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Analyzing Passive Design Retrofits using Pareto Front Optimization to Reduce Operational Carbon in Commercial Laboratory Spaces

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Abstract

Buildings are one of the leading sources of carbon emissions in the world. Most of the carbon emissions are released during the operation phase of the building. It is essential for buildings to provide thermal and visual comfort for the users. In the case of existing buildings, it is necessary to offer retrofit solutions so that the operational carbon emissions can be reduced without compromising on the other essential factors. In this study a Multi-Objective Optimization (MOO) of passive design strategies was conducted for a commercial laboratory in India situated in a moderate climate zone. The design variables considered for the study are wall and roof insulation, glazing material, window-wall ratio (WWR), depth of shading device and the number of shading devices used. The objective functions are: 1. reduced energy use intensity and operational carbon emissions, 2. increased thermal comfort hours and 3. increased daylight autonomy. Rhinoceros and grasshopper software along with Ladybug and Honeybee plug-ins were used for the study which resulted in 1296 iterations. MOO technique namely Pareto front optimization was used to optimize the objective functions. Out of 1296 solutions (excluding base case), 72 solutions were non-dominated. Two methods are described in the study to identify the recommendations for retrofit. The first method describes a Heuristic method of selection using Design Explorer recommending 5 good solutions. In the second method a factor is evolved to identify the 5 best solutions in sequential order. The overall study recommends the use of EPS insulation for the RCC roof, WWR of 20% on all sides, 3 horizontal shading devices of depth 0.75 m for all window openings. When compared with the base case scenario, this solution minimizes the EUI by 3.7%, maximizes average TCH by 106.6% and maximizes average DA by 66.9%. The overall operational carbon emissions are reduced by 7095.6 kgCO_2.

1. Introduction

The built environment is responsible for a significant portion of global energy usage accounting for 40%, energy-related greenhouse gas emissions accounting for 30%, waste production, and resource utilization [1]. Embodied and operational carbon emissions make up 30%–40% of global carbon emissions annually. Greenhouse Gases especially Carbon Dioxide are a significant reason for global warming. Industrialization, urbanization and modernization aid in the increase in the world's energy consumption [2]. In the Indian context, 33% of energy usage is utilized by buildings, and it is rising at a rate of 8% annually [3]. Researchers must recognize and take into account several dynamic processes that are occurring around us, including global climate change; the depletion of fossil fuel reserves; growing organizational flexibility; rising occupant needs and comfort expectations; and rising awareness of the relationship between the indoor environment and occupant health and wellbeing, and consequently their productivity [4].

In 1992 a study was conducted at the Massachusetts Institute of Technology by scientists based on computer modeling of five variables: population, industrialization, pollution, food production and resource depletion. Most scenarios led to an overshoot going beyond the limits of global resources, followed by a collapse of global society in the second half of the 21st century. This research was published in the book The Limits to Growth [5]. Since 1995, 195 nations have participated in the Conference of the Parties, which reviews the application of the Convention, the Kyoto Protocol, and the Paris Agreement and adopts decisions for the further development and application of these three agreements [6].

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Nomenclature

AC	*Air Conditioning*
ASHRAE	*American Society for Heating, Refrigerating and Air Conditioning Engineers*
CEI	*Carbon Emission Intensity*
CO_2	*Carbon dioxide*
CV RMSE	*Coefficient of Variation of Root Mean Square Error*
DA	*Daylight Autonomy*
DBT	*Dry Bulb Temperature*
E	*Emissivity*
EUI	*Energy Use Intensity*
GRIHA	*Green Rating for Integrated Habitat Assessment*
IMAC	*Indian Model for Adaptive Comfort*
LBNL	*Lawrence Berkley National Laboratory*
MBE	*Mean Bias Error*
MOO	*Multi-Objective Optimization*
NBC	*National Building Code*
NMBE	*Normalized Mean Bias Error*
NV	*Naturally ventilated*
OCE	*Operational Carbon Emissions*
RCC	*Reinforced Cement Concrete*
RMSE	*Root Mean Square Error*
sDA	*Spatial Daylight Autonomy*
TCH	*Thermal Comfort Hours*
U	*Thermal transmittance*
UDI	*Useful Daylight Illuminance*
VLT	*Visual Light Transmittance*

By adopting the Kyoto Protocol in 1997, the European Union, together with 37 industrialized nations and economies in transition, established legally bound carbon reduction objectives. Over the five years from 2008 to 2012, these goals come up to an average 5% decrease in greenhouse gas emissions compared to 1990 levels [7]. At COP 21 the Paris agreement was adopted and approved by 196 Parties in 2015 aiming to keep global warming far below 2 oC - 1.5oC, relative to pre-industrial levels [8]. There was agreement on the necessity and significance of reaching net zero emissions during the second half of the century [9]. Besides China and the United States, India was the third leading contributor to Carbon Dioxide Emissions in 2018. India must decarbonize large sectors of its economy including transportation, power, and real estate to achieve net zero by 2070-a vision shared by our Prime Minister Dr. Narendra Modi in COP 26 [10].

Based on estimations from the USAID ECO-III Project for 2014 and 2015, approximately 840 million sq.m of building floor area in India is accounted for commercial spaces [11]. Between 2005 and 2030, the built environment would grow five times, with over 60% of the commercial built space having air conditioning by then[12]. By 2050, the commercial floor area expansion in India would be five times the current floor area projection, or 450%, based on an effective compound annual growth rate (CAGR) of 5% [13].

ASHRAE defines thermal comfort as the condition of mind that expresses satisfaction with the thermal environment [14]. According to NBC, 2016 the recommended temperature range for thermal comfort is between 180C to 300C and a relative humidity level ranging from 30% to 70% [15]. It also recommends the indoor comfort temperature conditions for air-conditioned (AC) offices to be between 25 °C and 30 °C with optimum condition at 27.5 °C generally for all the five climatic zones [15]. The IMAC model was developed by Manu S et al., which included a comprehensive study with 6330 responses from 16 commercial buildings of various typologies namely AC buildings, NV buildings and mixed mode buildings situated in different climatic zones in India resulting in comfort temperature range of each month for [13].

A MOO technique namely Pareto front optimization is used to chose strategies that can achieve all the objective of the study that is to minimize operational carbon and energy consumption; maximize thermal comfort hours and maximize daylight autonomy. In the space of objective functions for multi-objective optimization problems (MOOPs), the Pareto front idea denotes a collection of answers that are not dominated by one another but are nonetheless better than the other solutions in the search space [16]. Even with extremely complicated issues, there is always a need for a single solution. For this reason, multi-objective optimization approaches help find an optimum solution that is ultimately Pareto optimal—at least in the weak sense—and as such, it must be a member of the Pareto front [17]. Pareto fronts allow us to make informed decisions, as they provide trade off solutions to achieve the defined objectives [18]. The necessity for research on carbon-neutral buildings is highlighted by the fact that the road to carbon neutrality is still largely unknown. To achieve a reduction in GHG emissions and specifically carbon emissions from buildings, the use of passive strategies while designing building envelopes is inevitable. While decreasing the operational carbon of the building, the significance of thermal comfort and daylight in commercial laboratories cannot be ignored. Hence, the paper explores various retrofit strategies that can be used towards low carbon buildings while improving thermal comfort hours and daylight autonomy in the building through pareto front optimization technique.

1.1. Literature studies

Existing literature related to MOO associated with energy use, operational carbon, comfort hours and daylighting were reviewed. Building retrofit solutions can be optimized in order to achieve multiple objectives at the same time through trade off solutions.

Researchers have used MOO studies to improve the building performance and energy efficiency in various types of buildings [19-23]. Gauch et al., evolved a methodology using MOO to optimize carbon and cost savings in the early design stage [24]. Renewable energy integration in buildings have also been incorporated in recent optimization studies resulting in low energy buildings or NZEBs [25-29]. Zhai et al., evolved envelope design recommendations by using parametric design, building performance simulation and NSGA 2 optimization technique simultaneously in the early design stage [30]. In order to make design decisions aligning with environmental goals Ji et al., evolved the generalizable generative-design-based performance optimization framework to improve thermal comfort, daylighting and solar radiation in buildings [31]. Toutou et al., achieved a 110% improvement in spatial daylight autonomy and a 3.5% reduction in EUI by using a genetic algorithmic method and tools such as Grasshopper, Octopus, Energy plus, Open studio, Radiance and Daysim for achieving energy-efficient building solutions [32]. The

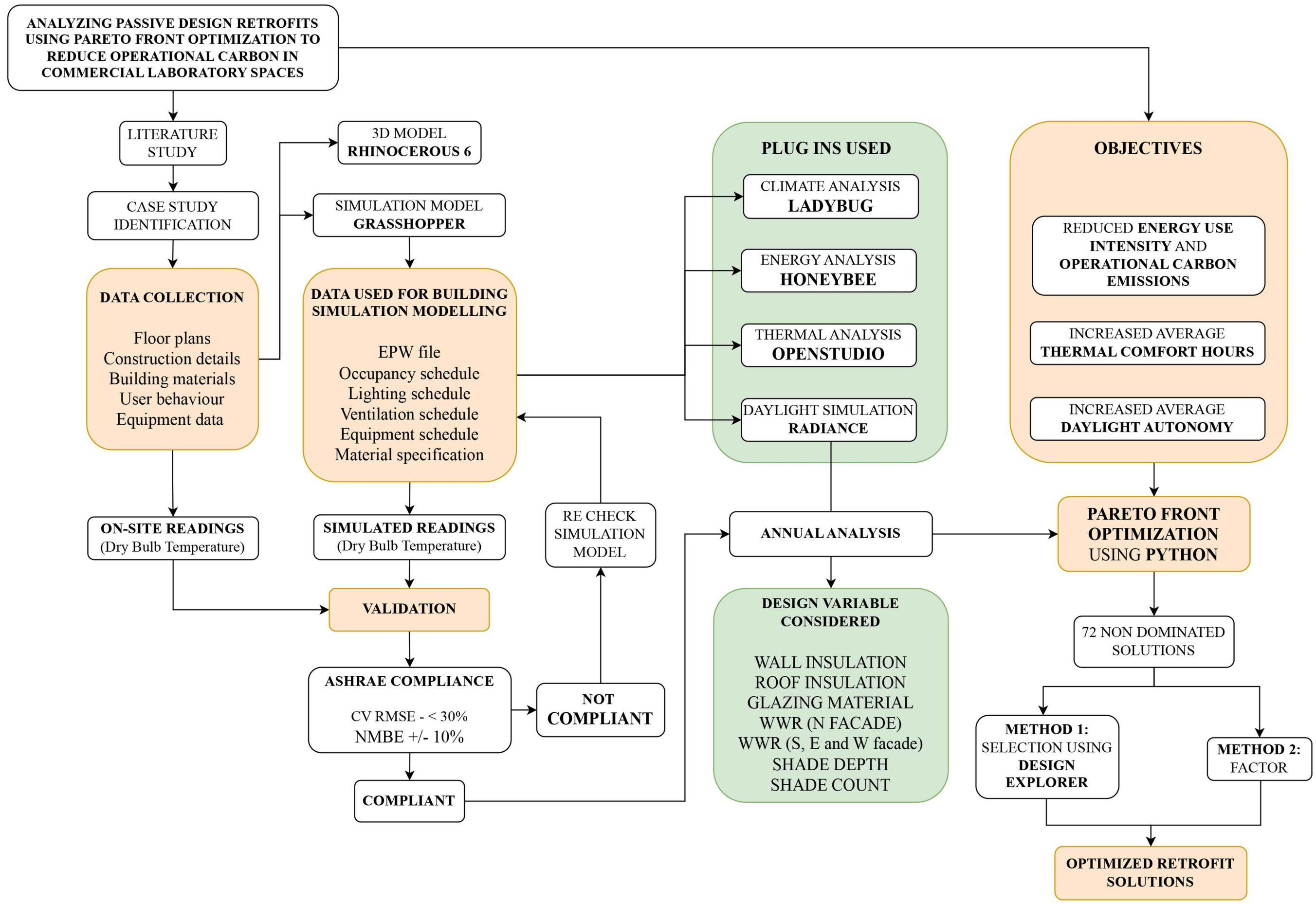

Fig. 1. Methodology Flow chart.

method focused on design variables such as including window-to-wall ratio (WWR), window materials, construction materials, and shadings [32]. MOO studies on building performance have been conducted by many researchers where future climate changes are also considered [33-35]. MOO approach was used in the study involving an office park by Luo et al., considering building parameters such as building envelope, energy consumption, thermal comfort, embodied carbon, renewable energy and economy [36]. In a study by Zhan et al., 20 different design variables were considered to optimize six objective functions in older apartments of Northern China [37]. Among the design variables different WWR were considered for all the facades for the iterations similar to the methodology adopted in the current study [36-38].

45% reduction in energy utilization was achieved annually for HVAC loads when a MOO genetic algorithm was employed to improve building envelope design factors including window size and insulation thickness in a study by D. Gossard [39]. The study conducted by Haoran Wu presents a framework to evaluate EUI, UDI and Thermal discomfort time percentage by investigating design parameters namely open able-window-area-ratio (OWR), window-wall-ratio (WWR), solar-heat-gain-coefficient (SHGC), louver depth, and wall thickness [40]. Qianyun Zhou and Fan Xue conducted a study on residential buildings in Hong Kong where reduction of 0.42% energy consumption and 9.71% improvement in sDA was achieved using Pareto front optimization and various passive design strategies such as window, corridor design and layout [38]. Zhou et al., used energy and economic analysis to determine the optimal insulation thickness for outside walls and the roof of an office building utilizing the building envelope energy-saving technology (BEEST) [41]. MOO studies have been conducted to improve the building performance in regions with Mediterranean climate [42-47]. Talaei et al., conducted research on WWR and shading devices optimization for school buildings in desert, semi arid and Mediterranean climates of Iran [48].

The current study aims to formulate a method to recommend the best optimized solutions for retrofit. After thorough review of the existing literature, the research gap identified was the lack of optimized retrofit solutions for a mixed mode commercial building in moderate climate to achieve reduced Energy Use Intensity, increased Thermal comfort hours and increased daylight autonomy.

2. Methodology

This study aims to optimize various passive design strategies to derive retrofit solutions for an existing building to achieve reduced operational carbon, increased thermal comfort hours and increased daylight autonomy. In this regard, as many design variables are considered simultaneously, few of the best solutions can be recommended which will further help us to achieve multiple objectives at the same time. Various design iterations impact the

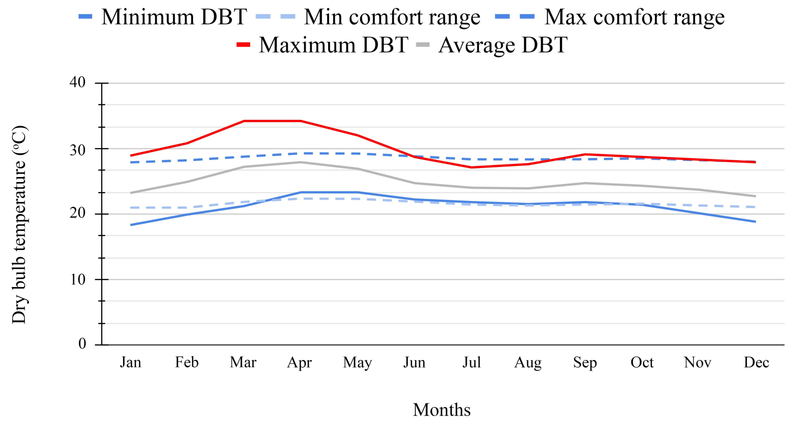

Fig. 2. Average Daily Dry Bulb Temperature graph with IMAC comfort range for Mysore climate for a year.

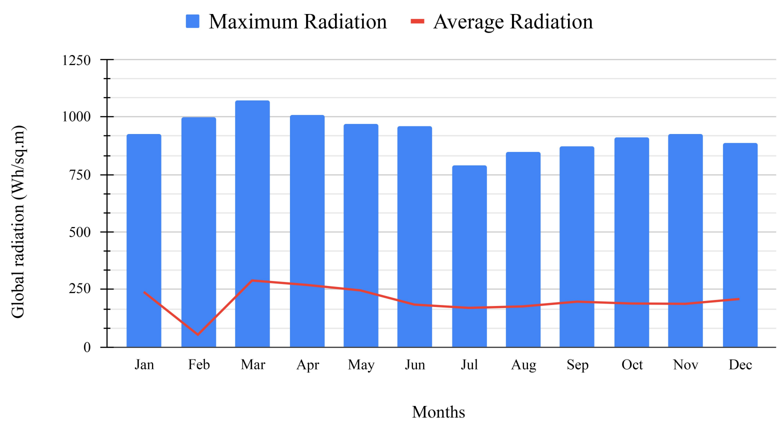

Fig. 3. Average Daily Relative annual global radiation graph for Mysore climate for a year.

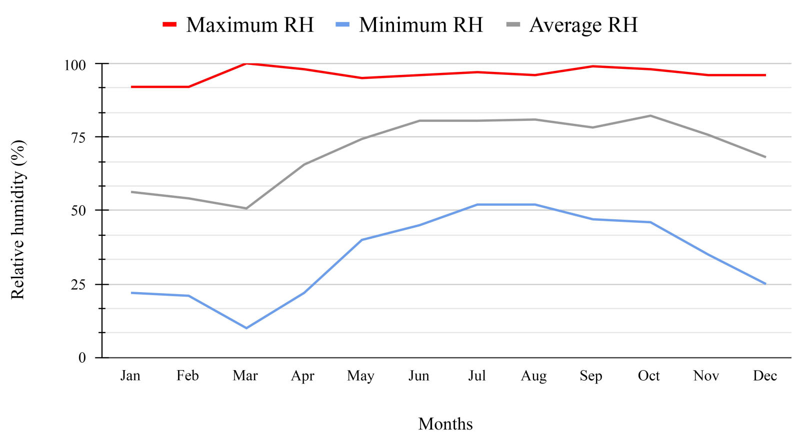

Fig. 4. Average Daily Relative Humidity graph for Mysore climate for a year.

building performance differently hence it is very crucial to identify the passive design variables to be considered for the study. For this study, the design variables chosen are: Wall insulation, Roof insulation, Glazing material, Window-Wall ratio, Depth of shading device and Number of shading devices used. The overall framework of the study is summarized as a flow chart in Fig. 1. The building under study is a Commercial Lab located in Mysore, India. Field measurements inside the building were carried out from 24th October 2023 to 27th October, 2023. Simulation model of the same building was done using Rhinoceros 6 and Grasshopper 3D software which was validated with the field measurements taken on site. The validated model was further used for annual analysis of the building with respect to the above defined objectives. Since the objectives are multiple and conflicting, a multi objective optimization technique known as the Pareto Front Optimization is used to explore a tradeoff between these objectives. The Pareto Front consists of a set of unique solutions that are not dominated or improved by any other

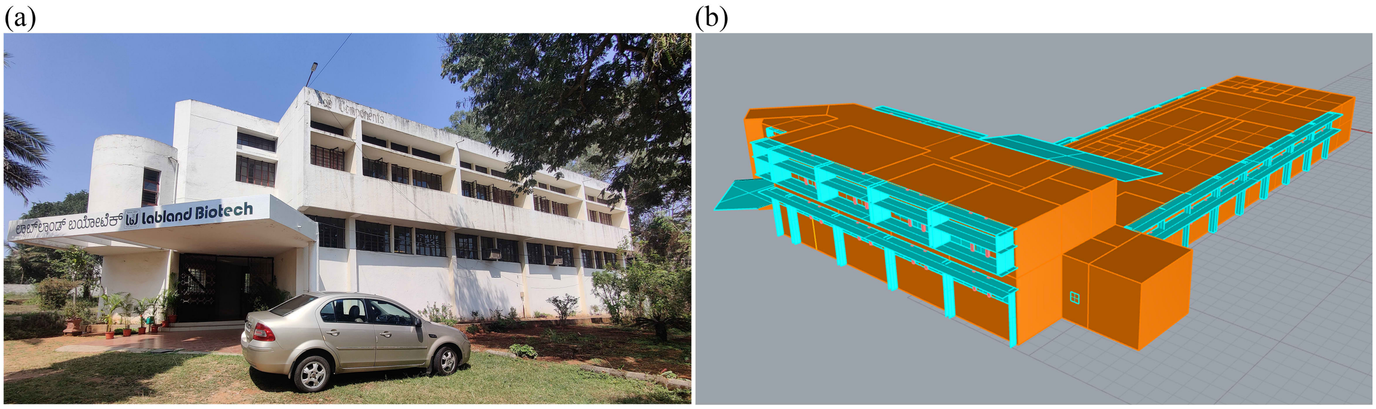

Fig. 5. (a) Commercial Lab (left) located in Mysore, India and its (b) building simulation model (right).

Table 1. Features of Existing building.

Parameters	**Properties**	**Value**
Building level	Total Built up Area	1231.72 sq.m
	Total Area of NV zones	702.4 sq,m
	Total Area of AC zones	529.32 sq.m
	Building geometry	L shape
	Naturally Ventilated Rooms	16 rooms
	Air Conditioned rooms	20 rooms
	Total Occupancy	62
Wall	Material	Brick, 230mm
	U value	1.95 W/m^2 K
Roof	Material	RCC, 150mm
	U value	3.53 W/m^2 K
Glazing	Material	Single, Clear glass
	U value	5.818 W/m^2 K
	SHGC	0.818
	VLT	0.884
Window – Wall ratio	North	12.8%
	South	28.4%
	East	21.18%
	West	20.09%

solutions with respect to any or all the objectives. The non dominated solutions are chosen from the pareto front. The solutions are further refined by introducing bias based on various criteria and building standard practices. The study primarily focuses on spaces that have a scope for using passive design strategies such as offices and training room for further retrofitting. Spaces such as laboratories and growth conditioning rooms that are highly dependent on active strategies such as artificial lighting and air conditioning have less scope to incorporate passive design strategies, hence such spaces are the secondary focus of the study.

2.1. Climate context

The building under study is situated in Mysore, India at 12.3° North Latitude and 76.7° East Longitude. Based on NBC [15] 2016 classification, Mysore is classified as moderate climate. The Koppen climate classification system categorizes Mysore's climate as Aw, which stands for Tropical Savanna climate. Mysore generally experiences hot summers, a significant monsoon season with high relative humidity levels and mild winters. The temperature ranges from 34.2°C in summers (March to May) with high radiation levels from to 18.3^0C in winters (December to February) with an average annual temperature of 24.84^0C with low radiation levels as shown in Figs. 2 and 3.

High humidity levels are present during monsoons whereas low humidity levels are experiences in the drier months of winter and early summer resulting in an annual average relative humidity of 70.5% as observed in Fig. 4.

2.2. Description of the case study

A commercial laboratory facility situated in moderate climatic zone with a built up area of 1231.72 sq.m is studied (Fig. 5). The building typology under study is a commercial building with mixed mode ventilation. The office spaces are naturally ventilated with a scope to use daylight. The laboratory spaces are mostly air-

Fig. 6. (a) Ground floor plan and (b) First floor plan of the existing Commercial laboratory.

Table 2. CV RMSE and NMBE achieved for the simulated model of Commercial Lab.

Parameter	ASHRAE compliance	Room 02	Room 05	Training room
CV RMSE	< 30%	2.75%	10.63%	9.25%
NMBE	± 10	0.1%	0.2%	0.3%

conditioned as per the laboratory requirements providing less scope for the use of daylight and natural ventilation. The building consists of many office spaces and laboratory spaces that utilize a large amount of operational carbon. As the spaces are used by a large number of people it is crucial to provide spaces that have thermal comfort which is indeed challenging to acquire in naturally ventilated spaces.

2.3. Validation

For the study, data collection was done which included collection of floor plans, building materials used, occupancy details, equipment details and user behaviour. In the overall building, field measurements were taken in three rooms – Office 2, Office 5 and Training room. Office 2 is situated in the ground floor whereas Office 5 and Training room is situated in the first floor as seen in Fig. 6. Dry bulb temperature (DBT) readings of the selected rooms were recorded at every 5 minute interval using Onset HOBO U12-012 Temperature and Humidity data logger. The data loggers were placed on the working table in each room at a height of 0.8m to 0.9m. These rooms were continuously monitored for four days from 24th October 2023 to 27th October, 2023 simultaneously.

The basic features of the building were modeled using Rhinoceros 6 and Grasshopper 3D. Honeybee and Ladybug plug-ins were used to further simulate the existing building condition using the inputs shown in Table 1. Schedules for occupancy, lighting, equipment, infiltration and ventilation were provided in detail for every room as per ECBC, 2017 standards [49].

These readings were later compared with the DBT simulation readings derived from the grasshopper model. Statistical indices namely CV RMSE and NMBE are used to calibrate the simulation model by comparing the predicted values against the existing values of the hourly baseline model using the formula as shown in equation (1), (2) and (3) below according to ASHRAE standard 14 guidelines [50]. ASHRAE standard 14 provides recommended values of CV-RMSE and NMBE for evaluating monthly and hourly baseline models. On comparison, the error was found to be in compliance with the standard guidelines as shown in Table 2.

The RMSE is defined as the square root of the mean of the squared differences between the measured values $\widehat{Y_i}$ and the simulation values Y_i, calculated using equation (1). The CV

Table 3. Passive design measures considered for each parameter.

Parameter	Options	Assembly	Value
Wall, U value	1	Brick wall	1.95 W/m²K
	2	Brick wall + EPS	0.51 W/m²K
	3	Brick wall + Cork Slab	0.69 W/m²K
	4	Brick wall + Particle board	0.96 W/m²K
	5	Brick wall + Coir board	0.54 W/m²K
Roof, U value	1	RCC roof	3.86 W/m²K
	2	RCC roof + EPS	0.59 W/m²K
	3	RCC roof + Cork Slab	0.85 W/m²K
	4	RCC roof + Particle board	1.3 W/m²K
	5	RCC roof + Coir board	0.63 W/m²K
Glazing, U value	1	Single glazing (Clear)	5.73 W/m²K
	2	Double glazing (Clear)	2.71 W/m²K
	3	Double glazing, LowE and LowVLT	1.45 W/m²K
	4	Quad glazing, Low solar and LowE	0.61 W/m²K
Glazing, VLT	1	Single glazing (Clear)	0.884
	2	Double glazing (Clear)	0.786
	3	Double glazing, LowE and LowVLT	0.371
	4	Quad glazing, Low solar and LowE	0.451
Window Wall Ratio (North facade)	1		20%
	2		40%
	3		60%
Window Wall Ratio (West, East and South facade)	1		20%
	2		40%
	3		60%
Depth of Shading device – metre (Horizontal)	1		0.45 m
	2		0.6 m
	3		0.75 m
Number of Shading device - (Horizontal)	1		1 no.
	2		2 nos.
	3		3 nos

RMSE is calculated as the ratio of the root mean squared error (RMSE) to the mean of the dependent variable which is calculated using equation (2). The mean bias error (MBE) is used to assess the bias of a simulating model by calculating the average difference between the simulated values and the actual values, without considering their direction. The NMBE is a metric used to normalize the MBE index, making it comparable across different datasets and it is calculated using equation (3). The smaller the CV-RMSE and NMBE, the closer the predicted values are to the actual values.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Y_i-\hat{Y}_i)^2}{n}} \tag{1}$$

$$CV\ RMSE = \frac{RMSE}{\bar{Y}}\ x\ 100 \tag{2}$$

$$NMBE = \frac{\sum_{i=1}^{n}(Y_i-\hat{Y}_i)}{n\bar{Y}}\ x\ 100 \tag{3}$$

Where Y_i is the i-th field DBT (^{0}C) measurement taken in the three rooms, $\hat{Y}_i$ is the corresponding DBT (^{0}C) measurement predicted by the simulation model of the respective rooms, n is the total number of data points and $\bar{Y}$ is the average of the measured DBT (°C) values over the analysis period [51]. A lower value of CV RMSE and NMBE ensures that the predicted values are closer to the observed values further validating the baseline model for further retrofit analysis and optimization [51].

2.4. Objectives for Optimization

The aim of the study is to provide retrofit design solutions by carefully considering multiple objectives and suggesting the best possible design interventions. The objectives considered in the study are as follows:

1. Minimizing Energy Use Intensity (EUI) and OCE (Operational Carbon Emissions)
2. Maximizing Daylight Autonomy (DA)
3. Maximizing Thermal Comfort Hours (TCH)

The design variables considered for the study are: Wall insulation, Roof insulation, Window Glazing, Window Wall Ratio, Shade Depth and Number of shades. The passive design measures and the iterations considered for the analysis are compiled in Table 3.

2.5. Performance metrics

2.5.1. Energy Use Intensity and Operational Carbon

Energy Use Intensity is an indicator of the energy efficiency of a building's design and/or operations which is calculated by dividing the total energy consumed by the building in one year by the total gross floor area of the building expressed in energy units per square feet or metre [52]. EUI was calculated for the NV rooms and AC rooms which was a cumulative of 36 rooms. EUI is calculated by using mathematical equation (4) and is expressed in kWh/sq.m The total energy used by the building is quantified by considering heating load, cooling load, lighting load and equipment load. This factor is used to analyze the benchmarks set for building design and operation.

$$Energy\ use\ Intensity\ (EUI) = \frac{Total\ energy\ used\ by\ the\ building}{Total\ Gross\ Floor\ Area} \quad (4)$$

Carbon Emission Intensity (CEI) includes all the operational carbon emissions divided by the gross floor area [53] as expressed in the equation (5). It is expressed in kg CO_2/sq.m. Operational Carbon Emissions are the emissions associated with energy used to operate the building or in the operation of infrastructure [54] which is expressed in kg CO_2 and calculated using equation (6). Conversion factor of 0.8 tCO_2/MWh is used to determine the CEI for the study based on the data collected from the Central Electricity Authority of India, version 18 [55]. These metrics help us to understand the energy performance of the building.

$$Carbon\ Emission\ Intensity\ (CEI) = EUI\ x\ Conversion\ factor \quad (1)$$

$$Operational\ Carbon\ Emission\ (OCE) = CEI\ x\ Total\ Floor\ Area \quad (2)$$

2.5.2. Thermal Comfort Hours

The IMAC (Indian model for Adaptive Comfort) model was used for the calculation of the number of hours in a year where the rooms were in thermal comfort condition. The thermal comfort temperature range for each month, for a mixed mode commercial building operating in a moderate climate was derived from the IMAC model. This is the only adaptive comfort standard that is relevant for the mixed mode commercial buildings in Indian context which helps in reducing energy consumption and carbon emissions while maintaining comfort, productivity and well-being of occupants [13]. Also, for this calculation, rooms which operate with natural ventilation and with occupancy of more than two hours on a working day were considered which include six offices and a training room. These rooms were occupied for at least 8 hours on 260 working days. Hence, out of the 2080 working hours in a year, the thermal comfort hours for these seven rooms were calculated and an average value was considered for further optimization. The average thermal comfort hours metric expressed as 'hours' helps us to quantify the number of working hours in which thermal comfort is achieved in a year.

2.5.3 Daylight Autonomy

It is defined as the percentage of the occupancy time during the year when a minimum illuminance threshold is met by daylight alone considering overcast sky conditions throughout the year [56]. DA is the percentage of annual work hours during which all or part of a building's lighting needs can be met through daylighting alone [57]. According to green building rating system GRIHA (Green Rating for Integrated Habitat Assessment), office buildings need achieve a minimum of 25% DA mandatorily for compliance whereas 30% DA and 35% DA will help to gain 2 points and 4 points for the building. The rooms using daylight for the ambient lighting is considered for the quantification of daylight autonomy. The recommendations for illumination levels needed for these rooms were taken from NBC, 2016 [15] which were 150lux – 750lux for offices and 200lux to 500lux for lecture rooms. Hence, for the second and third objective 7 rooms which were naturally ventilated and Non Air Conditioned were considered for the study, this included six office rooms in the ground floor and first floor and one training room in the first floor. Radiance settings for the

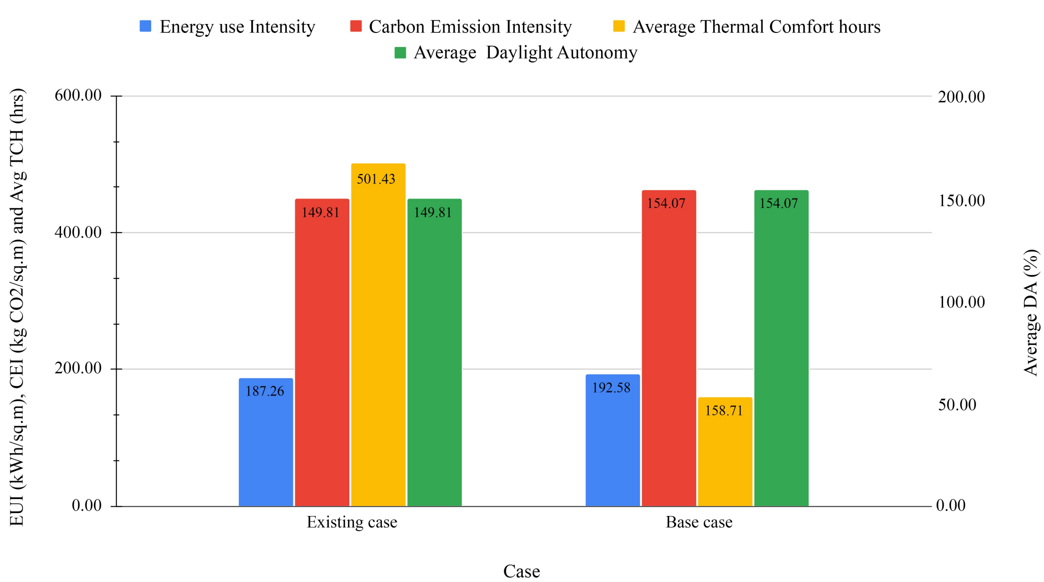

Fig. 7. Comparison of Energy Use Intensity, Carbon Emission Intensity, Average Thermal Comfort Hours and Average Daylight Autonomy of Existing Case and Base Case.

simulation model namely ambient bounces (ab) was set to 2, ambient divisions (ad) was set to 5000 and limit weight (lw) was set to $2e^{-05}$, as recommended by LBNL (Lawrence Berkley National Laboratory) [58]. These setting helped to achieve better accuracy of the base case model upon which iterations were performed in the study.

2.5.4. Base case formulation

The existing building was modelled using Rhinoceros 6 as shown in Fig. 5 and further simulated with Grasshopper script using Ladybug and Honeybee plug-ins. The existing building model performance was analysed and EUI and CEI was 187.26 kWh/sq.m and 149.8 kgCO_2/sq.m respectively. The OCE for this case was 184522 kgCO_2 which was quantified using equation (6). The average TCH was 501 hrs whereas the average DA was 12.58%. The building uses simple construction; however, due to the existing shading device high thermal comfort hour and very low daylight autonomy was achieved. The model was simplified in order to thoroughly understand the effect of each design variable on the EUI, TCH and DA. A base case model was formulated in which the shading devices were removed. The base case model was simulated and it was observed that, EUI and CEI was 192.58 kWh/sq.m and 154.06 kgCO_2/sq.m respectively. The OCE for this case was 189766.66 kgCO_2. The average TCH was 158 hrs whereas the average DA was 39.21%. On comparing the building performance of the existing building model and the base case model, it can be seen that the EUI, CEI and OCE is higher, TCH is lower and DA is higher as seen in Fig. 7. The base case model is considered for further analysis based on the three objectives.

Six design variables namely Wall insulation, Roof insulation, Window Glazing, Window Wall Ratio, Shade Depth and Number of shades were used for a bi-variate analysis to understand the impact of each variable on EUI, Average TCH and Average DA. Considering the six design variables, permutation and combination was done and 1296 iterations were derived from the validated model by using ladybug and honeybee plug-ins in Grasshopper script. For each of the 1296 iterations, the EUI, TCH and DA was calculated for further analysis. Pareto front optimization technique was done using Python software which resulted in identifying 72 non-dominated solutions. The solutions are further analyzed to find the best design recommendations for retrofit.

3. Results

3.1. Design variables

Design variables considered for the study are insulation, glazing, window-wall ratio, and shading devices.

3.1.1. Insulation

Thermal insulation is a technique to control heat flow for providing indoor thermal comfort with minimal energy use [59]. The existing building uses a conventional wall and roof assemble consisting of Brick wall with cement plaster and RCC Roof. Insulation material shown in Table 3 namely EPS, cork slab,

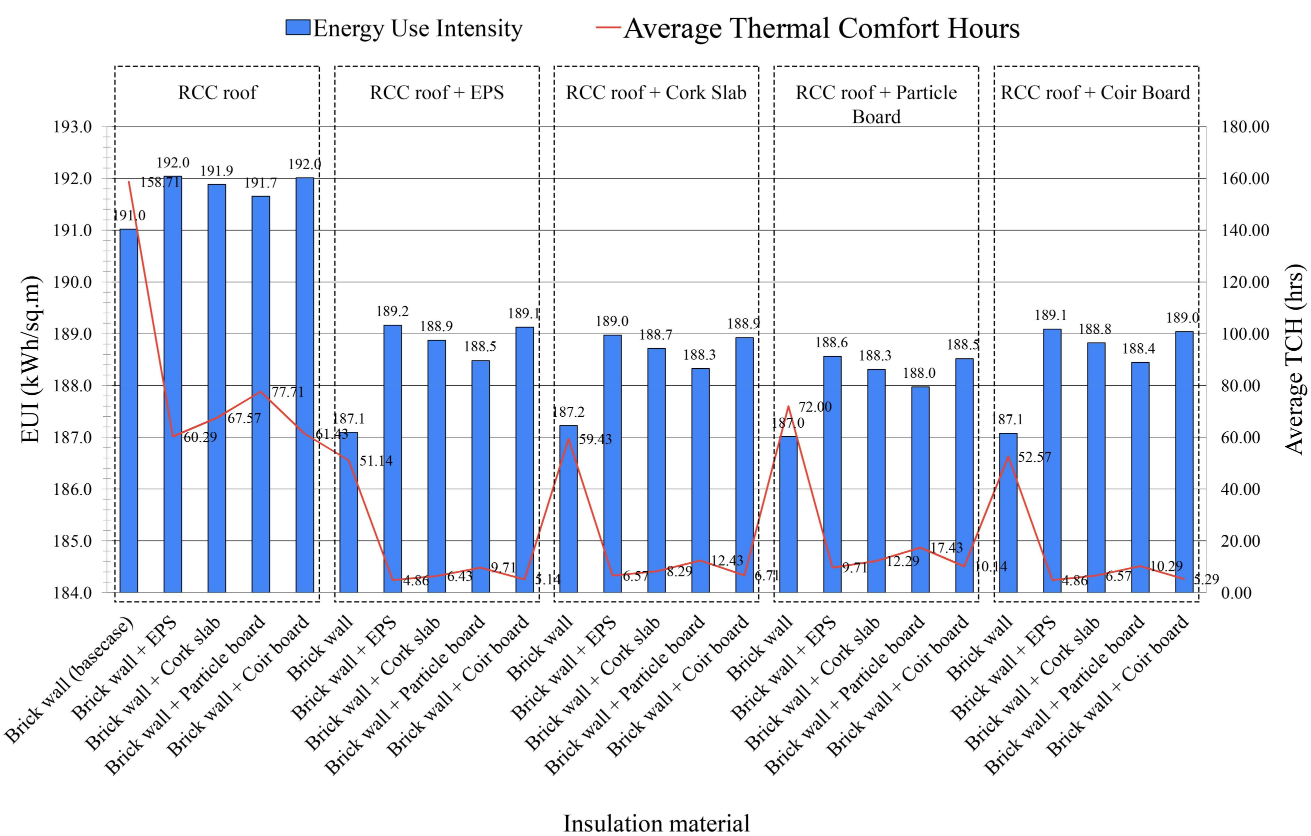

Fig. 8. Effect of wall insulation and roof insulation on the energy use intensity and the average thermal comfort hours of the building.

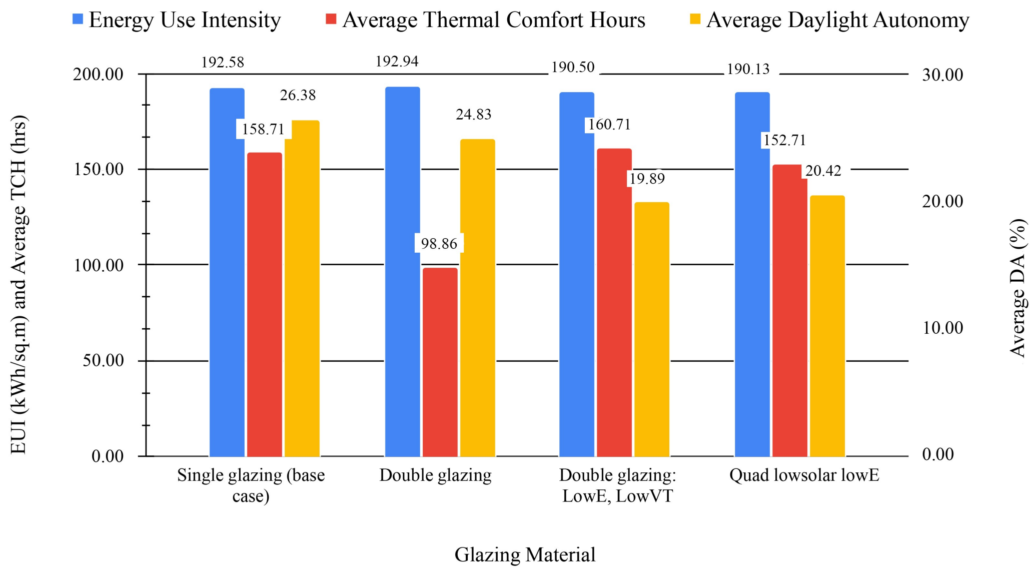

Fig. 9. Effect of various glazing material on Energy Use Intensity, Average Thermal Comfort Hours and Average Daylight Autonomy.

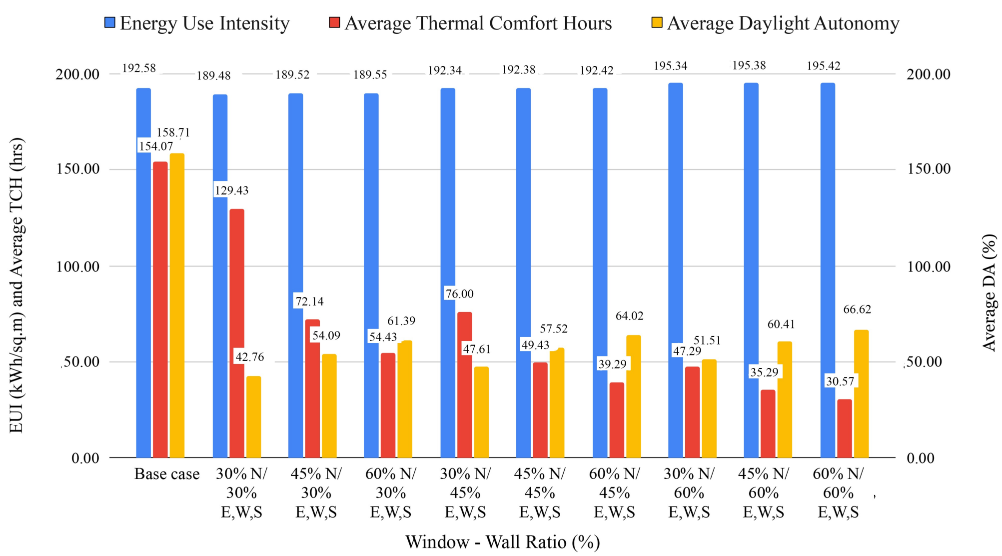

Fig. 10. Effect of various Window – Wall Ratio on Energy Use Intensity, Average Thermal Comfort Hours and Average Daylight Autonomy.

particle board and coir board of 5cm thickness was considered for retrofit. Various permutations and combination are explored among these options. For instance EUI and average TCH is quantified by using RCC roof with EPS insulation for the roof assembly and simultaneously changing the wall insulation material with the options mentioned in Table 3. The effect of insulation on the EUI and TCH of the building is shown in Fig. 8. The wall and roof finish remains same before and after using insulation, hence no changes are observed with the average DA of the building. Significant change is not observed with EUI, a maximum of 2% reduction in EUI was observed with the use of EPS insulation for RCC roof and brick wall. However, the average TCH is the highest for the base case compared to the other iterations. The use of insulation does not improve the overall TCH of the building. The conventional wall and roof assembly maintains the building in the thermal comfort range. RCC roof with EPS insulation performs better is minimizing EUI whereas the base case option performs better in maximizing average TCH, hence only the conventional material is used in the iteration process. This helps us to narrow down the number of iterations involved in the study to 1296.

3.1.2. Glazing material

Windows are an important component in the design of the building envelope as it enhances daylight, manage heat gain, and allow natural ventilation thereby improving the comfort [60]. Single glazed clear windows are used in the existing building as shown in Table 1. In order to study the effect of various glazing on the EUI, average TCH and Average DA on the existing building – double glazed windows, double glazed (low Emissivity and low Visual Transmittance) windows and quadruple glazed (low Solar and low Emissivity) windows as mentioned in Table 3 were used. On comparison with the base case 1.27% reduction in EUI was observed with the use of quadruple glazed windows and 1.26%

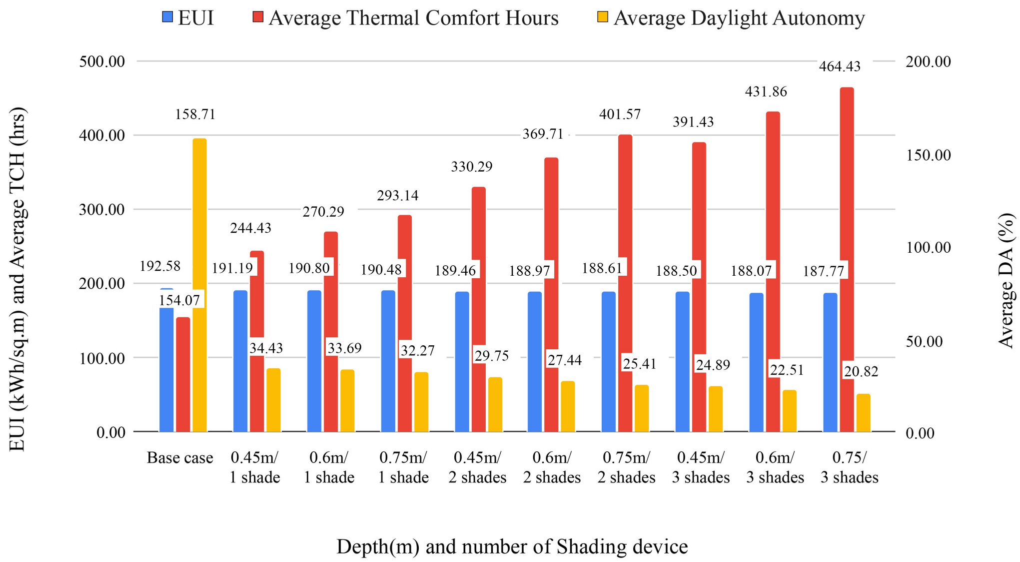

Fig. 11. Effect of shading devices on Energy Use Intensity, Average Thermal Comfort Hours and Average Daylight Autonomy.

Table 4. Passive design measures considered for optimization.

Parameter	Options	Assembly	Value
Wall, U value	1	Brick wall	1.95 W/m²K
	2	Brick wall + EPS	0.51 W/m²K
Roof, U value	1	RCC roof	3.86 W/m²K
	2	RCC roof + EPS	0.59 W/m²K
Glazing, U value	1	Single glazing (Clear)	5.73 W/m²K
	2	Double glazing (Clear)	2.71 W/m²K
	3	Double glazing, LowE and LowVLT	1.45 W/m²K
	4	Quad glazing, Low solar and LowE	0.61 W/m²K
Glazing, VLT	1	Single glazing (Clear)	0.884
	2	Double glazing (Clear)	0.786
	3	Double glazing, LowE and LowVLT	0.371
	4	Quad glazing, Low solar and LowE	0.451
Window Wall Ratio (North facade)	1		20%
	2		40%
	3		60%
Window Wall Ratio (West, East and South facade)	1		20%
	2		40%
	3		60%
Depth of Shading device – metre (Horizontal)	1		0.45 m
	2		0.6 m
	3		0.75 m
Number of Shading devices - (Horizontal)	1		1 no.
	2		2 nos.
	3		3 nos

increase in the average TCH was observed for the case of double glazed (low Emissivity and low Visual Transmittance) windows. Improvements in Average DA were not seen in any of the cases when compared with the base case as seen in Fig. 9.

3.1.3. Window Wall Ratio

The window-to-wall ratio (WWR) is measure in building design, representing the proportion of window area to the total exterior wall area [61]. In the existing building, WWR for the various facades as shown in Table 1 was used for the base case. The iterations for WWR considered for the study are explained in Table 3. For the study, three options of WWR namely 30%, 45% and 60% was used which was further considered for various permutations and combinations. For instance, iterations were explored by keeping the WWR for the south, west and west facade at 30%, 45% and 60% and simultaneously changing the WWR for north facade as shown in Fig. 10. This was done as the north facade receives significantly lesser direct sunlight compared to the other facades. The horizontal axis in Fig. 10 shows the WWR used in north facade and the WWR used in east, west and south facade. On comparison with the base case EUI decreased by 1.61% with the use of 30% WWR on all facades whereas the average DA improved by 69.89% with the use of 60% WWR on all facades. The average TCH was not improved for any iteration when compared with the base case.

3.1.4. Shading device

For the study the various iterations considered are depth of horizontal shading devices 0.45m, 0.6m and 0.75m used for window openings and the number of shading devices used i, e. 1, 2 and 3, as compiled in Table 3 and various permutations and combinations were explored. Shading devices are not used in the base case scenario. For instance iterations were explored by keeping the depth of shading devices at 0.45m, 0.6m and 0.75 and simultaneously changing the number of shading devices as shown in Fig. 11. On comparison with the base case, 2.5% reduction in EUI and 192.6% increase in average TCH were observed when 3 horizontal shading devices with a depth of 0.75m were used in the building as seen in Fig. 11. The horizontal axis in Fig. 11 shows depth of shading device used and the number of shading devices used. The average daylight autonomy was not improved for any iteration when compared with the base case.

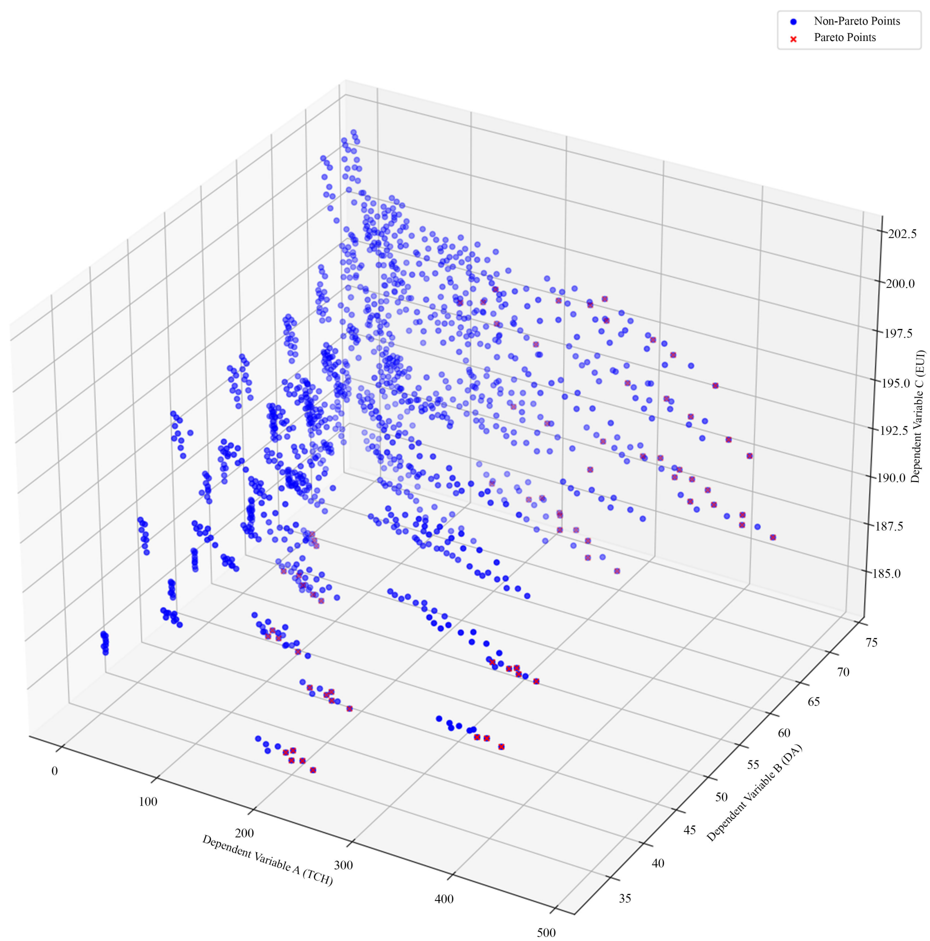

Fig. 12. Pareto optimal points and solution space for commercial lab.

Table 5. 72 Pareto front solutions for the existing building.

Wall (U-Value)	Roof (U value)	Window (U value)	WWR (N)	WWR (S, W, E)	Shade (Depth)	Shade (Number)	EUI	TCH	DA
1.95	3.86	5.73	20	20	0.6	1	190.03	398.14	65.71
1.95	3.86	0.61	20	20	0.6	1	188.52	354.86	41.96
1.95	0.59	0.61	20	20	0.6	1	184.28	168.29	41.96
1.95	0.59	1.45	40	20	0.75	1	184.53	95	45.99
1.95	3.86	5.73	60	20	0.75	1	189.84	274.57	70.96
1.95	0.59	5.73	60	20	0.75	1	185.9	157.29	70.96

1.95	0.59	1.45	60	20	0.75	1	184.61	48.71	54.53
1.95	3.86	5.73	60	60	0.75	1	195.78	213	72.99
1.95	0.59	5.73	60	60	0.75	1	194.28	109.14	72.99
1.95	3.86	5.73	20	20	0.45	2	190.25	422.57	65.62
1.95	0.59	5.73	20	20	0.45	2	186.61	265.29	65.62
1.95	0.59	1.45	40	20	0.45	2	184.95	100.29	45.93
1.95	0.59	1.45	20	20	0.6	2	184.58	210.14	32.89
1.95	3.86	0.61	20	20	0.6	2	188.46	371.71	41.93
1.95	0.59	0.61	20	20	0.6	2	184.18	185.86	41.93
1.95	0.59	1.45	40	20	0.6	2	184.64	106.86	45.91
1.95	3.86	5.73	60	60	0.6	2	195.99	246.14	72.98
1.95	0.59	5.73	60	60	0.6	2	194.64	133.43	72.98
1.95	3.86	5.73	20	20	0.75	2	189.63	451.57	65.58
1.95	0.59	5.73	20	20	0.75	2	185.59	295.14	65.58
1.95	3.86	1.45	20	20	0.75	2	188.52	402.71	32.75
1.95	0.59	1.45	20	20	0.75	2	184.32	216.86	32.75
1.95	3.86	0.61	20	20	0.75	2	188.34	381.29	41.93
1.95	0.59	0.61	20	20	0.75	2	183.97	191.29	41.93
1.95	3.86	5.73	40	20	0.75	2	189.64	359.43	69.34
1.95	0.59	0.61	40	20	0.75	2	184.05	83.86	54.01
1.95	3.86	5.73	60	20	0.75	2	189.67	316.57	70.91
1.95	0.59	5.73	60	20	0.75	2	185.64	197.29	70.91
1.95	3.86	5.73	60	40	0.75	2	192.72	290.29	72.33
1.95	0.59	5.73	60	40	0.75	2	189.81	170.71	72.33
1.95	3.86	5.73	60	60	0.75	2	195.41	263.29	72.98
1.95	0.59	5.73	60	60	0.75	2	193.71	148	72.98
1.95	3.86	5.73	20	20	0.45	3	190.19	452.29	65.49
1.95	0.59	5.73	20	20	0.45	3	186.53	295.57	65.49
1.95	0.59	1.45	20	20	0.45	3	184.83	218.14	32.82
1.95	3.86	0.61	20	20	0.45	3	188.58	378.71	42.02
1.95	0.59	0.61	20	20	0.45	3	184.39	190.43	42.02
1.95	0.59	0.61	60	20	0.45	3	184.71	38.43	60.15
1.95	3.86	5.73	60	60	0.45	3	196.5	261	72.98
1.95	0.59	5.73	60	60	0.45	3	195.48	146.71	72.98
1.95	3.86	1.45	20	20	0.6	3	188.6	412	32.77
1.95	0.59	1.45	20	20	0.6	3	184.48	228	32.77
1.95	3.86	5.73	40	20	0.6	3	189.83	377.71	69.26
1.95	0.59	5.73	40	20	0.6	3	185.93	241.57	69.26
1.95	3.86	5.73	60	20	0.6	3	189.85	335	70.86
1.95	0.59	5.73	60	20	0.6	3	185.95	211.71	70.86
1.95	0.59	1.45	60	20	0.6	3	184.61	65	54.54
1.95	0.59	0.61	60	20	0.6	3	184.41	40.86	60.13
1.95	3.86	5.73	20	40	0.6	3	192.97	422.57	67.76
1.95	3.86	5.73	20	20	0.75	3	189.49	483.43	65.47
1.95	0.59	5.73	20	20	0.75	3	185.38	326.43	65.47
1.95	3.86	1.45	20	20	0.75	3	188.43	426.57	32.72
1.95	0.59	1.45	20	20	0.75	3	184.19	239	32.72
1.95	3.86	0.61	20	20	0.75	3	188.26	399	41.89
1.95	0.59	0.61	20	20	0.75	3	183.86	210	41.89
1.95	3.86	5.73	40	20	0.75	3	189.51	394.14	69.23
1.95	0.59	5.73	40	20	0.75	3	185.41	258.86	69.23

1.95	0.59	1.45	40	20	0.75	3	184.25	127.29	45.89
1.95	0.59	0.61	40	20	0.75	3	183.94	94.29	53.78
1.95	3.86	5.73	60	20	0.75	3	189.53	355	70.84
1.95	0.59	5.73	60	20	0.75	3	185.43	230.43	70.84
1.95	0.59	1.45	60	20	0.75	3	184.18	69.57	54.51
1.95	0.59	0.61	60	20	0.75	3	184.16	43.29	60.1
1.95	3.86	5.73	20	40	0.75	3	192.44	444.14	67.75
1.95	0.59	5.73	20	40	0.75	3	189.41	282.29	67.75
1.95	3.86	5.73	40	40	0.75	3	192.45	365.14	70.84
1.95	3.86	5.73	60	40	0.75	3	192.47	330.71	72.33
1.95	0.59	5.73	60	40	0.75	3	189.43	206.71	72.33
1.95	3.86	5.73	20	60	0.75	3	195.06	400.14	69.03
1.95	3.86	5.73	40	60	0.75	3	195.06	340.57	71.67
1.95	3.86	5.73	60	60	0.75	3	195.08	311.57	72.97
1.95	0.59	5.73	60	60	0.75	3	193.18	189.71	72.97

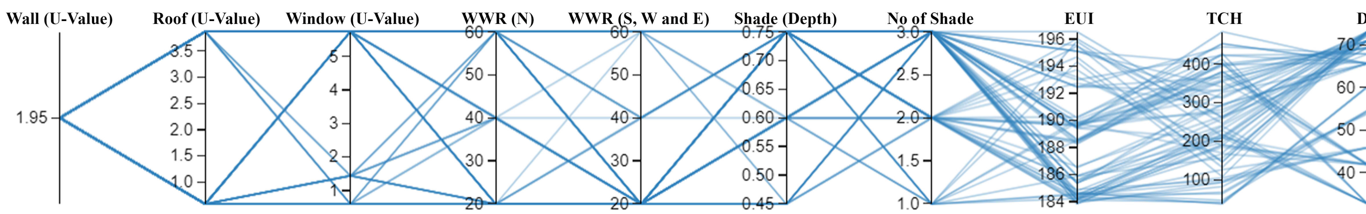

Fig. 13. Parallel Coordinate Plot of the 72 Non-dominated solutions showing Design variables and Performance metrics.

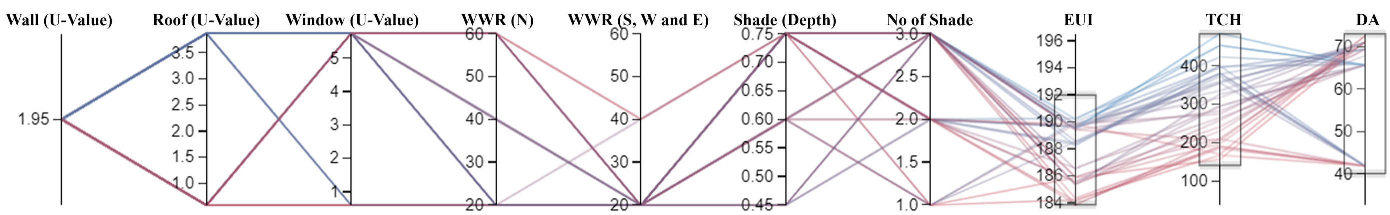

Fig. 14. Parallel Coordinate Plot (PCP) of the 37 non-dominated solutions performing better than the base case scenario.

Based on the analysis made with respect to each of the design variables, the following options were considered for the further studies as compiled in Table 4 which was simulated using grasshopper script along with Ladybug and Honeybee plug-ins.
The following options, upon various permutations and combinations resulted in 1295 iterations for the base case model (1296 iterations in total). It can be understood that the design variables considered for the study has an impact on the performance metrics used i.e. EUI, average TCH and average DA as seen in Fig. 8 to Fig. 11. However, it is challenging to make conclusions by quantifying the combined effect of multiple combinations of these design variables based on this analysis; hence a multi-objective optimization technique was used.

4. Pareto Front Optimization

Pareto front optimization technique was performed on the 1296 iterations. The dependent variables namely, EUI (Dependant variable A), average TCH (Dependant variable B), average DA (Dependant variable C) and independent variables namely wall insulation, roof insulation, window glazing, WWR for north façade, WWR for west, east and south façade, depth of shading device and number of shading devices were defined in the Python script. The objective functions of the study that needs to be optimized are to minimize EUI, maximize average TCH and maximize average DA. The three objectives are assumed to have equal weight age. Iteration is considered to be dominant compared to another iteration based on the objective functions defined. A solution is considered non-dominated if the values of one iteration is as good as the other iteration in all the three dependant variables (A, B and C). The non-dominated solutions should have higher values among dependant variable B and dependant variable C whereas, lower values among dependant variables A. The script was coded to compare the dependant variables of an iteration with the corresponding dependant variables of the rest of the iterations to identify non-dominated solutions. With this method 72 non-dominated solutions were identified.

Table 6. 37 non-dominant solutions that perform better than the base case scenario.

Wall (U-Value)	Roof (U value)	Window (U value)	WWR (N)	WWR (S, W, E)	Shade (Depth)	Shade (Number)	EUI	TCH	DA
1.95	3.86	5.73	20	20	0.6	1	190.03	398.14	65.71
1.95	3.86	0.61	20	20	0.6	1	188.52	354.86	41.96
1.95	0.59	0.61	20	20	0.6	1	184.28	168.29	41.96
1.95	3.86	5.73	60	20	0.75	1	189.84	274.57	70.96
1.95	3.86	5.73	20	20	0.45	2	190.25	422.57	65.62
1.95	0.59	5.73	20	20	0.45	2	186.61	265.29	65.62
1.95	3.86	0.61	20	20	0.6	2	188.46	371.71	41.93
1.95	0.59	0.61	20	20	0.6	2	184.18	185.86	41.93
1.95	3.86	5.73	20	20	0.75	2	189.63	451.57	65.58
1.95	0.59	5.73	20	20	0.75	2	185.59	295.14	65.58
1.95	3.86	0.61	20	20	0.75	2	188.34	381.29	41.93
1.95	0.59	0.61	20	20	0.75	2	183.97	191.29	41.93
1.95	3.86	5.73	40	20	0.75	2	189.64	359.43	69.34
1.95	3.86	5.73	60	20	0.75	2	189.67	316.57	70.91
1.95	0.59	5.73	60	20	0.75	2	185.64	197.29	70.91
1.95	0.59	5.73	60	40	0.75	2	189.81	170.71	72.33
1.95	3.86	5.73	20	20	0.45	3	190.19	452.29	65.49
1.95	0.59	5.73	20	20	0.45	3	186.53	295.57	65.49
1.95	3.86	0.61	20	20	0.45	3	188.58	378.71	42.02
1.95	0.59	0.61	20	20	0.45	3	184.39	190.43	42.02
1.95	3.86	5.73	40	20	0.6	3	189.83	377.71	69.26
1.95	0.59	5.73	40	20	0.6	3	185.93	241.57	69.26
1.95	3.86	5.73	60	20	0.6	3	189.85	335	70.86
1.95	0.59	5.73	60	20	0.6	3	185.95	211.71	70.86
1.95	3.86	5.73	20	20	0.75	3	189.49	483.43	65.47
1.95	0.59	5.73	20	20	0.75	3	185.38	326.43	65.47
1.95	3.86	0.61	20	20	0.75	3	188.26	399	41.89
1.95	0.59	0.61	20	20	0.75	3	183.86	210	41.89
1.95	3.86	5.73	40	20	0.75	3	189.51	394.14	69.23
1.95	0.59	5.73	40	20	0.75	3	185.41	258.86	69.23
1.95	3.86	5.73	60	20	0.75	3	189.53	355	70.84
1.95	0.59	5.73	60	20	0.75	3	185.43	230.43	70.84
1.95	3.86	5.73	20	40	0.75	3	192.44	444.14	67.75
1.95	0.59	5.73	20	40	0.75	3	189.41	282.29	67.75
1.95	3.86	5.73	40	40	0.75	3	192.45	365.14	70.84
1.95	3.86	5.73	60	40	0.75	3	192.47	330.71	72.33
1.95	0.59	5.73	60	40	0.75	3	189.43	206.71	72.33

The non-dominated solutions or pareto points for the existing commercial lab can be seen in Fig. 12 as a 3D graph. A 3D Pareto frontier refers to a visualization technique used in multi-objective optimization to represent the Pareto front in three dimensions. The 1296 iterations are represented as dots in the solution space whereas the pareto points is represented with a ‘x’ mark on the dot. The design variables and the performance matrices of the 72 non dominating solutions are presented in Table 5. The solutions are represented in Fig. 13 as a Parallel Coordinate Plot (PCP) by using Design Explorer v2 which is an open source web tool. The ranges of non-dominated solutions recommended by the pareto front optimization technique for the three objectives are identified. It can be observed in Fig. 13 that U value of 1.95 W/m^{2}K (Brick wall) for wall assembly is recommended by the pareto front for all the 72 solutions. This shows that improving the U value of the wall assembly does not help in achieving the objective of our study. U value of 0.59 W/m^{2}K (RCC roof with EPS insulation) for roof assemble is recommended for 40 solutions whereas U value of 3.86 W/m^{2}K (RCC roof) is observed for 32 solutions proving that lower U value of roof assembly helps in achieving the objectives. U value of 5.73 W/m^{2}K (Single glazed panel) is recommended for 42 solutions whereas 1.45 W/m^{2}K (Double glazing, LowE and LowVLT) and 0.61 W/m^{2}K (Quad glazing, Low solar and LowE) is recommended for 15 solutions each regarding glazing material.

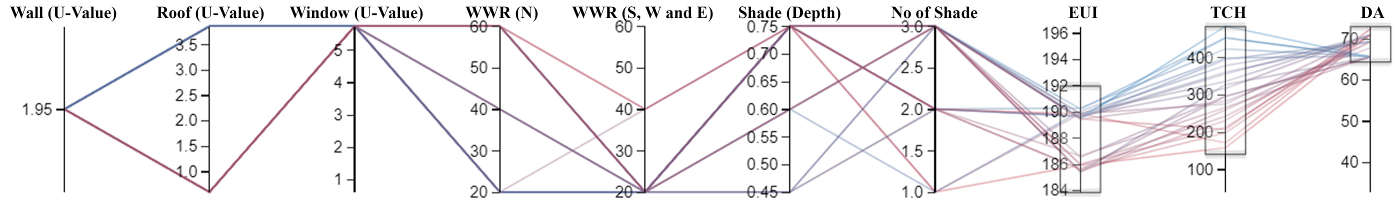

Fig. 15. Parallel Coordinate Plot (PCP) of the 27 non-dominated solutions after selecting 65% to 73% Average DA range.

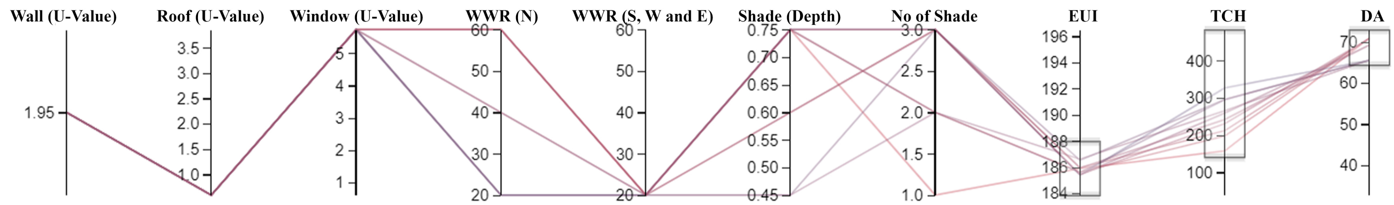

Fig. 16. Parallel Coordinate Plot (PCP) of the 9 non-dominated solutions for EUI range of 185.38 kWh/sq.m to 186.61 kWh/sq.m.

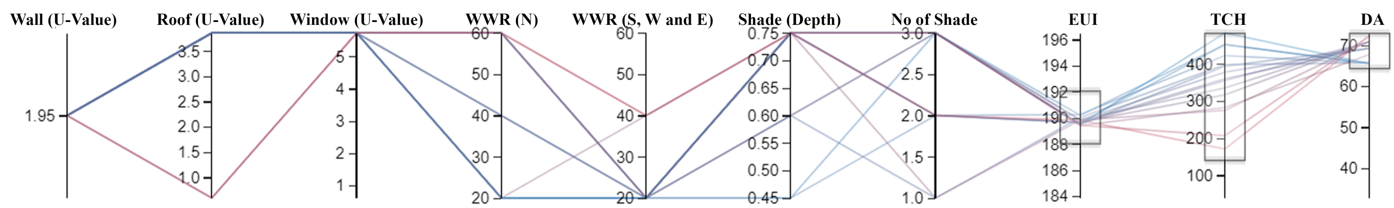

Fig. 17. Parallel Coordinate Plot (PCP) of the 18 non-dominated solutions for EUI range of 189.41 kWh/sq.m to 192.47 kWh/sq.m.

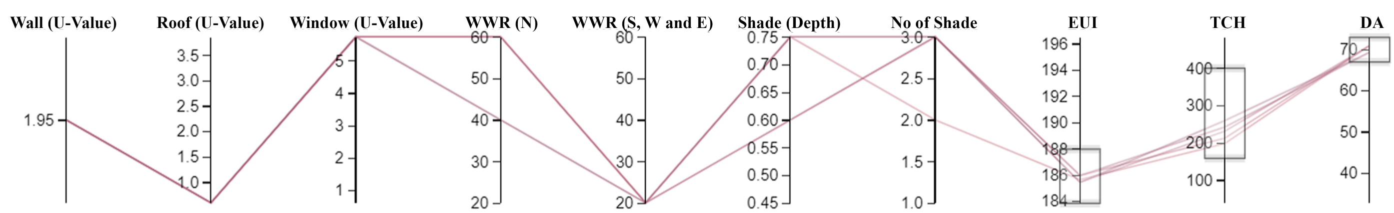

Fig. 18. Parallel Coordinate Plot (PCP) of the top 5 best solutions among the 1296 iterations.

The normal double glazed with U value of 2.71 W/m^{2}K was not recommended by the pareto front. Most solutions show that the single glazed panel is sufficient to achieve the objectives. 31, 13 and 28 solutions were observed for the WWR of north façade at 20%, 40% and 60% respectively. 52, 8 and 12 solutions were observed for the WWR of south, east and west façades at 20%, 40% and 60% respectively. Overall, it can be summarized that 20% WWR works best for all the facades and has the most influence on the objectives. Horizontal shading device of depth 0.75 m was recommended by 43 solutions, whereas horizontal shading device of depth 0.45 m and 0.6 m was recommended by 11 and 18 solutions respectively. The use of 3 horizontal shading devices was recommended by 40 solutions however the use of 1 and 2 horizontal shading devices was recommended by 9 and 23 solutions respectively. Hence, it can be concluded that 3 numbers of shading devices of depth 0.75 m has the most influence on the objectives.

The pareto points identified by the optimization technique are considered as non dominated solutions which means, each data point present on the pareto front is superior when compared to the other points on the solution space [62]. Hence, none of the other solutions are performing better than the non dominated set of solutions; however these non dominated solutions may not necessarily meet all the objectives framed in the study. In order to narrow down the selection, the solutions that perform worse than the base case scenario are identified. These solutions are not

Table 7. 5 best retrofit solutions among the 9 non-dominated solutions for EUI range of 185.38 kWh/sq.m to 186.61 kWh/sq.m.

Wall (U-Value)	Roof (U value)	Window (U value)	WWR (N)	WWR (S, W, E)	Shade (Depth)	Shade (Number)	EUI	TCH	DA
1.95	0.59	5.73	20	20	0.45	2	186.61	265.29	65.62
1.95	0.59	5.73	20	20	0.75	2	185.59	295.14	65.58
1.95	0.59	5.73	20	20	0.45	3	186.53	295.57	65.49
1.95	0.59	5.73	20	20	0.75	3	185.38	326.43	65.47
1.95	0.59	5.73	40	20	0.75	3	185.41	258.86	69.23

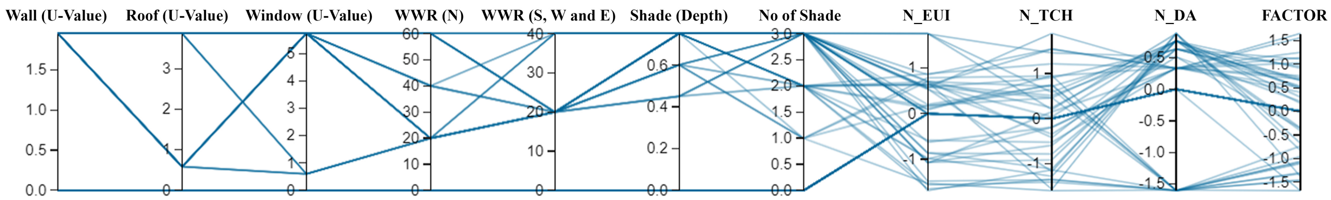

Fig. 19. Parallel Coordinate Plot (PCP) of the 37 non-dominated solutions performing better than the base case scenario after EUI, average TCH and average DA are normalized

considered for recommendations as design solutions even if one among the three objectives is not satisfied.

4.1.1. Energy use intensity and Carbon Emission Intensity

Minimizing the EUI and CEI for the existing building is the first objective considered for the study. In the base case scenario considered for the study, EUI is 192.58 kWh/sq.m. The non-dominated solutions derived from the pareto front optimization technique shows that the EUI and CEI ranges from 183.85 kWh/sq.m to 196.5 kWh/sq.m and 147.08 kgCO2/sq to 157.20kgCO2/sq.m respectively as seen in Table 5. In the base case scenario considered for the study, EUI is 192.58 kWh/sq.m and CEI is 154.06 kgCO_2/sq.m. A maximum of 4.52% reduction in EUI and CEI can be achieved in the base case scenario by incorporating passive design retrofit strategies alone to the existing commercial lab. Among the non-dominated solutions, 14 solutions perform worse than the EUI and CEI of the base case.

4.1.2. Thermal Comfort hours

Maximizing the Average Comfort Hours for the base case scenario is the second objective of the study. Among the non-dominated solutions, the average TCH ranges from 38.42 hours to 483.42 hours as seen in Table 5. The average TCH is 158 hrs for the base case scenario. A maximum of 205.96% increase in the average TCH can be achieved by incorporating passive design retrofit strategies for the base case scenario. Among the non-dominated solutions, 17 solutions perform worse than the average TCH of base case scenario.

4.1.3. Daylight autonomy

Maximizing the average DA for the base case scenario is the third objective of the study. Among the non-dominated solutions, the average DA ranges from 32.71% to 72.98% as seen in Table 5. The average DA is 39.21% for the base case scenario. 86.14% increase in the average DA of the commercial lab can be achieved by incorporating these passive design strategies for the base case scenario. Among the non-dominated solutions, 8 solutions perform worse than the average DA of base case scenario.

4.2. Optimized design solutions: Method 1

39 non-dominated solutions performed worse than the base case scenario regarding one or more objectives considered for the study. The remaining 37 non dominated solutions perform better than the base case scenario regarding all the three objectives. These solutions are presented as a PCP in Fig. 14 and the values are presented in Table 6.

On analyzing the distribution of the 37 non-dominated solutions, it can be observed that 10 solutions have average DA that ranges from 40% to 45% whereas 27 solutions have average DA that ranges from 65% to 73% as seen in Fig. 15. By considering the average DA range of 65% to 73% the EUI ranges from 185.38 kWh/sq.m to 190.24 kWh/sq.m.

Among the 27 solutions with average DA ranging from 65% to 73%, it can be observed that the EUI is concentrated in the range of 185.38 kWh/sq.m to 186.61 kWh/sq.m and 189.41 kWh/sq.m to 192.47 kWh/sq.m. Among the 9 solutions with lower range of 185.38 kWh/sq.m to 186.61 kWh/sq.m as seen in Fig. 16, the average TCH ranges from 197.2 hours to 326.4 hours.

However, for the 18 solutions with higher range of 189.41 kWh/sq.m to 192.47 kWh/sq.m as seen in Fig. 17, the average TCH ranges from 170.7 hours to 483.4 hours.

The main objective of the study is to design low operational carbon buildings, hence the 9 solutions with lower range of EUI is considered. Among these 9 solutions, the best 5 solutions which result in a higher range of average TCH is selected and presented as a PCP as seen in Fig. 18.

The 5 best solutions that can be recommended as best design retrofit solutions are also presented in Table 7. Based on this method, all the five best retrofit solution recommend the use of Brick wall, RCC with EPS insulation, and single glazed windows. Among the 5 solutions, 4 solutions recommend 20% WWR on all facades with 2 or 3 horizontal shading devices of 0.45m or 0.75m work effectively. Whereas, one solution recommends 40% WWR for the north façade and 20% WWR for all other facades with 3 shading devices of 0.75m. By incorporating this solution, EUI of 185.41 kWh/sq.m to 186.61 kWh/sq.m, CEI of 148.3 kgCO_2/sq.m to 149.28 kgCO_2/sq.m, average TCH of 258.8 hrs to 326.42 hrs

Table 8. 37 Non-dominated solutions with normalized values of EUI, average TCH and average DA.

Wall (U-Value)	Roof (U value)	Window (U value)	WWR (N)	WWR (S, W, E)	Shade (Depth)	Shade (Number)	N_EUI	N_TCH	N_DA	FACTOR
1.95	3.86	5.73	20	20	0.6	1	0.78	0.94	0.34	0.5
1.95	3.86	0.61	20	20	0.6	1	0.18	0.46	-1.59	-1.31
1.95	0.59	0.61	20	20	0.6	1	-1.52	-1.59	-1.59	-1.67
1.95	3.86	5.73	60	20	0.75	1	0.7	-0.42	0.77	-0.35
1.95	3.86	5.73	20	20	0.45	2	0.87	1.21	0.34	0.68
1.95	0.59	5.73	20	20	0.45	2	-0.58	-0.52	0.34	0.4
1.95	3.86	0.61	20	20	0.6	2	0.16	0.65	-1.6	-1.1
1.95	0.59	0.61	20	20	0.6	2	-1.55	-1.4	-1.6	-1.44
1.95	3.86	5.73	20	20	0.75	2	0.62	1.53	0.33	1.24
1.95	0.59	5.73	20	20	0.75	2	-0.99	-0.19	0.33	1.13
1.95	3.86	0.61	20	20	0.75	2	0.11	0.75	-1.6	-0.95
1.95	0.59	0.61	20	20	0.75	2	-1.64	-1.34	-1.6	-1.29
1.95	3.86	5.73	40	20	0.75	2	0.63	0.51	0.64	0.53
1.95	3.86	5.73	60	20	0.75	2	0.64	0.04	0.77	0.17
1.95	0.59	5.73	60	20	0.75	2	-0.97	-1.27	0.77	0.47
1.95	0.59	5.73	60	40	0.75	2	0.69	-1.56	0.88	-1.37
1.95	3.86	5.73	20	20	0.45	3	0.85	1.54	0.33	1.02
1.95	0.59	5.73	20	20	0.45	3	-0.62	-0.19	0.33	0.75
1.95	3.86	0.61	20	20	0.45	3	0.2	0.73	-1.59	-1.07
1.95	0.59	0.61	20	20	0.45	3	-1.47	-1.35	-1.59	-1.46
1.95	3.86	5.73	40	20	0.6	3	0.7	0.71	0.63	0.65
1.95	0.59	5.73	40	20	0.6	3	-0.86	-0.78	0.63	0.7
1.95	3.86	5.73	60	20	0.6	3	0.71	0.24	0.76	0.3
1.95	0.59	5.73	60	20	0.6	3	-0.85	-1.11	0.76	0.5
1.95	3.86	5.73	20	20	0.75	3	0.56	1.88	0.32	1.64
1.95	0.59	5.73	20	20	0.75	3	-1.08	0.15	0.32	1.55
1.95	3.86	0.61	20	20	0.75	3	0.08	0.95	-1.6	-0.73
1.95	0.59	0.61	20	20	0.75	3	-1.68	-1.13	-1.6	-1.05
1.95	3.86	5.73	40	20	0.75	3	0.57	0.9	0.63	0.95
1.95	0.59	5.73	40	20	0.75	3	-1.06	-0.59	0.63	1.1
1.95	3.86	5.73	60	20	0.75	3	0.58	0.46	0.76	0.65
1.95	0.59	5.73	60	20	0.75	3	-1.06	-0.91	0.76	0.91
1.95	3.86	5.73	20	40	0.75	3	1.74	1.45	0.51	0.21
1.95	0.59	5.73	20	40	0.75	3	0.53	-0.34	0.51	-0.36
1.95	3.86	5.73	40	40	0.75	3	1.75	0.58	0.76	-0.41
1.95	3.86	5.73	60	40	0.75	3	1.75	0.2	0.88	-0.67
1.95	0.59	5.73	60	40	0.75	3	0.54	-1.17	0.88	-0.82

and average DA of 69.23% to 65.47% can be achieved. When compared with the base case, this solutions minimizes the EUI and CEI by 3.09% to 3.73%, maximizes average TCH by 106.6% to 63.83% and maximizes average DA by 76.5% to 66.9%.

4.3. Optimized design solutions: Method 2

The 5 best solutions that can be recommended are presented in Table 7, however they are not ranked. In order to do that, the 37 non-dominated solutions which perform better than the base case scenario presented in Table 6 are considered and the values of the three objective functions namely EUI, average TCH and average DA are normalized as seen in Table 8. The values are presented as a PCP in Fig. 19.

The normalization of the data is done using the standard score mathematical equation (7),

$$z = \frac{x-\mu}{\sigma} \quad (7)$$

where z is the standardized absolute value of raw score X. μ is the mean of the population and σ is the standard deviation of the population [63].

Based on the three objectives of the study, a factor is derived by using equation (8). Table 8 shows a series of factors derived for the 37 non-dominated solutions.

$$FACTOR = (Average\ TCH + Average\ DA) - EUI \quad (8)$$

Table 9. Sequential order of 5 best non-dominated solutions.

Wall (U-Value)	Roof (U value)	Window (U value)	WWR (N)	WWR (S, W, E)	Shade (Depth)	Shade (Number)	N_EUI	N_TCH	N_DA	FACTOR
1.95	3.86	5.73	20	20	0.75	3	0.56	1.88	0.32	1.64
1.95	0.59	5.73	20	20	0.75	3	-1.08	0.15	0.32	1.55
1.95	3.86	5.73	20	20	0.75	2	0.62	1.53	0.33	1.24
1.95	0.59	5.73	20	20	0.75	2	-0.99	-0.19	0.33	1.13
1.95	0.59	5.73	40	20	0.75	3	-1.06	-0.59	0.63	1.1

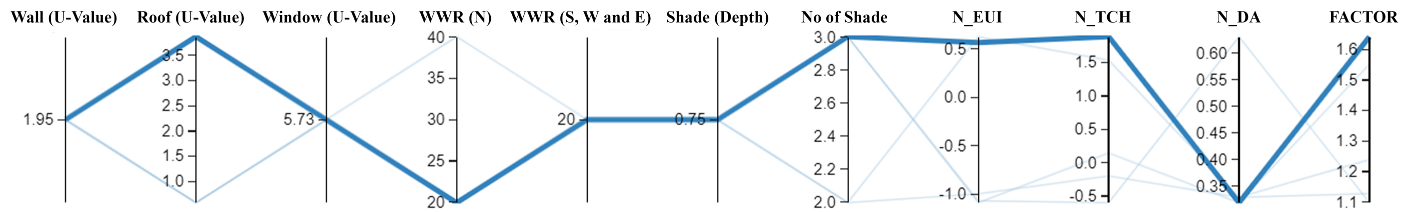

Fig. 20. PCP of the best solution highlighted among the 5 non dominated solutions.

The three dependent variables in equation (8) namely EUI, average TCH and average DA are used in a linear combination. The main objective of the study is decrease EUI, increase TCH and increase DA. In order to do that equal weight age is given to all the three objective functions. In the equation, Average TCH and Average DA are added as the values of these variables need to be improved when compared to the base case scenario, whereas EUI is subtracted as this variable needs to be reduced. The factor with the highest value performs the best. The factor will be higher provided the values of Average TCH and Average DA is higher and the value of EUI is lower. The 5 best solutions are identified using this method and are presented in a sequential order in Table 9. PCP of the best solution among these 5 solutions is highlighted in Fig. 20.

Hence the resultant maxima highlighted in Fig. 20 is recommended as the best solution among all the 1296 iterations. Based on this method, the best retrofit solution would be to use EPS insulation for the RCC roof, WWR of 20% on all sides, 3 horizontal shading devices of depth 0.75 m for all window openings. Single glazed windows and brick wall assemble is best suited for the objectives of the study. By incorporating this solution, EUI of 185.38 kWh/sq.m, CEI of 148.3 $kgCO_2$/sq.m average TCH of 326.42 hrs and average DA of 65.46% can be achieved. When compared with the base case, this solution minimizes the EUI and CEI by 3.7%, maximizes average TCH by 106.6% and maximizes average DA by 66.9%. The operational carbon is reduced from 189766.66 $kgCO_2$ to 182670.97 $kgCO_2$.

5. Discussions

When buildings are not efficiently designed by using these passive design strategies, users need to depend on active strategies increasing the energy use and operational carbon of the building [64]. Thermal comfort and visual comfort are important parameters that ensure workers to use the space efficiently for a prolonged period of time. Passive design strategies contribute significantly in achieving thermal and visual comfort in commercial buildings. Hence it is important to analyse the existing buildings which have a scope for retrofit regarding energy use, thermal comfort and visual comfort. While it is easier to incorporate passive design measures as retrofit solutions considering a focused singular objective, it is necessary to identify optimized solutions which align with multiple-objectives. This study mainly focuses on retrofitting buildings to low carbon buildings along with improving thermal comfort and visual comfort of the users.

A similar study was done in UAE by Abdeen et al., where passive design strategies such as U value of insulation and glazing material and incorporation of window shading devices were considered to reduce energy use and discomfort hours by using MOO approach [65]. Design variables such as Wall and Roof composition, glazing type, WWR and window shading similar to the current study was used by Zahra Benaddi et al., to optimize Carbon emissions, cost and discomfort hours for various climatic zones [66]. Their design recommendation to include insulation in the roof assembly aligns with the current study [66]. According to study by Rahul Verma et al., which involved 18 Indian cities, he concluded that buildings situated in moderate climate require thinner heat resistance material in comparison to composite regions, hence most of the solutions in the current study recommends roof with EPS insulation [62].

According to the study by E.D. Giouri et al., on high rise office buildings situated in Mediterranean climatic regions to achieve reduction of energy demand, maximize energy production, and increase comfort levels in a building since they lead to reduced solar heat gains and reduced cooling loads, findings suggest that WWR of 20% for all facades were optimal which aligns with the current study [67]. Also, the study [67] concluded that the U value of wall and window glazing has the least impact on EUI similar to the current study.

Shading device optimization was done on education buildings in Savzevar city by Dokhanian et al., using MOO technique considering the 3E factors – Energy, Economic and Environmental factors which concluded that among 3600 iterations, simple horizontal overhang of 1m length performs the best [68]. The number and depth of shading devices used in this research [68] was one of the important variables to influence the

EUI of the building as observed in the current study. In order to improve the thermal comfort and energy efficiency in NV offices situated in Burkina Faso, Nathan Zoure and Vincenzo Genovese concluded that horizontal shading devices and 30% WWR reduces EUI by 14.9% and improves sDA by 50% [69].

Similar to the current study Mohammad Hakimazari et al., has also used Grasshopper and Python to perform MOO in order to improve sDA, Daylight Glare Probability, EUI, and Thermal comfort by 43.6%, 52.77%, 13.9, and 3.696%. The use of design variables related to WWR and shading devices in the office spaces of Tehran, Iran highlights the influence of these design variables on the energy, thermal and visual comfort parameters similar to the current study [70]. Most references have used sDA and UDI, as daylight parameters for visual comfort in their study but the authors have selected DA because in the Indian context the GRIHA rating system used DA parameter in order to improve the efficiency of the building [71].

The limitation of the study is that economical factors are not considered in the MOO study, however, when it comes to material selection, best suited or locally available materials are prioritized. Further, potential of renewable energy options were not explored which could enable the building to reach zero carbon status. Also, the study does not quantify the payback period for the investments taken up through the retrofit design recommendations.

6. Conclusion

In this study pareto front optimization technique has aimed to reduce operational carbon emissions in the building along with improving the thermal and visual comfort for the users of the building. This paper mainly focuses on the influence of passive design strategies in mixed mode commercial building located in moderate climatic zone. Six design variables were used namely, wall insulation, roof insulation, glazing material, window-wall ratio (WWR), depth of shading device and the number of shading devices in order to optimization EUI, CEI, TCH and DA. The authors were able to recommend best optimized design solutions for retrofit in the areas of energy, carbon, daylight and comfort using two methods. The study helps us to quantify the improvements achieved regarding the three objectives for this case. The findings of the study are as follows:

- The improvements seen with respect to the energy consumption in buildings is less compared to vast improvements observed in the areas of daylight and comfort. Reduction of energy consumption by 3.9% was the maximum that could be achieved without considering the other objectives.
- The best solution recommended by both the methods is the use of EPS insulation for the RCC roof, WWR of 20% on all sides and 3 horizontal shading devices of depth 0.75 m for all window openings resulting in the reduction of EUI by 3.7%, increase in average TCH by 106.6% and increase in average DA by 66.9%.
- The researchers were able to conclude with certainty that few materials used in the base case scenario works best hence, keeping us from making unnecessary and unwanted changes that do not cater to the objective. In this case, brick wall and single glazed windows work efficiently to achieve the three objectives of the study.
- Among the design variables considered for the study shading devices have the most impact on reducing the EUI, CEI and TCH of the building. WWR has the most impact on the average DA in the building.

This study provides optimum design recommendations to transform buildings into low carbon buildings. These are practical solutions that also improve the thermal comfort and visual comfort in the building. Hence, it is important to consider multiple objectives consecutively during the decision making process of building retrofit.

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Contributions

Lahari Vishwanath: Literature study, Research gap identification, Research methodology framework, Field Data Collection, 3D modelling, Building simulation modelling, Data Analysis, Original Draft Preparation. D Kannamma: Research methodology framework, Optimization, Instrument Procurement, Editing draft, Revision, Overall Project Supervision.

Declaration of competing interest

The authors declare no conflict of interest.

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