Aswan University Journal of Science and Technology Volume 5, issue 2, June 2025

Multi-Objective Optimization of Building Envelopes in Hot Arid Climates: A Pareto Front Analysis Approach

Nada Tarek, Asmaa Omar, and Ayman Ragab*

Department of Architecture, Faculty of Engineering, Aswan University, Aswan, Egypt.

Abstract

This study presents a methodology for optimizing the envelope of a multi-story residential building in hot arid regions, focusing on multi-objective optimization of cooling energy consumption, CO_2 emissions, and operative temperature. The optimization variables include building proportions, window-to-wall ratio (WWR), glazing types, and roof surface albedo. Cooling energy requirements were calculated using Design Builder, based on key assumptions such as local climatic conditions, building orientation, material properties, occupancy patterns, and HVAC system specifications. The optimization process employed the Non-dominated Sorting Algorithm (NDS) to identify optimal solutions. The multi-objective optimization aimed to minimize cooling energy consumption, and CO_2 emissions, and maintain operative temperature in an acceptable range simultaneously. The results indicate that no solutions achieve lower cooling energy consumption without compromising other objectives. However, prioritizing the minimization of cooling energy suggests optimal values of building proportion at 0.5, WWR at 10%, single clear glass with a thickness of 0.3, and roof surface albedo at 0.1. This method helps decision-makers choose optimal solutions based on their priorities. This study not only provides theoretical insights but also delivers actionable guidelines for architects and engineers. By leveraging the Pareto front methodology, decision-makers can address the specific challenges of designing energy-efficient buildings in hot arid climates, where cooling energy demands are exceptionally high. This work underscores the applicability of advanced optimization techniques in achieving sustainability goals in rapidly urbanizing regions.

Keywords: Pareto front; Non-dominated Sorting Algorithm; Cooling energy; Operative temperature; CO_2 emissions.

1. Introduction

Egypt characterized by its hot and arid climate, experiences substantial demand for cooling energy, particularly during the summer months [1, 2]. This demand has intensified due to increasing urbanization and a rising population, resulting in heightened air conditioning usage across residential, commercial, and industrial sectors [3, 4]. The prevailing high temperatures and low humidity levels in Egypt foster conditions conducive to air conditioning throughout much of the year. Rapid urban growth, especially in southern regions, has led to a significant rise in the number of buildings requiring cooling solutions [5]. Additionally, rising incomes have made air conditioning more accessible to a broader segment of the population, further driving up demand [6, 7]. Compounding this issue, many existing buildings are equipped with outdated or inefficient cooling systems, contributing to increased energy consumption. The soaring demand for cooling energy exerts considerable pressure on Egypt's electricity grid [8].

*Corresponding author E-mail: ayman.ragab@aswu.edu.eg
Received January 28, 2025, received in revised form, February 11, 2025, accepted February 11, 2025.

(ASWJST 2021/ printed ISSN: 2735-3087 and on-line ISSN: 2735-3095) https://journals.aswu.edu.eg/stjournal

During peak summer months, cooling demands can surpass the grid's capacity, resulting in power shortages and blackouts. This situation poses significant economic and social challenges, adversely affecting businesses, industries, and the general population [9]. In response to the escalating demand for cooling energy and its implications for the electricity grid, Egypt has implemented several strategies [10, 11]. These initiatives include promoting energy-efficient cooling technologies and appliances, encouraging sustainable building practices—such as using natural ventilation and locally sourced materials like limestone and clay bricks to reduce energy consumption in Egypt's hot climates—expanding the adoption of renewable energy sources, and implementing smart grid technologies [12, 13]. By embracing these measures, Egypt aims to reduce its reliance on fossil fuels for cooling energy, enhance energy security, and mitigate the environmental impacts associated with excessive energy consumption [14].

To address the challenges posed by the rising demand for cooling energy in Egypt, it is essential to explore innovative solutions that enhance building performance while minimizing energy consumption [15-17]. The increasing reliance on air conditioning systems, combined with the limitations of outdated technologies, underscores the need for more efficient design methodologies in architecture. In this context, simulation-based optimization emerges as a critical tool for architects and engineers, enabling them to create high-performance buildings that meet stringent energy efficiency criteria. By integrating advanced optimization techniques, such as multi-objective optimization algorithms (MOOAs), designers can effectively balance competing demands—such as energy efficiency, thermal comfort, and cost-effectiveness—while addressing the unique climatic challenges of the region [18]. This alignment of architectural design with energy demands not only mitigates the strain on Egypt's electricity grid but also contributes to broader sustainability goals, paving the way for innovative building solutions that are crucial in the face of escalating energy requirements. Given the pressing challenges of climate change and urbanization, optimizing building envelopes has become essential for achieving energy sustainability in hot arid climates [19, 20]. This study aligns global sustainability frameworks, such as the UN Sustainable Development Goals, particularly Goal 11 (Sustainable Cities and Communities) and Goal 13 (Climate Action), by addressing the energy and thermal efficiency of residential buildings.

2. Related Work

In contemporary architectural design, simulation-based optimization has emerged as a highly effective methodology for meeting various stringent requirements associated with high-performance buildings, including low-energy structures, passive houses, green buildings, net-zero energy buildings, and zero-carbon buildings [21]. Designers frequently encounter conflicting design criteria, such as the need to minimize energy consumption while maximizing thermal comfort, or to reduce energy costs while keeping construction expenses low [11, 22]. As a result, multi-objective optimization is often more applicable than single-objective optimization in these scenarios. This led researchers to adopt MOOAs to identify optimal trade-offs among competing design objectives [23-25]. While it is evident that efficient MOOAs are crucial for discovering optimal solutions without resorting to numerous time-intensive simulations, the effectiveness of these algorithms in the context of building optimization remains inadequately explored, primarily due to a lack of empirical research. Due to the extensive range of design variables in building energy models, coupled with their discrete, non-linear, and highly constrained nature, simulation outcomes typically exhibit multi-modal and discontinuous characteristics. This results in discontinuities within the objective functions associated with building optimization problems (BOPs). Consequently, optimization algorithms that rely on the assumption of smoothness often demonstrate inefficiency [26, 27].

In contrast, stochastic population-based multi-objective optimization algorithms (MOOAs), such as evolutionary optimization and swarm intelligence, are better suited to navigate the discontinuities present in the search space. Numerous studies have investigated the effectiveness of various optimization algorithms in single-objective and multi-objective BOPs. Wetter and Wright [28] compared the Hooke-Jeeves algorithm and a genetic algorithm (GA) for optimizing building energy consumption, finding that the GA outperformed Hooke-Jeeves, which often converged to a local minimum. Wetter and Wright [26] also evaluated eight algorithms—including Coordinate Search, Hooke-Jeeves, particle swarm optimization (PSO), hybrid PSO-Hooke-Jeeves, the simple GA, and others—across simple and complex building models. They concluded that the GA consistently approached the best minimum, while hybrid algorithms like PSO-Hooke-Jeeves achieved significant cost reductions with more simulations. Further studies highlight the relative performance of these algorithms under various conditions. For example, Kampf et al. [29] found that CMA-ES/HDE performed better than PSO-Hooke-Jeeves for benchmark functions with lower dimensions, while PSO-Hooke-Jeeves excelled in higher-dimensional problems. Similarly, Lee et al. [30] demonstrated that the differential evolution algorithm achieved comparable results to PSO and better average solutions than GA in solving the optimal chiller loading problem. Tuhus-Dubrow and Krarti [31] reported that GA outperformed PSO and sequential search methods in complex building envelope designs, requiring fewer iterations while maintaining high accuracy. Bichiou and Krarti [32] found that both GA and PSO achieved optimal solutions faster than sequential search methods, offering similar results with reduced computational time.

Recent advancements include combining Bayesian optimization with other algorithms. Chengjin et al. [33] developed an optimization framework integrating Bayesian optimization with extreme gradient boosting trees (BO-XGBoost) and NSGA-II, which effectively balanced energy consumption, daylighting, and thermal comfort in residential buildings. Vukadinović et al. [34] explored NSGA-II in optimizing passive solar design elements, such as window-to-wall ratios, to minimize energy requirements and discomfort hours in a detached passive building. These studies collectively suggest that stochastic population-based optimization algorithms, such as evolutionary algorithms and swarm intelligence, generally outperform traditional methods and are well-suited for BOPs. However, the cost reduction achieved depends not only on the algorithm's characteristics but also on parameter configurations [26, 29]. According to Wolpert and Macready [35], there is no universally superior algorithm for all optimization problems, indicating that selecting and tuning algorithms often involves trial and error [21]. However, the Pareto front-based NSGA-II algorithm provides significant advantages for multi-objective optimization. Its ability to visualize trade-offs among conflicting objectives, maintain diverse solutions, and effectively handle complex, non-linear problems makes it highly applicable to building envelope optimization. Additionally, NSGA-II's holistic approach ensures that energy efficiency, thermal comfort, aesthetic appeal, and cost are all integrated into the design process, enhancing sustainability and informed decision-making.

This study aims to conduct a comprehensive multi-objective optimization of the building envelope using Pareto front analysis to balance conflicting performance criteria, such as energy efficiency, thermal comfort, and environmental impact. By employing advanced optimization techniques, this research seeks to identify optimal design configurations that not only enhance the energy performance of buildings but also improve occupant comfort and reduce carbon emissions. The significance of this study lies in its potential to inform architects and engineers about effective design strategies that align with sustainability goals and regulatory standards. As the demand for high-performance buildings continues to grow, the findings of this research will contribute valuable insights into the design process, ultimately promoting more sustainable and resilient built environments.

Table 1. Summary of algorithms that have been used in previously investigated studies.

References	Hooke-Jeeves algorithm	Genetic algorithm (GA)	Coordinate Search algorithm	Particle swarm optimization (PSO)	Mesh-searching PSO	Hybrid PSO-Hooke-Jeeves algorithm	Simple GA	Nelder-Mead simplex algorithm	Discrete Armijo gradient algorithm	CMA-ES/HDE	Differential evolution algorithm	Lagrangian method	Sequential search method	NSGA-II
[28]	√	√												
[26]	√		√	√	√	√	√	√	√					
[36]						√								
[29]						√				√				
[30]		√		√								√		
[31]		√		√									√	
[32]		√		√										
[33]														√
[34]														√

3. Research Methodology

This study aims to perform a comprehensive multi-objective optimization of the building envelope using Pareto front analysis to balance conflicting performance criteria, including energy efficiency, thermal comfort, and environmental impact. Specifically, it investigates the effects of varying WWRs, glazing types, and roof surface albedo to enhance energy-efficient cooling in residential buildings situated in hot arid regions. The research is structured in two main phases. The first phase involves conducting year-round simulations utilizing weather data obtained from the meteorological station of Aswan University. Originally in CSV format, this data was converted to EPW format using the EnergyPlus weather statistics and conversion tool, serving as input for the Design-Builder software [37]. Additional input parameters, including construction details, openings, and HVAC systems, were derived from typical residential building configurations [38].

The study assumes that interior spaces are fully air-conditioned, with fixed occupancy hours reflecting traditional Egyptian lifestyles [39]. Information regarding the conventional daily routines of Egyptian families, as established by prior research [39, 40], was incorporated into the simulation software for analysis. Notably, indoor heat gains from occupancy and appliances, as well as energy demands for heating and lighting, were excluded from consideration. This exclusion was based on their negligible impact on total energy consumption in hot arid climates, where cooling dominates energy use due to high ambient temperatures and the minimal need for artificial lighting during extended daylight hours [16].

The second phase focuses on the optimization process, which includes multiple objective functions such as energy efficiency, thermal comfort, and environmental impact. The data collected in the first phase were organized into a CSV file containing 3600 records relevant to the targeted objectives: cooling electricity consumption (kWh), operative temperature (°C), and CO_2 emissions (kg). Using Python coding, the study identifies optimal solutions and design alternatives to achieve these objectives. The developed code employs the Pareto front concept, grounded in the NSGA-II algorithm. Figure 1 illustrates the overall framework for this study. To ensure the reliability of results, parameters such as WWR and roof surface albedo were selected as primary focuses. This decision was based on their significant influence on cooling energy performance in arid climates. WWR directly impacts solar heat gains and daylighting, while roof surface albedo affects heat absorption and reflection, making both critical for optimizing building envelopes in such regions. While Design Builder software provides robust simulation capabilities, its reliance on predefined climate data introduces some limitations. Future studies could enhance accuracy by integrating real-time climate data and dynamic occupancy models.

3.1. Study area

Aswan situated in southern Egypt on the eastern bank of the Nile River, lies at approximately 24.0934° N latitude and 32.9070° E longitude. The city experiences a desert climate, characterized by hot summers and mild winters [41]. During the hottest months, average temperatures range between 35°C and 38°C, with occasional heat waves pushing the temperature beyond 40°C [42]. In contrast, winter months are relatively cooler, with average daytime highs between 22°C and 26°C. Aswan receives minimal precipitation, with an average annual rainfall of just 2 mm [43].

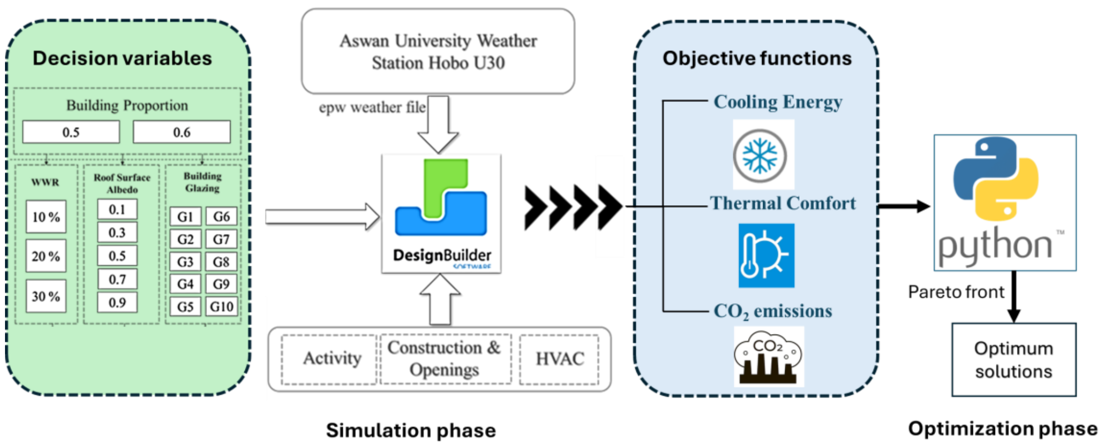


Figure 1. Schematic representation of the study framework.

3.2. Simulation input and model verification

The predominant building model underwent validation by comparing the simulated monthly energy consumption results with actual electricity usage data obtained from a residential building in Aswan. This building, with a total area of 200 m² and a height of 15 m, served as the reference for the simulation. To accurately represent the current state of the building, various input parameters were provided to the simulation software. The external walls comprise three layers: a 20 mm outer cement plaster layer, a 250 mm brick layer, and a 20 mm internal plaster layer. The building has a window-to-wall ratio of approximately 10%, while the roof surface features an albedo of 0.5. The windows are metal-framed with single-pane glazing that is 3 mm thick, exhibiting a Solar Heat Gain Coefficient (SHGC) of 0.861 and a U-value of 5.894 W/m²K. This detailed set of inputs allowed the simulation to replicate the building's performance closely. The validation process, comparing simulated energy consumption with recorded monthly electricity bills, showed a reasonably close match, with an average error of 2.4%, as illustrated in Figure 2. The thorough consideration of building dimensions, wall composition, window characteristics, and roof properties contributes to the accuracy and reliability of the energy performance assessment.

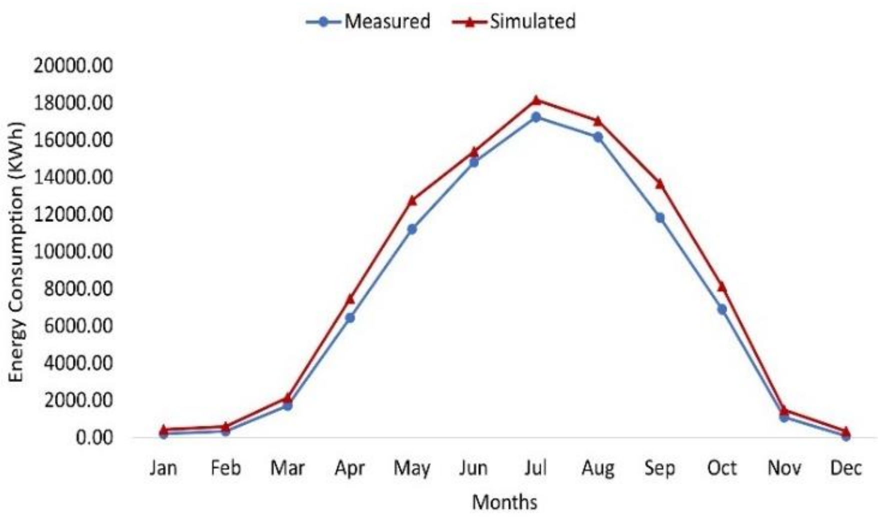


Figure 2. The building model verification.

3.3. Optimization Framework

To address the complex trade-offs in building design, this study employs a multi-objective optimization framework based on the NSGA-II algorithm. The framework identifies Pareto-optimal solutions by balancing three primary objectives: minimizing cooling energy consumption, reducing CO_2 emissions, and maintaining acceptable indoor operative temperatures.

3.3.1. Objective Functions

3.3.1.1. Cooling Energy

In hot arid regions, cooling energy consumption is a critical concern driven by extreme climatic conditions, making it a significant objective to be reduced during the initial stages of architectural design [44]. Typically, cooling energy usage is quantified in kWh. This objective aims to minimize the total cooling electricity, and it could be defined as follows:

$$E_c = \sum_{t=1}^{T} E_{c,t}$$

Where E_c is the total cooling electricity over time T.

The building envelope is instrumental in minimizing heat gain and lowering cooling loads. Consequently, retrofitting building envelopes to improve their energy efficiency represents a vital strategy for decreasing energy consumption.

3.3.1.2. Thermal Comfort

In hot arid regions, ensuring thermal comfort within buildings is paramount due to the extreme climatic conditions. Building envelopes play a crucial role in maintaining comfortable indoor temperatures by regulating heat transfer and solar radiation. Retrofitting building envelopes to enhance thermal comfort involves optimizing factors such as window to wall ratio (WWR), glazing types, and roof surface albedo. A key metric for assessing thermal comfort is the operative temperature, which considers both air temperature and mean radiant temperature. By retrofitting building envelopes to reduce heat gain and improve insulation, it is possible to create more comfortable indoor environments, reduce cooling energy consumption, and enhance overall building performance in hot arid regions.

3.3.1.3. CO_2 emissions

Cooling systems, particularly those powered by fossil fuels, contribute significantly to greenhouse gas emissions, including CO_2. In hot arid regions, where cooling energy consumption is high, reducing CO_2 emissions from cooling systems is a critical objective for sustainable building design and operation.

$$CO_2 = \sum_{t=1}^{T} CO_{2,t}$$

By retrofitting building envelopes to enhance energy efficiency and reduce cooling loads, it is possible to minimize the environmental impact associated with cooling energy consumption. This can involve implementing measures such as WWR, glazing types, and roof surface albedo to reduce the overall carbon footprint of buildings in these regions.

3.3.2. Decision variables

The primary aim of this study is to evaluate the impact of window-to-wall ratio (WWR), glazing types, and roof surface albedo on cooling energy consumption in two building configurations identified as effective strategies in previous studies [38, 45]. These variables are crucial in determining how different design elements influence energy efficiency, particularly in the context of hot climates like that of Aswan City.

3.3.2.1. Building Proportions

The effect of various width-to-length ratios (W/L) on cooling energy demand has been extensively explored. According to the research conducted by Ragab [38], optimizing the surface-to-volume ratio (S/V) is critical for minimizing cooling loads. In the present study, W/L ratios between 0.1 and 1 were investigated for a typical building area of 200 m², which is representative of multi-story residential buildings in Aswan. The study considers a maximum building height of 15m (equivalent to five stories), which is a common architectural feature in the region. Based on Ragab's findings, the optimal building proportions were identified as 0.5 and 0.6, which correspond to improved thermal performance. These proportions are adopted in this study, alongside an optimal building orientation of 90°, reflecting the most energy-efficient orientation for the selected proportions. The primary focus is to assess the influence of WWR, glazing types, and roof surface albedo on cooling energy demand for these specific configurations.

3.3.2.2. Window-to-Wall Ratio (WWR)

The WWR is a key determinant in building energy performance due to its influence on both solar heat gain and natural lighting. According to Egypt's national energy code, the maximum WWR allowed for south-facing facades is 40%, while for east- and west-facing facades, it is limited to 25% due to the intense solar radiation in these directions [16]. However, studies suggest that these guidelines may not be universally optimal. For instance, Karimi et al. [46] found that WWR values can significantly impact cooling loads depending on the building's orientation and the facade's exposure to sunlight. The study by Karimi et al. used BEopt™ energy simulation software to analyze different WWRs, revealing that windows positioned on southeast, south-southeast, south, and south-southwest facades have the greatest energy-saving potential. In contrast, windows on north, east, and west facades tend to increase cooling demand. The total energy consumption followed a U-shaped curve, with specific WWR values minimizing energy demand for each facade. An optimized WWR can lead to energy savings of up to 6.5%, while a poorly designed WWR (e.g., 0.7 on additional facades) may increase energy consumption by up to 29%. Thus, optimizing WWR for different facades is crucial to minimizing cooling energy use.

3.3.2.3. Glazing Types and Specifications

The selection of glazing plays a crucial role in reducing cooling energy demand, particularly in hot climates. Different glazing types, such as single-pane, double-pane, and triple-pane glass, offer varying levels of thermal insulation, primarily characterized by their U-values (W/m²K), Solar Heat Gain Coefficient (SHGC), and Visible Light Transmittance (VLT). These properties influence the amount of solar radiation admitted into the building, as well as the retention of heat indoors. In this study, multiple glazing types were evaluated for their ability to enhance energy efficiency. The focus was on clear glass with varying specifications, including thickness, gas fillings between the panes (e.g., argon or krypton), and coatings designed to reduce heat transfer. Double-pane windows filled with argon gas, for instance, can significantly reduce solar heat gain compared to single-pane alternatives, thus minimizing cooling loads. The specifications for the various glazing types considered in this study, including their U-values, SHGC, and VLT, are presented in Table 2.

3.3.2.4. Roof surface albedo

Surface albedo, a measure of a surface's reflectivity, significantly influences the amount of solar radiation absorbed and subsequently the heat emitted. Surfaces with high albedo values reflect more sunlight, reducing heat absorption, while those with low albedo values absorb more heat [47]. To evaluate the impact of roof surface albedo on cooling energy consumption, a range of albedo values (0.9, 0.7, 0.5, 0.3, and 0.1) was selected to represent various surface types, from light-colored to dark-colored and natural to artificial. This range aimed to assess the effects of surface reflectance on cooling energy requirements for maintaining comfortable indoor conditions. By comparing cooling energy consumption across different albedo values, the study sought to identify the optimal surface reflectance level for minimizing cooling energy and enhancing building energy efficiency

Table 2. Characteristics of glazing types.

Types	Specifications	U-value (w/m² K)	Solar Heat Gain Coefficient (SHGC)
G1	Single clear glass with thickness 0.3	5.894	0.861
G2	Single clear glass with thickness 0.6	5.778	0.819
G3	Double clear glass each one is 3mm and 6mm argon	2.884	0.763
G4	Double clear glass each one is 3mm and 6mm Air	3.159	0.762
G5	Double clear glass each one is 6mm and 6mm argon	2.829	0.702
G6	Double clear glass each one is 6mm and 6mm Air	3.094	0.7
G7	Triple clear glass each one is 3mm and two layers of argon with 6mm thickness	1.93	0.683
G8	Triple clear glass each one is 3mm and two layers of Argon air with 6mm thickness	2.178	0.682
G9	Triple clear glass each one is 6mm and two layers of argon with 6mm thickness	1.893	0.611
G10	Triple clear glass each one is 3mm and two layers of air with 6mm thickness	2.132	0.609

3.3.3. The Implementation Algorithm

The NSGA-II algorithm was chosen for its ability to efficiently handle multi-objective problems by identifying a diverse set of Pareto-optimal solutions. The algorithm uses a non-dominated sorting approach and a crowding distance metric to balance solution quality and diversity. To streamline the optimization process, a Python script was developed to implement the NSGA-II algorithm. The script integrates simulation outputs into the optimization framework, ensuring reproducibility and transparency.

This code snippet outlines the initialization phase for a multi-objective optimization problem focused on building performance, employing the NSGA-II algorithm, which is a well-established method for addressing non-dominated sorting-based multi-objective optimization challenges. The approach involves creating a custom optimization problem class, Building Optimization Problem, which defines parameter constraints for essential building design variables, including:

- WWR: A significant factor affecting natural lighting and thermal performance within buildings.
- Glazing Properties: These characteristics determine heat transfer and solar gain through windows, influencing overall energy efficiency.
- Surface Albedo: This parameter affects the reflectivity of building surfaces, thereby impacting their thermal behavior.

The lower and upper bounds for these variables are specified to create a constrained solution space, which ensures that the optimization process yields realistic and meaningful results.

This code snippet introduces an evaluate function, designed to calculate three critical objective functions for optimizing building performance: cooling energy consumption, CO_2 emissions, and operative temperature. Each objective is computed using domain-specific models (e.g., some_cooling_model, some_emission_model, and some_temperature_model), which are assumed to be predefined elsewhere in the code. The function's input variable, x, likely represents design variables or configurations such as material properties, geometric parameters, or operational settings. Following the evaluation function, the code initializes the NSGA-II algorithm, a robust method for multi-objective optimization. This process involves specifying key parameters such as population size, sampling methods, and crossover operators to ensure the algorithm effectively explores the solution space. These configurations are essential for identifying optimal trade-offs among the competing objectives of energy efficiency, environmental sustainability, and indoor thermal comfort.

The following code snippet addresses the solution of the previously defined multi-objective optimization problem. It leverages the minimize function from the optimization framework, applying the Building Optimization Problem class alongside the NSGA-II algorithm initialized earlier. Key parameters for the optimization process are defined as follows:

- n_gen=100: Specifies the total number of generations for the optimization process, determining how many iterations the algorithm will execute to refine and evolve the solutions.
- seed=1: Sets a fixed random seed to ensure reproducibility, allowing consistent replication of results across multiple runs.
- verbose=True: Enables detailed logging during the optimization process, providing progress updates and insights into the algorithm's performance.

Upon completion of the optimization, the code outputs the Pareto-optimal solutions, which represent the most favorable trade-offs among the competing objectives. These solutions, along with their corresponding objective values, are stored in res.X and res.F, respectively.

3.3.4. Pareto Front Visualization

The Pareto front was visualized using a 3D scatter plot, illustrating the trade-offs between cooling energy, CO_2 emissions, and operative temperature. The red markers indicate the optimal solutions, providing clear insights for decision-makers. This research investigates the complex interplay between building design parameters and their corresponding performance metrics, aiming to identify optimal configurations that balance energy consumption, environmental impact, and thermal comfort. Through a multi-objective optimization analysis, we leverage a Pareto optimization framework to identify Pareto-optimal solutions that represent the best trade-offs between these competing objectives. The study utilizes a dataset comprising various building design parameters, including building proportion, WWR, glazing type, and roof surface albedo. The dataset is enriched with performance metrics such as cooling electricity consumption, CO_2 emissions, and operative temperature. By employing a non-dominated sorting algorithm (NDS), the solutions have been classified based on their dominance across all objectives. This enables us to identify Pareto-optimal points that minimize cooling electricity consumption and CO_2 emissions while maintaining acceptable operative temperatures. The Pareto-optimal points are visualized in a 3D scatter plot, clearly representing the trade-offs between the objectives. 1% of optimum solutions have been defined to help the decision-makers. Additionally, the corresponding decision variables associated with these optimal points are extracted and saved for further analysis, facilitating the identification of optimal design configurations. This approach offers valuable insights into the complex relationship between building design parameters and performance metrics, enabling informed decision-making for sustainable and energy-efficient building practices.

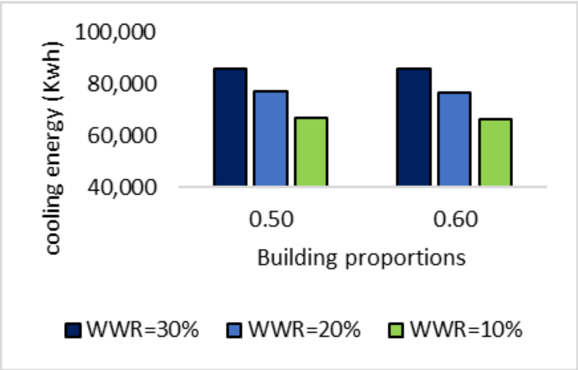
4. Result & Discussion

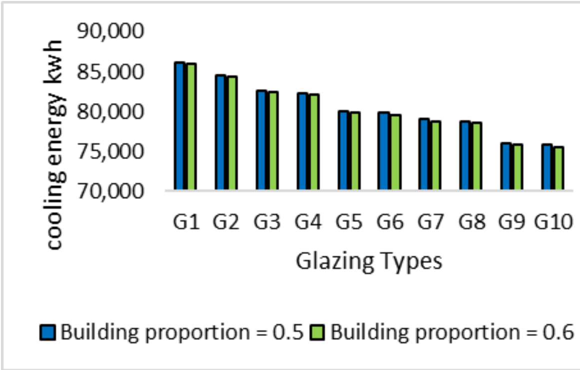
4.1. Simulation results

4.1.1. Cooling energy

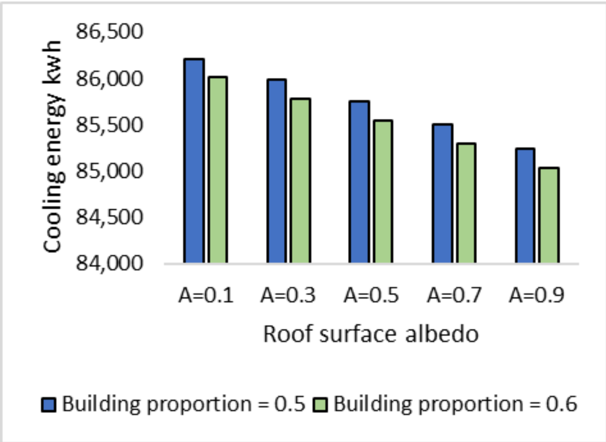
In the context of a sustainable built environment, optimizing energy consumption is crucial, particularly in regions characterized by hot and arid climates, such as Egypt. The design of buildings significantly influences their cooling energy requirements, making it essential to consider various decision variables. Among these, the window-to-wall ratio (WWR), building proportions, glazing types, and roof surface albedo play pivotal roles in determining energy efficiency. This study investigates the interactions among these variables, focusing on how they affect the cooling demands of buildings with proportions of 0.5 and 0.6. By analyzing these decision variables, the research aims to provide insights into effective strategies for reducing energy consumption and enhancing overall building performance.

Figure 3 presents the cooling energy required for (a) WWR, (b) glazing types, and (c) roof surface albedo. Higher WWR increases heat gain, with 30% WWR requiring the most cooling energy. For a building proportion of 0.5, the cooling energy consumption was calculated at 66,891.43 kWh, 77,074.81 kWh, and 86,206.77 kWh for WWRs of 10%, 20%, and 30%, respectively. Notably, a WWR of 10% achieved a significant improvement in energy efficiency, with a reduction of 22.41%. In a similar vein, a building proportion of 0.6 exhibited comparable performance with slight enhancements, achieving reductions of 22.87% and 10.83% for WWRs of 10% and 20%, respectively. Regarding glazing performance, single-glazing models were least efficient, while double-glazed G10 (two 6 mm panes with air) was most effective, improving efficiency by 12.03–12.13%. Other glazing types, including G6 (0.6 mm thick air-to-air thermal insulation), also demonstrated significant improvements in cooling energy demand, highlighting the importance of selecting appropriate glazing and insulation combinations for optimizing energy performance. Additionally, the research indicated that roof surface albedo had a minimal effect on cooling energy consumption, with improvements ranging from 0.26% to 1.12% for buildings with a proportion of 0.5, and 0.27% to 1.14% for those with a proportion of 0.6. These findings suggest that while adjustments to roof albedo can contribute to energy efficiency, their impact is relatively minor compared to other decision variables, such as WWR and glazing types. Overall, the study underscores the critical role of architectural design choices in enhancing energy efficiency and reducing cooling energy requirements in climates prone to high temperatures. The findings confirm the critical role of glazing types and WWR in determining energy efficiency, consistent with previous studies by Karimi et al. (2023). Practitioners can prioritize low-emissivity double or triple glazing to significantly reduce cooling loads. Moreover, although roof albedo has a minor impact, it can still be considered in cost-sensitive projects as a low-cost strategy for marginal energy savings





(a) (b)



(c)

Figure 3. The cooling energy with respect for (a) WWR, (b) glazing types, and (c) roof surface albedo.

4.1.2. Thermal comfort

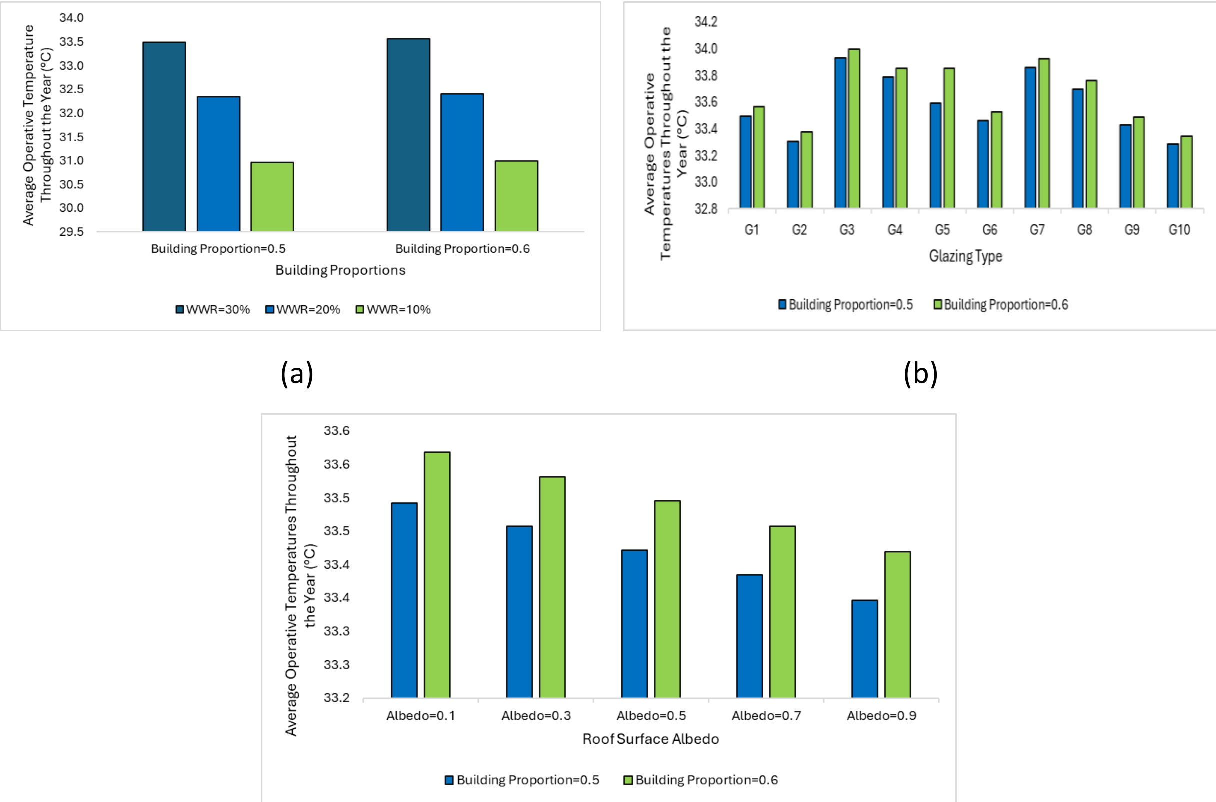
The window-to-wall ratio (WWR) and building proportions play a crucial role in influencing the thermal comfort and operative temperature of buildings. This study examined two building proportions, specifically 0.5 and 0.6. The findings revealed that increasing the WWR significantly raises heat transfer through the building envelope. A WWR of 30% was identified as a benchmark for evaluating other proportions due to its association with higher operative temperatures. For a building proportion of 0.5, the average operative temperatures recorded throughout the year were 31°C, 32.4°C, and 33.5°C for WWRs of 10%, 20%, and 30%, respectively. Notably, a WWR of 10% demonstrated the most substantial improvement, achieving an enhancement rate of 8.14%. In contrast, the WWR of 20% yielded a lower improvement rate of 3.53%. Figure 4 (a) illustrates the operative temperature average throughout the year (°C) for building proportion of 0.5 across various WWR values. The performance of a building proportion of 0.6 closely mirrors that of 0.5, with slight enhancements observed. Specifically, a building proportion of 0.6 can achieve operative temperature improvements of 8.32% and 3.57% for WWRs of 10% and 20%, respectively.

According to the study findings, glass type G3, which consists of two glass panes with a thickness of 3 mm filled with 6 mm of argon, resulted in the poorest operative temperature and thermal comfort, making it the least efficient option. Consequently, G3 was utilized as a benchmark for selecting optimal glazing types aimed at achieving ideal annual operative temperatures and enhancing thermal comfort.

For a building proportion of 0.5, the study identified that the operative temperature falls within a specific range, with G10 comprising two glazing panes of 6 mm thickness filled with 6 mm of air demonstrating the highest efficiency, showing an improvement rate of 1.96%. Other glass types exhibited varying improvement rates in decreasing order, including: 0.6 mm thick single-layered glass, 0.6 mm thick triple-layered glass with argon insulation, and 0.6 mm thick double-layered glass with air insulation. The analysis for a building proportion of 0.5 indicated that G10 provided the most effective glazing type among those studied, with an improvement rate of 1.94% compared to G3. Other glazing types showed improvement rates ranging from 0.21% to 1.88%. Figure 4 (b) illustrates the average operative temperatures throughout the year in terms of glazing types.

Further investigation into a building proportion of 0.6 revealed similar performance trends, with G10 again achieving a notable improvement rate of 1.96%. The study identified G2, G9, and G6 as the next most efficient glazing options among those evaluated. The operative temperature improvements for G7, G4, G8, G5, G1, G6, G9, and G2 were recorded at 0.21%, 0.43%, 0.69%, 1%, 1.31%, 1.41%, 1.50%, and 1.88%, respectively. Through thorough analysis, the study concluded that glass type G10 is the optimal choice for achieving the best operative temperature, with improvement rates ranging from 1.94% to 1.96%. This surpasses the performance of glass G9, which contributed to a temperature reduction of only 1.50% to 1.52%, despite utilizing argon as a thermal insulator. These findings corroborate previous research suggesting that using air as a thermal insulator between glazing panels can be more effective than using argon. Although argon is generally regarded as a superior insulator, its presence in glazing can lead to the formation of convection rings within the gas-filled gap, which diminishes insulation performance. Consequently, the effectiveness of argon as an insulator may be compromised in such scenarios.

The findings of this study indicate that roof surface albedo has a negligible impact on the operative temperature in buildings with proportions of 0.5 and 0.6. The observed improvement rates in operative temperature ranged from 0.10% to 0.43% for buildings with a proportion of 0.5, and from 0.11% to 0.45% for those with a proportion of 0.6. These results suggest that variations in roof surface albedo exert only a minor influence on the operative temperature necessary to maintain comfortable indoor conditions. Figure 4 (c) illustrates the average operative temperatures throughout the year (°C) and the improvement ratios for various building proportions in terms of roof surface albedo.



(a) (b)

(c)

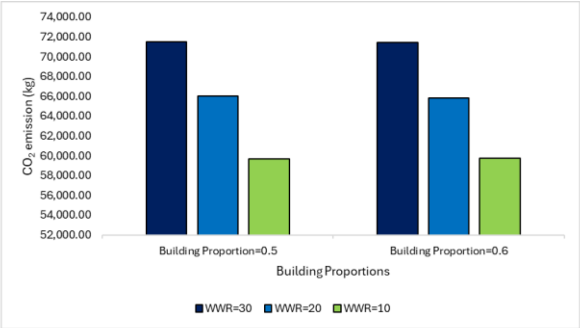
Figure 4. The indoor operative temperature in term of (a) WWR, (b) glazing types, and (c) roof surface albedo.

4.1.3. CO_2 emissions

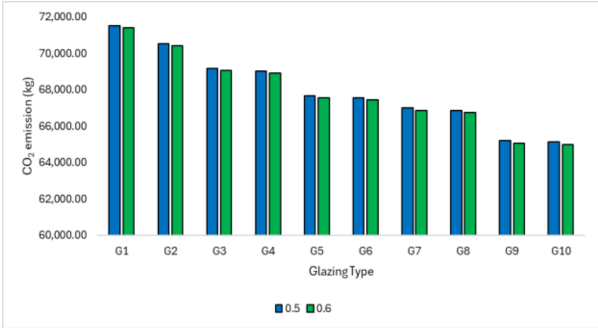
The study examined the impact of the selected decision variables on the CO_2 emissions in buildings. It was found that increasing the WWR significantly raises heat gain through the building envelope, with a benchmark of 30% leading to the highest cooling energy demand and corresponding CO_2 emissions. For a building proportion of 0.5, CO_2 emissions were recorded at 59,692.48 kg, 66,049.76 kg, and 71,506.38 kg for WWRs of 10%, 20%, and 30%, respectively. Notably, a WWR of 10% resulted in the most substantial reduction in emissions, achieving a decline of 19.79%, while a WWR of 20% offered a more modest improvement of 8.26%. Similarly, for a building proportion of 0.6, CO_2 emissions were slightly lower, with reductions of 19.57% and 8.45% for WWRs of 10% and 20%, respectively (Figure 5 (a)).

In terms of glazing performance, the study identified G1 as the least efficient option for minimizing electricity consumption and CO_2 emissions, serving as a reference for selecting optimal glazing types. The most effective option was G10, which consisted of three 6 mm thick glass panels filled with air, demonstrating an improvement rate of 9.82% compared to G1. Other glazing types exhibited varying degrees of effectiveness, with G10 also showing an improvement rate of 9.89% for buildings with a proportion of 0.6. The study further identified G9, G8, and G7 as the next most efficient glazing options, while other types like G2, G3, G4, G5, and G6 provided lower improvement rates (Figure 5 (b)).

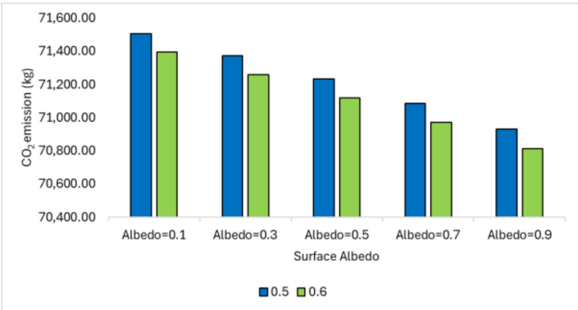
Additionally, the research indicated that roof reflectance had a negligible effect on CO_2 emissions for both building proportions, with reductions ranging from 0.18% to 0.81% for buildings with a proportion of 0.5, and from 0.19% to 0.82% for those with a proportion of 0.6 (Figure (c)). These findings suggest that while roof reflectance can play a role in overall energy efficiency, its impact on CO_2 emissions related to cooling energy consumption is limited.



(a)



(b)



(c)

Figure 5. The CO_2 for (a) WWR, (b) glazing types, and (c) roof surface albedo.

4.2. Optimization Process Based Pareto Front

The dataset analyzed consists of 3600 entries detailing key parameters influencing energy performance in a multi-story building. Key variables include cooling electricity (kWh), CO_2 emissions (Kg), operative temperature (°C), building proportion, WWR, glazing type, and roof surface albedo. 95 solutions have been observed as optimum solutions. Descriptive statistics indicate that the mean cooling electricity consumption is 90.85 kWh, with a standard deviation of 35.14 kWh, reflecting substantial variability in energy usage. The average CO_2 emissions are 1751.78 kg, while the operative temperature averages 22.56 °C, indicating a generally comfortable indoor environment. The correlation analysis reveals significant relationships among the studied variables. A strong positive correlation (R^2 = 0.79) exists between cooling electricity consumption and CO_2 emissions, implying that higher energy consumption leads directly to increased emissions. Similarly, there is a strong positive correlation between cooling electricity and operative temperature (R^2 = 0.80), indicating that elevated temperatures drive higher energy demand for cooling. Additionally, a significant positive relationship is observed between operative temperature and CO_2 emissions (R^2 = 0.76), suggesting that maintaining acceptable indoor thermal comfort increases emissions due to the energy required for cooling.

The Pareto front chart provides a visual representation of solutions that balance cooling energy consumption with other objectives, such as CO_2 emissions and operative temperatures. By analyzing the frequency distribution and cumulative frequency of cooling energy classifications, valuable insights into the trade-offs and potential for efficiency improvements can be obtained. The chart reveals that the highest frequency of occurrences is within the (74.53, 99.53] kWh classification, indicating that a significant portion of the solutions in the Pareto front fall within this range. Conversely, the lowest frequency of occurrences is within the (174.53, 199.53] kWh classification, which achieves the highest cumulative frequency (100%). Overall, the frequency of occurrences ranges from 1 to 31, while the cumulative frequency spans from 32% to 100%. It is crucial to note that the Pareto front consists of solutions that are not dominated by others, meaning there are no solutions that consume less cooling energy without compromising other objectives. The analysis of cooling energy classifications based on the Pareto front chart offers a comprehensive understanding of the trade-offs between cooling energy consumption and other objectives. By considering factors such as building size, climate, and occupancy patterns, decision-makers can make informed choices about energy-efficient cooling strategies. The 3D Pareto front chart illustrates the trade-offs between cooling electricity consumption, CO_2 emissions, and operative temperature. The red dots on the Pareto front represent the optimal solutions, considering all three objectives (Figure 6). By examining the chart, we can identify solutions that prioritize different objectives, such as reducing CO_2 emissions or improving operative temperatures. The chart shows clusters of points, particularly in the lower regions of cooling electricity consumption and CO_2 emissions. This suggests that there might be a limited range of feasible solutions in these areas.

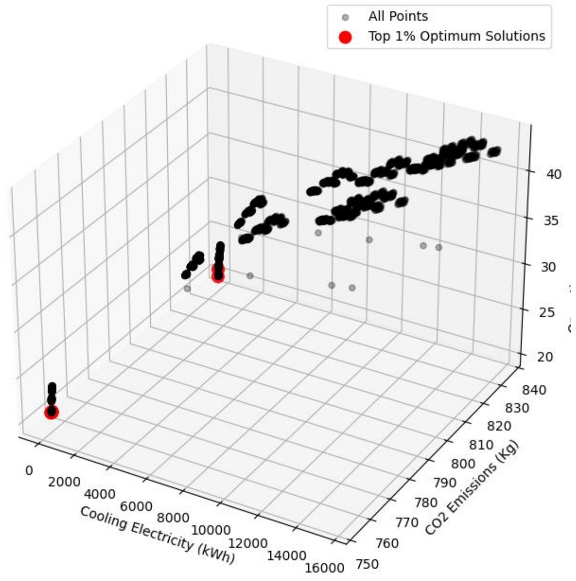


Figure 6. Pareto front chart for the optimal values.

5. Conclusion

This study presents a comprehensive analysis of building envelope optimization in hot arid regions, focusing on the trade-offs between cooling energy consumption, CO_2 emissions, and operative temperature. The findings highlight the critical contribution of building proportion and window-to-wall ratio (WWR) in optimizing cooling energy demand, thermal comfort, and CO_2

emissions, with lower proportions and reduced WWR significantly enhancing energy efficiency; similarly, the choice of glazing type, particularly double-glazed panels with air insulation, emerged as a pivotal factor for improving building performance, while roof surface albedo, though less impactful, offers marginal benefits as a cost-effective strategy in energy-sensitive projects. The multi-objective optimization approach employed in this research identified optimal solutions that balance these competing objectives. Key findings from the analysis include:

- The Pareto front reveals a trade-off between cooling energy consumption and CO_2 emissions, with higher energy consumption leading to increased emissions.
- Operative temperature is positively correlated with both cooling energy consumption and CO_2 emissions, indicating that maintaining comfortable indoor conditions requires additional energy and contributes to emissions.
- Building proportion, window-to-wall ratio, glazing type, and roof surface albedo are significant factors influencing energy performance.
- Optimal values for these parameters were identified based on the Pareto front analysis, providing guidance for building designers.

This study offers valuable insights into building envelope optimization, but further research is necessary to explore additional factors and refine the methodology. Future studies could incorporate dynamic simulations to account for variations in weather conditions and occupancy patterns. Additionally, a cost-benefit analysis would provide valuable insights into the economic implications of different building design strategies. To assess the robustness of the findings, sensitivity analysis could be conducted to evaluate the impact of uncertainties in input decision variables. Finally, applying the methodology to real-world building projects would help validate its effectiveness and practical applicability. By addressing these areas, future research can contribute to the development of more sustainable and energy-efficient building designs in hot arid regions. Future research could explore integrating machine learning models to predict energy performance under varying climatic conditions. Additionally, incorporating occupant behavior patterns into dynamic simulations would provide a more comprehensive understanding of energy consumption in residential buildings.

References

1. Abd Elrady, A.R.; Hassan, M.H. Conservation of morphological characters as an approach to thermal comfort. Signals Syst. A Primer MATLAB 2015, 15, 5729.
2. Mahmoud, A.R.A., Aly, A.M. and Hassan, M.H. Evaluating the thermal performance of urban spaces in aswan city “a case study of Saad Zaghloul street. JES. Journal of Engineering Sciences, 2015, 43(5), 766-782.
3. Tarek, D., El-Naggar, M., Sameh, H., Yousef, A. and Ragab, A. Energy Efficiency Coupled with Lightweight Bricks: Towards Sustainable Building: A review. SVU-International Journal of Engineering Sciences and Applications, 2023, 4(1), 1-28.
4. Ahmed, S.; El Attar, M.E.; Zouli, N.; Abutaleb, A.; Maafa, I.M.; Ahmed, M.M.; Ragab, A. Improving the thermal performance and energy efficiency of buildings by incorporating biomass waste into clay bricks. Materials 2023, 16, 2893.

5. Ragab, A. The Effects of Courtyard Envelope on the Energy Required for Cooling in the Hot Desert Climate. SVU-International Journal of Engineering Sciences and Applications, 2023, 4(2), 155-164.
6. Mohamed, A.F.; Amir, A.A.; Ragab, A. The effect of aerogel glazing on daylight and heat gain in school buildings in hot and dry climate. Environ. Dev. Sustain. 2024, 26, 1–22.
7. Mohamed, A.F.; Gomaa, M.M.; Amir, A.A.; Ragab, A. Energy, thermal, and economic benefits of aerogel glazing systems for educational buildings in hot arid climates. Sustainability 2023, 15, 6332.
8. Ragab, A.; Abdelrady, A. Impact of green roofs on energy demand for cooling in Egyptian buildings. Sustainability 2020, 12, 5729.
9. Park, S. Energy in Egypt. 2015. Available online: https://doi.org/10.1016/j.energy.2015.01.012 (accessed on 8 June 2025).
10. Gomaa, M.; Ragab, A. Investigating the spatial autocorrelation of surface-air temperature for different ground materials in hot desert climate. Egypt. Int. J. Eng. Sci. Technol. 2022, 39, 49–59.
11. Gomaa, M.M.; Othman, E.; Mohamed, A.F.; Ragab, A. Quantifying the impacts of courtyard vegetation on thermal and energy performance of university buildings in hot arid regions. Urban Sci. 2024, 8, 136.
12. Mahmoud, H.; Ragab, A. Thermal performance evaluation of unshaded courtyards in Egyptian arid regions. In Smart and Sustainable Planning for Cities and Regions: Results of SSPCR 2019, Volume 3; Springer: Cham, Switzerland, 2021; pp. 109–121.
13. Ragab, A.; Zouli, N.; Abutaleb, A.; Maafa, I.M.; Ahmed, M.M.; Yousef, A. Environmental and economic benefits of using pomegranate peel waste for insulation bricks. Materials 2023, 16, 5372.
14. Egyptian Electricity Holding Company. Annual Report 2022–2023; Egyptian Electricity Holding Company: Cairo, Egypt, 2024.
15. Fahmy, M.K.; Ahmed, M.M.; Ali, S.A.; Tarek, D.; Maafa, I.M.; Yousef, A.; Ragab, A. Enhancing the thermal and energy performance of clay bricks with recycled cultivated Pleurotus florida waste. Buildings 2024, 14, 736.
16. Ragab Mahmoud, A. Investigating the impact of different glazing types on the energy performance in hot arid climate. J. Adv. Eng. Trends 2022, 42, 69–84.
17. Gomaa, M.M.; El Menshawy, A.; Nabil, J.; Ragab, A. Investigating the impact of various vegetation scenarios on outdoor thermal comfort in low-density residential areas of hot arid regions. Sustainability 2024, 16, 3995.
18. Abdelhafez, M.H.H.; Aldersoni, A.A.; Gomaa, M.M.; Noaime, E.; Alnaim, M.M.; Alghaseb, M.; Ragab, A. Investigating the thermal and energy performance of advanced glazing systems in the context of Hail City, KSA. Buildings 2023, 13, 752.
19. Tarek, D., Ahmed, M.M., Hussein, H.S., Zeyad, A.M., Al-Enizi, A.M., Yousef, A. and Ragab, A. Building envelope optimization using geopolymer bricks to improve the energy efficiency of residential buildings in hot arid regions. Case Studies in Construction Materials, 2022, 17, p.e01657.
20. Abdelrady, A.; Abdelhafez, M.H.H.; Ragab, A. Use of insulation based on nanomaterials to improve energy efficiency of residential buildings in a hot desert climate. Sustainability 2021, 13, 5266.
21. Nguyen, A.-T.; Reiter, S.; Rigo, P. A review on simulation-based optimization methods applied to building performance analysis. In Applied Energy; Elsevier: Amsterdam, The Netherlands, 2014; Volume 113, pp. 1043–1058.
22. Mahmoud, H. and Ragab, A. Impact of urban geometry on cooling loads in Egypt: Case study: A social residential compound in New Aswan city. In 2020 9th International Conference on Power Science and Engineering (ICPSE), 2020, 71-75: IEEE.

23. Wang, W.; Zmeureanu, R.; Rivard, H. Applying multi-objective genetic algorithms in green building design optimization. Build. Environ. 2005, 40, 1512–1525.
24. Hamdy, M.; Hasan, A.; Siren, K. Impact of adaptive thermal comfort criteria on building energy use and cooling equipment size using a multi-objective optimization scheme. Energy Build. 2011, 43, 2055–2067.
25. Hamdy, M.; Palonen, M.; Hasan, A. Implementation of Pareto-archive NSGA-II algorithms to a nearly-zero-energy building optimisation problem. In Proceedings of the Building Simulation and Optimization Conference; London, UK, 2012.
26. Wetter, M.; Wright, J. A comparison of deterministic and probabilistic optimization algorithms for nonsmooth simulation-based optimization. Build. Environ. 2004, 39, 989–999.
27. Pernodet, F.; Lahmidi, H.; Michel, P. Use of genetic algorithms for multicriteria optimization of building refurbishment. Build. Environ. 2009, unpublished.
28. Wetter, M.; Wright, J. Comparison of a generalized pattern search and a genetic algorithm optimization method. In Proceedings of the 8th IBPSA Conference; Citeseer: Eindhoven, The Netherlands, 2003; Volume 3, pp. 1401–1408.
29. Kämpf, J.H.; Wetter, M.; Robinson, D. A comparison of global optimization algorithms with standard benchmark functions and real-world applications using EnergyPlus. J. Build. Perform. Simul. 2010, 3, 103–120.
30. Lee, W.-S.; Chen, Y.-T.; Kao, Y. Optimal chiller loading by differential evolution algorithm for reducing energy consumption. Energy Build. 2011, 43, 599–604.
31. Tuhus-Dubrow, D.; Krarti, M. Genetic-algorithm based approach to optimize building envelope design for residential buildings. Build. Environ. 2010, 45, 1574–1581.
32. Bichiou, Y.; Krarti, M. Optimization of envelope and HVAC systems selection for residential buildings. Energy Build. 2011, 43, 3373–3382.
33. Wu, C.; Pan, H.; Luo, Z.; Liu, C.; Huang, H. Multi-objective optimization of residential building energy consumption, daylighting, and thermal comfort based on BO-XGBoost-NSGA-II. Build. Environ. 2024, 254, 111386.
34. Vukadinović, A.; Radosavljević, J.; Đorđević, A.; Protić, M.; Petrović, N. Multi-objective optimization of energy performance for a detached residential building with a sunspace using the NSGA-II genetic algorithm. Sol. Energy 2021, 224, 1426–1444.
35. Wolpert, D.H.; Macready, W.G. No free lunch theorems for optimization. IEEE Trans. Evol. Comput. 1997, 1, 67–82.
36. Wetter, M. Generic Optimization Program User Manual Version 3.0.0; LBNL: Berkeley, CA, USA, 2009.
37. Abdelrady, A.; Abdelhafez, M.H.H.; Ragab, A. Use of insulation based on nanomaterials to improve energy efficiency of residential buildings in a hot desert climate. Sustainability 2021, 13, 5266.
38. Mahmoud, A.R. The influence of buildings proportions and orientations on energy demand for cooling in hot arid climate. SVU-International Journal of Engineering Sciences and Applications, 2022, 3(1), 8-20.
39. Attia, S.; Evrard, A.; Gratia, E. Development of benchmark models for the Egyptian residential buildings sector. Appl. Energy 2012, 94, 270–284.
40. Kamal, M., ElAttar, M., El-Naggar, M., Yousef, A. and Ragab, A. Thermal and Energy Efficiency of Roof Tiles Fabricated from Crushed Aluminum Slag and Kaolin Clay for Social Residential Buildings in Egypt. Aswan University Journal of Environmental Studies, 2023, 4(3), 83-102.

41. Elkhayat, K.; Abdelhafez, M.H.H.; Altaf, F.; Sharples, S.; Alshenaifi, M.A.; Alfraidi, S.; Ragab, A. Urban geometry as a climate adaptation strategy for enhancing outdoor thermal comfort in a hot desert climate. Frontiers of Architectural Research 2025, 14(2), 525-544.
42. Hassieb, M.M.; Ragab, A.; Mohamed, A.F. Quantifying the influence of window-to-wall ratio (WWR) on indoor air quality and thermal comfort: Classroom study in hot arid climates. In IOP Conf. Ser.: Earth Environ. Sci. 2024, 1396, 012025.
43. Aly, A.M.M.; Hassn, M.H.; Abdel Rady, Y.R.; Mohammed, A.T. The effect of using nano-materials in external openings on energy consumption in hot desert climate. J. Eng. Sci. 2020, 48, 468–477.
44. Tarek, N.; Aly, A.M.M.; Ragab, A. Energy-efficient passive cooling design for residential buildings in hot and arid climates: A parametric study. Aswan Univ. J. Sci. Technol. 2024, 4, 80–95.
45. Ahmed, A.E.; Suwaed, M.S.; Shakir, A.M.; Ghareeb, A. The impact of window orientation, glazing, and window-to-wall ratio on the heating and cooling energy of an office building: The case of hot and semi-arid climate. J. Eng. Res. 2023, in press.
46. Karimi, M.; Chikamoto, T.; Lee, M. Optimization of window area in buildings from the viewpoint of energy efficiency—Kabul, Afghanistan. In IOP Conf. Ser.: Earth Environ. Sci. 2023, 1196, 012010.
47. Taha, H.; Sailor, D.J.; Akbari, H. High-albedo materials for reducing building cooling energy use. 1992, unpublished.