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Improving Thermal and Energy Performance of Buildings Through Building Performance Simulation-Based Optimization: A Case Study of a Residential Villa in Cairo, Egypt

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Abstract. The building construction sector accounts for approximately 40% of global energy consumption and significantly contributes to greenhouse gas emissions, underscoring the urgent need for sustainable design practices. In hot-arid climates such as Cairo, Egypt, the dependence on energy-intensive cooling systems exacerbates these challenges, particularly in villa residences where conventional construction methods often overlook thermal performance. This study examines the potential of using building performance simulation-based optimization (BPSO) to enhance thermal and energy performance in a residential villa building in Cairo, Egypt. A baseline building model, reflective of typical local construction practices, was developed using Design Builder software with Energy Plus as the simulation engine. This model underwent parametric optimization of building envelope systems, specifically focusing on external walls and glazing systems configurations, evaluated across 25 design scenarios. The primary objective was to minimize energy consumption and related CO_2 emissions while ensuring indoor thermal comfort. The results indicated that the optimal building configuration, consisting of 160 mm-thick precast cement sandwich panels walls and 25 mm-thick double-insulated Low-E glazing, achieved a significant reduction in HVAC energy consumption and CO_2 emissions of up to 18.76% compared to the baseline building model. This study addresses a notable gap in simulation-based research of residential villas within hot-arid regions and offers a replicable framework for architects, developers, and policymakers to implement data-driven design strategies. Ultimately, it highlights the effectiveness of building performance simulation-based optimization in advancing thermal and energy efficiency and sustainability in Egypt's rapidly growing residential sector.

Keywords: Building Performance – Performance Optimization - Thermal Performance - Energy Efficiency – Building Performance Simulation.

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1 Introduction.

The construction sector plays a crucial role in global energy consumption, representing nearly 40% of total usage and contributing to approximately one-third of greenhouse gas emissions. This underscores its significance in sustainability initiatives. In hot-arid regions, such as Egypt, the demand for cooling systems constitutes a major aspect of residential energy consumption. [3] [12] [15]

Cairo, a rapidly expanding megacity with a population exceeding 20 million, encounters distinct challenges arising from extreme summer temperatures that often exceed 40°C. These challenges are exacerbated by urban heat island effects and an overreliance on energy-intensive air conditioning systems. Furthermore, conventional construction practices in Egypt frequently prioritize short-term cost savings at the expense of long-term performance. This approach results in buildings characterized by inadequate thermal insulation, excessive window glazing without sufficient shading, and ineffective strategies for natural ventilation. Consequently, these design deficiencies lead to issues such as overcooling, energy waste, thermal discomfort, and elevated operational costs for occupants. [1] [3]

Building performance simulation-based optimization (BPSO) has emerged as a significant methodology for bridging the gap between sustainable design theory and practical application. Unlike traditional prescriptive approaches that rely on generic energy standards, simulation-driven optimization utilizes parametric modeling, machine learning algorithms, and iterative design testing to identify the most efficient solutions tailored to specific building types and climatic conditions. Advanced tools such as Design Builder and Energy Plus empower architects to quantify the effects of various design variables, including wall insulation thickness, window-to-wall ratios, shading geometries, and glazing specifications, before the initiation of construction. This data-driven methodology not only reduces energy consumption but also enhances thermal comfort and decreases reliance on cooling systems. [9] [10]

Despite the validation of BPSO in temperate climates, its application in hot-arid regions, particularly within Egypt's residential sector, remains limited. Existing research has predominantly focused on large-scale commercial or multi-family housing projects, often neglecting the unique thermal challenges associated with residential villas, which represent a significant portion of Cairo's suburban housing stock. These villas frequently incorporate design features such as double-height atriums, extensive west-facing glazing, and uninsulated roof slabs, all of which contribute to excessive heat gain. Furthermore, while retrofitting existing buildings presents considerable potential for energy savings, there has been minimal systematic evaluation of cost-optimal retrofit packages for Egyptian villas utilizing multi-objective optimization techniques. [1] [7]

This study addresses significant gaps in existing research by conducting a comprehensive case study of a residential villa situated in Cairo, Egypt, which is currently experiencing rapid real estate development. The evaluation focuses on key performance indicators, including yearly cooling energy demand, indoor operative temperature, and the simple payback period for proposed interventions. The optimization process incorporates a thorough assessment of passive measures such as enhanced external walls and glazing systems insulation. The objective is to identify the optimal balance between energy consumption, CO_2 emissions, and conserving the environment.

This study underscores Egypt's comprehensive sustainability objectives by demonstrating how computational optimization can facilitate measurable reductions in energy consumption. The findings are particularly advantageous for architects, real estate developers, and governmental agencies seeking to implement effective, data-driven strategies that enhance building performance while preserving architectural aesthetics and adhering to homeowners' budgetary constraints.

2 Literature Review.

The application of building performance simulation-based optimization (BPSO) has garnered increasing attention within architectural and engineering research due to its potential to enhance overall building performance while promoting environmental sustainability. This review aims to summarize existing literature about the implementation of this analytical tool.

(Assad, Hosny, Elhakeem, & El Haggar, 2015) Presented integrated framework for sustainable building design serves as an optimization and simulation platform with four modules: a system builder for envelope options, a building integrator for overall design, a design evaluator for cost and energy assessment, and a design adaptation for optimization. This framework helps analyze cost and energy trade-offs in early design stages. A comparative analysis found that green designs can achieve lifecycle and yearly energy savings of 16.3% and 50%. [1]

(Samaan, Farag, & Khalil, 2018) Studied optimized cooling loads and daylighting in three drawing halls at Mansoura University using Design Builder with Energy Plus and Radiance. It found that improving window shading, glazing, and ventilation can decrease cooling loads by 26% to 31%. Skylight strips with an 8% window-to-roof ratio satisfy daylighting needs with minimal impact on cooling loads. [20]

(Mahmoud, Fahmy, Mahdy, Elwy, & Abdelalim, 2020) Conducted a simulation analysis on an administration building in Cairo to assess passive design features versus conventional construction. Passive elements included courtyards, a double-walled envelope, shading devices, and cross ventilation. Design Builder simulations with local weather data revealed an 11% reduction in energy consumption with passive design. [14]

(Gia, et al., 2022) Utilized a non-dominated sorting genetic algorithm with building simulation techniques to explore the trade-offs between investment costs and energy consumption. The method focuses on optimizing thermal envelopes, glazing, and energy systems in the early design phases. A case study of a non-residential building in Hanoi demonstrates that this approach significantly improves design performance over traditional methods. The optimal solutions provide a Pareto front, helping architects, engineers, and investors make informed decisions regarding energy efficiency. [9]

(Ebaid, 2023) Examined the impact of innovative and locally sourced building materials on wall construction in Egyptian residential buildings to enhance energy efficiency and thermal comfort. Six wall systems, including Marmox boards, aerogel panels, and local options like double walls and Mudbrick with strawbale, were analyzed through computer simulations. Results indicated that Mudbrick strawbale provided the best thermal performance, reducing energy consumption by 45% and discomfort hours to just 18. Innovative materials also showed promising results. Overall, alternative wall strategies using sustainable materials can achieve energy savings of 29% to 45% and reduce discomfort hours by over 50%. [7]

(Harshalatha, Patil, & Kini, 2024) Investigated simulation-based multi-objective optimization techniques to evaluate the impact of space layout on building energy efficiency. This approach integrates simulation tools with optimization algorithms to balance energy performance, user comfort, and costs. It highlights key factors like spatial configurations and orientation, discusses various modeling tools, and emphasizes the need for accurate energy assessments. The text also advocates for a framework that reduces cooling loads while optimizing layout and envelope parameters, contributing to sustainable architecture. [10]

This literature highlights the considerable potential of employing BPSO to enhance building performance in a specific geographic context. This study focuses on reducing energy consumption and carbon dioxide (CO_2) emissions through the application of BPSO in a proposed residential villa building in Cairo, Egypt, recognized for its hot-arid climate, an area that has not been previously explored through the lens of comprehensive building performance simulation-based optimization analysis. Advanced simulation tools are leveraged to assess the advantages of utilizing BPSO as a mechanism for improving overall building performance.

It is imperative that future research investigates the optimization of advanced material properties, enhances cost-effectiveness, and examines innovative integrations with smart building technologies.

3 Building Performance Simulation-Based Optimization (BPSO).

Building performance simulation-based optimization (BPSO) is an advanced technique that identifies design alternatives aligning with key performance objectives. It shares similarities with parametric analysis, which examines design performance variations by systematically adjusting variables. [6] [11]

This method visualizes trends to discover favourable characteristics like reduced energy consumption and carbon dioxide (CO_2) emissions while enhancing comfort and conserving the environment. [6] [11]

BPSO represents a significant advancement in the pursuit of enhancing overall building performance while promoting environmental sustainability. By integrating high-fidelity energy modelling with sophisticated optimization algorithms, such as genetic algorithms, particle swarm optimization, and Bayesian optimization, BPSO systematically investigates a wide array of design alternatives to identify optimal solutions that harmonize energy efficiency, thermal comfort, operational expenses, and environmental impact. [10] [11]

This methodology facilitates the assessment of crucial parameters, including building orientation, envelope characteristics, HVAC system configurations, and the incorporation of renewable energy sources, all while considering the dynamic interactions among these factors under diverse climatic conditions. [10] [11]

Recent progress in machine learning techniques, particularly in surrogate modeling and reinforcement learning, has considerably accelerated the optimization process, enabling computationally efficient multi-objective trade-off analyses, even for intricate and nonlinear building systems. Moreover, the integration of BPSO with real-time building performance data through digital twins enhances predictive accuracy and supports adaptive control strategies aimed at continuous operational optimization. [6] [9] [10]

As global building regulations and sustainability certifications, including LEED, BREEAM, and net-zero energy standards, become increasingly rigorous, BPSO offers a robust, data-driven framework designed to minimize lifecycle carbon emissions, decrease energy consumption, and improve resilience without compromising occupant well-being. Its application is particularly vital in the context of climate change mitigation, wherein optimized building designs can play a critical role in decarbonizing the built environment while ensuring economic feasibility. [6] [9] [10]

4 Methodology.

This study utilizes a simulation-based optimization methodology to identify the most effective performance parameters for building envelope systems, with particular emphasis on external walls and glazing systems. The primary objective is to use a building performance simulation-based optimization (BPOS) process to improve both thermal and energy performance while minimizing associated CO_2 emissions in the hot arid climate of Cairo, Egypt.

A representative model of a residential villa will be developed utilizing Design Builder software (version 7.3.1.003 – educational edition), as shown in Figure 1. This model incorporates local construction methodologies and climatic data pertinent to the hot-arid climate of Cairo, Egypt. The software is recognized for its user-friendly interface, which facilitates effective assessments of the environmental performance of both newly constructed and existing buildings. It significantly reduces the modelling time and enhances productivity by employing Energy Plus (version 9.4.0.002) as the simulation engine. This engine plays a crucial role in calculating energy consumption across various metrics, including cooling, heating, ventilation, lighting, process loads, and other essential variables necessary to achieve the analysis objectives. [5]

Figure 2 illustrates the study strategy, which evaluates two scenarios of a proposed residential villa building model in Cairo, Egypt. The baseline model for the residential villa employs conventional external walls and glazing systems. This model will undergo simulation and optimization utilizing building performance simulation software. The optimization process will compare five local options for external walls systems and five local options for external glazing systems to identify the most effective scenario for thermal and energy performance while reducing related CO_2 emissions within the climate of Cairo, Egypt. Subsequently, the optimized model of the residential villa will be simulated to contrast the results between the baseline scenario and the optimized scenario.

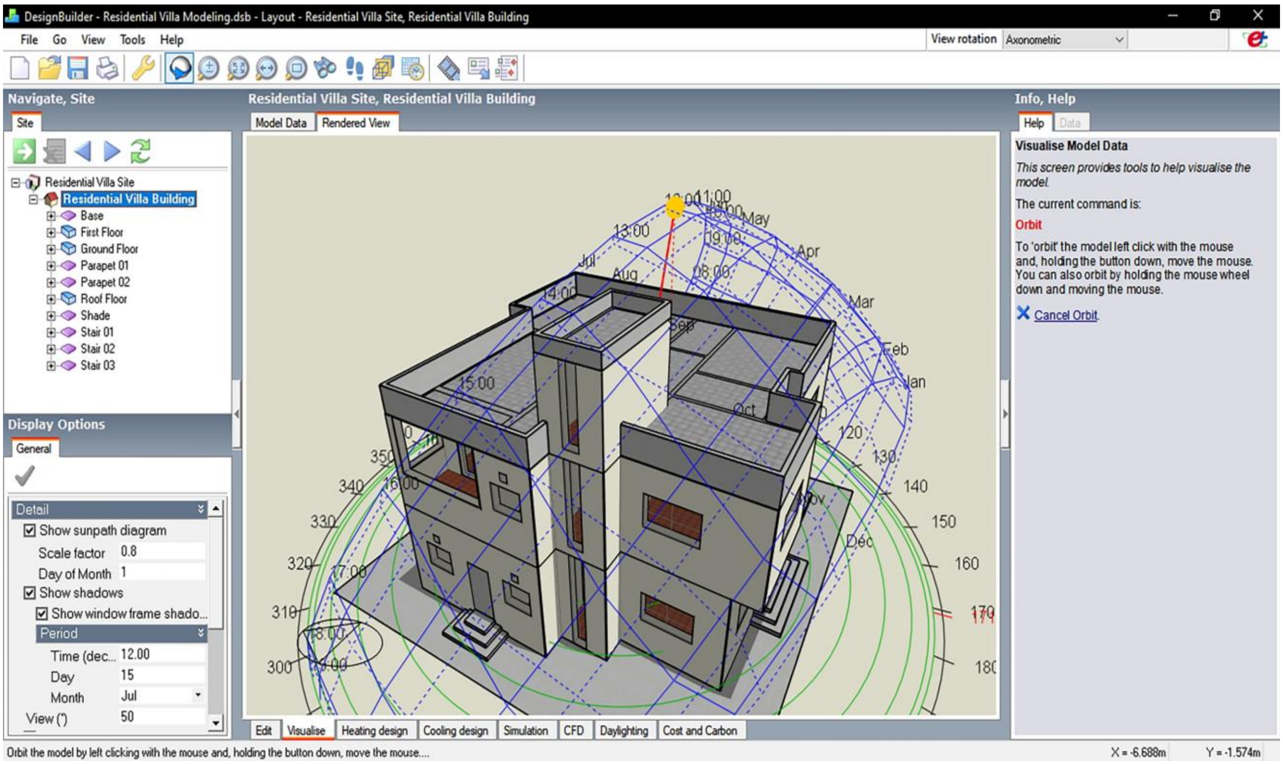


Figure (1) Design Builder Software Interface [5]

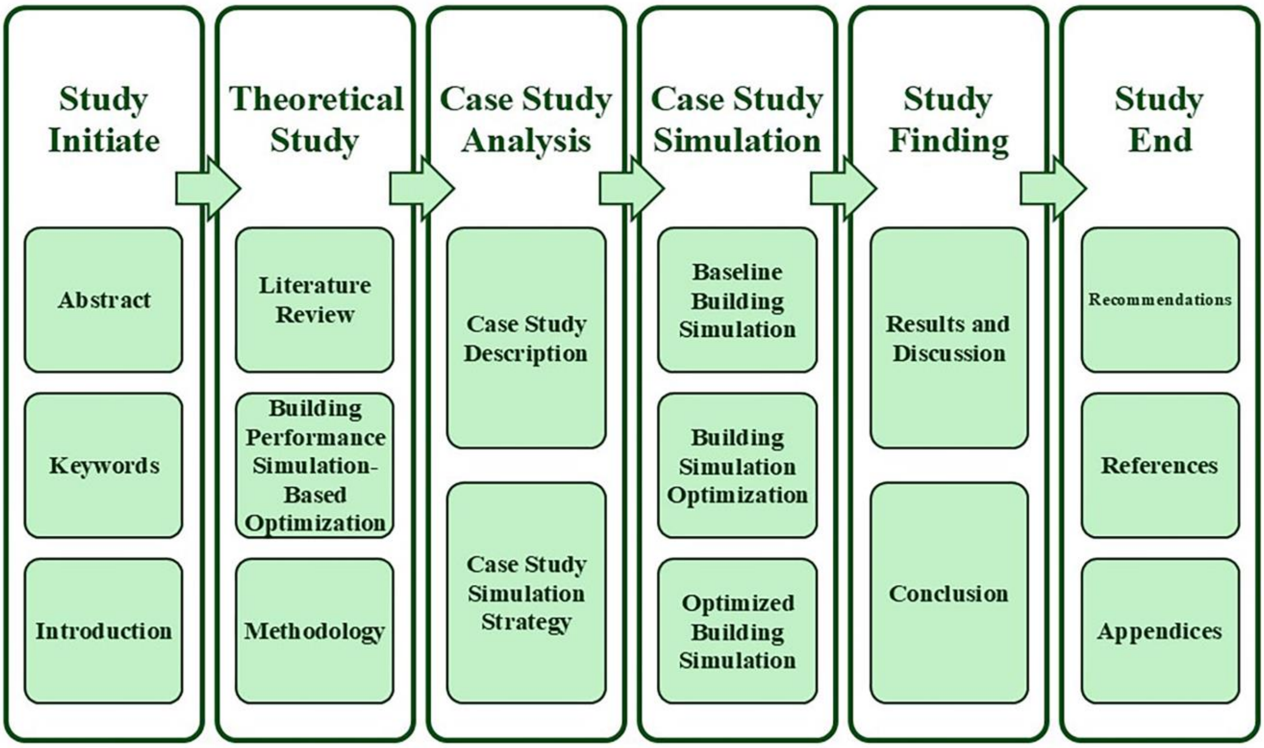


Figure (2) Study Strategy Workflow Diagram

This analysis will elucidate the advantages of employing a building performance simulation-based optimization process to select the best building envelope systems to enhance buildings' thermal and energy efficiency while minimizing associated CO_2 emissions in a local climatic condition.

5 Residential Villa Case Study Analysis.

This study aims to simulate a proposed residential villa building model in Cairo, Egypt, utilizing conventional materials and systems as a baseline for comparative analysis to implement a building performance simulation-based optimization process to identify the most locally appropriate envelope materials and systems to enhance thermal and energy efficiency and reduce CO_2 emissions.

5.1 Case Study Description.

The proposed design for the residential villa building, as depicted in Figure 3, features a meticulously planned layout. The ground floor comprises an entrance, reception area, dining space, office, kitchen, toilet, staircase, and lobbies. The first floor is designed to include a living area with an adjacent terrace, a master bedroom equipped with a dressing area and restroom, two additional bedrooms, a buffet area, a toilet, a staircase, and a lobby. The rooftop accommodates a staircase that provides access to an open roof space. The building is designed with a footprint area measuring 163.06 m² and a total area of 329.20 m², featuring a ceiling height of 3.50 meters. It has been engineered to support an occupancy density of 0.033 people per m². The heating, ventilation, and air conditioning (HVAC) system will be meticulously calibrated, utilizing separate split units to ensure a comfortable indoor temperature of 24 °C during the summer months and 22 °C throughout the winter months. The construction process will employ conventional local techniques to ensure the use of durable materials and a well-considered internal layout. The villa will utilize natural gas as its primary energy source for water heating, complemented by electricity to power various devices and systems.

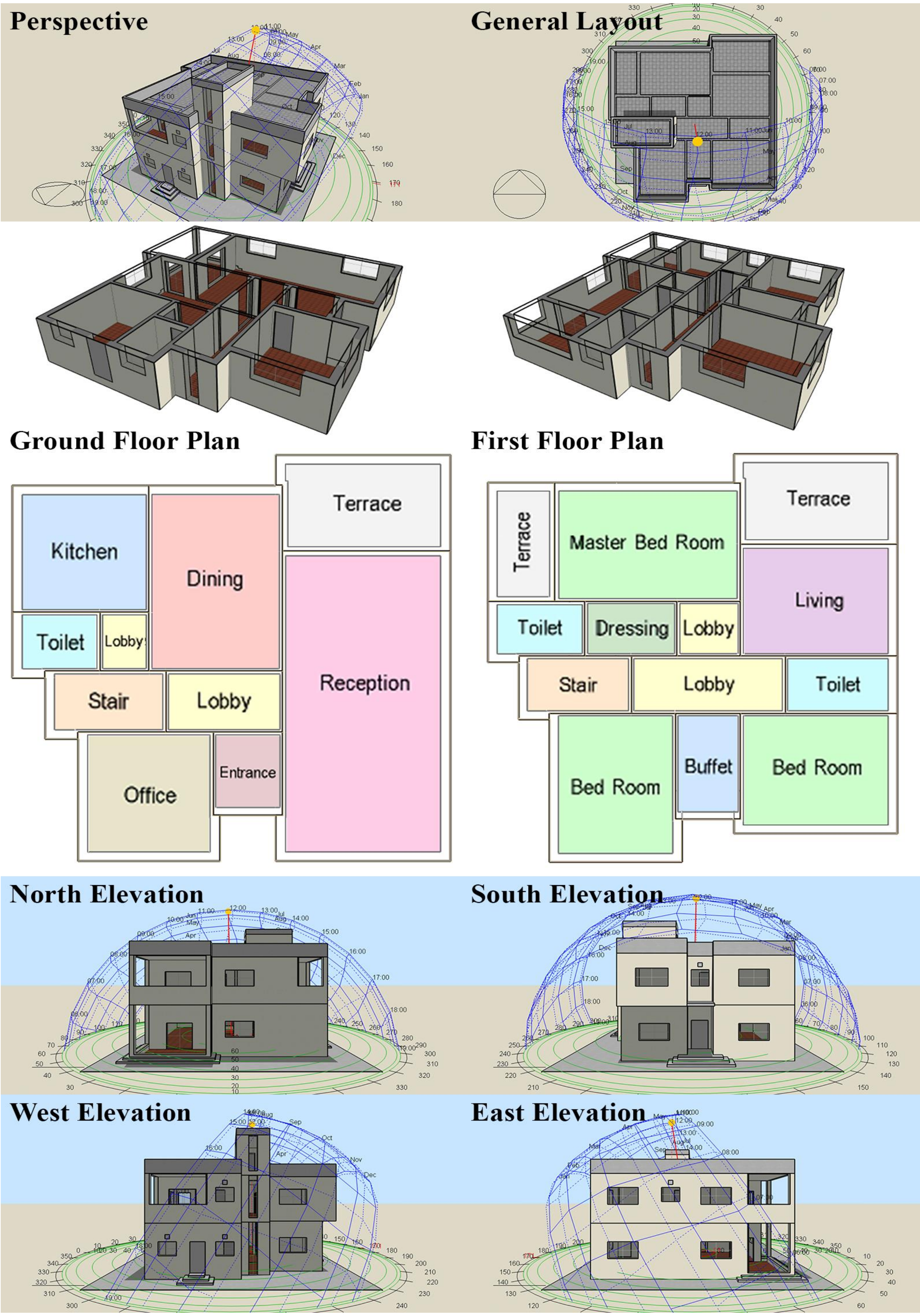


Figure (3) Proposed Residential Villa Building Model Overview [5]

5.2 Case Study Simulation Strategy.

The simulation strategy entails a comparative analysis of two distinct residential villa building model scenarios.

The first scenario is represented by a baseline building, which features a conventional external wall system (external wall type A) constructed from 250 mm-thick concrete blocks. These walls are finished with 30 mm-thick external sand-cement plaster and 20 mm-thick internal sand-cement plaster, in addition to utilizing conventional external glazing system (external glazing type A) composed of a single 6 mm-thick clear glass panel.

Within this baseline building model, a building performance simulation-based optimization process will be employed to compare five local alternatives for external wall systems and five local alternatives for external glazing systems. The objective of this comparison is to identify the most effective scenario for thermal and energy performance while reducing related CO_2 emissions in the climate of Cairo, Egypt.

The second scenario is an optimized building that employs the highest performing external walls and glazing system types identified through the building performance simulation-based optimization process.

Both scenarios utilize the same building materials and systems for all remaining components to facilitate a consistent comparison. The simulation will comprehensively evaluate various factors, including the analysis of cooling and heating designs, site data, comfort levels, internal gains, solar influences, and assessments of fabric and ventilation.

Furthermore, it will encompass a breakdown of fuel usage and a total analysis, an evaluation of CO_2 emissions, system load analysis, as well as an assessment of embodied and equivalent carbon.

5.3 Residential Villa Baseline Building Simulation.

A comprehensive simulation analysis was performed on the baseline building model of the residential villa, utilizing conventional building materials and systems.

The external walls of the building, classified as external wall type A, consist of 250 mm-thick concrete blocks, which are subsequently covered by a 30 mm-thick layer of external sand-cement plaster and a 20 mm-thick layer of internal sand-cement plaster. The overall thermal transmittance (U-value) for these external walls is measured at 1.371 W/m^2K. [5]

The external glazing of the building, classified as external glazing type A, is made up of a single 6 mm-thick clear glass panel. The overall thermal transmittance (U-value) for this external glazing is recorded at 5.778 W/m^2K. [5]

The data presented in Figure 4 demonstrates that thermal gains and losses through the external walls and glazing systems of the building significantly impact the heating, ventilation, and air conditioning (HVAC) system. Over the years, the total energy consumption for HVAC cooling has been approximately 73,216.28 Wh/m^2, while the total energy consumption for HVAC heating has amounted to around 3,639.20 Wh/m^2. Consequently, the total yearly energy consumption for the HVAC system is calculated to be 76,855.48 Wh/m^2. Additionally, the building's total carbon dioxide (CO_2) emissions for the year reached 46,574.37 kg/m^2. [5] (Appendix 1)

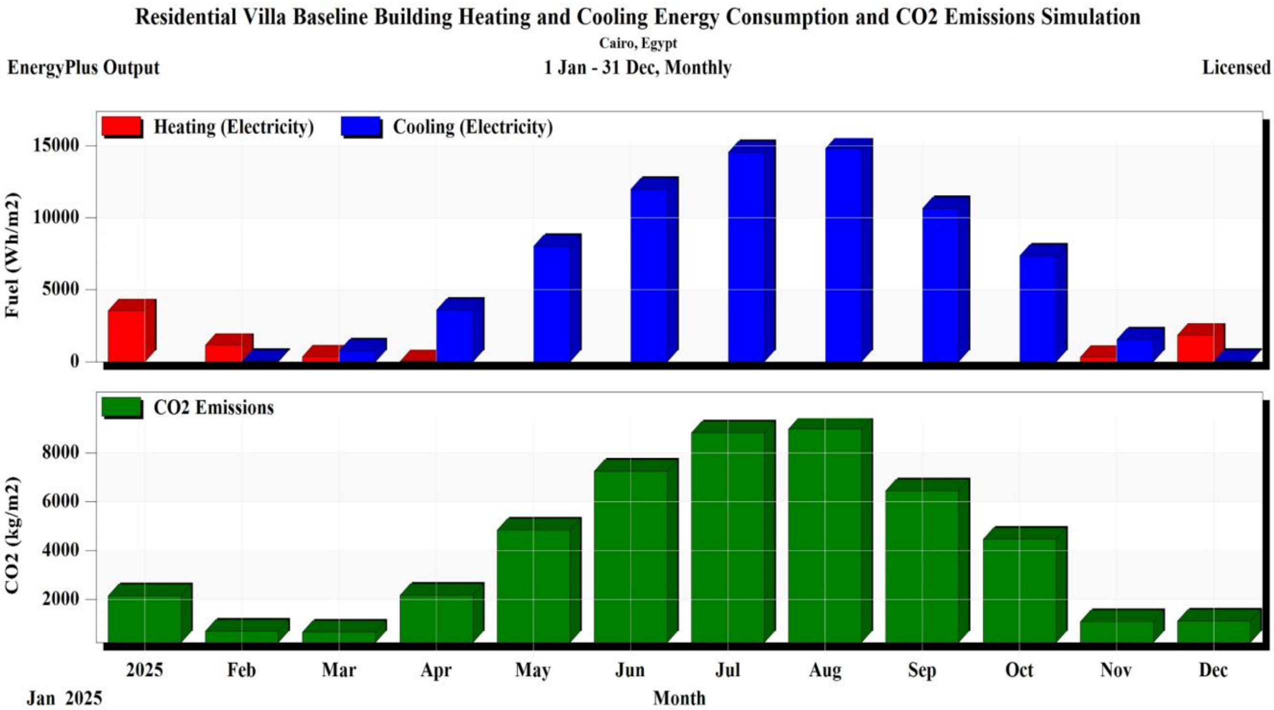


Figure (4) Residential Villa Baseline Building Heating and Cooling Energy Consumption and CO_2 Emissions Simulation [5]

5.4 Residential Villa Building Simulation Optimization.

In the baseline building model, a building performance simulation-based optimization process was utilized to evaluate twenty-five proposed scenarios, incorporating five local alternatives for external wall systems, as detailed in Table 1, and five local alternatives for external glazing systems, as outlined in Table 2. The primary objective of this optimization is to identify the most effective scenario for minimizing building energy consumption while concurrently reducing associated CO_2 emissions in the climate of Cairo, Egypt. This optimization process also involves the calculation of five additional outputs, including heat gains and losses through external walls, heat gains and losses through external glazing, solar heat gains, cooling energy consumption, and heating energy consumption.

Table (1) Residential Villa Building External Wall System Alternatives [2] [4] [5] [13] [16]

Wall Type	Wall Materials	Wall Layers	Wall Thermal Transmittance (U-value)
Wall Type (A) 300 mm-thick Single Concrete Block Wall	• 30 mm-thick Sand-Cement Plaster. • 250 mm-thick Concrete Block. • 20 mm-thick Sand-Cement Plaster.		Thickness (m) 0.3000 Km - Internal heat capacity (KJ/m2-K) 141.5680 Upper resistance limit (m2-K/W) 0.730 Lower resistance limit (m2-K/W) 0.730 U-Value surface to surface (W/m2-K) 1.787 R-Value (m2-K/W) 0.730 **U-Value (W/m2-K) 1.371**

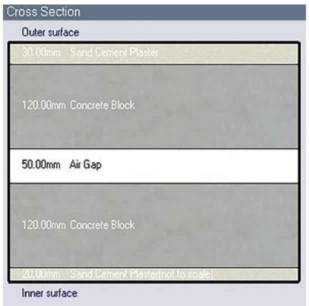
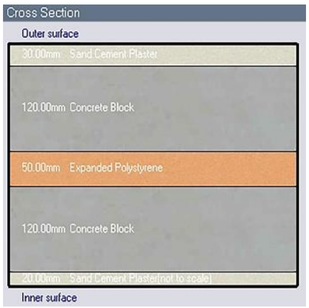
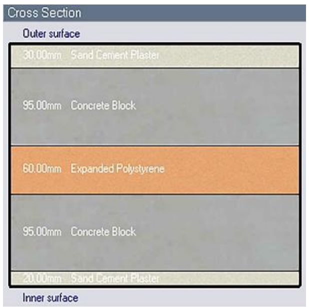
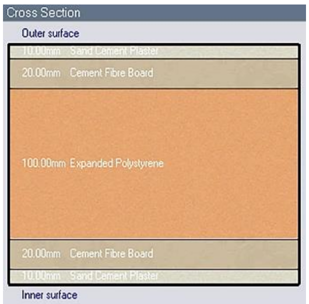
Wall Type (B) 340 mm-thick Double Concrete Block Wall	• 30 mm-thick Sand-Cement Plaster. • 120 mm-thick Concrete Block. • 50 mm-thick Air Gap. • 120 mm-thick Concrete Block. • 20 mm-thick Sand-Cement Plaster.		Thickness (m) 0.3400 Km - Internal heat capacity (KJ/m2-K) 141.5680 Upper resistance limit (m2-K/W) 0.890 Lower resistance limit (m2-K/W) 0.890 U-Value surface to surface (W/m2-K) 1.389 R-Value (m2-K/W) 0.890 **U-Value (W/m2-K) 1.124**
Wall Type (C) 340 mm-thick Double Insulated Concrete Block Wall	• 30 mm-thick Sand-Cement Plaster. • 120 mm-thick Concrete Block. • 50 mm-thick Expanded Polystyrene (EPS) Panel. • 120 mm-thick Concrete Block. • 20 mm-thick Sand-Cement Plaster.		Thickness (m) 0.3400 Km - Internal heat capacity (KJ/m2-K) 141.5680 Upper resistance limit (m2-K/W) 1.960 Lower resistance limit (m2-K/W) 1.960 U-Value surface to surface (W/m2-K) 0.559 R-Value (m2-K/W) 1.960 **U-Value (W/m2-K) 0.510**
Wall Type (D) 300 mm-thick Single Thermal Insulation Concrete Block Wall	• 30 mm-thick Sand-Cement Plaster. • 250 mm-thick Thermal Insulation Concrete Block. • 20 mm-thick Sand-Cement Plaster.		Thickness (m) 0.3000 Km - Internal heat capacity (KJ/m2-K) 141.5680 Upper resistance limit (m2-K/W) 2.112 Lower resistance limit (m2-K/W) 2.112 U-Value surface to surface (W/m2-K) 0.515 R-Value (m2-K/W) 2.112 **U-Value (W/m2-K) 0.473**
Wall Type (E) 160 mm-thick Precast Cement Sandwich Panels Wall	• 10 mm-thick Sand-Cement Plaster. • 140 mm-thick Precast Cement Sandwich Panels. • 10 mm-thick Sand-Cement Plaster.		Thickness (m) 0.1600 Km - Internal heat capacity (KJ/m2-K) 22.1490 Upper resistance limit (m2-K/W) 3.364 Lower resistance limit (m2-K/W) 3.364 U-Value surface to surface (W/m2-K) 0.313 R-Value (m2-K/W) 3.364 **U-Value (W/m2-K) 0.297**

Table (2) Residential Villa Building External Glazing System Alternatives [2] [5] [13]

Glazing Type	Glazing Materials and Layers	Glazing Thermal Transmittance (U-value)
Glazing Type (A) 6 mm-thick Single Clear Glass	• 6 mm-thick Clear Glass Panel.	Calculated Values Total solar transmission (SHGC) 0.819 Direct solar transmission 0.775 Visible transmittance 0.881 U-value (ISO 10292/ EN 673) (W/m2-K) 5.718 **U-Value (W/m2-K) 5.778**

Glazing Type (B) 25 mm-thick Double Clear Glass	• 6 mm-thick Clear Glass Panel. • 13 mm-thick Air Gap. • 6 mm-thick Clear Glass Panel.	Calculated Values Total solar transmission (SHGC) 0.703 Direct solar transmission 0.604 Visible transmittance 0.781 U-value (ISO 10292/ EN 673) (W/m2-K) 2.785 **U-Value (W/m2-K) 2.665**
Glazing Type (C) 25 mm-thick Double Insulated Clear Glass	• 6 mm-thick Clear Glass Panel. • 13 mm-thick Argon Gas Gap. • 6 mm-thick Clear Glass Panel.	Calculated Values Total solar transmission (SHGC) 0.704 Direct solar transmission 0.604 Visible transmittance 0.781 U-value (ISO 10292/ EN 673) (W/m2-K) 2.626 **U-Value (W/m2-K) 2.511**
Glazing Type (D) 25 mm-thick Double Low-E Glass	• 6 mm-thick Low-E Glass Panel. • 13 mm-thick Air Gap. • 6 mm-thick Low-E Glass Panel.	Calculated Values Total solar transmission (SHGC) 0.584 Direct solar transmission 0.467 Visible transmittance 0.666 U-value (ISO 10292/ EN 673) (W/m2-K) 1.622 **U-Value (W/m2-K) 1.545**
Glazing Type (E) 25 mm-thick Double Insulated Low-E Glass	• 6 mm-thick Low-E Glass Panel. • 13 mm-thick Argon Gas Gap. • 6 mm-thick Low-E Glass Panel.	Calculated Values Total solar transmission (SHGC) 0.589 Direct solar transmission 0.467 Visible transmittance 0.666 U-value (ISO 10292/ EN 673) (W/m2-K) 1.410 **U-Value (W/m2-K) 1.371**

Following the optimization process undertaken, a total of twenty-five scenarios were simulated to ascertain the optimal external walls and glazing systems for the proposed residential villa building situated in Cairo, Egypt. The aim was to determine the most effective configuration for thermal and energy performance while minimizing associated CO_2 emissions.

Figure 5 illustrates the results of the building optimization process, highlighting the optimal scenario, as indicated by the marked red point, which is further elaborated in Appendix 2. This optimal scenario incorporates external wall type E, consisting of 160 mm-thick precast cement sandwich panels, and external glazing type E, which comprises a 25 mm-thick double-insulated Low-E glass panel.

Appendix 2 presents a comparative analysis of twenty-five scenarios, which evaluates all combinations of five external wall types and five glazing types to identify the optimum systems that minimize energy consumption and, consequently, reduce CO_2 emissions.

The outcomes of the optimization simulations diverge from the baseline building scenario, which utilizes external wall type A paired with external glazing type A, resulting in a yearly energy consumption of 17,773,190.79 kWh and an associated yearly CO_2 emission of approximately 10,770,543.17 kg. In contrast, the optimal scenario employs external walls type E alongside external glazing type E, achieving a yearly energy consumption of 13,645,302.46 kWh and producing a yearly CO_2 emission of roughly 8,269,045.27 kg. [5]

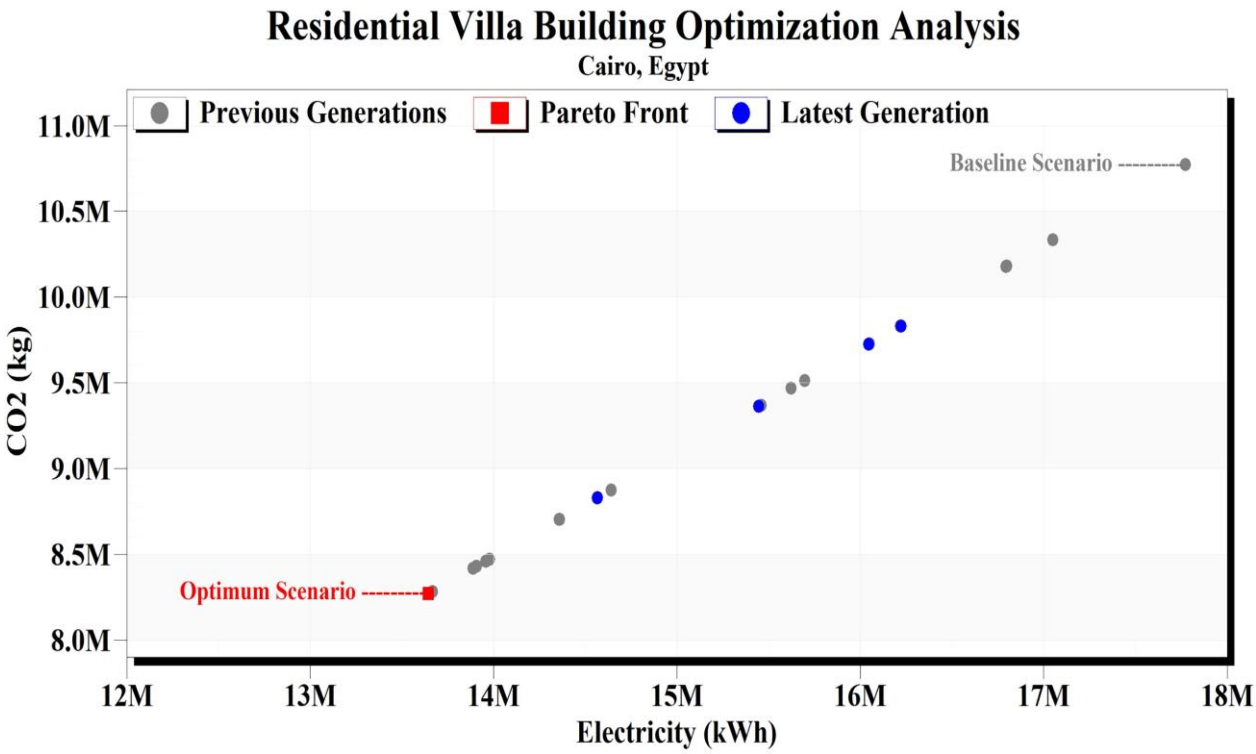


Figure (5) Residential Villa Building Optimization Analysis [5]

5.5 Residential Villa Optimized Building Simulation.

A comprehensive simulation analysis was performed on the optimized building model of the residential villa, utilizing the highest performing external wall and glazing system types identified through the building performance simulation-based optimization process.

The optimum external walls of the building, classified as external wall type E, using a precast cement sandwich panels wall, consist of 100 mm-thick expanded polystyrene (EPS) panels, which are subsequently covered by a 20 mm-thick layer of external and internal cement fiber boards and a 10 mm-thick layer of external and internal sand-cement plaster. The overall thermal transmittance (U-value) for these external walls is measured at 0.297 W/m²K. [5]

The optimum external glazing system of the building, classified as external glazing type E, is made up of a double 6 mm-thick double Low-E glass panel filled with a 13 mm argon gas gap. The overall thermal transmittance (U-value) for this external glazing is recorded at 1.371 W/m²K. [5]

The data presented in Figure 6 demonstrates that thermal gains and losses through the external walls and glazing systems of the building significantly impact the heating, ventilation, and air conditioning (HVAC) system. Over the years, the total energy consumption for HVAC cooling has been approximately 59,633.28 Wh/m², while the total energy consumption for HVAC heating has amounted to around 2,805.63 Wh/m². Consequently, the total yearly energy consumption for the HVAC system is calculated to be 62,438.91 Wh/m². Additionally, the building's total carbon dioxide (CO_2) emissions for the year reached 37,837.93 kg/m^2. [5] (Appendix 3)

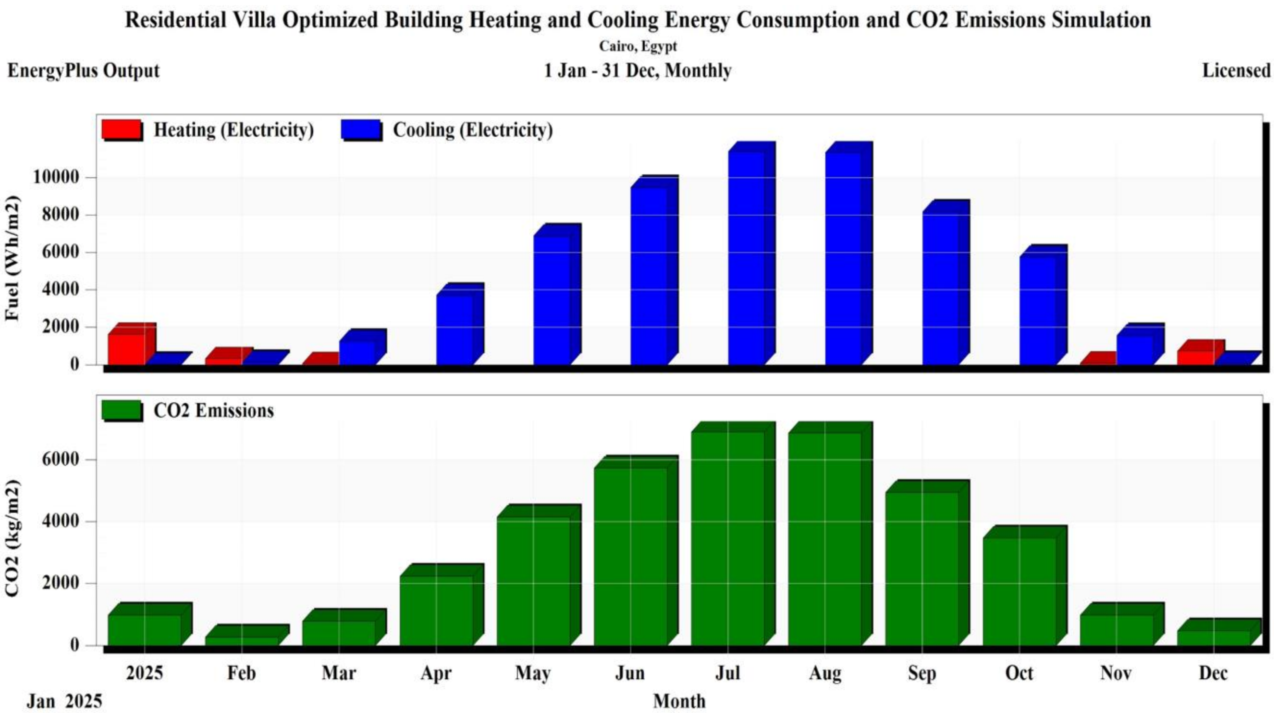


Figure (6) Residential Villa Optimized Building Heating and Cooling Energy Consumption and CO_2 Emissions Simulation [5]

6 Results and Discussion.

This study investigates the potential of utilizing building performance simulation-based optimization (BPSO) to enhance the thermal performance and energy efficiency of a proposed residential villa building in Cairo, Egypt. To carry out this study, building performance simulation software was employed, specifically Design Builder Software (Version 7.3.1.003) and Energy Plus (Version 9.4.0.002). The analysis involved a comparative evaluation of two distinct villa scenarios: a baseline building model that incorporates conventional external walls and glazing systems, and an optimized building model that features the most effective external walls and glazing system derived from a building performance simulation-based optimization process. The primary objective of this investigation was to assess the advantages of implementing BPSO to enhance overall building performance while simultaneously promoting environmental sustainability.

The proposed villa is designed as a two-story building, featuring a footprint area of 163.06 m^2 and a total area of 329.20 m^2, with a ceiling height of 3.50 meters. The energy systems for the building incorporate individual water heaters powered by natural gas, while electricity will be utilized for other appliances. The villa is intended to support an occupancy density of 0.033 persons/m^2. The HVAC system will comprise separate split units, meticulously calibrated to maintain temperatures of 24 °C during the summer months and 22 °C during the winter months. [5]

The baseline building model integrates a conventional external wall system (wall type A) constructed from 300 mm-thick single concrete blocks. This assembly achieves an overall thermal transmittance (U-value) of 1.371 W/m²K for the external walls. Additionally, the conventional external glazing system (glazing type A) comprises a single 6 mm-thick single clear glass, which exhibits an overall thermal transmittance (U-value) of 5.778 W/m²K. [5]

The optimized building model incorporates the most effective type of external wall, derived from the building performance simulation-based optimization process (wall type E). This wall system utilizes 160 mm-thick precast cement sandwich panels. The overall thermal transmittance (U-value) for these external walls is measured at 0.297 W/m²K. Furthermore, the optimal external glazing system (glazing type E) comprises 25 mm-thick double-insulated Low-E glass. The overall thermal transmittance (U-value) for this external glazing system is recorded at 1.371 W/m²K. [5]

The analysis illustrated in Figure 7 from the simulation study demonstrates a substantial decrease in yearly heating and cooling energy consumption and a reduction in CO_2 emissions when comparing the baseline building model scenario to the optimized building model scenario. Specifically, the results indicate a decline in yearly energy consumption from 76,855.48 Wh/m² in the baseline building scenario to 62,438.91 Wh/m² in the optimized building scenario. Furthermore, there is a noteworthy reduction in CO_2 emissions from 46,574.37 kg/m² in the baseline building scenario to 37,837.93 kg/m² in the optimized building scenario. [5]

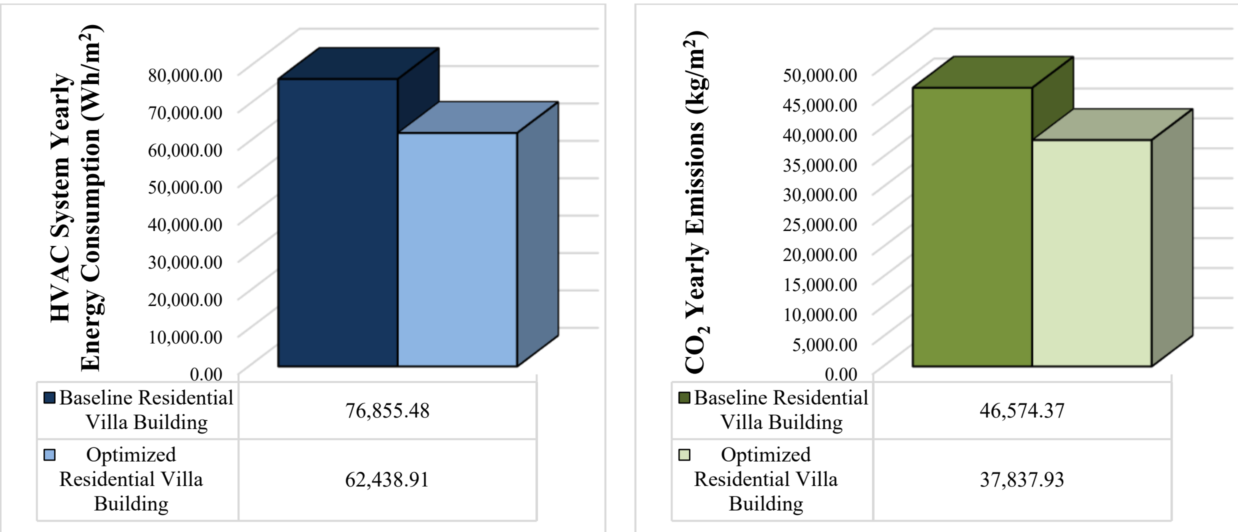


Figure (7) Building Yearly Heating and Cooling Energy Consumption and CO_2 Emissions [5]

The findings of this study indicate that the implementation of building performance simulation-based optimization for a proposed residential villa building model in Cairo, Egypt, serves as an effective tool for selecting optimal local building materials and systems that are well-suited to the regional climate. This approach has the potential to achieve a significant reduction of up to 18.76% in HVAC energy consumption. Additionally, this methodology contributes to a corresponding decrease in associated CO_2 emissions by the same margin of 18.76%.

A strong emphasis on economic factors will be essential in future research, especially when the simulation's primary goal is to assess financial viability. Evaluating the costs of different building materials is crucial for promoting sustainability in the construction sector. This focus on economic feasibility is important for developing strategies that encourage environmentally responsible practices in building design and construction. It can be applied when selecting alternative building materials and accurately integrating their costs into the simulation process to assess their financial impact.

Building performance simulation-based optimization process represents an advanced methodology for enhancing the overall performance of buildings while fostering environmental sustainability. By utilizing sophisticated computational tools, building performance simulation-based optimization process enables the thorough evaluation of a wide array of design, materials, and systems alternatives, allowing for the optimization of critical parameters such as energy efficiency, thermal comfort, daylighting, and HVAC system performance. This evidence-based approach significantly reduces the dependence on trial-and-error techniques, leading to decreased energy consumption and operational costs while ensuring adherence to sustainability standards.

Moreover, building performance simulation-based optimization process promotes the effective integration of renewable energy systems and passive design strategies, contributing to the minimization of carbon emissions and the overall reduction of environmental negative impacts. Consequently, it emerges as an essential instrument for realizing high-performance, environmentally responsible buildings that are aligned with global sustainability objectives.

7 Conclusion.

This study has highlighted the significant potential of building performance simulation-based optimization (BPSO) as a transformative methodology aimed at enhancing thermal and energy efficiency in residential buildings located in hot-arid climates, particularly in Cairo, Egypt. By implementing a parametric optimization process using Design Builder and Energy Plus, this study systematically examined and evaluated twenty-five combinations of local external walls and glazing systems alternatives to determine the optimal building envelope configuration for a residential villa.

The findings from the simulations and optimization indicate that substantial improvements in both thermal comfort and energy performance can be achieved through informed decisions regarding envelope design. The optimal configuration, consisting of 160 mm-thick precast cement sandwich panels (wall type E) and 25 mm-thick double-insulated Low-E glass (glazing type E), led to a notable reduction in yearly cooling and heating loads compared to the baseline scenario, which employed conventional 300 mm-thick concrete blocks for external walls and a 6 mm-thick single-glazed clear glass. Specifically, the optimized scenario achieved an 18.76% reduction in total HVAC energy consumption, along with a similar decrease in associated CO_2 emissions, thereby underscoring the direct environmental benefits of data-driven envelope optimization.

Importantly, this study fills a notable gap in the existing literature by focusing on low-rise residential buildings within the context of Cairo, a sector that has been underrepresented in previous BPSO studies that typically emphasize institutional or multi-family structures. The case study approach provides a nuanced understanding of local construction practices, material availability, and climatic stressors, offering actionable insights for both new construction and retrofitting efforts in similar environmental and urban conditions.

Furthermore, the study validates the application of multi-objective simulation-based optimization in a hot-arid climate, which historically presents challenges due to intense solar radiation, significant diurnal temperature variations, and limited passive cooling opportunities. The capacity of BPSO to adapt to context-specific variables emphasizes its utility as a strategic decision-making tool that connects architectural design with sustainable engineering.

In conclusion, the integration of advanced simulation tools and optimization algorithms can play a vital role in Egypt's broader transition towards energy-efficient and climate-resilient buildings. As demonstrated by this case study, even small adjustments in building envelope design can result in considerable environmental and economic benefits when guided by a data-driven methodology.

Future research should build on this foundation by incorporating real-time operational data through digital twin frameworks, exploring adaptive control strategies, and assessing the integration of renewable energy systems. By doing so, simulation-based optimization can be positioned not merely as a technical tool but also as a key component of Egypt's sustainable urban development strategy.

8 Recommendations.

To improve the overall performance of buildings using building performance simulation-based optimization (BPSO) in Egypt, policymakers, developers, architects, and engineers are advised to consider the following actionable strategies derived from the findings of this study.

8.1 Recommendations for Policymakers.

- Integrate building performance simulation-based optimization into building codes and standards to improve overall building performance.
- Offering incentives like tax credits, grants, or subsidies for projects using these methods would be beneficial to encourage the adoption of building performance simulation-based optimization and improve building performance beyond regulations.
- Promote research and training by funding academic and industry efforts to enhance building performance simulation-based optimization algorithms, improve interoperability, and ensure real-world applicability.

8.2 Recommendations for Developers, Architects, and Engineers.

- Incorporate building performance simulation-based optimization in the conceptual design phase to evaluate energy efficiency, daylighting, and thermal comfort, minimizing costly redesigns later.
- Enhance passive design by optimizing building performance through simulation. This will improve building orientation, shading, natural ventilation, and envelope design for greater efficiency.
- Achieve harmony between aesthetics and performance by aligning architectural innovation with energy efficiency and carbon reduction through iterative optimization based on simulations.

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10 Appendices.

10.1 Appendix (1): Residential Villa Baseline Building Heating and Cooling Energy Consumption and CO_2 Emissions Simulation. [5]

Residential Villa Baseline Building Heating and Cooling Energy Consumption and CO2 Emissions Simulation

Cairo, Egypt

EnergyPlus Output — **1 Jan - 31 Dec, Monthly** — **Licensed**

Month												
Heating (Electricity)	3563.97	1155.41	335.39	0.83	0.00	0.00	0.00	0.00	0.00	0.00	303.19	1844.38
Cooling (Electricity)	0.00	11.34	756.38	3578.37	8004.15	11972.41	14542.35	14824.71	10639.19	7363.41	1509.43	14.54
CO2 Emissions	2159.76	707.05	661.61	2168.99	4850.51	7255.27	8812.66	8983.77	6447.34	4462.22	1098.45	1126.50

10.2 Appendix (2): Residential Villa Building Optimization Analysis. [5]

Scenario		Objective		Additional Output					Options Alternatives	
No.	Category	Electricity Consumption (kWh)	CO2 Emissions (kg)	Walls Gains (kWh)	Glazing Gains (kWh)	Solar Gains (kWh)	Cooling Electricity (kWh)	Heating Electricity (kWh)	External Glazing Type	External Wall Type
1	Baseline	17773190.8	10770543.2	91.77	-11949.69	54072.98	21718.73	2136.73	Type (A)	Type (A)
2		14360413.7	8702402.25	-239.46	-7637.94	47646.58	18216.21	817.43	Type (C)	Type (E)
3		13907523	8427950.77	61.78	-5693.25	43647.21	17544.43	911.73	Type (E)	Type (C)
4		13959021.5	8459158.83	28.66	-6169.97	44206.88	17623.89	893.73	Type (D)	Type (D)
5		13889902.1	8417272.47	88.97	-5969.83	43647.21	17489.65	955.9	Type (D)	Type (C)
6		15453854.2	9365026.56	636.96	-5468.87	43647.21	19078.75	1591.63	Type (E)	Type (B)
7		14359093.3	8701602.12	-228.41	-7780.75	47646.58	18195.26	843.3	Type (B)	Type (E)
8		14642395.8	8873283.25	-169.27	-7553.63	47646.58	18520.02	892.51	Type (C)	Type (D)
9		13978707.7	8471088.63	2.46	-5892.95	44206.88	17680.28	851.07	Type (E)	Type (D)
10	Optimum	13645302.5	8269045.26	-104.92	-6248.23	44206.88	17280.37	813.01	Type (E)	Type (E)
11		16051801.5	9727382.3	306.03	-7250.22	47087.01	19814.1	1656.95	Type (B)	Type (B)
12		15622691.1	9467341.65	-257.07	-12111.73	53513.65	19586.14	1201.58	Type (A)	Type (C)
13		16793512.4	10176858.7	457.07	-7214.83	47646.58	20626.68	1872.1	Type (C)	Type (A)
14		16800136.2	10180872.7	485.2	-7358.72	47646.58	20613.44	1902.07	Type (B)	Type (A)
15		17051129.3	10332974.3	-23.52	-11841.21	53513.65	20954.63	1891.15	Type (A)	Type (B)
16		15459515.9	9368457.51	-317.88	-12424.65	54072.98	19471.4	1077.09	Type (A)	Type (E)
17		14641732.1	8872881.06	-153.47	-7696.17	47646.58	18500.73	918.27	Type (B)	Type (D)
18		14566342.8	8827195.19	-122.66	-7348.31	47087.01	18378.55	951.86	Type (C)	Type (C)
19		16218393.5	9828336.93	917.79	-5853.72	44206.88	19861.72	1888.2	Type (D)	Type (A)
20		15697227.2	9512510.44	-291.47	-12328.08	54072.98	19727.74	1139.54	Type (A)	Type (D)
21		13666991.5	8282188.79	-123.25	-5970.73	44206.88	17340.49	770.88	Type (D)	Type (E)
22		16222787	9830999.39	871.93	-5576.01	44206.88	19905.24	1836.66	Type (E)	Type (A)
23		15447459.2	9361151.18	678.62	-5745.88	43647.21	19033.44	1642.25	Type (D)	Type (B)
24		14566683.5	8827401.66	-106.27	-7490.54	47087.01	18360.12	978.28	Type (B)	Type (C)
25		16046006.7	9723870.61	280.6	-7107.13	47087.01	19828.06	1627.34	Type (C)	Type (B)

10.3 Appendix (3): Residential Villa Optimized Building Heating and Cooling Energy Consumption and CO_2 Emissions Simulation. [5]

Residential Villa Optimized Building Heating and Cooling Energy Consumption and CO2 Emissions Simulation

Cairo, Egypt

EnergyPlus Output — **1 Jan - 31 Dec, Monthly** — **Licensed**

Month												
Heating (Electricity)	1621.70	330.18	56.46	0.00	0.00	0.00	0.00	0.00	0.00	0.00	76.96	720.33
Cooling (Electricity)	6.41	114.98	1243.22	3690.83	6867.49	9464.79	11391.37	11335.47	8165.24	5742.86	1543.29	67.33
CO2 Emissions	986.64	269.77	787.60	2236.64	4161.69	5735.65	6903.16	6869.29	4948.13	3480.17	981.87	477.32