MULTI-OBJECTIVE OPTIMIZATION OF BUILDING ENVELOPE FOR DAYLIGHT AND ENERGY PERFORMANCE IN HOT AND DRY INDIAN CLIMATE

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ABSTRACT

The climate-responsive envelope design is the principal component for maintaining the indoor environment. This research presents a multi-objective optimization (MOO) approach to evaluate visual comfort and energy performance. A hypothetical building plan situated in the hot and dry climate of Ahmedabad (23.07° N, 72.63° E), India is chosen as a case study. The optimization was initiated with a Rhinoceros Grasshopper, and the Octopus plugin was used to perform optimization. Spatial Daylight Autonomy (sDA), Spatial Glare Autonomy (sGA), and Energy Use Intensity (EUI) were taken as performance objectives. The design variables such as wall window ratio (WWR), window height, shading configuration, window assembly, wall materials, aspect ratio, building form, and orientation are integrated into the optimization to identify Pareto optimal solutions. This study illustrates that the optimal trade-off solution can reduce the EUI by 31.09% and enhance the sDA and sGA by 93% and 18.58%, respectively, compared to the worst-performing Pareto solutions. The outcomes of this work help building professionals for the designing, and renovation of building envelopes in hot and dry climates and contributing to creating a sustainable built environment.

Keywords: Visual comfort, Energy efficiency, Muli-objective optimization, Envelope design

1. Introduction

The building sector of India is the principal consumer of total primary energy (TPE) supply and it consumed 596 million tons of TPE in 2018 [1-2]. Bureau of energy efficiency (BEE), reported that buildings consumed 33% of total generated electricity in 2018-19, and it may fold by 3 to 5 times by 2031 [3]. The continuous, significant growth in building built fabric and their respective energy demands are responsible for leading to GHG emissions [4]. Indian energy outlook report 2021 states that 160 million tons of CO_2 come from the direct use of fossil fuels in buildings, and 460 million tons of indirect emissions come from the use of electricity [5]. Therefore, high- performance building design becomes the prime concern to achieve energy efficiency in the building sector [6]. There are various iterative challenges in building design that affect the building's energy demand. The challenges include visual comfort from natural lighting, thermal comfort from natural ventilation, indoor air quality, energy demand, and life cycle cost [7-8]. Various building envelope parameters have an iterative correlation with these challenges [9]. Meanwhile, high-performance building design has become an extensive research area in architectural design. Therefore, the computational optimization process provides a plausible design solution by

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exploring the wide range of design possibilities [10]. This process provides trade-off solutions by transforming the design problem into a mathematical domain [11]. Past research focused on solving the various challenges of building design. Maintaining visual comfort inside the building space is a crucial task. It enhances occupant productivity, reduces mental stress, and minimizes the use of artificial lighting demand. Besides, achieving thermal comfort is the most challenging task in the hot and dry climate to maintain an indoor thermal environment [12-13]. Approximately 70% of the world's total energy consumption was used to maintain a desirable indoor environment in buildings [14]. It is essential to find a balance between a building's energy needs and the quality of its indoor environment [15]. In this context, C. Marino et al. (2017). optimize the window wall ratio (WWR) in the Italina climate and its significant impact on building energy demand. This research established the relationship between WWR, glazing typology, and energy demand [16]. Fang and Cho (2019) optimized the building geometry including building depth, roof ridge, location of skylight, louvers length, and their significant impact on daylight and operational energy. This work was conducted in three different US climates, and it reveals that robust geometry design reduces the energy demand by 17–20% and enhances the useful daylight illuminance (UDI) by 28–38% [17]. Lee et al. (2013) investigate the potential of window performance in the Asian climate. In this research, the thermophysical properties of glazing, orientation, and WWR were taken into account as design variables to identify the trade-off solution in terms of minimum energy use. It also illustrates the most influential control parameters that affect heating, cooling, and lighting demand by exploring regression analysis [18]. There are various indices available to access and quantify the daylight in terms of quantity of natural light, uniform distribution of daylight, and glare. A number of past studies are available based on two or three objective optimizations including daylight, thermal comfort, and energy [19]. A lack of studies was available that focused on building façade design to reduce disturbing glare, enhance daylight penetration, and reduce energy demand. Therefore, this research presents a multi-objective optimization approach for envelope design, exploring a wide range of design possibilities. Wall window ratio (WWR), window height, shading configuration (horizontal and vertical), window assembly, thermophysical properties of glass, wall materials, aspect ratio, building form, and orientation were taken into account as design variables during optimization. Three objectives, such as Spatial Daylight Autonomy (sDA), Spatial Glare Autonomy (sGA), and Energy Use Intensity (EUI), were investigated by exploring defined design variables in Rhinoceroses Grasshopper with the Octopus plugin. Finally, Pareto optimal solutions were generated, and a trade-off solution was identified that satisfied all objectives. This research illustrates that the optimal trade- off solution reduces the EUI by 31.09% and enhances the sDA and sGA by 93% and 18.58%, respectively, compared to the worst-performing Pareto solutions. The outcomes of this research help building professionals design and renovate building envelopes in hot and dry climates, contributing to creating a sustainable built environment.

2. Methodology

This section presents the methodological approach used for this research. This research work comprises four sequential steps. The first steps include the based model development and selection of input design variables; the second step demonstrates the defined objectives functions; the third step illustrates the multi-objective optimization set-up; and finally, the generation of Pareto solutions. Fig. 1 shows the optimization workflow that is used in this research.

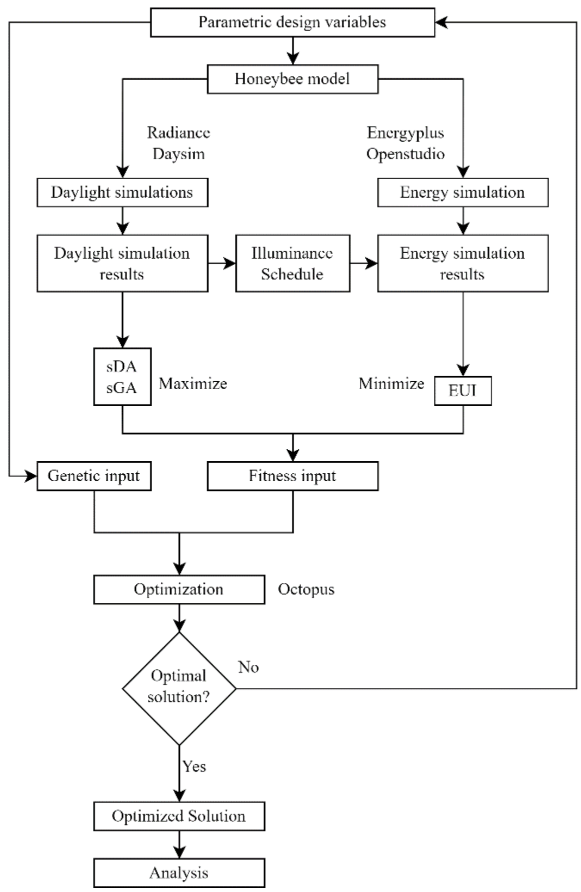

Fig. 1: Methodological flowchart of optimization process.

2.1. Case study

A base model was a hypothetical rectangle-shaped building plan situated in Ahmedabad city, hot and dry climate (Köppen climate classification: BSh) of India was taken into account for the analysis. Ahmedabad heaving extremely hot summer and cold winter climatic conditions. Therefore, envelope design is a complex architectural concept in this region. In this research, the authors considered all envelope parameters as design variables, which are listed in Table 1. The range of design parameters taken is based on typical architectural scenarios in the city. Table 2 reports the wall materials and their thermophysical properties used for optimization. Table 3 reports the conductivity and solar heat gain coefficient (SHGC) value for glass material. Thermophysical properties of glass and wall material were taken from the Indian database and energy conservation building code [20].

Tab. 1: Envelope design variables used for optimization

Design variable	Ranges	Deviation	Unit
V_1: Glass U-value	Shown in Table 2		
V_2: SHGC			

V_3: Wall conductivity (U-value)	Shown in Table 3		
V_{4-7}: WWR- north, south, east west	10 - 70	5	%
V_8: Window height	0 – 2	0.1	meter
V_9: Window sill height	0-1.5	0.1	meter
V_{10-13}: External louver depth – north, south, east, west	0.1-1.5	0.1	meter
V_{14-17}: Louvers count- north, south, east, west	1-5	1	-
V_{18}: Slits angle	0 - 50	5	degree
V_{19-22}: Vertical fins depth-north, south, east, west	0.1 - 1	0.1	meter
V_{23-26}: Vertical fins count-north, south, east, west	1-5	1	-
V_{27}: Orientation	0-360	15	degree
V_{28}: Aspect ratio	1:2.5	0.1	-

Tab. 2: Wall material and their properties used for optimization

Material name	**Thickness (m)**	**Conductivity (W/mK)**	**Density (kg/m^3)**	**Specific heat (J/kgK)**
Compressed stabilized earth brick (CSEB)	0.2	.588	1630	908
Flyash brick	0.23	.802	1844	924
Ariated concreate block (AAC)	.2	.169	608	875
Cellular low weight block (CLWC)	0.23	.193	693	932
Clay brick	0.23	0.969	2119	916.1

Tab. 3: Glass type and their properties used for optimization

Glass type	**U-value ((W/m^{2}K)**	**SHGC (%)**
Glass 1	1.66	0.45
Glass 2	1.43	0.24
Glass 3	2.87	0.55
Glass 4	2.87	0.25

2.2. Performance Objectives

In this work, three building performance objectives were investigated as Spatial Daylight Autonomy (sDA), Spatial Glare Autonomy (sGA) and Energy Use Intensity (EUI).

2.2.1. Spatial Daylight Autonomy (sDA)

It is a metric that assesses the annual sufficiency of ambient daylight level in the interior environment and is defined as the percentage of the analysis area that meets the minimum standard of daylight illumination for a specified portion of the operating hour annually [21]. Example The term "sDA300/50%" refers to the proportion of floor space that receives at least 300 lux for at least 50% of occupied hours per year on the horizontal work plane. It was calculated using Eq. 1.

$$ssssss_{xx/yy\%} = \frac{\sum_{ii}(wwww_{ii} \times DDDD)}{\sum_{ii} pp_{ii}} \in [0,1] \quad \text{(eq. 1)}$$

With $$wwww_{ii} = \begin{cases} 1 & iiww \;\; ssss \geq ssss_{lliilliill} \\ 0 & iiww \;\; ssss < ssss_{lliilliill} \end{cases}$$

Where x is the reference illuminance level, y is the time fraction, and p_i are the points belonging to the calculation grid.

2.2.2. Spatial Glare Autonomy (sGA)

It is the fraction of occupied time in which daylighting glare probability is less than 40%. Example (sGA40%/5% displays the percentage of a space where the risk of daylight glare exceeds 40% for no more than 5% of the time the space is inhabited. The EN 17037:2018 European Daylight Standard also specifies the 5% level for glare assessments [22].

2.2.3. Energy Use Intensity

It is a metric used to quantify the energy performance of a building. It represents the sum of all electricity, fuel, district heating/cooling, etc. divided by the gross floor area (including both conditioned and unconditioned spaces). In the study, the total load is calculated as the sum of cooling, heating and lighting loads.

2.3. Multi-objective Optimization

In this research, a 3D graphics modeling tool Rhinoceros was used for modeling. An octopus plugin of Grasshopper was used to perform multi-objective optimization. The Honeybee (HB) open studio engine was used for energy simulation and daylight simulation was performed using Radiance engine. Grid is assigned with ‘HB Sensor Grid from Rooms’ component for daylight assessment. The lighting sensors were placed at a grid size of 0.6 m and 0.8 m from the floor. The artificial lighting load was defined as 9.5 W/m^2 as per ECBC. Occupancy and lighting schedule were set as per ASHRAE standard for commercial buildings. The natural ventilation was scheduled as per Indian model of adaptive comfort (IMAC) temperature range for each month of Ahmedabad city. Therefore, the air-conditioning load was calculated based on the IMAC model.

3. Result and discussion

The optimization process was carried out by setting up algorithmic constraints. The strength Pareto evolutionary algorithm (SPEA-2) and hyperreduction algorithm were used to converge the Pareto solutions. Assigned the optimization termination criteria as the maximum generation, and population size is 50 and 50, respectively. Besides, elitism, crossover, mutation rate, and mutation probability are 0.5, 0.8, 0.9, and 0.2, respectively. The Octopus successfully converged all the solutions as shown in Fig. 2. Each point in this figure demonstrates the optimized design solutions.

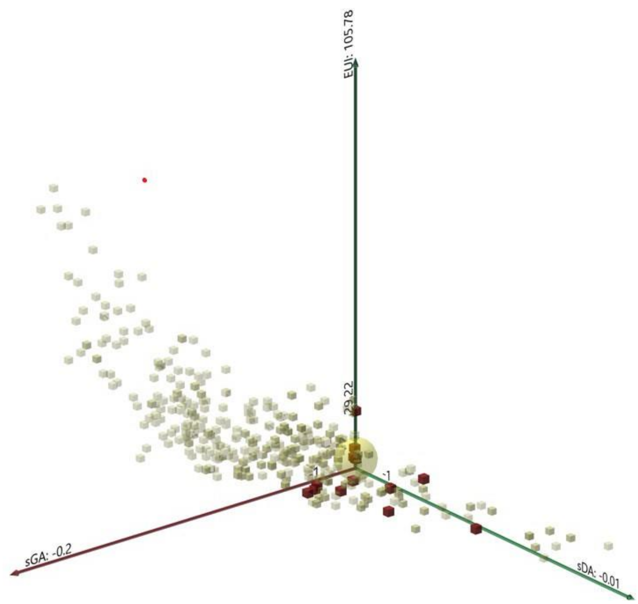

Fig. 2: Tri-objective Pareto solutions during optimization.

The axeview diagram of performance objectives generated by Octopus is presented in Fig. 3. Each line represents a design solution. The lines connect the values for EUI, sGA and sDA. The best trade-off solution that satisfies all the defined performance objectives is shown in the yellow colour line in Fig. 3. Furthermore, the building design parameter values for trade-off solutions are reported in Table 4. It shows that the wall conductivity has a significant impact on the energy demand. Therefore, a lower U-value of wall material reduces heat penetration in the space and reduces cooling energy demand. Besides, WWR plays the major role in balancing daylight and energy demand. The north-south façade building, with a 40% and 50% WWR ratio, provides the best results in energy efficiency and daylight. Window louvers are used to reduce the glare in the space and enhance the natural light in the space. The maximum glare comes from the south-east side. Therefore, increasing the louvers count at a defined angle reduces the glare as well as the heat inside the space due to solar radiation. Moreover, the authors compared the trade-off optimal solutions and the worst-performing Pareto solutions, and their values are reported in Table 5. It reveals that the optimal trade-off solution reduces the EUI by 31.09% and enhances the sDA and sGA by 93% and 18.58%, respectively, compared to the worst-performing Pareto solutions.

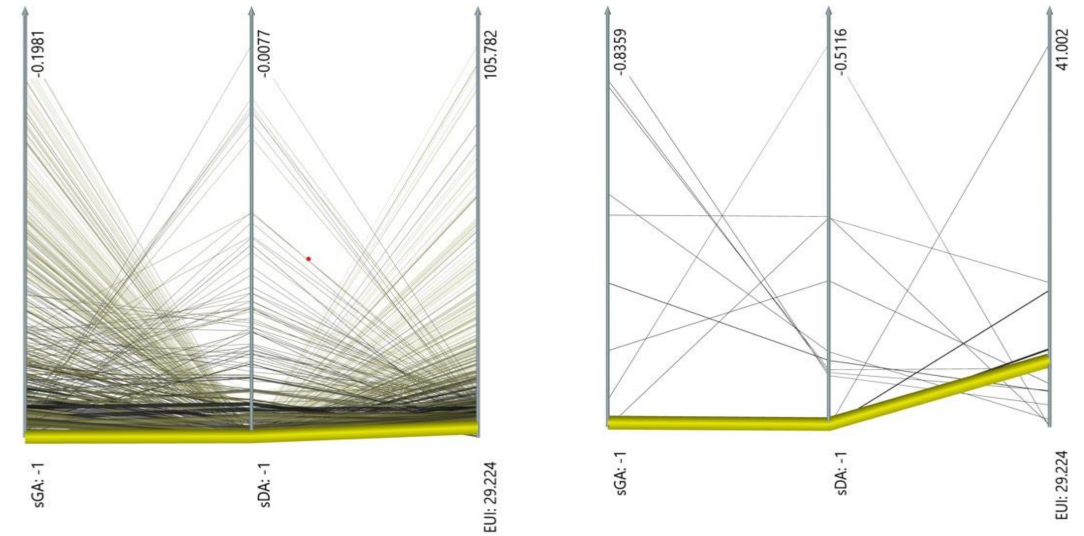

Fig. 3: Axe view diagram of performance objectives and trade-off solution.

Table 5: Best trade-off solution and worst Pareto optimal solutions

EUI (kWh/m^2/yr.)		sDA (%)		sGA (%)	
Optimal	Worst	Optimal	Worst	Optimal	Worst
31.292	41.02	99.61	51.35	99.8	84.16

Table 4: Optimal trade-off solution design variable during optimization

Parameter	Optimal trade-off solution	Unit
Aspect ratio	1.28	-
Orientation	N-S	-
WWR N	0.4	%
WWR E	0.6	%
WWR S	0.5	%
WWR W	0.4	%
Height	2	Meter
Horizontal shading devices		
Louver depth N	0.1	Meter
Louver depth E	0.2	Meter
Louver depth S	0.2	Meter
Louver depth W	0.3	Meter
Louver angle (^{o})	45	Degree
Louver count N	7	-
Louver count E	9	-
Louver count S	8	-

Louver count W	7	-
Vertical shading devices		
Fin depth N	0.15	-
Fin depth S	0.3	-
Fin count N	7	-
Fin count S	4	-
MATERIALS		
U Value for wall material	0.24	W/m^2K
U value for glass	2.87	W/m^2K
SHGC	0.55	-
Trade-off solution		
EUI	31.292	kWh/m^2 /yr.
sDA	99.61	%
sGA	99.8	%

4. Conclusion

This research proposes a multi-objective optimization process for early design stage decision-making of building façade design. The optimization process investigates the daylight and energy performance of a hypothetical commercial building. A Rhinoceroses tool with an Octopus plugin was used to explore the 22-building façade design variable with a wide range of design possibilities and identify the best trade-off solution. This study focused on efficient façade design in hot and dry climatic conditions (Köppen climate classification: BSh) of Ahmedabad, India. The outcomes of this study reveal that the optimal trade-off reduces the EUI by 31.09% and enhances the sDA and sGA by 93% and 18.58%, respectively, compared to the worst-performing Pareto solutions. The outcomes of this research help architects and building professionals to obtain an optimal solution for the early building designing stage in the hot and dry climate of India.

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