Optimizing Building Envelope Features: Towards Climate Responsive Energy Efficient Buildings in Hot Climates

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Optimizing Building Envelope Features: Towards Climate Responsive Energy Efficient Buildings in Hot Climates

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Abstract: *The building envelope plays a crucial role in a building's energy performance through its interaction with external and internal environment. This study examines the impact of various building envelope features on the energy efficiency of residential buildings in hot climates. Utilizing an empirically validated simulation model and a multi-objective optimization algorithm, the study assesses the effect of variations in envelope features, such as geometry and thermal properties, on its thermal performance. The multi-objective optimization aims to minimize cooling loads and discomfort hours. The study employs three different weather files representing various locations within the same hot climate context. The results underscore the significant influence of envelope parameters, demonstrating that optimization can reduce cooling loads by up to 22% compared to base case scenario. Among, 5900 tested cases, this study provides valuable insights into optimum solutions to improve energy efficiency in residential buildings through targeted enhancements in envelope design, ultimately contributing to more sustainable and comfortable living environments.*

Keywords: Cooling loads; thermal comfort; Hot temperature; Energy modeling; Residential buildings.

1. INTRODUCTION

Rapid urbanization, coupled with climate change and the global energy crisis, poses significant challenges to the construction industry. The building sector consumes about 35% of total energy consumption as reported by UN Environment Programme (UNEP) [1]. The residential buildings contribute toa significant portion of this consumption ranging from 50% to 70% depending on the country [2]. Increased energy consumption from traditional sources is widely recognized as a major contributor to CO2 emissions, exacerbating climate change and hindering the attainment of Sustainable Development Goals (SDGs) [3]. In this regard, enhancing the energy efficiency of residential buildings holds substantial potential to address these challenges.

Among various control and design strategies to improve the energy efficiency and occupant comfort in buildings, the building envelope plays a pivotal role [4]. It governs how buildings manage heat exchange between external and internal environments and regulates the amount of sunlight and heat entering the building [5]. Studies have shown that optimizing the building envelope can enhance the energy efficiency of buildings by heat gain reduction of up to 75% [6, 7]. In addition to its potential economic benefit by 18–14 % in life cycle cost reduction as reported by Zahra Benaddi, et al. [8].

Previous research on building envelope optimization incorporates various design control strategies. On the one hand, Koyun, et al. [9] evaluated the optimal configuration between opaque and transparent parts of the building to enhance envelope thermal performance. Similarly, Karimi, et al. [10] demonstrated that improper selection of window-to-wall ratio (WWR) across different facade orientations can increase energy consumption by up to 29%. Additionally, Talaei and Sangin [11] found out that optimizing shading systems alongside WWR could reduce Energy Use Intensity (EUI) by 25%. Shaeri, et al. [12] focused exclusively on WWR adjustments, analyzing their impact on annual solar heat gain, cooling load, heating load, and lighting consumption. Their findings revealed that WWR adjustments can effectively manage 16–25% of the tested building's energy load.

On the other hand, other studies examine enhancement of envelopes by controlling the thermal properties of wall structures and roofs [13, 14]. Numerous studies also focus on enhancing thermal behavior through the integration of advanced materials or technologies such as nanotechnologies, green wall facades, and Phase Change Materials (PCMs) [15, 16]. For instance, a study by Jaradat, et al. [17] demonstrated that incorporating PCMs into external building walls in residential buildings could save up to 5476.14 kWh annually, resulting in significant cost reductions and reduced greenhouse gas emissions. Kulumkanov, et al. [18] confirmed the potential annual energy reduction of up to 12%, arguing that PCM integration is a sustainable solution for building energy efficiency. Despite their proven high efficiency, their applicability is still limited due to their high costs, especially for developing countries [19].

From the findings of previous studies, despite the increased interest in studying building envelopes, their comprehensive optimization and adaptive design concerning building orientations remain limited. Previous studies lack proper justification of how climate impact and orientation parameters can affect the design of envelopes. In this respect, this study aims to comprehensively optimize different building envelope design features, either in terms of geometry or thermal properties of envelope materials. It aims to achieve low-cost modifications using nationally employed building blocks and preliminary design adjustments.

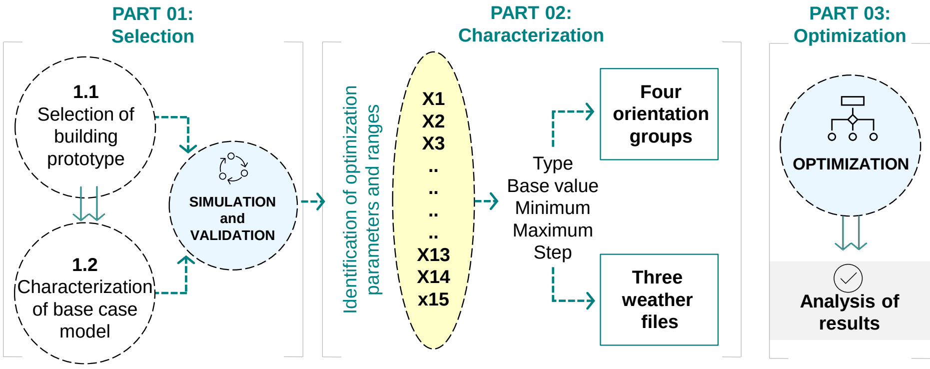

Fig. 1. research methodology.

2. MATERIALS AND METHODS

The research is structured into three phases: selection, characterization, and optimization as shown in Fig. 1. In phase one, the building prototype predominantly used in the study context is selected and characterized as the base case for simulation. This establishes a reference validated model for subsequent analysis. Phase Two focuses on the identification and characterization of key envelope parameters. Each parameter is identified according to its base case conditions, classified as either continuous or discrete variables, and assigned minimum and maximum ranges. This phase also defines the optimization steps that the algorithm follows to develop various scenarios, setting up the framework for exploring different configurations of the building envelope parameters. Phase three involves multi-objective optimization to reduce cooling load and discomfort hours by adjusting the identified parameters. The results are analyzed to determine the optimum configurations for energy efficiency and occupant comfort. By following this structured methodology, the research aims to systematically select, characterize, and optimize building envelope characters to improve energy efficiency and occupant comfort in the addressed context.

2.1 Description of the case study area

The study is conducted within the national context of Egypt, characterized by a hot-desert climate according to the Köppen climate classification. The selected building prototype is representative of the majority of residential buildings in Egypt [20, 21]. A typical residential building, consisting of four apartments per floor and five stories in height, has been chosen for testing. This prototype is prevalent across various Egyptian cities, including Alexandria, Cairo, and Aswan, with different orientations as depicted in Fig. 2.

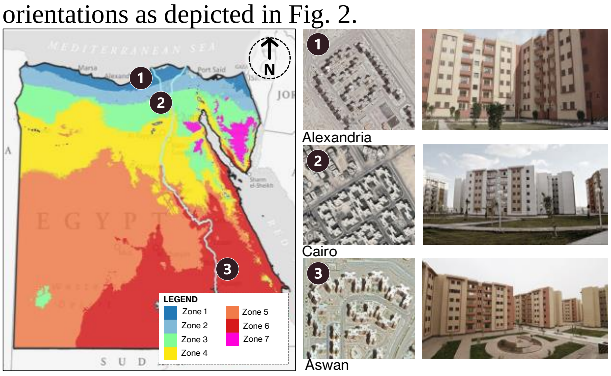

Fig. 2: map showing climate zones of Egypt and three locations selected for the study.

To ensure the study encompasses a range of climatic conditions, Alexandria, Cairo, and Aswan were selected, as they fall into distinct climate zones according to a study conducted by Hamed, et al. [22]. These cities exhibit variations in temperature profiles throughout the year, as shown in Fig. 3. Despite these climatic differences, the same building prototype, with identical envelope characteristics and construction specifications but different orientations, is employed across all locations.

The selection of Alexandria, Cairo, and Aswan as study areas is justified by their representation of Egypt's diverse climatic conditions. Alexandria, located on the Mediterranean coast, experiences a milder climate with significant seasonal variation. Cairo, situated in the middle of Nile delta, represents a more arid climate with higher temperature extremes. Aswan, in the southern part of the country, is characterized by extremely high temperatures and minimal precipitation. This diversity in climate zones allows for a comprehensive analysis of how different environmental conditions impact the energy performance and cooling load of residential buildings.[23].

The study utilizes an optimization algorithm to examine variations in optimal solutions across Alexandria, Cairo, and Aswan, each in four different orientations as shown in Fig. 4. Using the same building prototype with only orientation variations provides a controlled comparison. This approach helps identify optimal design strategies to enhance energy efficiency and reduce cooling loads in different climatic contexts. The investigation aims to understand how different orientations and temperature profiles influence the optimal envelope configurations to achieve these goals in diverse locations.

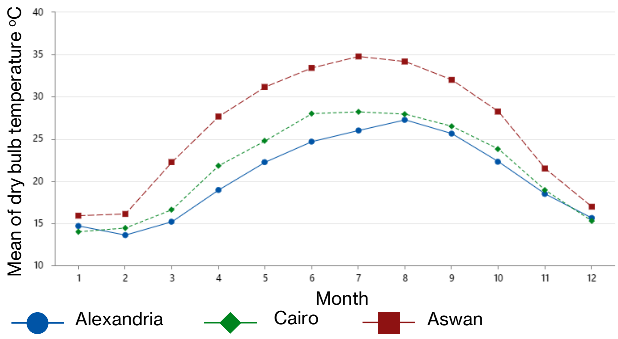

Fig. 3: variations in mean air temperature in the three cities.

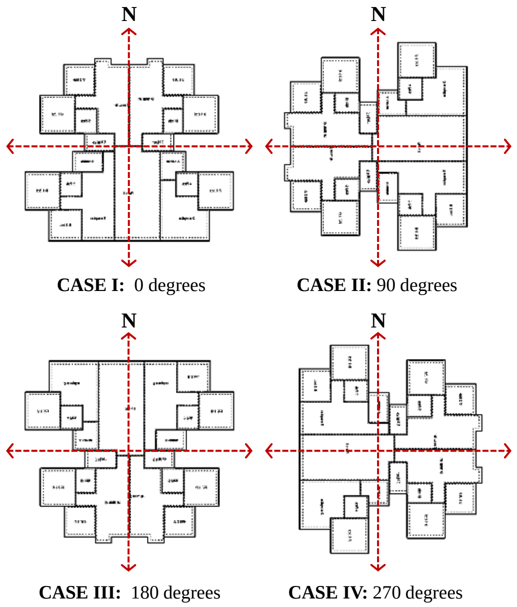

Fig. 4: orientation groups tested in the study.

2.2 Identification of optimization parameters

The study comprehensively addressed a set of 15 variables associated with building envelope characteristics, divided into two groups. The first group includes parameters related to thermal performance, such as external wall construction, roof thermal transmittance, and glazing type. The second group encompasses geometric parameters, including window-to-wall ratio (WWR) and local shading types. These parameters were optimized across four orientation groups and three selected locations to define the optimal solution for each case.

2.2.1 Thermal performance parameters

The thermal performance of external wall structures significantly impacts a building's energy demand. Enhancing thermal transmittance can improve efficiency by up to 66% [24]. According to the Egyptian Residential Energy Code (EREC), residential buildings in Egypt commonly use common bricks or cement concrete blocks for external wall constructions [25]. Given that residential buildings consume up to 40% of the total energy in Egypt as reported by national authorities, improving the thermal performance of external walls could substantially reduce energy consumption.

This study performs an optimization analysis on the two commonly used wall types. Additionally, it proposes using the same construction blocks but with an added air cavity to reduce the amount of heat entering interior spaces as provided in Fig. 5 and Table 1. Furthermore, the study performs optimization for four facades distinctly to understand the impact of different orientations on energy efficiency.

Table 1:types of tested external wall construction.

Type	Description	Thickness *mm*	U-value W/m^2K
A	Common brick	292	1.71
B	Common brick with air gap	432	1.34
C	Cement concrete block	292	1.47
D	Cement concrete block with air gap	432	0.78

Roof structures also contribute significantly to heat transfer into buildings [7]. Therefore, in addition to optimizing external wall thermal properties, the study examines three different U-values for thermal transmittance of flat roof construction: 0.94, 0.63, and 0.45 W/m²K. Additionally, the study tests the performance of single 6mm blue glazing, the base case, in comparison with 6mm blue double glazing.

Comprehensively testing external walls, flat roofs, and external glazing provides useful insights for enhancing the thermal performance of building envelopes.

2.2.2 Geometry related parameters

The window-to-wall ratio (WWR) refers to the proportion of a building's window area relative to its total wall area. WWR significantly affects building energy use and occupant comfort by influencing the amount of heat and daylight entering the building [26]. The sun's movement impacts this ratio across different façade orientations [27]. Therefore, the study optimizes WWR for the four main orientations North, East, South, and West to determine the optimum ratio for each façade distinctly.

Additionally, the study tests seven different local shading options. These options range from louvers to window overhangs, with variations in projections and louver designs evaluated to determine the optimum local shading for each of the four orientations. A detailed description of the tested shading types is provided in Table 2. Description of all parameters included in the optimization is provided in Table 3 and 4.

Table 2: description of tested local shading types.

Type	Description	Type	Description
LS-1	0.5 m PC overhang	*LS-5*	0.5 m Louvre
LS-2	1 m PC overhang	*LS-6*	1 m Louvre
LS-3	1.5 m PC overhang	*LS-7*	1.5 m Louvre
LS-4	2 m PC overhang		

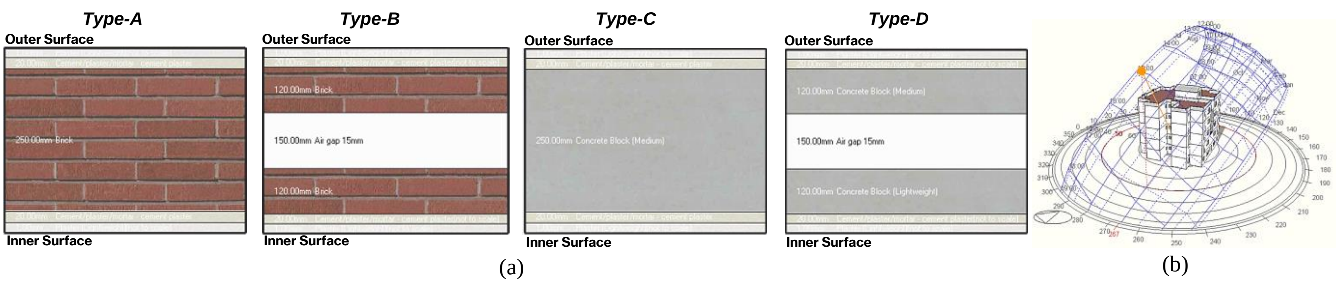

Fig. 5: (a) structural layers of tested external wall types, (b) sun path in relation to tested building.

Table 3: description of *continuous* variables and their ranges.

Parameter	Description	Base	Range	Step
X1	North WWR	35 %	10-80%	5
X2	West WWR	10%	10-80%	5
X3	South WWR	45%	10-80%	5
X4	East WWR	10%	10-80%	5
X5	Cooling setpoint temperature	22 ºC	21-24 ºC	1

Table 4: description of *categorial* variables and their options.

Parameter	Description	Base	Options
X6	North shading	none	7 options
X7	West shading		
X8	South shading		
X9	East shading		
X10	North U-value	1.71	4 options
X11	West U-value		
X12	South U-value		
X13	East U-value		
X14	Roof construction	0.49	3 options
X15	External window glazing	-	2 options

2.3 Model simulation and validation

To simulate the energy loads of the selected building, EnergyPlus is employed using DesignBuilder software. The prototype building, with a total area of 1261 m², is modeled with internal partitioning walls and assigned occupancy activities for each space, as shown in Fig. 6. Using empirical validation as recommended by ASHRAE Guideline 14–2014, the simulation model was validated against data collected through field experiment [28]. The results show error ranges from 0.3% to a maximum of 3%, confirming an acceptable level of accuracy for the simulation results as provided in Table 5. This high level of accuracy ensures that the model reliably represents real-world conditions, making it a robust tool for further analysis. Following this, NGSA-II optimization algorithm is used to perform multi-objective optimization analysis on the previously defined 15 envelope parameters.

3. RESULTS AND DISCUSSION

Results of the multi-objective optimization aiming at lowering cooling load and discomfort hours reveal notable variations across the three cities under study: Aswan, Cairo, and Alexandria. Aswan regularly exhibits the highest cooling energy use followed by Cairo and then Alexandria. This trend is attributed to Aswan's higher temperatures, which require more energy to achieve indoor thermal comfort.

Fig. 6: 3D plan view showing occupation activities of building zones.

Table 5: validation of simulated data using experimental measurements.

Parameter	Mean Measured ºC	Mean simulated ºC	Percentage of error %
*Ts, out**	30.2	30.4	0.2
*Ts, in**	28.1	27.9	0.6
*Tair, out**	29.1	28.9	0.3
*Tair, in**	29.2	28.7	0.9
*MRT**	28.7	27.3	3.0

**Ts, out: External Wall Surface Temperature; Ts, in: Internal Wall Surface Temperature; Tair, out: External air Temperature; Tair, in: Internal air Temperature; MRT: Room Mean Radiant Temperature.*

The scatter plots and regression fit lines for each city show distinct patterns as shown in Fig. 7. Aswan and Cairo show horizontal expansion in their scatter plots, indicating that achieving slight reductions in discomfort hours requires considerable increases in energy consumption. In contrast, Alexandria's results show vertical expansion, indicating that higher levels of comfort can be attained with comparatively lower energy loads.

Furthermore, Alexandria consumes around 50% less cooling load than Aswan to achieve nearly the same amount of discomfort hours. These findings underscore the need for tailored envelope design guidelines aimed at enhancing energy efficiency in each specific context. National building codes are therefore recommended provide detailed descriptions of optimal designs tailored to different climate zones, ensuring buildings are designed to maximize energy efficiency while meeting comfort requirements dictated by local climates.

The following sections of the study will explore optimal envelope configurations for thermal and geometric parameters to better explain these results.

3.1 Thermal parameter optimization results

The results reveal that the thermal transmittance of external walls varies according to building orientation, with optimal solutions exhibiting different U-values for external walls. Indicating that it could be more efficient to employ different U-values for each façade within a single building. For instance, the optimized solutions showed that the south-facing façades had the lowest

levels of thermal transmittance. This indicates that achieving the same thermal comfort and cooling load requirements for south-facing areas as for the more favorable north and east directions can be accomplished by optimizing thermal transmittance as shown in the parallel coordinates plot in Fig.10.
Furthermore, the two wall types, C and D, which employ an air cavity within traditional block types, demonstrated enhanced performance, achieving up to a 20% reduction in cooling load. This proves that air cavities into wall construction can significantly improve energy efficiency. This solution acts as an additional thermal barrier, reducing heat transfer and enhancing the overall thermal performance of the building envelope.
In terms of glazing type, the use of double glazing significantly improved the performance of the building envelope. Among the 264 optimal scenarios examined, 150 scenarios indicated that double glazing provided better performance, as illustrated in the scatter plot in Fig. 8. These findings support the implementation of double glazing as a standard practice for enhancing building efficiency.

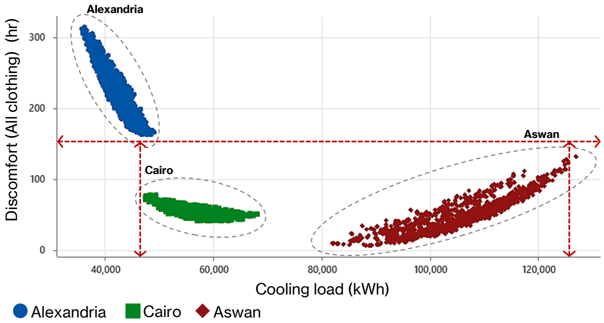

Fig. 7. scatter plot showing multi-objective optimization results across three selected cities.

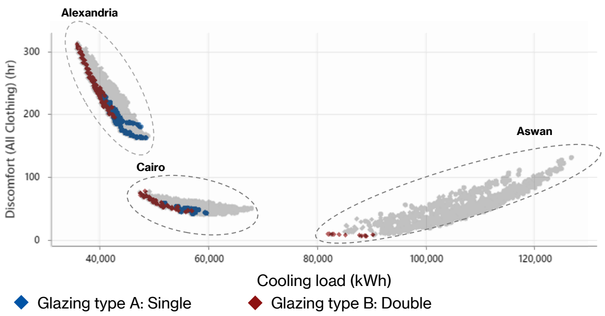

Fig. 8. scatter plot showing distribution of optimum solution employing single and double glazing across three tested cities.

3.2 Geometry parameters optimization results

Optimization of envelope geometry-related parameters shows that variations in WWR across the four main façades provide notable enhancements to cooling loads. The three cities tested, as mentioned earlier, exhibit different climatic contexts. The results also show different patterns in this respect, as illustrated in Fig. 9. For instance, Alexandria and Cairo show relatively similar patterns of WWR variations across the four façades. Alexandria exhibited the highest percentage of North-facing WWR, while Cairo had the largest ratio on the West façade.
Aswan, on the other hand, displayed a different behavior, with the West façade reporting the lowest WWR among the three tested areas. This difference can be attributed to Aswan's proximity to the equator compared to the other cities, which impacts the movement of the sun and, consequently, increases the amount of daylight and heat entering the spaces. The lower WWR on the South façade helps to mitigate excessive solar gain, reducing the cooling load. Furthermore, Aswan's unique climatic conditions require distinct design strategies to ensure thermal comfort and energy efficiency. Fig. 10 presents patterns of WWR across the tested orientations to help understand the effect of altering WWR on overall cooling load and thermal discomfort. These patterns highlight the importance of façade-specific design optimizations in improving building performance. By tailoring the WWR to each façade's orientation and climatic conditions, it is possible to achieve significant energy savings and enhance occupant comfort. In terms of local shading, Table 6 provides a comparison between optimal scenarios achieving minimum cooling load across the three tested areas in the four assessed orientations, denoting the optimal design of local shading in each case for each façade.

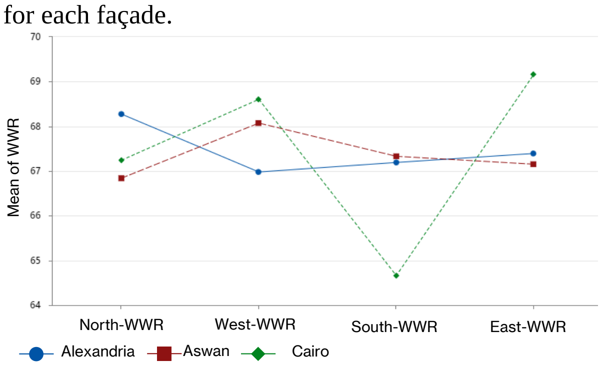

Fig. 9. variations in U-value across four facades to achieve optimum design.

Table 6: optimum design for local shading across four facades in three tested contexts.

Location	Min. load (kWh)	Discomfort hours	Building rotation	Optimum design of shading			
				NORTH	WEST	SOUTH	EAST
Alexandria	35829	307	CASE I: 0 degrees	*LS-2*	*LS-7*	*LS-2*	*LS-1*
Cairo	48216	77		*LS-7*	*LS-1*	*LS-6*	*LS-1*
Aswan	82054	20		*LS-2*	*LS-7*	*LS-2*	*LS-1*
Alexandria	38446	254	CASE II: 90 degrees	*LS-6*	*LS-7*	*LS-1*	*LS-7*
Cairo	51120	55		*LS-5*	*LS-2*	*LS-1*	*LS-1*
Aswan	88636	12		*LS-6*	*LS-7*	*LS-1*	*LS-7*
Alexandria	36397	296	CASE III: 180 degrees	*LS-5*	*LS-3*	*LS-4*	*LS-6*
Cairo	47345	47		*LS-2*	*LS-3*	*LS-2*	*LS-2*
Aswan	81883	10		*LS-5*	*LS-4*	*LS-6*	*LS-3*
Alexandria	38253	254	CASE IV: 270 degrees	*LS-3*	*LS-1*	*LS-5*	*LS-7*
Cairo	51677	54		*LS-3*	*LS-7*	*LS-2*	*LS-3*
Aswan	90120	9		*LS-1*	*LS-3*	*LS-2*	*LS-2*

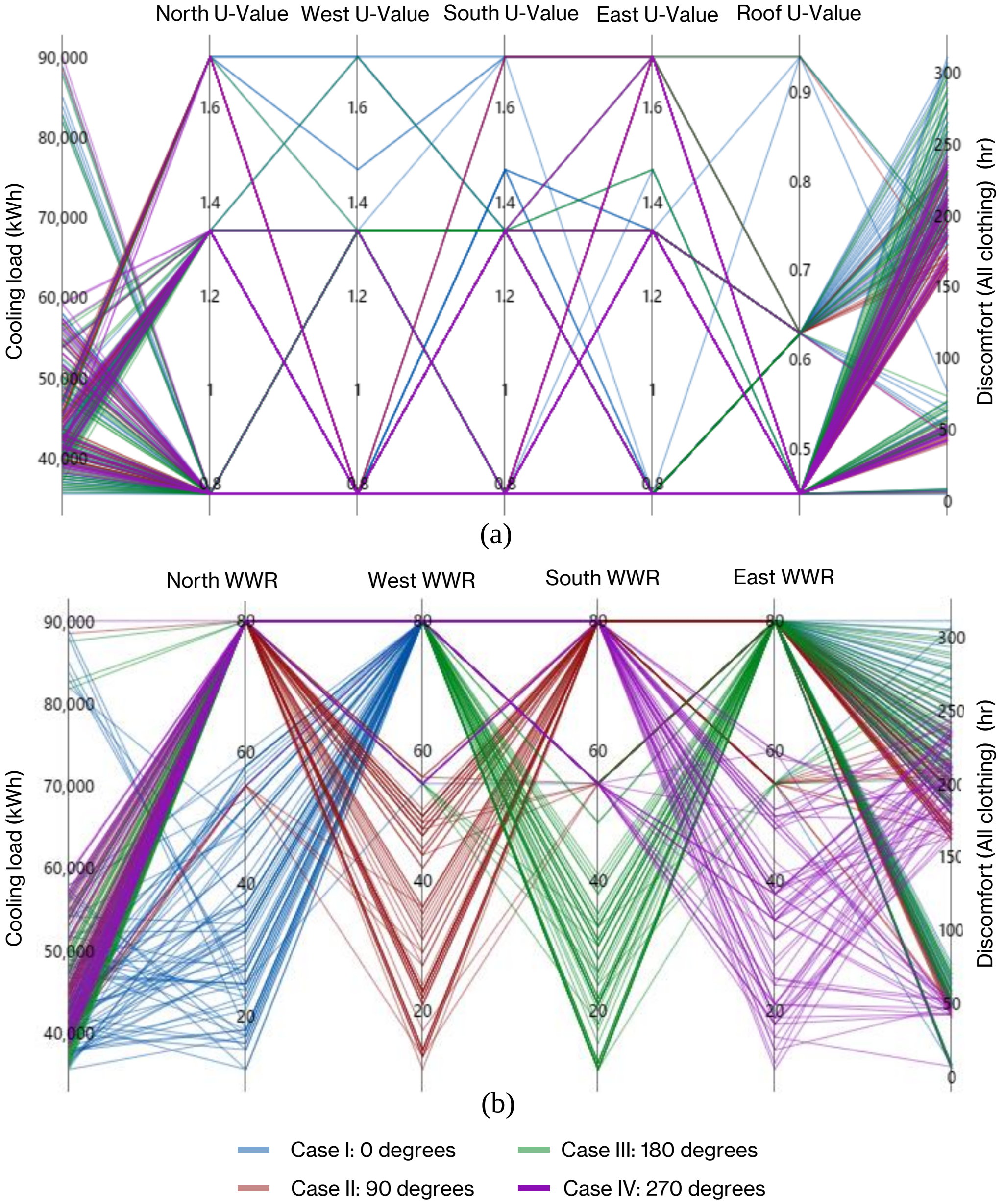

Fig. 10: parallel coordinates plot showing (a) variation of U-value across facades, and (b) optimum configuration of WWR both in relation to discomfort and cooling loads.

4. CONCLUSION AND FUTURE WORK

This research emphasizes the role of building envelope design in improving energy efficiency for buildings, in hot climates. Using a validated simulation model and a multi objective optimization algorithm the study shows that targeted improvements in envelope features like properties and geometric layouts can effectively lower cooling demands and enhance thermal comfort. The study's key findings indicate that optimized envelope designs can lead to significant reductions in cooling loads. It also highlights differences in solutions among three different hot climate locations of Aswan, Cairo and Alexandria. Aswan, known for its temperatures exhibited the highest cooling energy consumption compared to Cairo and Alexandria.

Optimal thermal transmittance values varied based on building orientation suggesting the advantages of using U-values for each facade. Additionally incorporating air cavities in wall structures and utilizing double glazing were identified as methods to improve performance and achieve up to a 20% decrease in cooling loads.

The results of optimization demonstrated that variations in WWR across facades had a significant impact on cooling loads.

The study revealed distinct patterns for each city, emphasizing the importance of façade-specific design optimizations for each specific context distinctly.

Overall, the study underscores the necessity of tailored envelope design guidelines in national building codes to address specific climatic contexts. By adopting these optimized strategies, buildings can achieve higher energy efficiency and enhanced occupant comfort, to achieve more sustainable performance of buildings.

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