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DEVELOPMENT OF SIMEC-OPT FRAMEWORK FOR OPTIMIZING GLAZING PARAMETERS ENHANCING RESIDENTIAL BUILDING THERMAL COMFORT AND ENERGY PERFORMANCE

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Abstract

While glazed buildings have become a symbol of modern construction with their aesthetic appeal, there is a lack of research specifically focusing on the influence of glazing parameters on energy consumption and occupant comfort in residential buildings, especially in tropical climate zones. The study is focused on developing a simulation-based framework for optimizing the glazing parameters of multi-storied residential buildings in Indian climate zones to enhance thermal comfort and energy performance using a baseline model in Mumbai, India. Optimal configurations, identified through the study, suggest potential improvements of up to 30% in energy efficiency and 8% in thermal comfort compared to a baseline design considered in the study. The findings aim to inform architects, builders, and policymakers about tailored glazing configurations in various Indian climates.

Introduction

As global carbon emissions attributed to buildings reach nearly 42 percent, the emphasis on sustainable and energy-efficient building design has become paramount (Architecture 2030, 2023). The key to achieving sustainability in the building sector is the exploration of energy consumption patterns so as to take up energy-conserving measures for the same. An assessment by the Bureau of Energy Efficiency (BEE) shows that in India, lighting and air conditioning use 80 percent of the energy in commercial buildings, whereas fans, lighting, and refrigerators use maximum energy in residential buildings (Kaja, 2015). The energy demands of a building are significantly influenced by its envelope which serves as the primary connection between the external environment and the interior spaces. The architectural world is witnessing a surge in the popularity of providing more glass as a major material in the building envelope (Ayyad, 2011). Glass offers transparency and a sleek, contemporary look that enhances the architectural appeal of structures. Glass allows natural light to enter buildings, positively impacting occupant well-being as exposure to natural light has been linked to improved state of mind, increased alertness, and enhanced productivity (Golmohammadi et al., 2021). As countries such as India experience urbanization and economic growth, there is a desire to shift to contemporary architectural styles that incorporate more glass in the envelopes. However, when it comes to building energy efficiency, the choice and application of glass can significantly influence the outcome. One of the primary challenges with glass in tropical climates is excessive heat gain. Tropical climates typically experience intense and prolonged sunlight which can lead to a greenhouse effect inside buildings, causing them to overheat. This, in turn, requires more energy for air conditioning and cooling, leading to increased energy costs and carbon emissions (Sayed and Fikry, 2019). Hence, the performance of selected glass is of paramount importance in controlling energy consumption.

The process of selecting glass has become increasingly intricate due to the wide array of glass options available, ranging from performance-oriented attributes to aesthetic considerations. Usta and Zengin (2022) performed energy modeling for an office building, considering four distinct types of glazing, to assess the influence of various window glazing properties on the building's energy performance while maintaining consistent indoor thermal and visual comfort conditions. The findings of the study demonstrated that the utilization of appropriate glazing materials could lead to a substantial reduction in energy consumption, specifically about 25% (Usta et al., 2022). Though the study showcased significant improvement in energy consumption, the lack of validation of the model raises concerns about the reliability of the simulated results. Further, the methodology outlined in the study appears to have a limited scope regarding glazing variations as it considers only four types of glazing models. Khalaf et al. (2019) investigated the impact of façade and shading systems on the energy performance of school buildings in Istanbul, emphasizing the need for a balance among lighting energy, heating, and cooling energy. The authors presented a case study comparing traditional clear double-layer windows with various glazing and shading alternatives and revealed a significant energy consumption reduction when using proper glazing and shading systems. However, the authors overlooked the user comfort and the potential effect of glazing and shading type on the productivity of students (Khalaf et al., 2019). Kumar et al., (2018) investigated the thermal performance of commercial and residential buildings constructed with various building materials and window glass types in five different climatic zones of India. The findings demonstrated that, among the eighty building models analyzed, the building featuring a mud brick wall and south-facing bronze-reflective glass windows exhibited the most significant energy savings in terms of minimizing heat gain. While this study made valuable strides in understanding energy efficiency in residential buildings, it beckons further considerations to understand the broader impact of glazing choices. With the increasing prevalence of remote work, residential spaces have become multifunctional and serve as both living and working areas, enhancing the significance of factors such as productivity and comfort in residential buildings. While the above studies make significant contributions to the aspect of energy efficiency, the impact of different glazing options on occupant comfort in residential environments remains underexplored. ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers) defines thermal comfort as the conditions in which occupants of a space feel satisfied with their thermal environment (ASHRAE Standard 55). Further, due to the intricate nature of building models, computer simulations emerge as an efficient, comprehensive, and highly accurate method. Naji et al., (2021) used a multi-objective optimization approach using TRNSYS (Transient System Simulation Tool) and EnergyPlus to enhance the envelope components of prefabricated houses across six distinct climate zones in Australia. Optimization with multiple objectives involves the simultaneous consideration of conflicting goals, such as minimizing energy consumption while maximizing occupant comfort. This requires evaluating trade-offs between different design options to identify the most optimal solution that satisfies multiple criteria. The authors in this study considered energy efficiency, thermal comfort, and daylight illuminance as objectives. The results demonstrated significant improvements in various aspects of building performance compared to a baseline design. Compared to a baseline design, the life cycle cost of the optimal solution was reduced by 27-31%, indicating cost savings over the building's lifespan. Further, thermal discomfort hours were reduced by 6-55% (Naji et al., 2021). In a similar study by Ran et al. (2023), DesignBuilder was used, which employs a non-dominated sorting genetic algorithm (NSGA-II), to optimize building energy, comfort, and cost. The optimal solution reduced energy use by 21.1%, and improved thermal comfort by 32.4%, but increased initial investment cost by 35.3% for a reference building in Beijing. However, the above studies focus on various construction aspects, such as building materials, orientation, and insulation, rather than explicitly addressing the direct impact of glazing types. The studies also oversee the importance of validating building models with real-time data to authenticate consumption patterns and occupant behavior. Bridging this gap in literature would provide valuable insights for architectural regulations and building design, especially in the context of Indian climate zones. India is a vast country with different climate patterns and temperature ranges, from the tropical conditions in the south to the colder climates in the north. With residential buildings already accounting for a significant portion of India's energy consumption i.e., 20.4% projections suggest that by 2032, this percentage will increase sevenfold to reach 36.5% emphasizing the need for more sustainable practices in residential buildings (BEE, 2021). Addressing this need, the study is focused on the selection of optimum glazing type and Window-to-Wall ratio (WWR) that help build energy-efficient and thermally comfortable residential buildings.

Methodology

The study employs a simulation-based framework – SIMEC-Opt, illustrated in Figure 1, to find the optimum glazing configuration that reduces heat gains and improves thermal comfort. The building is modeled in DesignBuilder, including detailed information regarding materials, characteristics of HVAC systems, schedules, and occupant behavior. Further, to understand the impact of glazing, an essential aspect involved the identification of glazing properties that will define glazing configurations. Glazing parameters such as U-value and Solar Heat Gain Coefficient (SHGC) are defined from glass types available in the Indian market. Next, optimization is carried out with the objectives of minimizing electricity consumption and maximizing thermal comfort by considering varied glazing options, and WWR to identify optimal combinations for different climate zones. The climate of India has been classified into five climate zones by BEE (BEE, 2021). BEE, in its Handbook of Replicable Residential Designs, has identified five representative cities corresponding to these climate zones. The five climate zones and their associated cities are detailed in Table 1. These 5 cities have been selected as they are a fair representation of the climate characteristics of the zone and have a high residential development potential in the coming years (Handbook of Replicable Residential Designs, 2021). Weather data files are obtained from climate.onebuilding in the EnergyPlus Weather (EPW) format. These EPW files provide comprehensive meteorological data necessary for building energy simulations, including parameters such as temperature, humidity, wind speed, solar radiation, and precipitation (climate.onebuilding).

Table 1: Climate Zones of India and their representative city

Climate Zone	City
Hot and Dry	Aurangabad
Temperate	Bengaluru
Warm and Humid	Bhubaneshwar
Composite	Lucknow
Cold	Srinagar

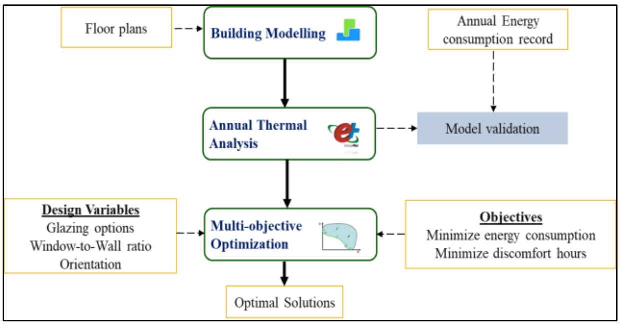


Figure 1: SIMEC-Opt Framework

Energy consumption is quantified by assessing the building's annual lighting, cooling, and heating demands, while thermal comfort is evaluated by calculating annual discomfort hours. Discomfort hours refer to the duration of time during which the indoor environmental conditions within a building fall outside the range considered comfortable for occupants. The criteria are often aligned with industry standards for acceptable indoor temperature and humidity levels. Discomfort hours in DesignBuilder are aligned with ASHRAE Standard 55, which defines the conditions for thermal comfort in indoor environments (DesignBuilder Software Ltd).

Modelling

Model Description

DesignBuilder is chosen as the tool for modeling and analysis in this study as it offers flexible geometry input, extensive material libraries, and load profiles and utilizes EnergyPlus as its simulation engine (DesignBuilder Software Ltd). Using the original drawing files, a residential quarter is replicated in the DesignBuilder software. This building with its actual glazing configuration and WWR, serves as the base model for this study, representing a typical apartment complex in India. In practical applications, the number of windows and building materials differ across geographical locations. Since the present research is designed to assess the impact of various glazing systems, the same building model is employed across all locations, ensuring consistency and comparability in the study. The building was originally located in Mumbai, a city characterized by warm and humid climate conditions, as per the BEE classification (BEE, 2021).

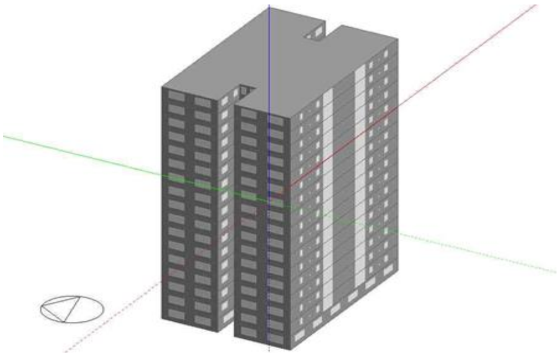


Figure 2: Model of the building

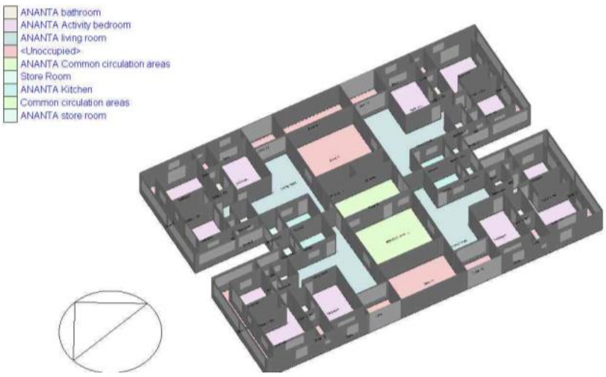


Figure 3: Floor plan of the building

Table 2: Specifications of the building envelope

Component	Layers	Material	U-value (W/m^{2}K)
External Wall	3	1.25 cm cement plaster + 22.5 cm brick + 1.25cm cement plaster	2.192
Internal Wall	3	1.25 cm cement plaster + 20 cm brick + 1.25cm cement plaster	2.335
Roof	2	1 cm RCC + 1 cm lime concrete	2.939
Floor	1	10mm ceramic tiles + 50 mm cement screed + 150 mm concrete floor slab	2.562
Glazing	1	Single clear glass 6 mm	5.88

Table 3: Zone-wise HVAC details of the building

Zones	Ventilation	Lighting	Cooling	Heating
Bedroom 1	Mixed mode	On	On	On
Bedroom 2	Mixed mode	On	On	On
Bedroom 3	Mixed mode	On	Off	Off
Living Room	Mixed mode	On	Off	Off
Kitchen	Mixed mode	On	Off	Off
Storeroom	Mixed mode	On	Off	Off
Bathroom 1	Mechanically ventilated	On	Off	Off
Bathroom 2	Mechanically ventilated	On	Off	Off
Bathroom 3	Mechanically ventilated	On	Off	Off

The building comprises a total of sixteen floors, with each floor accommodating four individual units. These units are equipped with three bedrooms, a kitchen, a store room, three bathrooms, and a living room. Additionally, the ground floor of the building is designated for parking. A visual representation of the building and the floor plan for each level is provided in Figure 2 and Figure 3, respectively. Detailed specifications of the building's envelope and the U-value of components are outlined in Table 2 (ECBC, 2017). The model is equipped with two-pane sliding windows (50% openable area) of aluminum frame and single-glazed clear glass of 6 mm thickness with SHGC of 0.88 and a U-value of 5.8 W/m^{2}K.The HVAC systems in each zone within the apartments are outlined in Table 3. The building follows a specific operational schedule for each zone, considering that occupants are outside and have office working hours starting at 9 am to 6 pm hence occupants are considered active at the house only in hours other than office hours on weekdays and active all day on weekends (Rethnam and Thomas, 2023).

Model Validation

To validate the model, the monthly electricity consumption data for the building is collected from the regional Estate office and then compared with the simulated energy consumption for the Mumbai location. DesignBuilder uses detailed information about the building, including its geometry, materials, HVAC systems, schedules, occupant behavior, and weather data for the required location to simulate annual building performance. The actual annual energy consumption for the building is given to be 223922 kWh, while the simulated value stood at 210065.6 kWh, resulting in a difference of 6.2%, which lies in the acceptable range of error for building energy simulation models (Xu et al., 2017).

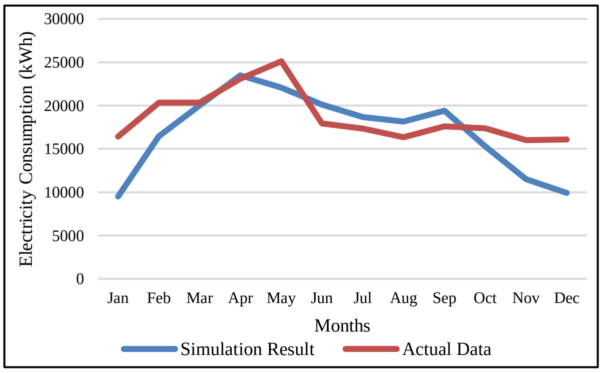


Figure 4: A graphical comparison of monthly total energy consumption between simulated and actual data

Figure 5 below provides a graphical representation of the monthly comparison between simulated and actual energy consumption (kWh). Furthermore, discomfort hours are also calculated by DesignBuilder, in compliance with ASHRAE guidelines, by running detailed energy simulations. The software considers various factors such as indoor temperatures, humidity, airspeed, and other environmental conditions over a year. It uses this data to quantify the duration of time when indoor environmental conditions deviate from the ASHRAE-defined comfort range. Annual discomfort hours of the building are determined to be 1048.46 hours out of 8760 hours annually after the model validation.

Optimization Configuration

Furthermore, the validated model of the building is again simulated for annual energy performance and thermal comfort with initial glazing configuration and WWR for all the representative cities. To find the best design options in each climate zone, the optimization is carried out in the next step considering design variables, glazing configuration, and WWR. Glazing options are provided in Table 4.

Table 4: Glazing types involved in parametric analysis

Glazing options	SHGC	U-value (W/m^{2}K)
Glazing 1	0.24	1.6
Glazing 2	0.53	1.8
Glazing 3	0.34	1.8
Glazing 4	0.3	3.7
Glazing 5	0.14	3.6
Glazing 6	0.41	4.8
Glazing 7	0.47	5.7
Glazing 8	0.69	5.7
Glazing 9	0.49	5.8
Glazing 10	0.58	5.70
Glazing 11	0.42	4.60
Glazing 12	0.34	4.00
Glazing 13	0.45	5.30
Glazing 14	0.33	5.00
Glazing 15	0.44	5.80
Glazing 16	0.38	1.70
Glazing 17	0.59	5.40
Glazing 18	0.29	1.70
Glazing 19	0.21	1.70
Glazing 20	0.38	5.70

For WWR, the range is set from a maximum of 80% to a minimum of 20%, with steps of 5% increments. This means that WWR values are considered at 80%, 85%, 70%, 75%, and so on, down to 20%. The in-built module “Optimization” of DesignBuilder is utilized for conducting multi-objective optimization in this study. Further, objective functions, which quantify the goal as minimizing energy consumption and minimizing discomfort hours, are defined. The optimization process involves an advanced evolutionary algorithm, NSGA- II (Non-dominated Sorting Genetic Algorithm II). As depicted in Table 5, a Simulated Binary Crossover (SBX) with a crossover probability of 0.9 and a mutation probability of 0.1 is used in the optimization process, which includes a population size of 100 individuals. Selection is done using a Binary tournament, and optimization is carried out for a 1000-generation termination criterion to reach optimal design solutions. Finally, NSGA II finds a set of Pareto-optimal solutions in a Pareto front (where no solution is better than the other), which represent trade-offs between conflicting objectives, energy consumption, and discomfort hours (Singh Rajput and Thomas, 2023).

Table 5: NSGA II parameters

Parameter	Value
Population size	100
Crossover Type	Simulated Binary Crossover
Mutation probability	0.1
Crossover probability	0.9
Selection process	Binary Tournament
Termination criterion	1000 generations

Results

Baseline configuration simulation results

Table 6: Baseline configuration simulation details

City	Electricity Consumption (kWh)	Discomfort Hours (hours)
Aurangabad	166638.50	828.55
Bengaluru	142195.60	1181.64
Bhubaneshwar	210194.40	1012.73
Lucknow	184967.80	1033.54
Srinagar	117669.62	1346.13

Table 6 showcases the simulation outcomes for the annual energy performance and thermal comfort, considering the initial glazing configuration and WWR for the representative cities across the five climate zones in India. In the base case simulation results, Bhubaneshwar has electricity and discomfort hours similar to Mumbai's. It could be attributed to the fact that they both belong to warm and humid climates. Bhubaneshwar also has the highest electricity consumption and discomfort hours, followed by Lucknow, which has a composite climate. Srinagar is last, followed by Bengaluru, which has a temperate climate.

Optimization Result

The optimization analysis aimed at minimizing the annual electricity consumption (in kWh) and minimizing the annual discomfort hours (in hours) involving design variables, WWR, and various glazing options, for each representative city, led to a specific number of iterations to find optimal solutions as detailed in Table 7.

Table 7: Number of iterations and optimal solutions of each representative city

City	Iterations	Number of Optimal Solutions
Aurangabad	196	19
Bengaluru	242	62
Bhubaneshwar	200	30
Lucknow	213	32
Srinagar	242	54

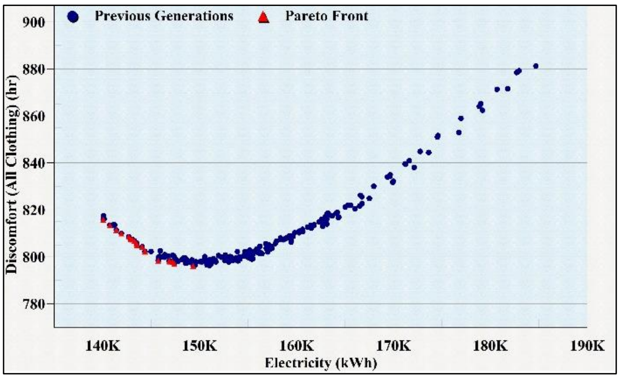


Figure 5: Pareto graph result of Aurangabad

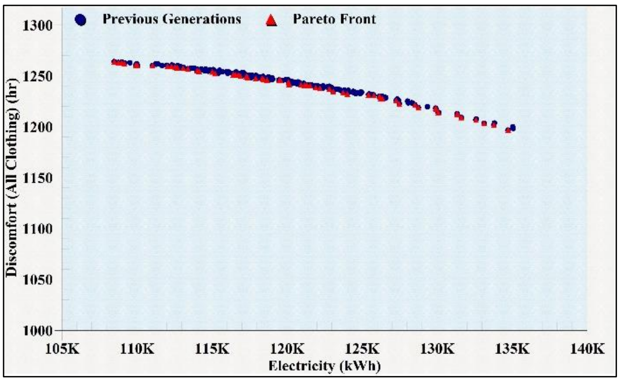


Figure 6: Pareto graph result of Bengaluru

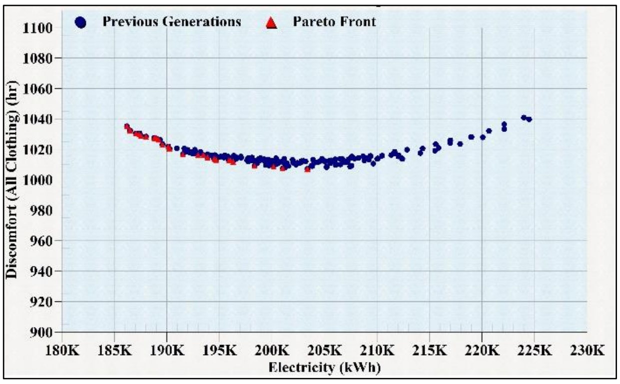


Figure 7: Pareto graph of Bhubaneshwar

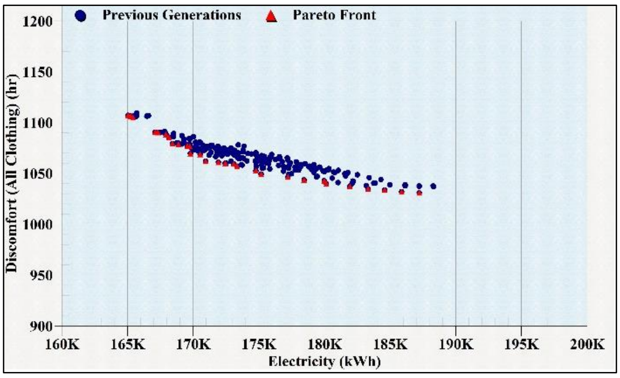


Figure 8: Pareto graph of Lucknow

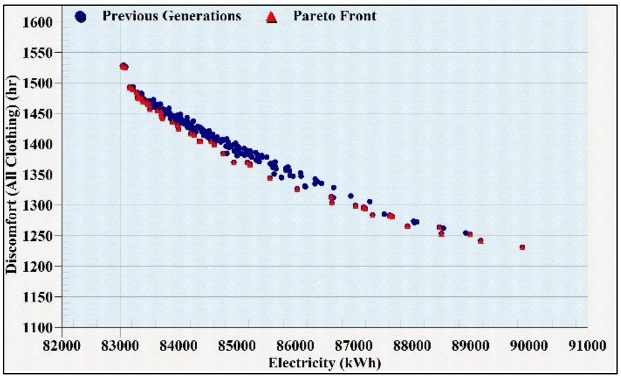


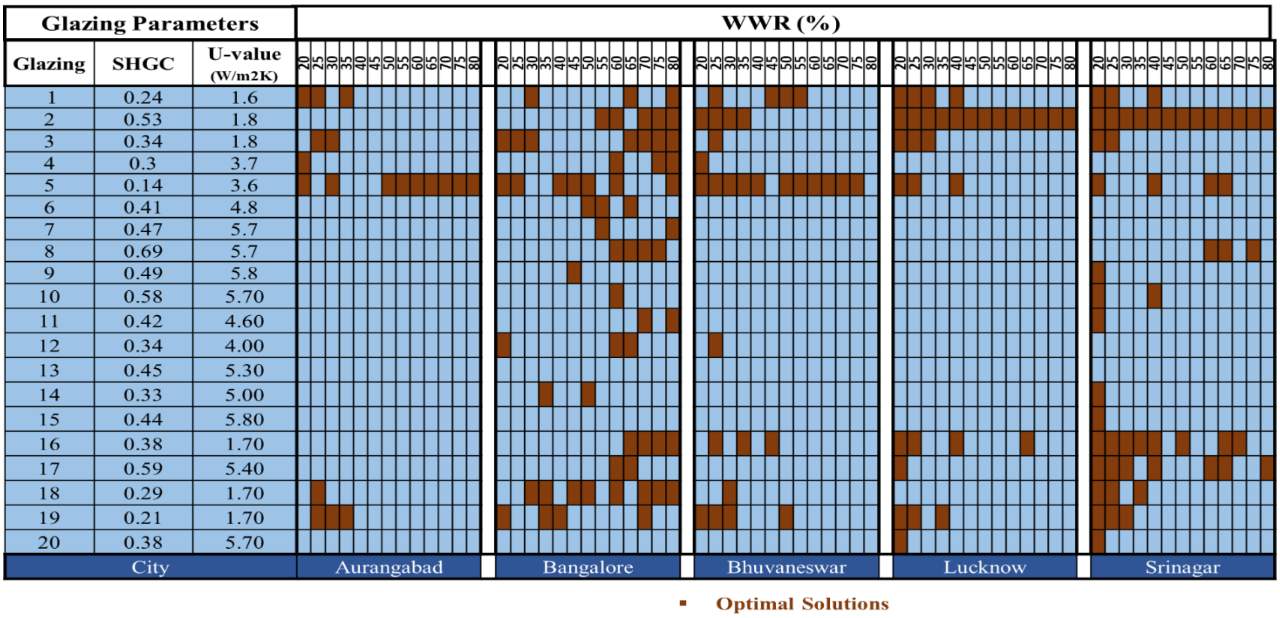
Figure 9: Pareto graph of Srinagar

The Pareto-front graph of the optimization analysis of each city is presented in Figure 5, Figure 6, Figure 7, Figure 8, and Figure 9. The optimization results illustrated a trade-off relationship between electricity consumption and discomfort hours. The electricity consumption and discomfort hours of optimal solutions of each city are compared with the values of the respective city baseline configuration which is equipped single clear glass of 6 mm and 30 % WWR. Aurangabad demonstrated a 10% to 16% reduction in electricity consumption and a 4% reduction in discomfort hours. However, for Bengaluru, this reduction ranged from 5 to 24%, while discomfort hours showed no potential for improvement. In Bhubaneshwar, optimal solutions lead to a 3 to 11% reduction in electricity consumption and a minimal change in discomfort hours. Lucknow, on the other hand, experienced a decrease in electricity consumption by up to 11% and also showed negligible potential for improvement in discomfort hours. Srinagar displayed up to 30% reduction in electricity consumption and up to 8% decrease in discomfort hours. Overall, the results indicated significant improvements in some cities, while others showed minimal enhancements compared to the baseline scenario. Comparable to outcomes of research conducted in Dubai on a two-story building, wherein double glazing resulted in a 9.3% reduction in energy consumption, the results of Aurangabad's (hot and dry climate) energy saving resonate closely (Abdeen et al., 2024).

The optimum solutions with minimum electricity consumption and minimum discomfort hours for each city are illustrated as a decision matrix in Figure 10. Along the top horizontal axis, WWR ranges from 20 to 80 with increments of 5. On the bottom x-axis, cities representing distinct climate zones are listed. The y-axis denotes glazing types numbered from 1 to 20. In this matrix, each block represents possible glazing configurations with different glazing types and WWR. Notably, blocks highlighted in brown signify the optimal configuration of glazing type and WWR for each respective city. These configurations strike a balance between reducing electricity usage and minimizing discomfort hours, tailored to the specific climatic conditions of each location. In Aurangabad, which represents a hot and dry climate, optimal configurations commonly included Glazing 5, 19, and 1. WWR for Glazing 5, which has the lowest SHGC, ranged from 20% to 80%, and for Glazing 1 and Glazing 19 ranged from 20% to 35%. with WWR ranging from 20% to 40%. Bengaluru, representing a temperate climate, tended to favor Glazing 18, Glazing 5, and Glazing 3, with recommended WWR falling between 20% to 80%. Bhubaneshwar, representing a warm and humid climate, showed optimal solutions with Glazing 5 and WWR varying from 20% to 75%. Lucknow, representing a composite climate, tended to benefit from Glazing 2 over all the WWR and from Glazing 1, and Glazing 16, with WWR between 20% to 40%. In Srinagar, representing a cold climate, optimal configurations include Glazing 2 for Glazing 16, and Glazing 17, with WWR ranging from 20% to 80%.

Discussion

The results suggested specific recommendations for different climatic zones regarding the selection of glazing properties. In hot and dry climates, and warm and humid climates, glazing with lower SHGC values and moderate U-values to minimize solar heat gain. Composite climates are recommended to have a mix of U-values and SHGC values when choosing glazing, demonstrating the need for a balanced approach in composite climates. In cold climates, the glazing options with lower U-value and relatively higher SHGC are found to be suitable. This is



Glazing Parameters			WWR (%)												
Glazing	SHGC	U-value (W/m2K)	20	25	30	35	40	45	50	55	60	65	70	75	80
1	0.24	1.6	■	■		■									
2	0.53	1.8													
3	0.34	1.8		■	■										
4	0.3	3.7	■												
5	0.14	3.6	■		■				■	■	■	■	■	■	■
6	0.41	4.8													
7	0.47	5.7													
8	0.69	5.7													
9	0.49	5.8													
10	0.58	5.70													
11	0.42	4.60													
12	0.34	4.00													
13	0.45	5.30													
14	0.33	5.00													
15	0.44	5.80													
16	0.38	1.70													
17	0.59	5.40													
18	0.29	1.70		■											
19	0.21	1.70		■	■	■									
20	0.38	5.70													
City			Aurangabad												

Glazing Parameters			WWR (%)												
Glazing	SHGC	U-value (W/m2K)	20	25	30	35	40	45	50	55	60	65	70	75	80
1	0.24	1.6			■							■			■
2	0.53	1.8								■	■		■	■	■
3	0.34	1.8	■	■	■							■	■	■	■
4	0.3	3.7									■			■	■
5	0.14	3.6	■	■			■	■	■		■				■
6	0.41	4.8							■	■		■			
7	0.47	5.7								■					■
8	0.69	5.7									■	■	■	■	
9	0.49	5.8						■							
10	0.58	5.70									■				
11	0.42	4.60											■		■
12	0.34	4.00	■								■	■			
13	0.45	5.30													
14	0.33	5.00				■			■						
15	0.44	5.80													
16	0.38	1.70										■	■	■	■
17	0.59	5.40									■	■			
18	0.29	1.70			■	■		■	■		■		■	■	■
19	0.21	1.70	■			■	■						■		
20	0.38	5.70													
City			Bangalore												

Glazing Parameters			WWR (%)												
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City			Bhuvaneswar												

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15	0.44	5.80	■												
16	0.38	1.70	■	■	■	■	■		■			■	■		
17	0.59	5.40	■	■	■		■				■	■			■
18	0.29	1.70	■	■		■									
19	0.21	1.70	■	■	■										
20	0.38	5.70	■												
City			Srinagar												

■ **Optimal Solutions**

Figure 10: Decision Matrix of glazing solutions for minimum electricity consumption and maximum thermal comfort

because the total heat gain through the glazing of the building is given by relative heat gain (RHG), which combined accounts for both conductive and radiative heat transfer. Conductive heat transfer depends on the temperature difference between the building's interior and the outside environment and is influenced by the U-value. Radiative heat transfer is related to the amount of solar radiation entering the building and is influenced by the SHGC of glass. In tropical climates where temperature differences are minimal, conductive heat transfer plays a minor role, making SHGC more critical than U-value. Conversely, in colder and temperate climates such as Srinagar and Bengaluru, the U-value of glazing options becomes a more critical factor in reducing heat loss. The results also recommend relatively higher SHGC for cold climates so as to facilitate passive heating. The decision matrix derived through the optimization analysis can serve as a valuable guideline for updating building codes, standards, and sustainability regulations. By promoting the adoption of energy-efficient building envelopes tailored to local climatic conditions, policymakers can support the transition towards more sustainable and resilient built environments.

Conclusions

This study aimed to establish a simulation-based framework, SIMEC-Opt for optimizing glazing parameters in Indian residential buildings, employing a validated model of a residential building across diverse climate zones in India. By performing optimization analysis in the study, glazing configuration and WWR as design variables, the best solutions were identified, revealing the potential for significant improvements in both energy efficiency and thermal comfort. Across representative cities in different climate zones, the study demonstrated reductions in electricity consumption ranging from 3% to 30%, coupled with improvements in discomfort hours of up to 8%. Discomfort hours showed minimal variation across a few climate zones, suggesting that factors such as air velocity, ventilation, and occupant preferences may be more influential in analyzing thermal comfort.

The SIMEC-Opt framework represents a significant advancement in the field of building optimization, particularly concerning the selection of glazing parameters to enhance energy efficiency and thermal comfort in residential buildings. Through its simulation-based approach and multi-objective optimization algorithm, SIMEC-Opt offers a systematic and comprehensive methodology for identifying optimal glazing configurations tailored to specific climate zones. By considering a wide range of glazing options and window-to-wall ratios, SIMEC-Opt enables architects, builders, and policymakers to make informed decisions that maximize energy savings while ensuring occupant comfort across diverse environmental conditions. The framework's novel features, including its focus on Indian residential buildings and its consideration of multiple performance metrics, contribute to its effectiveness and relevance in addressing the pressing challenges of sustainable building design and construction.

While the study takes into account the diverse climate zones within India, it's important to note that building characteristics, energy consumption patterns, and occupant behavior also exhibit variability across different regions. The study's findings may be specific to certain typologies of residential buildings reducing the generalizability of results. Factors such as cost, government policies, local building laws, and technological feasibility may also influence the practicality of adopting the recommended solutions. The optimization framework primarily focused on glazing configurations and window-to-wall ratios, neglecting other critical building components such as walls and roofs. Though the narrow focus of the study confined to glazing allowed for a detailed examination of the unique characteristics and effects of glazing on building performance, integrating the wall and roof materials into the analysis can provide a more holistic understanding of building performance. While the study focused on representative cities across different climate zones in India, the underlying principles and optimization approach are transferable to similar climatic regions worldwide. As such, the recommendations can inform building design and retrofitting projects in various geographical contexts, contributing to global efforts to mitigate climate change and reduce energy consumption in the built environment.

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