UNLOCKING ENERGY EFFICIENCY OF BUILDING ENVELOPE THROUGH PASSIVE RETROFITTING

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Summary

The thermal and visual comfort of occupants is a primary concern in a building when we talk about its optimal performance. HVAC systems are utilized in a building to maintain thermal comfort as per the standards provided by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) and health societies. Passive strategies optimize the energy required to provide occupant comfort without relying on mechanical and electrical systems. Passive strategies improve thermal comfort for occupants by maximizing natural ventilation, minimizing thermal fluctuations, and controlling solar heat reflection or absorption. The present study examines the effect of retrofitting different passive techniques on the thermal and visual comfort of a building. The retrofitting techniques considered for the assessment are window layers, window colours, insulation location in walls and roof, infiltration, insulation material and thickness, window local shading, and reflective surface. The integration of these tactics will result in a reduction of total energy consumption by regulating thermal conditions and daylight levels per specific needs. The utilization of passive retrofitting as input parameters is employed to fulfil the objective functions, while a non-sorting genetic algorithm (NSGA2) is utilized to optimize the results. The study illustrates that employing passive strategies in a building can yield energy savings of up to 36% compared to a conventional building.

Keywords: passive techniques, optimization, NSGA2, building energy performance, occupant comfort

1. Introduction

In India, the building industry is experiencing remarkable development, with a forecast of over 40% construction in the upcoming two decades. The building sector alone accounts for more than thirty percent of the total electricity consumption in India. Further, with new constructions, the energy demand would increase, necessitating the urgent optimization of building energy demand in both new and extant buildings (Bureau of Energy Efficiency | A Statutory Body under Ministry of Power, Government of India.). With a growing interest in energy conservation and environmental protection, the effective utilization of various passive strategies in buildings is garnering attention, as it predominantly depends on climate. (Ali et al., 2020) predicted thermal comfort of office rooms in Delhi by varying insulation material types and thicknesses for building envelopes and windows with different glazing materials and blinds. Thermal comfort satisfaction improved by nearly 30% in the environment created by retrofitting passive strategies.(Alsayed & Tayeh, 2019) Determine the optimal insulation thickness based on the life cycle cost analysis for a building situated in Palestine. Investment costs for Polystyrene (I1) and Polyurethane (I2) are 83 and 171.43 $/m3, respectively. Despite this, (I2), with half the thickness of (I1), can provide the same optimal financial benefits. (Rosti et al., 2020) Analyzed the optimal insulation thickness for Iranian climate zones using a life cycle cost analysis. According to the findings, less than 40 mm of insulation material was required for ACC block walls. (Garg et al., 2016) analyzed the performance of a cool roof, which reduces the surface temperature by reflecting solar radiation, resulting in less heat ingress in building space. The average and maximum reduction in indoor air temperature for the room with a white reflective roof at VNHM School is 2.1°C and 5.0°C, respectively. (G et al., 2018) Different types of window glasses were used to control building cooling and heating burdens through experimental and theoretical research. The effect of grey reflective glass resulted in the most significant annual energy and cost savings across different climates.

For central Italy, (Pisello et al., 2015) analysis of a novel type of green roof that included the benefits of both green and cool roofs found that it decreased the total amount of indoor overheating periods in summertime by 98.2%, with only minimal adverse effects in winter. (He et al., 2020) objective was to measure the variations in the summer and winter thermal energy performance of standard, cool, and green roofs in Shanghai. The results showed that, compared to a typical roof, a cool roof had an average cooling effect of 3.3°C, and a green

10.18086/swc.2023.06.10 Available at http://proceedings.ises.org

roof had an average cooling effect of 2.9°C. According to (Bozonnet et al., 2011), the cool roof reduces the mean exterior surface temperature by over 10°C even in moderate climates, with slight alteration at lower temperatures but a significant effect at higher temperatures. (Androutsopoulos et al., 2017) evaluated the thermal energy performance of a cool roof-incorporated building located in Athens. Summertime demand for energy for ventilation was vividly lowered by 30%, but annual heating energy usage only increased marginally by 12%. In order to assess the efficiency of retrofitting green and cool roofs for lowering the energy burden for offices in Central London (Virk et al., 2015) undertook modelling research. When it comes to preventing summertime overheating, cool roofs have been found to be more beneficial than green roofs. In comparison to cool and green roofs, insulation was perhaps the most efficient energy reduction solution. For numerous boundary conditions determined by optical, thermal, meteorological, and hydrological circumstances, (Kolokotsa et al., 2013) undertook comparative analytical research using the Energy Plus programme on the ability of green roofs and cool roofs to reduce urban heat islands. It has been discovered that cool roofs and green roofs can considerably enhance urban environments and lower energy use.

To optimize the thickness of thermal insulation, (Ozel, 2014) examined how the placement of insulation affects the ever-evolving heat-transfer traits of building outer walls. The cost estimate over a building's 20-year lifespan is employed to pinpoint the optimal insulation thickness. Factors like the yearly mean time lag and decrement are heavily influenced by the insulation's location. However, the insulation's placement doesn't alter the ideal insulation thickness or the annual gearbox loads. (Rosti et al., 2020) investigated the optimal thickness of insulation for both modern and traditional external walls across various Iranian climatic regions. Their findings suggested an insulation thickness requirement of less than 4 cm, which is considerably lower compared to values cited in other countries.

Furthermore, (Yuk et al., 2023) intended to investigate how an old building with an exposed roof structure affects energy efficiency. Instead of standard insulation, a vacuum insulation panel (VIP) retrofit approach is utilized due to the distinctive characteristics of the structure. The potential for passive shading and thermal barriers in multi-story hotel buildings to save energy in the northern hemisphere has been the main focus of the study conducted (Alhuwayil et al., 2023). The outcomes showed that both locations and outdoor weather had a big impact on how much energy could be saved by each choice. A critical review completed on the potential method that enables regulated variation in the heat transfer rate through building envelopes over time is dynamic insulation (Fawaier & Bokor, 2022). According to some research findings, using a dynamic insulating air type could help achieve low heat loss ($U < 0.1$) all the way down to almost zero. Finding insulation for a building envelope is still vital since static, dynamic, and vacuum insulation have challenges with balancing the yearly local environmental conditions and energy components of a building envelope. In addition to the insulating properties and integration techniques, a contradiction occurs in locations with noticeable seasonal variation. As a result, selecting the proper insulation material and inclusion technique for a building's envelope depends greatly on the local climate.

Although significant heat gain or loss occurred through windows in buildings, this had an impact on how comfortable the inhabitants were in terms of temperature. Buildings without windows have the potential to conserve energy, but doing so is not advised, given the advantages of natural light for a comfortable environment in both the visual and biological senses (Hee et al., 2015). An experimental study conducted by (An et al., 2022) focused on seasonal temperature fluctuations and the electricity consumption for cooling and heating in the context of a slim double-skin window (SDSW). Their findings revealed that the energy usage with SDSW was 17.4% lower than double-glazing, 7% lower than double-skin façade, and 2.3% higher than hybrid double-skin façade. To address the imperative of reducing cooling and heating demands across varying climate zones, (G et al., 2018) explored multiple practical and conceptual sun control window solutions in their investigation encompassing eight building orientations and three different climates, grey reflective glass emerged as the most promising option, resulting in substantial annual cost savings for both cooling and heating. The key factor for achieving the greatest net savings was the glass's minimal solar direct transmittance. In a separate analysis, (Valladares-Rendón et al., 2017) evaluated solar-control strategies and optimal building orientations to effectively implement façade shading mechanisms for energy conservation. Their results demonstrated that passive methods significantly reduced solar radiation, leading to remarkable energy savings varying from 4.64% to 76.57%.

For WWR of 40% or above, the latter approach is always the most energy-efficient, even though sun control glass without a shade is the most economical choice overall. (Zeyninejad Movassag & Zamzamian, 2020) investigates double-glazing air flow windows with integrated blinds quantitatively and only takes into account the winter interior mode for future evaluations.(Piffer et al., 2022) analyzed visual qualities of window assemblies with integrated water layers. The findings support earlier research that found that adding water to glazing increases visible light transmittance (VLT) values whilst lowering solar transmittance (ST) rates when compared to glazing without water. Increased water layer thickness in water-based windows (WBWs) reduces direct solar gain but has no effect on VLT values. The optical performance of a WBW is not significantly affected by the number of "glass-water" interfaces on it. Finding glazing for a window system is still important because both static and dynamic glazing have issues with balancing the visual and energy aspects of a window. In places with distinct seasonal fluctuation, contradiction occurs in addition to the glazing properties itself. As a result, the surrounding climate plays a crucial role in choosing the right glass for buildings.

Using the Non-dominated Sorting Genetic Algorithm (NSGA-2), (Lapisa et al., 2018) assessed the effectiveness of passive cooling for low-rise commercial buildings across diverse climates. Their study indicated that, in specific regions, passive cooling techniques could effectively eliminate summertime thermal discomfort without necessitating active cooling systems. The research also identified optimal design criteria for passive approaches such as reflective roofs and nocturnal natural ventilation. In the context of constructing passive buildings in hot and humid regions of Hong Kong, (Chen et al., 2018) introduced a simulation-based optimization approach. By considering equally weighted objectives related to lighting and cooling energy, the final NSGA-2-based solution achieved an energy demand of 35.73 kWh/m^2. A NSGA-2 multi-optimization approach has been developed by (Merlet et al., 2022) for retrofitting solutions designed particularly for windows and building walls. The two main differences were related to the building that was selected for retrofitting, and the improved functionality of each suggested fabric for the retrofit. In order to forecast and improve the energy performance of naturally ventilated buildings in hot and humid regions while considering climate change's consequences(Gonçalves et al., 2024) studied to address a research gap. At the building size, however, climate change significantly impacts thermal performance and might cause a reduction of up to 11% (in 2020) and 39% (in 2050).

The present study aims to reduce energy demand by using passive design strategies in building envelopes by fulfilling the occupant's comfort in space. The current study intends to investigate how the passive techniques will affect buildings in the Indian composite environment in terms of lowering solar heat gain and heat loss. The proposed study looks at the combined impact of different passive methods on the building's visual and thermal performance. The study also discusses the benefits and difficulties of adopting integrated passive techniques for a given climatic zone in a building envelope. A set of passive strategies is applied in the building model with thermal and optical properties variations. A two-story building model is used to optimize energy consumption and determine the appropriate insulation materials and glazing requirements necessary to ensure the well-being of the occupants.

2. Research Approach

The two-story building model located at the DESE IIT Delhi is used to assess passive strategies. The investigation will demonstrate the energy-saving potential of passive strategies in the Indian climate. The rendered view of the model building is depicted in Figure 1. The thermal and optical properties of the base case building model are derived from previous research conducted by the authors (Verma et al., 2023; Verma & Rakshit, 2023). In the present study, the NSGA2 algorithm is used to optimize the objective functions. The Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) determines the optimal point from the Pareto front. In accordance with the finest optimal point, the energy-saving potential of passive strategies at various locations will be demonstrated.

The methodology was created to investigate buildings' thermal and visual energy performance with passive features such as different types of glazing for windows, insulation, reflecting roofs, etc. A numerical examination is carried out using the Design Builder software to determine the energy performance and optimize energy use.

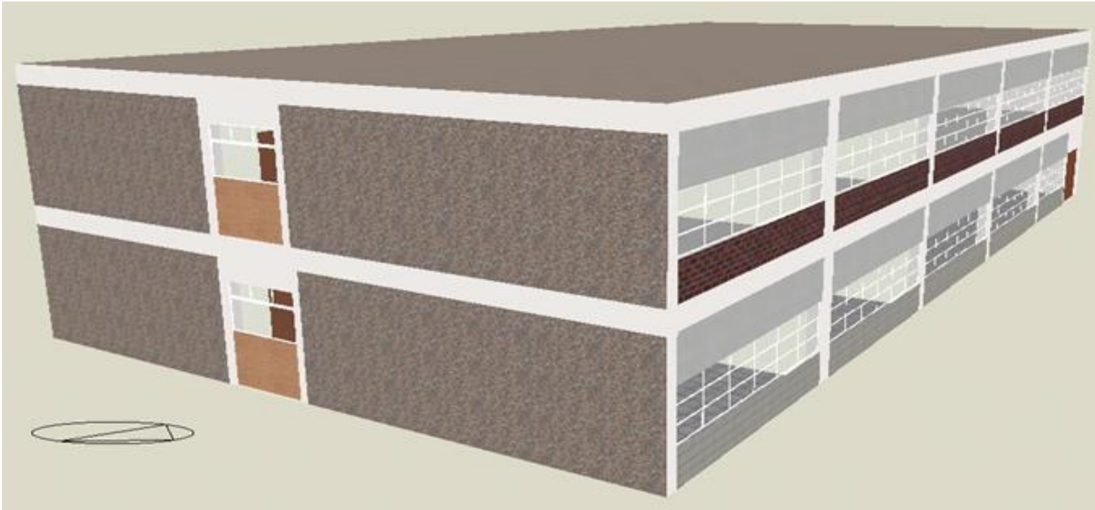

Figure 1:Rendered view of reference building model

The standard weather data of New Delhi, Jaisalmer, Chennai, and Bengaluru, representing composite, hot and dry, warm and humid, and temperate climates, respectively, located in India, is selected for computational study. These climatic regions exhibit the susceptibility and complexity of the Indian climate in passive selection. In order to determine the most effective arrangement of passive techniques for air-conditioned buildings, this study will use these four cities as sample locations for distinct climate zones. The average annual weather characteristics details of sample cities are mentioned in Table 1. The effectiveness of passive strategies largely varies with building climatic zones.

Table 1: Details of annual average weather characteristics of sample cities

Locations	Latitude & Longitude	Alti-tude (m)	Average global horizontal radiation (Wh/m^2)	Average direct normal radiation (Wh/m^2)	Mean -max DBT (°C)	Mean -min DBT (°C)	Mean -max RH (%)	Mean -min RH (%)	Mean -max wind speed (m/s)	Mean -min wind speed (m/s)
New Delhi	28°34'N 77°12'E	216	410	384	30.7	19.9	83	40	1.0	0
Jaisalmer	26°53'N 70°55'E	231	490	535	33.7	22.2	64	32	5	2
Chennai	13°0'N 80°10'E	16	478	412	32.8	25.1	90	49	2	0
Bangalore	12°58'N 77°34'E	921	494	466	28.9	20	92	42	2	0

Building energy retrofit options are introduced in Table 2. The variation in insulation material thermal properties, thickness, and location are mentioned in Table 3, Table 4, and illustrated in Figure 2, respectively. The placement of insulation location in the building envelope does not affect the thermal resistance; however, this may change the energy demand by changing the heat penetration time in the building envelope. The window-to-wall ratio in the building envelope assists in maintaining visual comfort, but it enhances the heat gain through the transparent part of the building envelope. Different window thicknesses and a combination of glasses can reduce heat penetration while maintaining visual comfort. In this study, single-glazing and double-glazing windows with numerous thicknesses were considered to find the optimal window combination for the building envelope. The detailed glazing variation in the building envelope is shown in Table 5. Furthermore, local shading is also selected to reduce the direct radiation falling on the glazing surface in summer. The variation in local shading is described in Table 6. The proposed methodology aims to diagnose and optimize the cooling-heating and cooling-lighting energy demand in buildings, as illustrated in Figure 3.

In the context of multi-objective optimization, these metrics are referred to as decision variables. The choices for each decision variable are provided depending on the various building envelope components, such as the walls, roof, and windows. The passive measures for building envelope: thermal insulation, insulation thickness, insulation location, window glazing type, infiltration, and reflective roof are defined with several variations. Insulation material works as a heat barrier in the building envelope. These materials' thermal conductivity, specific heat, density, and thickness help in the calculation of heat resistance and storage capacity. Variations in material and incorporation in the building envelope give different heat resistance capacities of the building envelope for particular thicknesses. The present study develops a numerous combination of material, thickness, and location of placement in building roofs and walls. The variation in insulation material thermal properties, thickness, and location are mentioned in Table 3, Table 4, and illustrated in Figure 2, respectively. The placement of insulation location in the building envelope does not affect the thermal resistance; however, this may change the energy demand by changing the heat penetration time in the building envelope. The window-to-wall ratio in the building envelope assists in maintaining visual comfort, but it enhances the heat gain through the transparent part of the building envelope. Different window thicknesses and a combination of glasses can reduce heat penetration while maintaining visual comfort. In this study, single-glazing and double-glazing windows with numerous thicknesses were considered to find the optimal window combination for the building envelope. The detailed glazing variation in the building envelope is shown in Table 5. Furthermore, local shading is also selected to reduce the direct radiation falling on the glazing surface in summer. The variation in local shading is described in Table 6. The proposed methodology aims to diagnose and optimize the cooling-heating and cooling-lighting energy demand in buildings, as illustrated in Figure 3.

Table 2: Specifications of retrofitting strategies

Decision variables	Examined options	Scenarios	
Wall insulation, thickness, and location	Three types of insulation materials, fibreglass, polyurethane foam, and expanded polystyrene (see Table 3 for properties), incorporated at three locations illustrated in Figure 2 for thickness mentioned in Table 4	First scenario	Second scenario = first scenario + RR
Roof insulation, thickness, and location	Three types of insulation materials, fibreglass, polyurethane foam, and expanded polystyrene (see Table 3 for properties) incorporated at two locations illustrated in Figure 2 for thickness mentioned in Table 4		
Window glazing	Single-layer and double-layer glazing with different thicknesses and colours as noted in Table 5		
Infiltration	Inflitration ranges from 0.2 to 0.4 (ac/h)		
Window local shading			
Reflective roof (RR)	Reflective surface at the roof		

Table 3: Detailed thermal properties of insulating materials

Insulation material	**Density (kg/m^3)**	**Specific heat (J/kg-K)**	**Thermal conductivity (W/m-K)**
Fiberglass	48	843	0.04
Polyurethane foam (PUF)	30	1800	0.026
Expanded polystyrene (EPS)	15	1300	0.038

Table 4: Selected insulation thickness and material for wall and roof

Structure	**Material constraints**	**Thickness constrains (mm)**

Walls	Polyurethane foam, Fiberglass, Expanded polystyrene	$10 \leq t \leq 110$
Roof		$10 \leq t \leq 150$

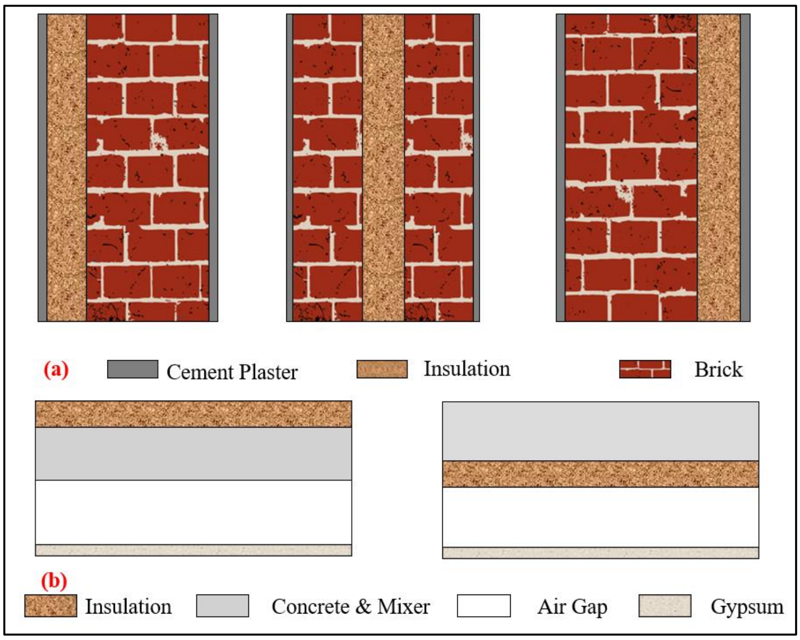

Figure 2: Building retrofitting setup for incorporation of insulation (a) wall (b) Roof

Table 5: Window glazing retrofitting options for optimization.

Glazing type	Clear	Bronze color	Green color	Grey color	Blue color
Single Layer (Sgl) [glass (mm)]	3 and 6	3 and 6	3 and 6	3 and 6	6
Double layer (Dbl) [(glass -air-glass) (mm)]	3-6-3 6-13-6	3-6-3 3-13-3 6-6-6 6-13-6	3-6-3 3-13-3 6-6-6 6-13-6	3-6-3 3-13-3 6-6-6 6-13-6	6-6-6 6-13-6
Total (Design variable for glazing)					25

Table 6: Window local shading variation to control heat gain and lighting.

Local shading	Overhangs	Louvers
Length (m)	0, 0.5, 1.0, 1.5, 2.0	0.5, 1.0, 1.5

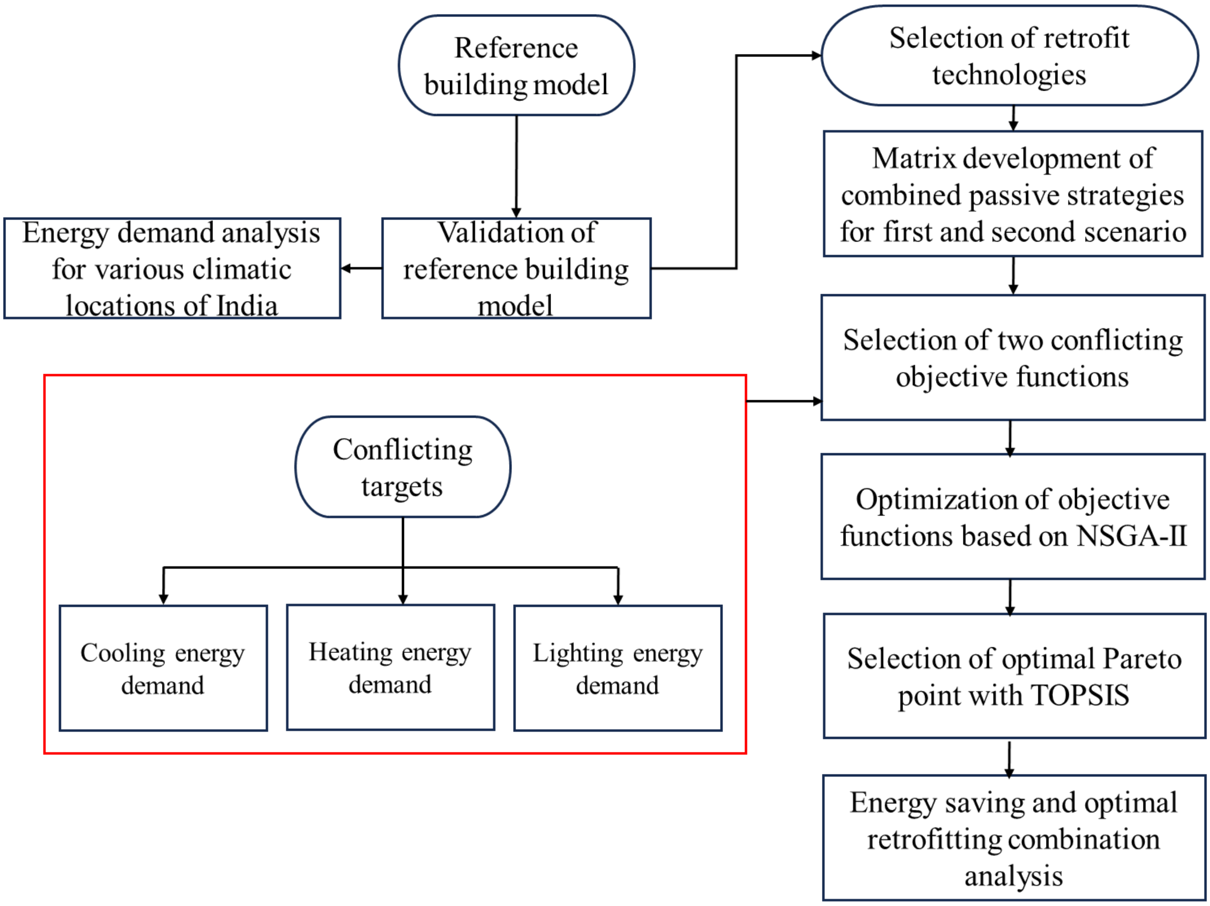

Figure 3: Framework of study

Conduction Transfer Function (CTF) for Inside heat flux

$$q''_{ki}(t) = -Z_o T_{i,t} - \sum_{j=1}^{nz} Z_j T_{i,t-j\,\delta} + Y_o T_{o,t} + \sum_{j=1}^{nz} Y_j\, T_{o,t-j\,\delta} + \sum_{j=1}^{nq} \varphi_j\, q''_{ki,t-j\delta} \qquad \text{(eq. 1)}$$

Conduction Transfer Function for outside heat flux

$$q''_{ko}(t) = -Y_o T_{i,t} - \sum_{j=1}^{nz} Y_j T_{i,t-j\,\delta} + X_o T_{o,t} + \sum_{j=1}^{nz} X_j\, T_{o,t-j\,\delta} + \sum_{j=1}^{nq} \varphi_j\, q''_{ko,t-j\delta} \qquad \text{(eq. 2)}$$

X_j= Outside CTF coefficient, j = 0, 1,…nz. Y_j = Cross CTF coefficient, j = 0, 1,…nz. Z_j = Inside CTF coefficient, j = 0, 1,…nz. φ_j = Flux CTF coefficient, j = 1, 2,…nq. T_i = Inside face temperature T_o = Outside face temperature q''_{ko} = Conduction heat flux on the outside face q''_{ki}= Conduction heat flux on inside face.

3. Results and discussion

To comprehensively gauge the efficiency of passive approaches in air-conditioned (AC) buildings across diverse climatic zones, weighing the energy demand of cooling, lighting, and heating in retrofitted and non-retrofitted structures is essential. This section delves into the Pareto-optimal solution for numerous scenarios indicated in Table 2 within the methodology section. The primary objective, when evaluating passive construction is to diminish the cooling, lighting, and heating loads, along with their corresponding electricity consumption. To ascertain the most favorable energy demands for cooling, lighting, and heating, the TOPSIS decision-making technique is employed. The weight assigned to TOPSIS is determined by the ratio of cooling, lighting, and heating energy demand, as elucidated in Figure 4. The findings of this current investigation aim to provide a comprehensive grasp of how alterations to the building envelope respond to diverse climatic regions. Whether positioned externally or within the walls, insulation in the building envelope proves to be a suitable strategy. Among the three previously discussed insulation materials, polyurethane insulation is superior in enhancing overall building efficiency. In the initial scenario after the execution of TOPSIS on the Pareto front, as illustrated in Figure 5 and Figure 6, it becomes evident that achieving optimal performance for building roof and wall envelopes necessitates insulation thickness ranging from 110 to 150 mm and 70 to 110 mm, respectively, in different cities. Moreover, the evaluation of infiltration rates, ranging from 0.2 to 1.4 air

changes per hour (ACH), was conducted as detailed in Table 2. The calculated results for all climatic locations consistently advocate minimizing infiltration to 0.2 ACH in the present context.
Furthermore, based on the combination highlighted in Table 5, it was established that double-layer green air windows with dimensions of 6 mm/13 mm offer the most suitable solution across all climatic regions. All climatic locations require some amount of local shading. In the current scenario, 0.5 m overhang is preferred for locations except hot and dry climates represented by Jaisalmer. Furthermore, the Pareto points of optimization results of the second scenario are shown in Figure 5 and Figure 6, with the name Pareto Front with CR. The graph clearly shows that after implementing the second scenario, cooling energy demand decreased dramatically, but lighting and heating energy demand increased. In the second scenario, total energy demand was reduced significantly, as the insulation material requirement for the roof case also reached 0 mm for Bengaluru and only 10 mm. for other climates. There is no variation in the remaining passive parameters, which can be considered the optimum values found in the first scenario.
The energy consumption comparison of the first scenario and second scenario with reference case illustrated in Figure 7 for all climatic locations with optimization objective cooling-heating and cooling-lighting. In the first scenario, the cooling-heating objective function was 29.8 %, 30.9%, 34.8%, and 19.4% for New Delhi, Jaisalmer, Chennai, and Bengaluru, respectively. However, for cooling lighting, 23.7%, 27.9%, 33.2%, and 17.1% energy savings were achieved for New Delhi, Jaisalmer, Chennai, and Bengaluru, respectively. After the incorporation of the second scenario, energy savings reached up to 34.6%, 34.7%, 36.1%, and 29.2% for corresponding climatic cities in the cooling-heating objective. However, calculated energy savings for cooling-lighting were achieved up to 31.4%, 32.1%, 34.5%, and 25.8% in New Delhi, Jaisalmer, Chennai, and Bengaluru, representing composite, hot and dry, warm and humid, and temperate climates, respectively.

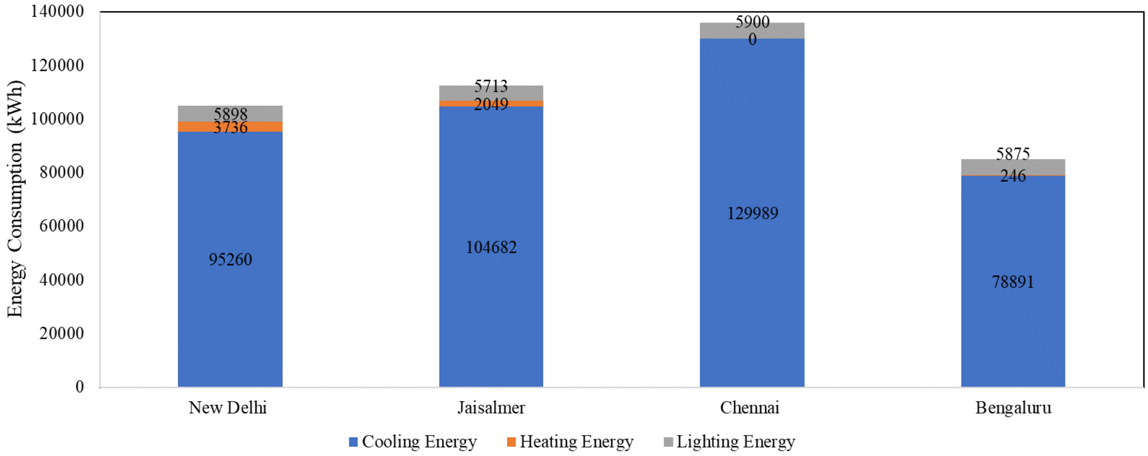

Figure 4: Cooling, heating, and lighting load of reference building for various locations

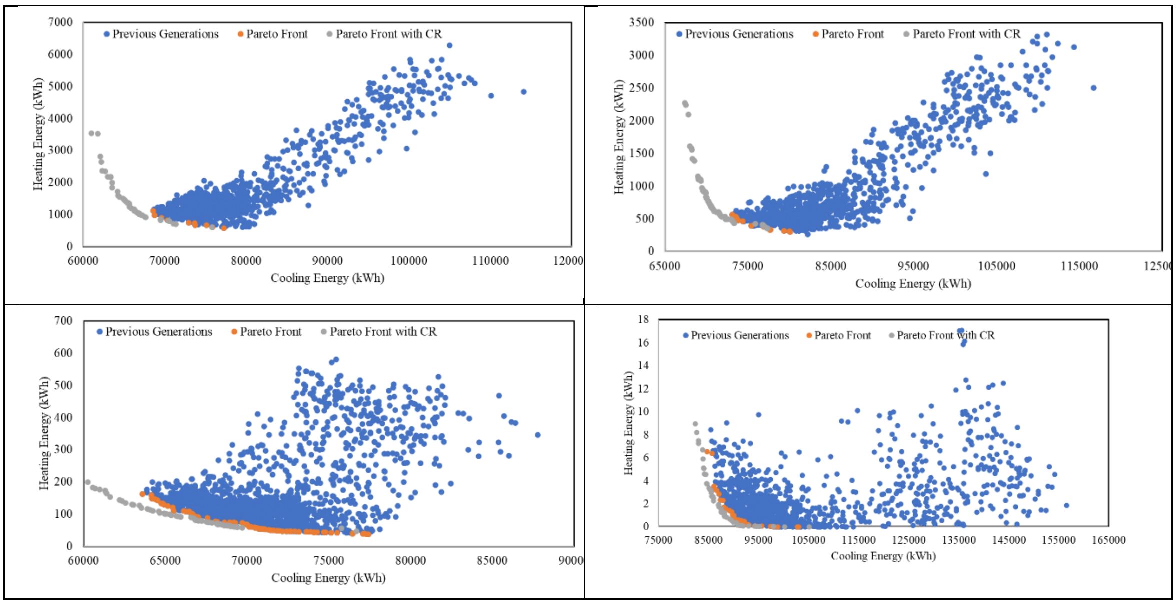

Figure 5: Pareto front of cooling and heating optimization (a) New Delhi (b) Jaisalmer (c) Bengaluru (d) Chennai

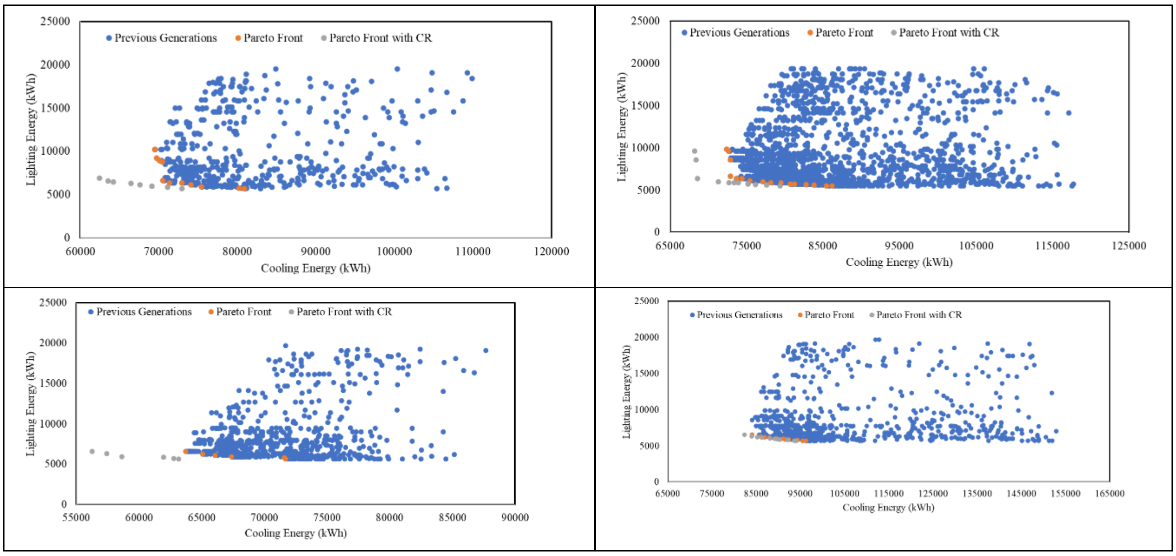

Figure 6: Pareto front of cooling and lighting optimization (a) New Delhi (b) Jaisalmer (c) Bengaluru (d) Chennai

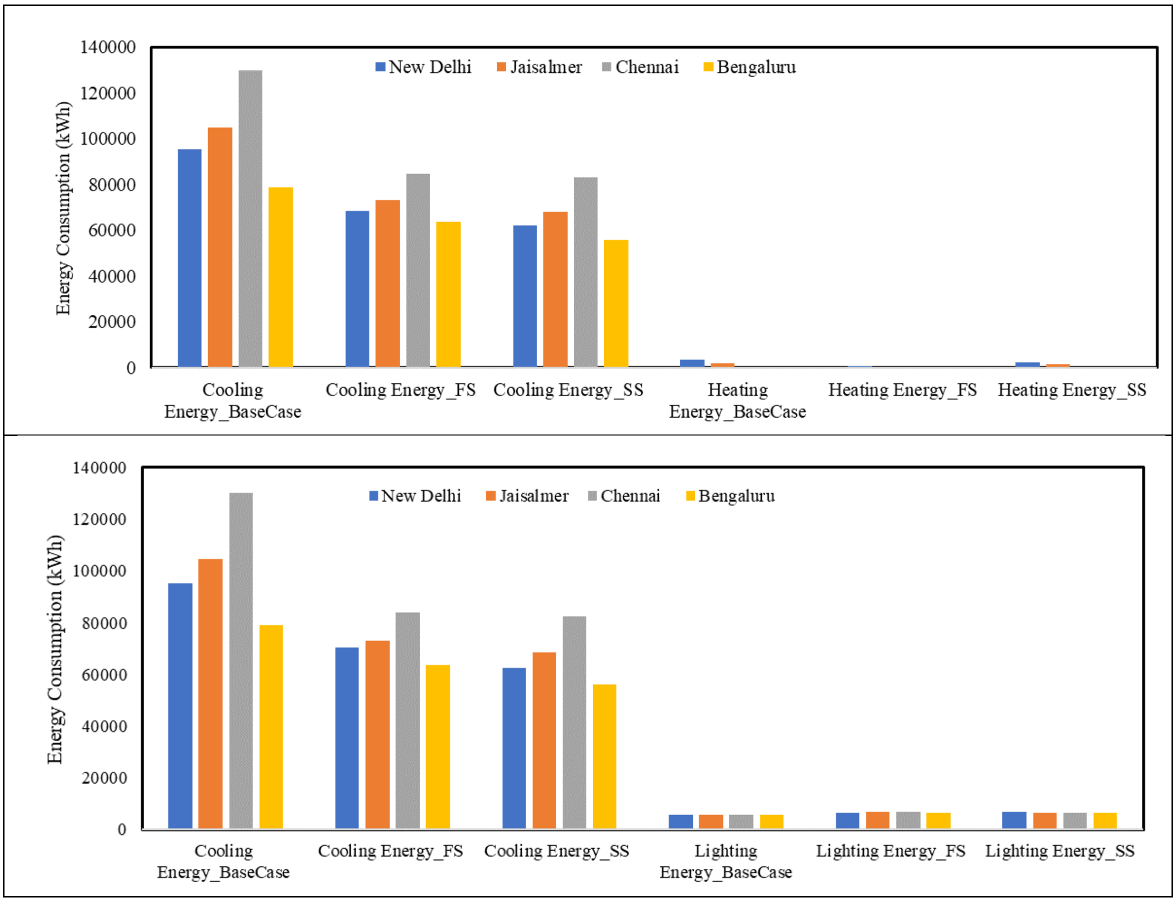

Figure 7: Comparison of energy consumption in (a) cooling-heating (b) cooling-lighting

Conclusions:

This study is innovative in that it uses reflective surfaces to find insulating materials of minimal thickness. Using the simulation program Design Builder, a computational model was created. For the aforementioned scenarios, numerical research was carried out using the verified reference model in various climates. The impact of passive strategies highlighted in the first and second scenarios on lowering the energy demand within buildings in four Indian cities representing different climates. Based on existing findings, the following design requirements for reducing building energy use can be established:

- Existing building design characteristics can be greatly optimized in order to determine the building's sustainability quotient. Total HVAC loads can be lowered by 36% by changing certain aspects of the building envelope.

- Building infiltration needs to be minimized to lower the building energy demand for all four climatic locations.
- It is recommended that green-colored double-paned windows be installed to improve thermal building performance irrespective of climate and thermal resistance.
- The reflective coating on the roof reduces building energy demand and reduces the thickness of the insulation required for optimal performance. Roof insulation thickness requirements for all climatic zones achieved 0 mm for Bengaluru and only 10 mm for other climates.

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