking many initiatives towards this objective.

It has been observed that it is usually difficult to experiment with material and construction in a government project. The Public Works Department (PWD) has a set of material specifications as given in the 'Schedule of Rates', and norms for construction practices, that have to be adhered to. These specifications or standards are rarely modified to reflect the changing scenario of the construction industry wherein new innovative materials of better quality and more efficient construction processes are being introduced in the market at a fast pace. Also, most of the projects have a limited budget. The emphasis, therefore, is to cut down on the short-term expenditure. Overlooking the long-term needs of the buildings leads to increased wear and tear making the envelope inefficient.

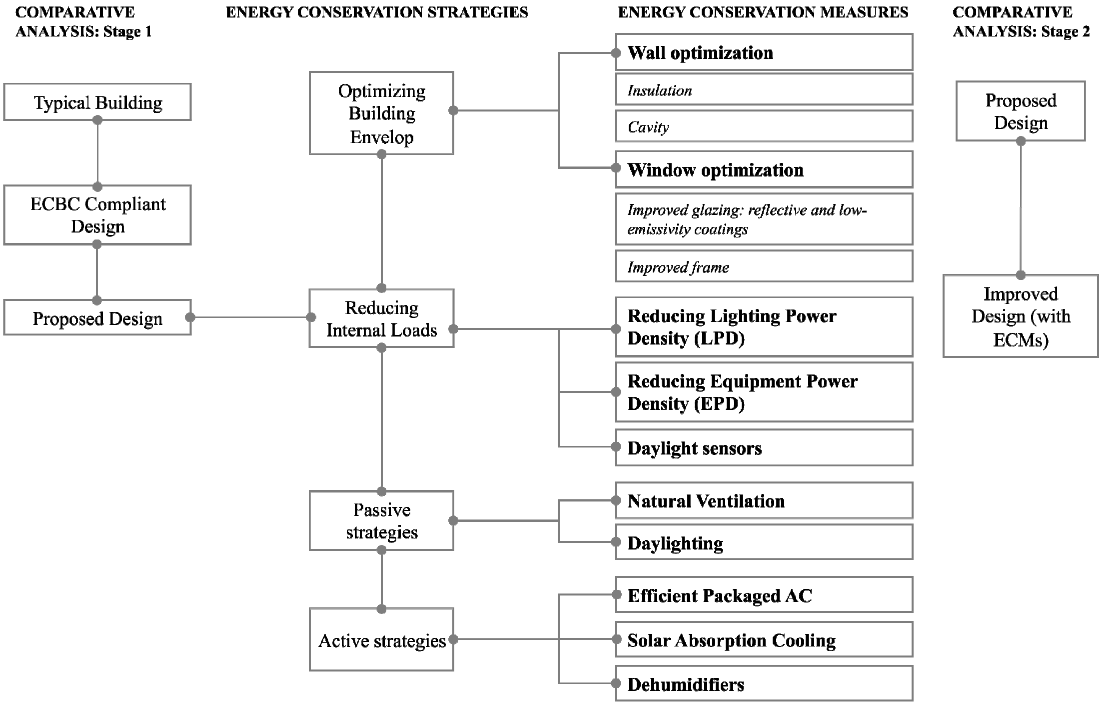

Figure 1, Process followed for ECBC compliance, showing various ECMs

Maintaining the flow of continuous exchange between the client, the architect and other stakeholders was a major issue. At various stages, it seemed that the project timeline was never pinned down, especially when it came to formal approvals and the documentation process; things either moved too fast or slowed down to the extent of reaching an absolute standstill.

We also faced a few challenges in terms of finding appropriate technological solutions for services like air-conditioning. The conditioned area within the building is small and usually the only option for such a building and function is a packaged direct expansion system or splits. This is the most commonly used system type in the country. These systems, however, cannot dehumidify the air. Most of the low-energy air conditioning (and dehumidification) solutions available in the market were either not cost effective to use in such a small building or were high maintenance requiring more manpower than the facility would be able to afford.

Simulation-based Analysis

Since the process of building energy simulation was new for both the architect and the clients, we had to continuously interact with them in order to understand and extract information required as simulation inputs. For example, the programmatic requirements of the facility were very vague initially. Gradually, through discussions, we narrowed down on the schedules of occupancy, number of occupants for each zone and their activities. These interactions also helped the architect to understand the program better and refine the space organization accordingly. More important, it helped us to understand the extent of detail we need to incorporate to get meaningful results from the simulations, and concurrently, which inputs were critical to receive from the clients/architect and which ones we could assume with certain level of reasoning in place.

The most challenging task, however, was to design for climatic conditions of high humidity, high temperature ranges and low wind speeds, almost all the year round. While such a scenario would have been easy to handle if the building was to be made air-tight and completely conditioned, it had to be ruled out to demonstrate a mixed-mode system which could be termed as more climate responsive in nature. A mixed-mode system involves natural ventilation and it was unclear from our initial analysis if this was a reasonable strategy.

We followed a two-pronged approach to building energy simulation. In order to understand the impact of various Energy Conservation Measures (ECMs) on the Energy Performance Index (EPI) of the proposed design, we modeled the two most prominent zones (namely A and B for the following discussion) within the building that function as the exhibition and demonstration halls and, put together, account for almost half of the building area (volume) were modeled as air-conditioned zones, while the rest of the building was modeled with provision for natural ventilation. The modeling was done in DesignBuilder which uses EnergyPlus engine for simulation. The various ECMs based on the ECBC requirements were incorporated within the proposed case to arrive at an ECBC compliant improved case. The methodologyfollowed is described in Figure 1. Based on the impact of ECMs on the EPI of the proposed design, we were able to select the ones we thought were most appropriate in terms of availability, ease of execution and cost-effectiveness.

The second part of the analysis was to model zones A and B as mixed-mode zones with provision to switch between air-conditioning and natural ventilation. The challenge towards accurate modeling of a mixed-mode system was in specifying the temperature setpoints for cooling and ventilation so that both would work in tandem within the same zone. We developed a mixed-mode strategy where the zone air would be cooled down using natural ventilation whenever the outdoor conditions were favourable and when the zone air temperature would go beyond cooling temperature setpoint (because of rise in outdoor dry bulb temperature), the cooling system would kick-in to maintain the zone air temperature at the given cooling setpoint. It was difficult to understand how these setpoints interacted and what would be the temperature range within which cooling and natural ventilation would work most efficiently. The runs showed that mixed mode zones are comfortable only during the winter months. The climate in Kolkata is predominantly warm and the results showed that during these months the window were never open and therefore, the mixed-mode system did not work. This meant that even though we have provided for natural ventilation, the cooling in mixed-mode zones was always on during occupied hours and we could not see any benefit in terms of cooling energy savings.

Based on this finding, it was decided that focusing on EPI values was not the correct way to capture the advantages of natural ventilation. Rather, it was essential to work towards understanding thermal comfort in a naturally ventilated building in this type of climate. The following text provides a detailed description of the analysis.

Thermal Comfort analysis

The objective of this analysis was to be able to predict thermal comfort sensation within the proposed building with reasonable level of accuracy given the limited amount of time and resources. The entire building was modeled as consisting of 15 thermal zones each corresponding to a spatial zone. Zones A and B (discussed earlier) were modeled as air-conditioned / mixed-mode zones. The rest of the zones were naturally ventilated with provisions for ceiling fans. Four cases were modeled and simulated to understand and compare the impact of mixed-mode cooling, natural ventilation and increased air speed (ceiling fans) on the PMV-PPD.

The first set of simulation runs (Run 1) has mixed-mode for zones A and B while all other zones are naturally ventilated. In the second set of runs (Run 2), zones A and B are conditioned without mixed-mode and the cooling setpoint is increased to 26 °C. Both the third and fourth set of simulation runs (Run3 and 4) were modeled with natural ventilation in all zones, with cases in Run 4 having the capability to use ceiling fans to reduce energy use (Table 1).

Table 1, Description of Runs modeled for Thermal Comfort analysis

RUN	DESCRIPTION	HVAC	NAT-VENT	MIXED-MODE
1	Cooling setpoint 24 °C	On	On	On
2	Cooling setpoint 26 °C	On	Off	Off
3	Without Ceiling fans	Off	On	Off
4	With Ceiling fans	Off	On	Off

Results from EnergyPlus simulation runs reported hourly PMV values for occupied periods for each zone of the building, using Fanger's comfort model algorithms (EnergyPlus, 2009). PMV calculations are based on the six parameters of mean air temperature, mean radiant temperature, relative humidity, air speed, clothing and activity level. It is a mathematical model and does not account for any of the adaptive mechanisms wherein: 'if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort' (Nicol and Humphreys, 2002). Even though the PMV model is well validated and is known to predict thermal comfort in air conditioned buildings reasonably well, it has shown to predict thermal sensations warmer than occupants actually feel in case of naturally ventilated buildings (Brager and de Dear, 1998). For such buildings an adaptive model was proposed which is dependent on one single variable of mean monthly outdoor temperature.

Fanger and Toftum (2002) proposed an extension of the PMV model to bridge the gap arising due to discrepancies between the results of the mathematical and the adaptive models. This extension is based on two adaptive mechanisms of expectation and change in metabolic rate. Expectation is a psychological adaptation which recognizes that an occupant's past thermal experiences have a direct impact on his expectations of comfort (Brager and de Dear, 1998). Change in metabolic rate is a behavioral adaptation which acknowledges that people slow down their activity when they feel warm (Fanger and Toftum, 2002).

The extension of the PMV model thus formed the basis of this analysis. To be able to model the impact of change in metabolic rate, a spreadsheet for calculating PMV PPD was developed based on ASHRAE Thermal Comfort algorithms. Hourly PMV PPD for occupied hours were calculated for occupied periods using hourly data for zone mean air temperature, mean radiant temperature and relative humidity from the simulation output. Metabolic rate was assumed to be 60 W/m2 for light office work, and a clo value of 0.75 for winters (Oct-Mar) and 0.5 for summers (Apr-Sep).

The calculated PMV results were then modified to account for slowing down of metabolic rate. For every unit of PMV above the neutral, the metabolic rate was reduced by 6.7%, as per the PMV extension model. The resultant PMV was then adjusted by multiplying it with an expectancy factor 'e' of 0.7 to account for the fact that the occupants are used to living in warm conditions and their expectation of comfort in an indoor environment are more relaxed. For example, if there are many air-conditioned buildings in a given region, the occupants would have a higher level of expectation of comfort because of the socio-economic and cultural context (Fountain et al., 1996). Similarly, if the occupants are habitual of living in a predominantly warm climate, their comfort setpoints get adjusted to the seasonal variation (or lack of it) or even long-term climatic changes which also contribute to their expectation of a warmer environment as opposed to if they had been living in a climatic zone where the warm periods are shorter.

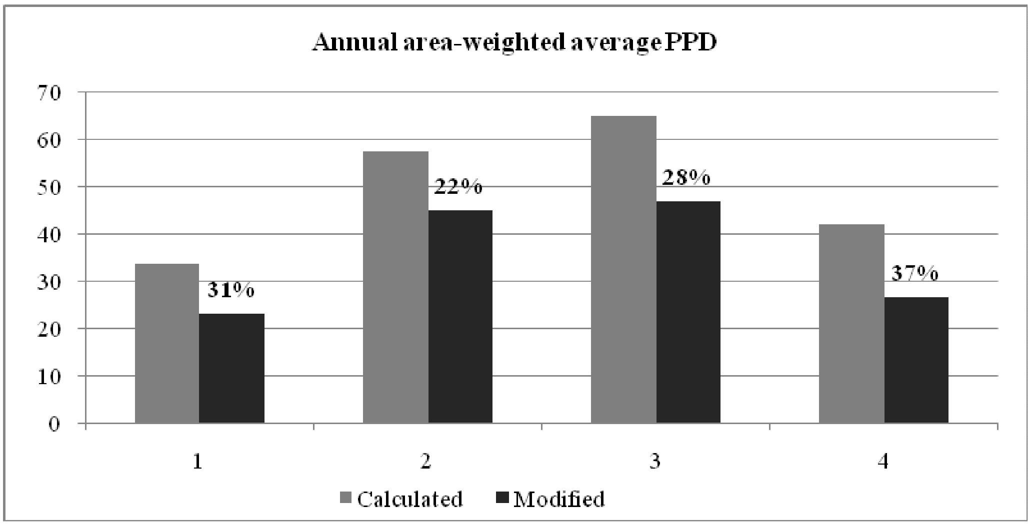

Figure 2, Annual area-weighted average PPD from calculated PMV and modified PMV (Data labels show percentage of reduction from calculated to modified PPD)

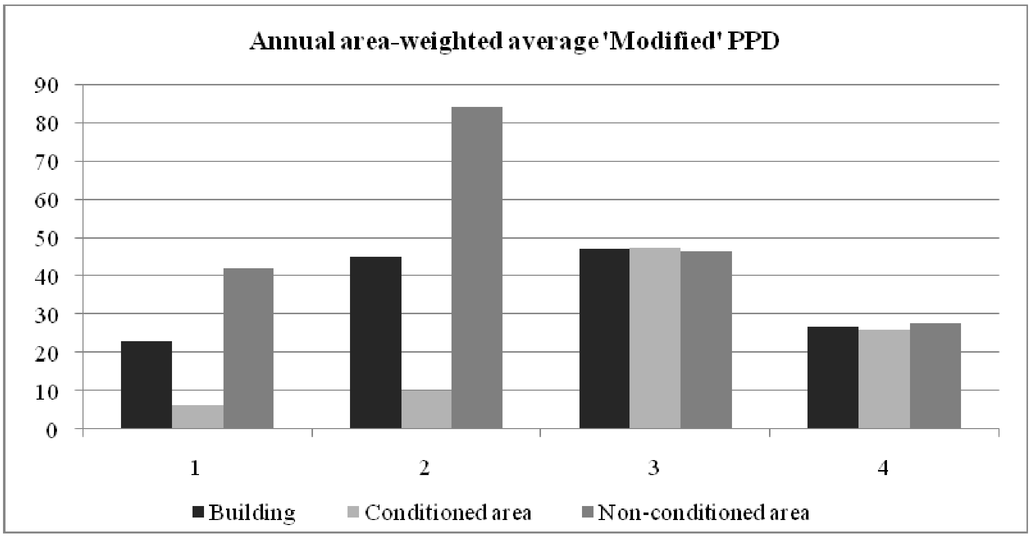

Figure 3, Annual area-weighted average modified PPD for conditioned and non-conditioned zones of the building

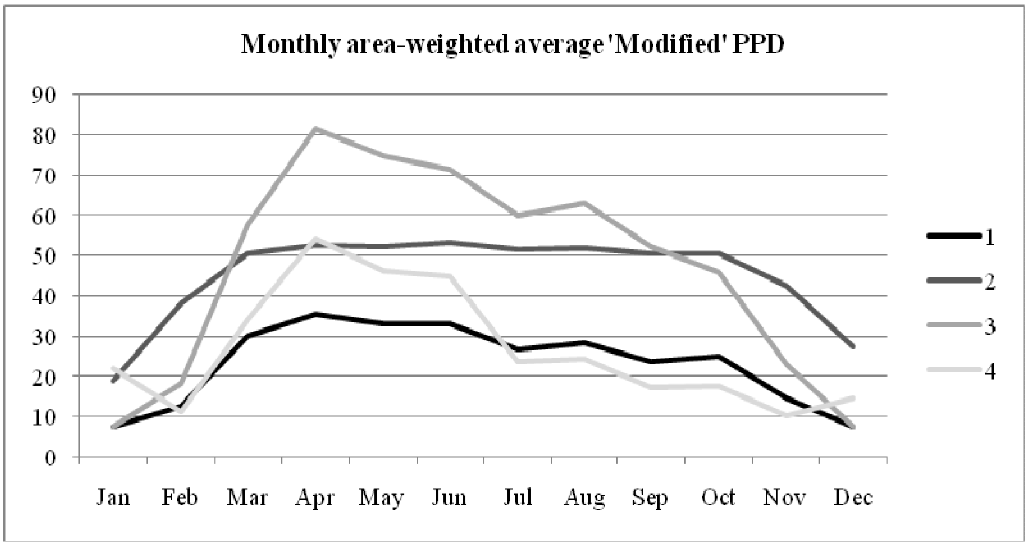

Figure 4, Monthly variation of area-weighted average modified PPD for the four runs

Results of the analysis are presented here in terms of zone area-weighted monthly and annual averages of hourly PPD values. Figure 2 shows that the Predicted Percentage of Dissatisfied decreases from 50% to 35% (on an average) when the PMV is modified to account for adaptive mechanisms, bringing the thermal comfort prediction closer to reality for mixed-mode buildings in warm and humid climates. The reduction is even more significant (37%) in case of Run 4 where ceiling fans lead to increased air speed.

In Figure 3, PPD increases from 1 to 2 in conditioned zones because of the increase in cooling setpoint temperature, and in non-conditioned zones because of unavailability of natural ventilation in Run 2. Switching off natural ventilation almost doubles the PPD in non-conditioned zones. Since both Runs 3 and 4 are both non-conditioned and naturally ventilated, the PPD levels are considerably high. They, however, decrease by almost half when air speed is increased to account for ceiling fans in Run 4. This indicates that controlling air speed with natural ventilation is a very important adaptive strategy, especially in the summer months, for a warm-humid climate like that of Kolkata.

Figure 4 shows monthly PPD values at a building level (area-weighted average of conditioned and non-conditioned zones). A very important observation to be drawn from this graph is that Run 1 with mixed-mode air conditioning and Run 4 with natural ventilation and ceiling fans, almost coincide, except during peak summer months of Apr-Jun. This indicates that air conditioning can be easily avoided during rest of the year through well-designed passive measures.

CONCLUSION: LESSONS LEARNT

Some of the experiences we have shared in this paper might be true for many other contexts and, therefore, are not novel. Nevertheless, since not much has been written to document the process of designing an energy efficient or a Code compliant building focusing on issues that we found were challenging on more than one levels, we have attempted to collate our experiences through this paper. The project is still a work in progress and we feel it is important to have another round of such documentation wherein we would be able to report more solutions rather than challenges of the situation.

In projects such as these, where multiple stakeholders are involved and some of the most critical issues are also the most challenging in nature, the importance of Integrated Design Process increases many-fold. In due course of the project, we realized that besides providing technical assistance, our role was increasingly becoming that of a facilitator. Having realized that, we felt that the most important task was to keep the interaction going in order to keep all the stakeholders in the loop. Gradually, we feel that it is very important to understand where to stop intermediating between two groups after a certain stage, for instance the architect and the product vendors, and encourage an exchange keeping our involvement to a minimum.

Results from the simulation exercise provided us with an important insight into the understanding of occupant thermal comfort for the given climatic conditions, reiterating the need for a revised thermal comfort model for a detailed building energy simulation analysis. Modeling of ceiling fans in both mixed-mode as well as naturally ventilated zones by changing (increasing) the zone air velocity showed that they have a far greater impact on improving thermal comfort than we realized - the results show a significant improvement in PMV in summer months due to increased air movement. The improved PMV does not fall within the comfort range but is an improvement nonetheless. This will also be helpful in future to understand the already established thermal comfort models in the context of Indian climatic conditions and to set-up a more relevant set of simulation inputs for further exercises.

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