

Chapter 74

Evaluation of Retrofitting Strategies to Optimize Thermal Performance of Naturally Ventilated Classrooms: A simulation-Based Approach



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Abstract The thermally comfortable environment in classrooms is significant to improve the performance and productivity of students. A substantial number of researches emphasize energy-saving potential, especially for forthcoming projects, whereas existing buildings in the world consume 40% of the energy to meet the desired indoor comfort conditions. Passive retrofitting strategies provide opportunities for reducing energy consumptions to achieve sustainability in the existing buildings. Presently, architects and designers are taking advantage of building simulation tools that can compare and optimize design alternatives before the installation. The objective of this study is to analyse the performance of twenty-two combinations of retrofitting solutions to optimize the thermal performance of existing classrooms in the Architecture Department located in Tiruchirappalli, India, by using a simulation-based approach. The simulation results showed that retrofitting strategy 1 (RS1—expanded polystyrene + shading device option 1 + night ventilation) was performed better among all other strategies to achieve maximum comfort hours (three times more than the actual comfort hours). However, retrofitting strategy 5 (RS5—shading device option 1 + night ventilation) was found as a cost-effective strategy which does not include any insulating materials. Retrofitting strategies such as the insulating materials and the shading devices were significant only with night ventilation.

74.1 Introduction

Sustainable development in the construction field is the rising call in most of the developing countries [1]. By reducing the energy demand to operate buildings, sustainable and energy-efficient buildings can be developed for the future [2]. The emerging of

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comfortable and energy-efficient buildings results as the key to a complicated optimization which involves a significant number of reliant variables [3]. On the other hand, a substantial number of researches emphasize energy-saving potential especially for forthcoming projects, whereas existing buildings in the world consume 40% of the energy to meet the desired indoor comfort conditions [1]. Retrofitting is one of the critical approaches for achieving sustainability in the existing building stock at a relatively low cost. Retrofitting solutions provide significant opportunities for reducing energy consumptions [4]. The characteristics of sustainable retrofitting should be most favourable, readily available and cost-effective. To find out the best retrofit alternatives, the role of architects, designers and technical experts is obligatory. Nowadays, architects and designers are taking advantage of building simulation tools that can compare and optimize design alternatives before the installation. Computational techniques and computer simulation tools have been efficiently used in building design stage, construction stage, operational stage, optimization and researches for eras [5]. These tools help to achieve goals such as cost reduction, energy savings and diminish environmental impacts and improve the comfortable built environment.

Public buildings became the primary source of energy consumption drastically over the last eras [6]. Educational institutions are the distinct types of buildings that have the prime objective to provide a stimulating learning/ teaching environment for the students and teachers [7]. Based on Annual Status of Higher Education of States and Union Territories in India (ASHE) 2017 report, the total number of universities in India has grown up from 602 in 2011–12 to 799 in 2015–16, growing at a compounded annual growth rate (CAGR) of 5.2%. The educational buildings use energy mainly to achieve thermal comfort. The human thermal environment, as a part of ergonomics, pacts with thermal comfort (i.e. whether an individual feel too cold, hot or sticky), particularly in their working environment. Thermal discomfort environment affects the productivity and performance of both students and teachers and hence creates unsatisfactory conditions. For this regards, the thermal comfort requirements in the classrooms of higher education institutes need serious attention.

This study is a sequence of previous research work [8] done by the authors who carried out an analysis on the thermal performance of existing classroom conditions of an architectural school at Tiruchirappalli, India, and proposed three major retrofitting solutions (design interventions) such as designing of shading devices, installation of insulating materials and night ventilation. The results from the previous study concluded that the addition of insulating materials was giving negative impacts (providing comfort hours less than existing comfort hours) in this context. Therefore, the authors further found a need to examine the performance of twenty-two combinations of retrofitting solutions to further optimize the thermal performance of existing classrooms by using a simulation-based approach.

74.2 Methodology

74.2.1 Location and Building Details

The building was chosen in Tiruchirappalli, Tamil Nadu, India (10°46' N, 78°43' E, 88 m AMSL), which has been classified under warm and humid climatic zone by National Building Code 2016 (NBC) of India. April, May and June represent the summer months, whereas December, January and February are relatively colder months. May is measured as the hottest of all the months with 38.1 °C as the maximum monthly mean temperature. Likewise, January is measured as the coolest with a mean monthly minimum temperature of 20.3 °C. The department of architecture of a higher educational institution, which had L configuration, was selected to perform this study. The case study building is a framed structure and consisted of four lecture halls (L1 & L2) at the first and second floor in the typical arrangements and five studio classrooms (S1 & S2) distributed on all the three floors (Fig. 74.1). Since L1 and L2 were identical in spatial arrangements, only L1 is considered for the analysis. All the classrooms and lecture halls were naturally ventilated spaces and had fans to enhance the wind movement. Table 74.1 shows the spatial characteristics of the selected classrooms.



Fig. 74.1 Classroom layout (typical) and view of case study building (Source: Author)

Table 74.1 Plan form and measurements of classrooms

Classroom	Plan form	Dimension (m)	Area (m ²)	Volume (m ³)
Ground floor studio 1 (GFS1)	Rectangle	9.5 × 16 × 4.2	152	638
First-floor studio 1 (FFS1)	Rectangle	9.5 × 16 × 4.2	152	638
Second-floor studio 1 (SFS1)	Rectangle	9.5 × 16 × 4.2	152	638
First-floor studio 2 (FFS2)	Rectangle	9.5 × 16 × 4.2	152	638
Second-floor studio 2 (SFS2)	Rectangle	9.5 × 16 × 4.2	152	638
First-floor lecture hall 1 (FFL1)	Square	9.5 × 8 × 4.2	76	319
Second-floor lecture hall 1 (SFL1)	Square	9.5 × 8 × 4.2	76	319

74.2.2 Modelling and Simulations

SketchUp software (version 2017) was used to create a three-dimensional model for the case study building. Integrated Environmental Solutions software (IES-version 2016) was employed in the calculation of the indoor operative temperature and comfort hours. To simulate the results, IES used variables such as air temperature, wind speed and mean radiant temperature from the weather data file (.epw) obtained from EnergyPlus.

Building envelope template. In the IES simulation software, all the walls (both internal and external) were assigned as solid brick walls of 0.23 m thick and cement plaster of 0.012 m thick on both the sides and whitewashed properly. Along with 0.15-m-thick reinforced cement concrete (RCC) flat slab, the weatherproof clay tiles of 0.075 m thick was given as roof assemblage. The floor finishes were of lightweight vitrified tiles. The doors were made up of 0.03-m-thick plywood which has a thermal conductivity value of 0.1300 W/mK. The windows had operable steel doors and fixed grills which were single glazed having the transmittance value of 0.780.

Thermal comfort template. The study used operative temperature and comfort hours to analyse the thermal performance of all the retrofitting strategies. The formula to calculate indoor operative temperature (neutral temperature) range for the naturally ventilated buildings by using Indian Adaptive Thermal Comfort (IMAC) model is as follows:

Neutral temperature (indoor operative temperature in °C) = 0.54 * outdoor temperature + 12.83. Here outdoor temperature is the thirty days outdoor running mean air temperature (°C) ranging from 12.5 to 31 °C [9]. According to NBC 2016, the 90% acceptability range for the India specific adaptive models for naturally ventilated buildings is ± 2.38 °C [10].

The thermal comfort hours are defined as the hours for which the simulated operative temperature falls within the range of IMAC indoor operative temperature comfort band. The values assigned in the simulation software for thermal comfort template are shown in Table 74.2.

Table 74.2 Thermal comfort inputs

Factors	Values
Working hours (annually)	1841 h
People’s schedule	From 09.00 AM to 05.00 PM (inclusive of break time)
People’s density	3.81/m ²
People’s activity—standing, sitting and writing	1.1 met
Clothing value	0.64 CLO
Ventilation type	Naturally ventilated
Comfort model	IMAC—Indian Adaptive Thermal Comfort Model

74.2.3 Retrofitting Strategies

The study analysed the indoor operative temperature and comfort hours of the existing building and identified the problems (Phase 1: Problem identification). The author proposed three retrofitting options in the pilot study to improve the thermal performance of the existing building are as follows.

Insulating materials. The primary aim of thermal insulation is to decrease the thermal conductance or U-value of walls. Table 74.3 shows the list of insulating materials of different categories from NBC 2016 used for this study.

Shading device design. The sun angles are essential to design shading devices. The author considered the solar chart of Tiruchirappalli city to design the shading devices (options 1 and 2) for western side walls (exposed mainly to solar radiation) of the building (Fig. 74.2).

- Shading device option 1 (To achieve maximum shading from April to September): HSA = -25°; VSA = 30°.
- Shading device option 2 (To achieve maximum shading from October to March): HSA = 40°; VSA = 30°.
- (Note: HSA = horizontal shadow angle; VSA = vertical shadow angle.)

Night Ventilation (NV). Night ventilation indicates the mechanism of natural ventilation at nighttime to bypass extreme heating and cooling of building envelope. A building with suitable thermal mass can reduce peak daytime temperature around 2 °C to 3 °C by adopting night ventilation. Table 74.4 highlights the macro flow inputs assigned in the software for night ventilation.

Table 74.3 Insulating materials specifications

S.No	Insulating material list	Density (Unit: Kg/m ³)	Thermal conductivity (Unit: W/mK)	Specific heat capacity (Unit: J/kg K)
1	Expanded polystyrene	25	0.035	1400
2	Glass wool	200	0.040	670
3	Polyurethane board	30	0.025	1400
4	Sheep wool	23	0.038	1300

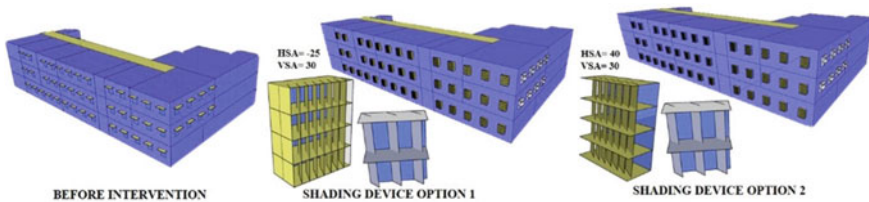


Fig. 74.2 Model of case study building with shading device options

Table 74.4 Macro flow inputs

Air exchange type		Window Open/Close Schedule
Window schedule	Without NV	Open From 09.00 AM to 05.00 PM
	With NV	Open continuously (24 h)
Window dimension		1.5 m × 1.8 m (for all the classrooms)

Combination of retrofitting strategies. Based on the results of the earlier pilot study, the authors further found a need to analyse the performance of combinations of design interventions to optimize the thermal performance of existing classrooms. Table 74.5 indicates the proposed twenty-two retrofitting strategies for this study. A colour code has been assigned to every retrofitting strategies for the analysis point of view.

Table 74.5 Colour coding details of retrofitting strategies (cluster wise)

Insulating material	Shading Device (SD)	Night ventilation	Combinations of Retrofitting Strategies (RS)	Name code	Cluster
1. Expanded polystyrene 2. Glass wool 3. Polyurethane board 4. Sheep wool	Option 1	Changing the window open/close schedule	Expanded polystyrene + SD option 1 + Night ventilation	RS 1	1
			Glass wool + SD option 1 + Night ventilation	RS 2	
			Polyurethane board + SD option 1 + Night ventilation	RS 3	
			Sheep wool + SD option 1 + Night ventilation	RS 4	
			SD option 1 + Night ventilation	RS 5	
			Expanded polystyrene + Night ventilation	RS 6	2
			Glass wool + Night ventilation	RS 7	3
			Polyurethane board + Night ventilation	RS 8	
			Sheep wool + Night ventilation	RS 9	
			SD option 2 + Night ventilation	RS 10	
			Glass wool + SD option 2 + Night ventilation	RS 11	
	Sheep wool + SD option 2 + Night ventilation	RS 12			
	Expanded polystyrene + SD option 2 + Night ventilation	RS 13			
	Polyurethane board + SD option 2 + Night ventilation	RS 14			
	Expanded polystyrene + SD option 1	RS 15	4		
	Glass wool + SD option 1	RS 16			
	Polyurethane board + SD option 1	RS 17			
	Sheep wool + SD option 1	RS 18			
	Expanded polystyrene + SD option 2	RS 19			
	Glass wool + SD option 2	RS 20			
	Polyurethane board + SD option 2	RS 21			
	Sheep wool + SD option 2	RS 22			
Before Intervention					

74.3 Results and Discussion

74.3.1 Phase 1: Problem Identification

The indoor operative temperature and comfort hours of all the classrooms were obtained from IES software as shown in Fig. 74.3. The X-axis signifies the months, whereas Y-axis (left and right) signifies the indoor operative temperature and the number of hours, respectively. The grey colour lines in the line graph indicate the indoor operative temperature of all the classrooms, whereas the yellow colour band indicates the IMAC thermal comfort range.

Based on the simulation results, the authors have identified the following problems (Fig. 74.3):

- The indoor operative temperature of all the classrooms is exceeding the IMAC thermal comfort range of Tiruchirappalli. During April, it is reaching its peak, and from March to September, the indoor operative temperature ranges of all the classrooms are increased drastically. This leads to discomfort situations to the occupants during their occupied hours.
- The comfort hours are comparatively significantly less than the total occupied hours in all the months. Especially from March to September, the comfort hours are ranging between 11 and 102 h which are approximate, twenty times less than occupied hours.

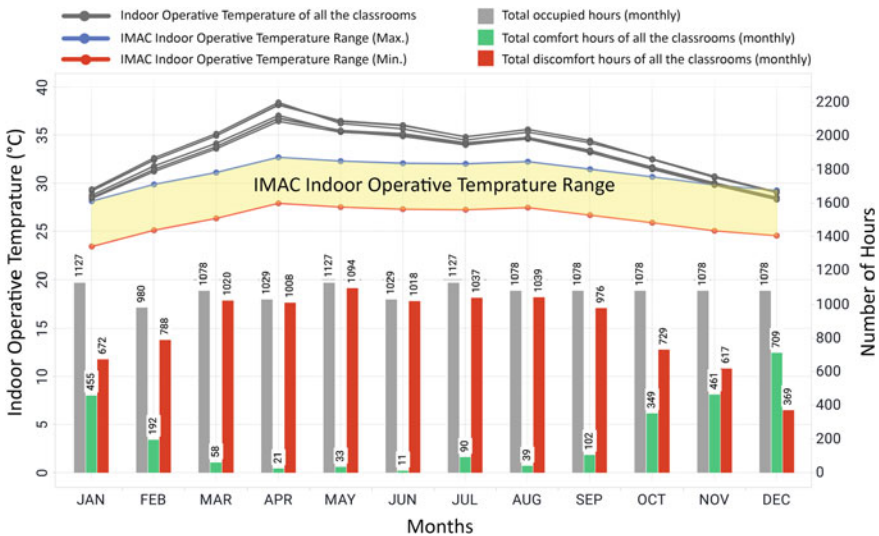


Fig. 74.3 Problem identification

74.3.2 Phase 2: Analysis of Retrofitting Solutions

To rectify the identified problems, the authors suggested the combinations of retrofitting solutions. Figure 74.4 represents the simulation results of the proposed twenty-two combinations of retrofitting strategies. The retrofitting strategies have been divided into four clusters based on the simulation results of comfort hours.

- Cluster one consists of four best-performing strategies (RS1, RS2, RS3 and RS4). All the four strategies in cluster one are achieving almost a similar number of comfort hours ranging from 1100 to 1200 h. From Fig. 74.4, it is evident that the strategies which have combined night ventilation and shading device option 1 along with insulating materials are performing the best. So, the role of night ventilation is significant to this context. In other words, the application of insulating materials is highly dependent on night ventilation. Besides, the performance of shading device option 1 is better than option 2.
- Cluster two consists of RS5 is found to be a cost-effective strategy which does not include any insulating materials. In this strategy, four classrooms are achieving comfort hours more than 1000 h, and the remaining three rooms are achieving more than 750 comfort hours.
- Clusters three and four are providing comfort hours ranging from 200 to 450 h. Explicitly, some retrofitting strategies (RS15 to RS22) have comfort hours which are less than the actual comfort hours (before intervention) because of the absence of night ventilation.

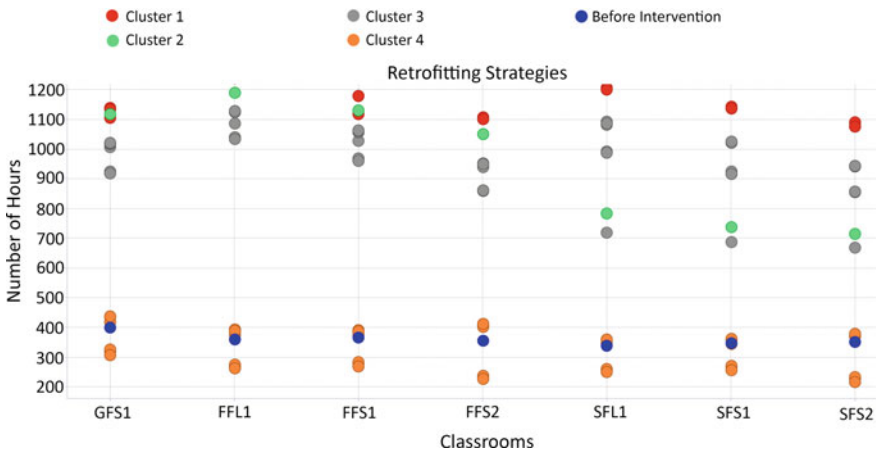


Fig. 74.4 Cluster of retrofitting strategies

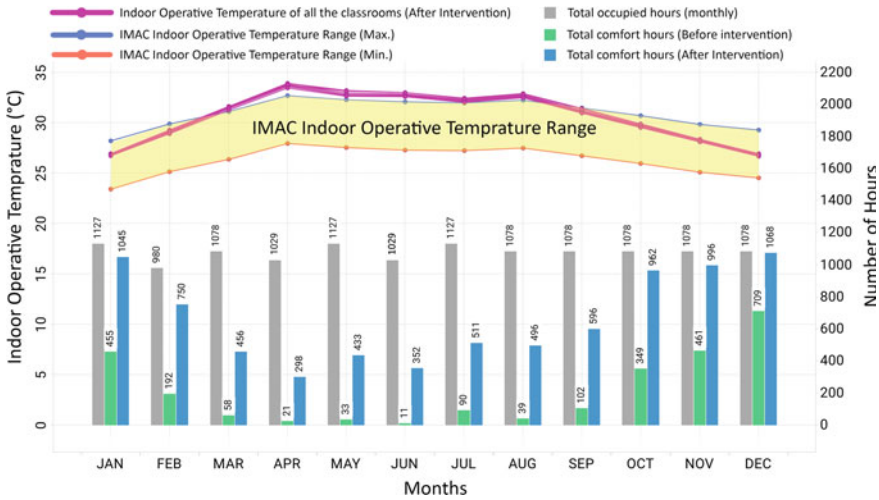


Fig. 74.5 Comparison graph of before and after retrofitting solutions for RS1

74.3.3 Selection of Optimal Solutions:

From the analysis, the authors have found that the retrofitting strategy 1 (RS1—polyurethane board + shading device option 1 + night ventilation) as the best-performing strategy. Figure 74.5 denotes the comparison graph of before and after applying RS1 in terms of both indoor operative temperature (line graph) and comfort hours (bar chart). The number of comfort hours for all the classrooms was significantly increased after optimization. The indoor operative temperature of classrooms is in between the comfort band from January to March and from August to December.

From April to July, the indoor operative temperature of all the classrooms is in between 28 °C and 33 °C, which is almost nearby in the range of IMAC comfort band. Among this temperature range, the users could achieve thermally comfortable environment by choosing their favourable adaptive options such as opening/ closing of windows and changing the seat positions.

74.3.4 Statistical Validation of RS1

A paired sample t-test was conducted to compare the monthly comfort hours of before and after applying RS1. The t-test results showed a significant difference in the monthly comfort hours of before (mean = 30, standard deviation = 32.14) and after applying RS1 (mean = 96.23, standard deviation = 41.62); $t(83) = -32.632, p < 0.001$. After applying RS1 (shading device option 1 + expanded polystyrene + night ventilation), the mean and standard deviation values have increased tremendously.

So the results indicate that the monthly comfort hours increased significantly after applying the RS1.

74.4 Conclusion

The primary objective of the study was to investigate the thermal performance of twenty-two combinations of retrofitting strategies, to find out the best-performing strategy to improve the indoor thermal environment in classrooms by using a simulation-based approach. Twenty-two retrofitting strategies were proposed and simulated using IES (version 2016) software. Based on the simulation results, the following are the findings of the study:

- RS1, RS2, RS3 and RS4 were performed nearly the same to achieve the maximum comfort hours and comfortable indoor operative temperature. RS1 (shading device option 1 + expanded polystyrene + night ventilations) was considered as the best in this cluster.
- RS5 (shading device option 1 + night ventilation) was considered as the cost-effective option because it achieved the maximum comfort hours in four classrooms out of seven, without the installation of insulating materials.
- Based on the simulation results, the role of night ventilation was significant to this context because the comfort hours were increased drastically (three times more than existing comfort hours).
- The addition of insulating materials without night ventilation was creating the negative impacts which were giving fewer comfort hours than the actual case. Thus, the strategies such as insulating materials and shading devices were significant only with night ventilation.

The results of this study can guide the architects, engineers and decision-makers to select the most favourable retrofitting strategies for warm and humid climates towards the enhancement of the thermal environments in classrooms. It is clear that the role of night ventilation is creating tremendous influences, but the authors are acknowledging the fact that the opening of windows during nighttime will create some safety and security issues. To overcome these issues, possible solutions such as providing iron mesh and security grills can be implemented. However, further studies on the limitations to assess other passive retrofitting strategies like the position of windows, window wall ratio (WWR), etc., can be explored. Moreover, the results of this study can be appropriate to the analogous building type and context only.

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