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Envelope Design Trade-offs for Low-carbon Residential Buildings in Dubai: A Simulation-based Multi-objective Optimization Study

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Abstract

Residential buildings in Dubai experience high cooling demand due to extreme climatic conditions, increasing both operational energy consumption and carbon-related environmental impacts. While previous studies have commonly focused on operational energy reduction, fewer investigations have simultaneously examined thermal comfort and embodied carbon implications within residential envelope optimization. This study investigates envelope design trade-offs for low-carbon residential buildings in Dubai through a simulation-based multi-objective optimization framework. A two-story residential villa prototype was developed in DesignBuilder and evaluated under Dubai climatic conditions using an EnergyPlus simulation engine and hourly weather data. Five envelope-related variables were optimized, including window-to-wall ratio, glazing type, external shading depth, wall construction, and roof construction, while occupancy, HVAC performance, ventilation, and operational schedules remained fixed. Optimization was conducted to identify balanced envelope solutions based primarily on annual site energy consumption and thermal discomfort, while embodied carbon was retained as a supporting material-impact indicator. The baseline model recorded an annual site energy use of 40,427.48 kWh/year, corresponding to 189.44 kWh/m^2·year, with 3,036.50 annual discomfort hours. Optimized solutions achieved reductions in annual site energy use to approximately 18,107 kWh/year, representing an improvement of nearly 55% relative to the baseline case. Results consistently favored moderate window-to-wall ratios, low-emissivity glazing, insulated roof assemblies, and external shading strategies. The findings provide practical guidance for climate-responsive residential envelope design in Dubai and contribute evidence for balancing operational and embodied environmental performance in cooling-dominated climates.

Keywords: Envelope Optimization; Residential Buildings; Dubai; Thermal Comfort; Embodied Carbon; Building Energy Simulation; Low-Carbon Design

1. Introduction

The buildings and construction sector remains one of the largest contributors to global energy demand and greenhouse-gas emissions, making decarbonization of the built environment central to climate mitigation efforts. Recent global assessments indicate that buildings account for approximately 34% of worldwide energy demand and 37% of energy- and process-related carbon dioxide (CO_2) emissions, while residential buildings represent nearly 70% of total building-sector energy demand [1,2]. These figures highlight the scale of the operational challenge associated with residential energy use and reinforce the urgency of improving building performance through climate-responsive and low-carbon design strategies [3–6].

The challenge becomes more pronounced in hot-arid regions, particularly across the Middle East and North Africa (MENA), where summer temperatures frequently exceed 40°C and cooling demand dominates electricity consumption patterns. Cooling already accounts for nearly half of peak electricity demand and approximately one-quarter of annual

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electricity use across several regional economies, while total electricity demand has tripled since 2000 and is projected to increase by a further 50% by 2035 [1]. Under these climatic and infrastructural pressures, reducing cooling-related operational demand has become a priority for residential sustainability, energy security, and long-term carbon mitigation.

Within this context, the building envelope, including glazing systems, walls, roofs, and external shading, plays a decisive role in regulating solar heat gain, conductive thermal transfer, and indoor thermal performance. In cooling-dominated climates, envelope-related decisions strongly influence both annual operational energy demand and occupant comfort by moderating exposure to extreme outdoor conditions. Previous research has consistently demonstrated that variables such as window-to-wall ratio (WWR), glazing specification, insulation level, and solar-control strategies can substantially alter residential energy performance, particularly in environments characterized by intense solar radiation and prolonged summer exposure [7–10]. Climate-responsive envelope optimization has therefore emerged as an important passive strategy for reducing cooling loads while maintaining acceptable indoor environmental conditions.

At the same time, the sustainability discussion surrounding residential buildings has expanded beyond operational energy performance alone. As operational efficiency improves, embodied carbon associated with construction materials increasingly contributes to total life-cycle environmental impact, creating new trade-offs between material intensity, operational savings, and long-term carbon performance [11–13]. Recent studies have emphasized the need to evaluate building performance through integrated approaches capable of simultaneously addressing energy demand, material sufficiency, and environmental impact rather than treating these considerations independently [13–15].

Dubai represents a particularly relevant environment for investigating residential envelope performance under these competing constraints. Classified as a hot desert climate (BWh) and ASHRAE climate zone 1B, Dubai experiences prolonged periods of extreme heat, high solar exposure, and elevated night-time temperatures that limit passive thermal relief. Unlike climates where nocturnal cooling can offset daytime heat accumulation, Dubai frequently records persistently high evening temperatures, intensifying dependence on mechanical cooling systems. Furthermore, coastal humidity effects during summer periods increase thermal stress and complicate indoor environmental control. Under such conditions, residential envelope decisions, including glazing type, insulation strategy, solar shading, and façade openness, become critical determinants of operational energy use, indoor comfort, and environmental performance [16–18].

Environmental design research has increasingly emphasized the importance of simulation-based optimization frameworks for identifying balanced envelope solutions capable of reducing cooling demand while avoiding unintended environmental burdens. Multi-objective approaches informed by evolutionary optimization methods have demonstrated strong potential for evaluating trade-offs among competing performance objectives in residential buildings, particularly where energy demand, comfort, and carbon considerations interact simultaneously [19]. Recent work on hot-arid residential buildings has further reinforced the importance of balancing material sufficiency, operational performance, and life-cycle environmental impact when selecting envelope strategies for cooling-dominated climates [13].

1.1. Research Gap

Despite substantial progress in building-performance optimization, several limitations remain within the literature. Many studies in hot climates prioritize operational energy reduction while paying comparatively limited attention to thermal comfort implications or embodied carbon consequences associated with material selection [20,21]. Other investigations examine façade variables such as window-to-wall ratio, shading, or glazing independently, limiting understanding of how envelope components interact under climate-specific conditions [10,22].

Optimization approaches using evolutionary and genetic algorithms have demonstrated strong potential for identifying high-performance design alternatives, particularly in building energy analysis [19,23]. However, geographically specific residential studies for Gulf cities remain comparatively limited, especially those examining detached housing typologies under Dubai climatic conditions. Recent multi-city optimization investigations have further demonstrated that glazing, shading systems, and envelope variables may produce substantially different performance outcomes across locations despite broad climatic similarities, emphasizing the importance of city-specific studies [4,13]. Similarly, recent envelope optimization research has reinforced the importance of balancing multiple objectives rather than pursuing energy reduction alone, particularly where solar exposure and cooling intensity are dominant environmental factors [4,5,7,13].

Furthermore, limited research has comprehensively examined the interaction between operational energy demand, thermal comfort, and embodied carbon in Dubai residential envelopes using a simulation-based optimization framework. This gap creates uncertainty for architects and designers seeking practical guidance regarding the combined influence of glazing type, window-to-wall ratio, roof insulation, wall construction, and shading depth in cooling-dominated climates.

Aim, Objectives, and Contribution

This study addresses these limitations by investigating envelope design trade-offs for low-carbon residential buildings in Dubai through a simulation-based multi-objective optimization framework. A representative residential villa prototype was developed and simulated under Dubai climatic conditions using DesignBuilder and EnergyPlus, while maintaining fixed operational assumptions related to occupancy, ventilation, internal gains, and HVAC efficiency. The analysis focuses specifically on five influential envelope variables: window-to-wall ratio, glazing specification, external shading depth, roof construction, and wall construction.

The study pursues four objectives: (1) to establish the baseline environmental performance of a representative Dubai residential prototype; (2) to evaluate how key envelope variables influence annual energy consumption, thermal comfort, and embodied carbon; (3) to identify trade-offs between energy performance and thermal comfort while considering material-related environmental implications; and (4) to provide practical envelope recommendations for climate-responsive residential design in Dubai. By combining operational and embodied environmental considerations within a constrained yet practically applicable optimization framework, the study contributes a decision-support approach for architects and environmental designers working in hot-arid urban environments. This perspective aligns with emerging discussions on environmentally informed decision-support systems, where sustainability outcomes increasingly require balancing competing operational, material, and environmental objectives through structured evaluation frameworks [4,6,13,18,24].

2. Materials and Methods

2.1. Study Area and Climatic Context

The study was conducted for Dubai, United Arab Emirates, a rapidly urbanizing city characterized by high cooling demand and prolonged hot-weather conditions. According to the Köppen climate classification, Dubai is categorized as BWh (hot desert climate) and is further classified as ASHRAE climate zone 1B, indicating extreme summer temperatures, high solar exposure, and cooling-dominated building operation. The climatic profile is particularly relevant to residential envelope performance because elevated outdoor temperatures and limited nocturnal cooling increase dependence on mechanical air-conditioning systems [25,26].

Hourly climatic conditions were represented using the Dubai International Airport EnergyPlus Weather (EPW) file implemented in DesignBuilder. The weather dataset reports peak summer dry-bulb temperatures exceeding 42°C, while high night-time temperatures frequently restrict passive heat dissipation. In addition, the coastal setting of Dubai contributes intermittent humidity effects, increasing thermal stress during summer months. These environmental conditions make envelope-related variables—including glazing, insulation, and solar shading—critical determinants of operational performance and indoor comfort [5,7,17]. Climate-responsive envelope design has therefore become increasingly important for reducing cooling loads and improving building sustainability in Gulf environments [4,27].

2.2. Baseline Residential Prototype

A representative detached residential villa prototype was developed to reflect a simplified yet realistic residential typology appropriate to Dubai's low-rise housing context. The building consisted of two floors with a footprint of 12 m × 10 m, resulting in a conditioned floor area of 213.41 m^2 distributed across eight thermal zones. The zoning strategy differentiated between living areas, bedrooms, service spaces, and circulation zones to improve the realism of occupancy and thermal modeling.

The baseline envelope configuration adopted a 20% window-to-wall ratio (WWR) and double-clear glazing (3 mm/6 mm air cavity) without external shading. The roof assembly was modeled using a lightweight insulated flat-roof construction with a thermal transmittance of approximately 0.25 W/m^2K, while the external wall system employed insulated lightweight masonry construction. These assumptions were selected to establish a realistic reference case for envelope comparison under Dubai climatic conditions.

The building was modeled using a simplified Unitary Heat Cool HVAC system powered by electricity with a fixed cooling coefficient of performance (COP = 2.5) and heating COP of 2.0. Cooling and heating setpoints were maintained at 25°C and 20°C, respectively, with a cooling setback temperature of 28°C. Mechanical outdoor ventilation was modeled using a fixed minimum fresh-air rate of 10 L/s-person, while infiltration was maintained at 0.5 air changes per hour (ACH). Internal gains included a lighting density of approximately 5 W/m^2 and equipment density of 6 W/m^2, applied consistently across all occupied zones. Thermal comfort assessment was based on annual discomfort hours following ASHRAE Standard 55 criteria [28].

To improve methodological transparency and support reproducibility, the principal climatic, geometric, envelope, HVAC, and operational assumptions of the baseline residential model are summarized in Table 1. These parameters define the reference configuration against which all optimized envelope alternatives were evaluated.

Table 1 Baseline residential model assumptions and climatic characteristics for the Dubai case study

Category	**Parameter**	**Value**
Location	Study location	Dubai, United Arab Emirates
Climate	ASHRAE climate zone	1B
Climate	Köppen classification	BWh (hot desert climate)
Weather file	Weather station	Dubai International
Climate severity	Maximum dry-bulb temperature (0.4%)	42.9°C
Climate severity	Coincident wet-bulb temperature	23.6°C
Climate severity	Minimum night temperature (0.4%)	33.3°C
Geometry	Building type	Detached two-story residential villa
Geometry	Number of thermal zones	8
Geometry	Conditioned floor area	213.41 m^2
Geometry	Building volume	736.25 m^3
Envelope	Baseline WWR	20%
Envelope	Baseline glazing	Double clear glazing (3 mm / 6 mm air)
Envelope	Roof construction	Flat insulated roof (U-value = 0.25 W/m^2K)
Envelope	Wall construction	Lightweight concrete block with air gap and plasterboard
HVAC	HVAC system	Unitary Heat Cool
HVAC	Cooling COP	2.5
HVAC	Heating COP	2.0
Ventilation	Outdoor air rate	10 L/s-person
Airtightness	Infiltration rate	0.5 ACH
Internal loads	Lighting density	5 W/m^2
Internal loads	Equipment density	6 W/m^2
Thermal control	Cooling setpoint / setback	25°C / 28°C
Thermal control	Heating setpoint / setback	20°C / 12°C

Note**:** Annual simulations were conducted using the complete hourly Dubai International EPW weather file implemented in DesignBuilder. Climate conditions indicate a cooling-dominated environment with limited nocturnal thermal relief.

As shown in Table 1, the Dubai case study reflects a cooling-dominated residential context characterized by high outdoor temperatures and limited nocturnal thermal relief. The baseline model therefore establishes a realistic

reference scenario for evaluating how envelope modifications influence operational energy demand, thermal comfort, and embodied carbon performance.

2.3. Optimization Variables and Fixed Parameters

The study focused exclusively on envelope-related variables to isolate their influence on residential performance. Five decision variables were selected based on their established importance in hot-climate building performance studies and their direct relevance to residential cooling demand. These variables included:

- Window-to-wall ratio (WWR): 15–50%
- Glazing type: double-clear, low-emissivity, and solar-control glazing alternatives
- External shading depth: 0–2.0 m horizontal overhangs
- Roof construction: alternative insulated roof assemblies
- External wall construction: alternative insulated wall assemblies

The selected decision variables and fixed simulation parameters used in the optimization framework are summarized in Table 2. The selected ranges were chosen to reflect realistic envelope design alternatives relevant to residential applications in hot-arid climates while maintaining methodological consistency across simulations.

Table 2 Decision variables, optimization ranges, and fixed simulation assumptions

Category	Variable	Range / Option	Purpose
Decision variable	Window-to-wall ratio (WWR)	15–50%	Evaluate glazing exposure and solar heat gain
Decision variable	Glazing type	Double clear; low-emissivity; solar-control glazing	Assess solar and thermal performance
Decision variable	External shading depth	0.0–2.0 m	Reduce direct solar gains
Decision variable	Roof construction	Alternative insulated roof assemblies	Reduce conductive roof heat transfer
Decision variable	Wall construction	Alternative insulated wall assemblies	Improve thermal resistance
Fixed parameter	Building orientation	Constant	Eliminate orientation-related bias
Fixed parameter	HVAC system	Unitary Heat Cool	Ensure operational consistency
Fixed parameter	Cooling setpoint	25°C	Isolate envelope effects
Fixed parameter	Heating setpoint	20°C	Maintain consistency
Fixed parameter	Ventilation rate	10 L/s-person	Fixed fresh-air provision
Fixed parameter	Infiltration	0.5 ACH	Maintain airtightness consistency
Fixed parameter	Occupancy schedule	TM59 residential template	Standardize operational behavior
Fixed parameter	Lighting density	5 W/m^2	Constant internal load
Fixed parameter	Equipment density	6 W/m^2	Constant internal load

Note: Optimization was conducted using a multi-objective NSGA-II framework in DesignBuilder/EnergyPlus with a population size of 30, mutation rate of 0.40, and crossover rate of 1.00. Annual site energy consumption and thermal discomfort hours were evaluated through the optimization process, while embodied carbon was used as a supporting environmental indicator for interpreting envelope material implications.

By maintaining operational and behavioral assumptions constant, the optimization framework isolates the influence of envelope-related interventions and allows performance differences to be attributed directly to variations in glazing, shading, thermal resistance, and façade openness.

To maintain methodological consistency and avoid confounding effects, several parameters remained fixed across all simulations. These included occupancy schedules, HVAC system efficiency, cooling and heating setpoints, infiltration rate, ventilation rate, lighting density, equipment density, and building orientation. This approach ensured that

observed performance differences could be attributed directly to envelope modifications rather than operational variability [9,20].

2.4. Simulation and Optimization Framework

Building performance simulations were conducted using DesignBuilder with the EnergyPlus simulation engine, a validated platform widely adopted for dynamic building energy assessment [29]. A multi-objective optimization framework based on the Non-Dominated Sorting Genetic Algorithm II (NSGA-II) was employed to explore trade-offs between competing performance objectives [19]. Genetic algorithm-based optimization has been widely recognized for identifying balanced building-design solutions under complex and multidimensional constraints [23,30].

Optimization settings included a population size of 30, mutation rate of 0.40 and a crossover rate of 1.00. The optimization was executed for a fixed number of generations (30) until convergence in Pareto improvement was observed. The optimization evaluated annual site energy consumption and thermal discomfort hours as primary performance objectives, while embodied carbon was assessed as a supporting criterion for interpreting material-related trade-offs**.**

3. Results

3.1. Baseline Performance

The baseline simulation established the environmental performance of the reference residential villa under Dubai climatic conditions prior to optimization. The annual simulation covered 8,760 hours and produced a total site energy consumption of 40,427.48 kWh/year, corresponding to an energy use intensity (EUI) of 189.44 kWh/m^2·year. Cooling demand represented the dominant end-use category, accounting for approximately 88.22% of total annual site energy, confirming the strong cooling dependency of residential buildings in Dubai's hot-arid environment. Interior lighting and equipment represented comparatively smaller shares of annual consumption, accounting for 4.82% and 6.97%, respectively. These findings reinforce the importance of envelope-related interventions capable of reducing solar heat gain and conductive thermal transfer in cooling-dominated climates [8].

Thermal comfort performance further demonstrated the environmental challenges associated with residential operation in Dubai. Although the cooling system maintained the occupied cooling setpoint with only 77.50 occupied cooling setpoint-not-met hours, the building recorded 3,036.50 annual discomfort hours under the Simple ASHRAE 55 criterion, indicating persistent thermal stress despite mechanical cooling. These results suggest that operational cooling alone may be insufficient to maintain optimal indoor conditions when envelope performance remains limited. Similar findings have been reported in hot-climate building studies where excessive solar gains and envelope heat transfer substantially increase indoor thermal discomfort [21,27].

The embodied carbon inventory reported a total equivalent carbon footprint of 23,276.7 kgCO_2e, corresponding to 109.07 kgCO_2e/m^2. Roof and wall systems accounted for a substantial proportion of embodied impacts, highlighting the importance of material selection in low-carbon envelope design. Since shading systems were included as optimization variables, embodied carbon was retained as an evaluation metric to assess whether reductions in operational energy could be achieved without disproportionate increases in material-related environmental impacts [13,31].

3.2. Optimization Outcomes

The multi-objective optimization process generated a diverse set of feasible envelope alternatives, revealing substantial performance improvements relative to the baseline configuration. The best-performing optimized solution reduced annual site energy use to approximately 18,107 kWh/year, representing an improvement of approximately 55.2% compared with the baseline case. This reduction demonstrates the substantial influence of envelope modifications on cooling-dominated residential performance in Dubai and supports previous findings regarding the effectiveness of integrated façade optimization approaches [4,20].

The Pareto-optimal solution set further demonstrated that performance gains did not emerge from a single variable alone but rather from combined envelope interactions. Solutions exhibiting lower energy demand frequently balanced moderate glazing exposure with enhanced solar control and improved thermal resistance. Importantly, the optimization revealed that the lowest-energy solution was not necessarily identical to the lowest-discomfort alternative, reinforcing the need for trade-off evaluation rather than single-objective decision-making. This outcome aligns with previous multi-

objective building optimization studies showing that energy efficiency, comfort, and material impacts often exhibit competing relationships requiring balanced assessment [19,23].

To facilitate comparison between the reference case and representative optimized alternatives, Table 3 summarizes key performance indicators associated with the baseline model, the lowest-energy solution, the comfort-oriented solution, and a balanced-performance alternative extracted from the Pareto-optimal solution set.

Table 3 Representative performance outcomes of baseline and optimized envelope solutions

Scenario	Annual site energy (kWh/year)	EUI (kWh/m²·year)	Thermal discomfort (h/year)	Dominant envelope characteristics
Baseline model	40,427.48	189.44	3,036.50	20% WWR; double-clear glazing; no shading
Lowest-energy solution	18,107.08	84.85	2,261.38	28% WWR; double clear 6 mm/13 mm argon glazing; 1.0 m overhang; insulated roof and super-insulated wall
Comfort-oriented solution	19,187.22	89.91	2,227.13	22% WWR; double low-E glazing; 1.0 m overhang; insulated roof and enhanced insulated wall
Balanced-performance solution	18,513.85	86.75	2,343.38	24% WWR; double clear 6 mm/13 mm argon glazing; 0.5 m overhang; insulated roof and super-insulated wall

Note: The optimization process identified a best-performing envelope configuration capable of reducing annual site energy demand by approximately 55.2% relative to the baseline model. Representative Pareto solutions were selected to reflect energy minimization, comfort improvement, and balanced environmental performance rather than a single optimum outcome.

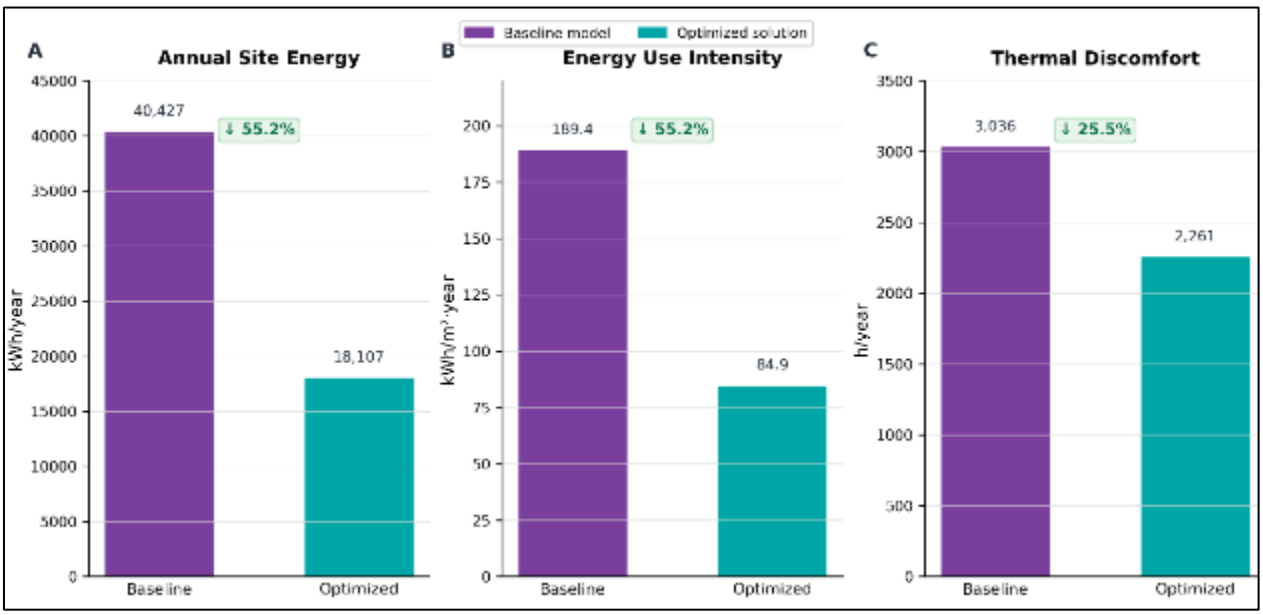

Figure 1 Comparative environmental performance of the baseline residential model and representative Pareto-optimal envelope solutions. The figure compares annual site energy consumption, energy use intensity (EUI), and thermal discomfort hours between the baseline villa and representative optimized alternatives. Results highlight the magnitude of operational improvement achieved through coordinated envelope optimization relative to the baseline configuration

The results presented in Table 3 demonstrate that meaningful operational improvements can be achieved without relying on a single optimum solution. Instead, the optimization process revealed multiple envelope configurations

capable of balancing competing priorities related to energy demand, thermal comfort, and embodied environmental impact.

To illustrate the magnitude of performance improvement achieved through envelope optimization, Figure 1 compares key indicators between the baseline model and representative optimized solutions.

The comparison confirms that coordinated envelope modifications substantially reduced annual energy demand while improving thermal performance relative to the baseline configuration.

Representative Pareto solutions were subsequently categorized into three groups: lowest-energy solution, comfort-oriented solution, and balanced-performance solution. This classification enabled interpretation of practical design priorities while avoiding overreliance on a single optimum. The balanced-performance alternative was considered particularly relevant for residential application because it achieved substantial operational improvements while maintaining acceptable thermal conditions and avoiding excessive material penalties.

To examine how façade openness and solar shading interact to influence energy performance, Figure 2 illustrates the relationship between window-to-wall ratio (WWR), shading depth, and energy use intensity (EUI) across representative optimized envelope configurations.

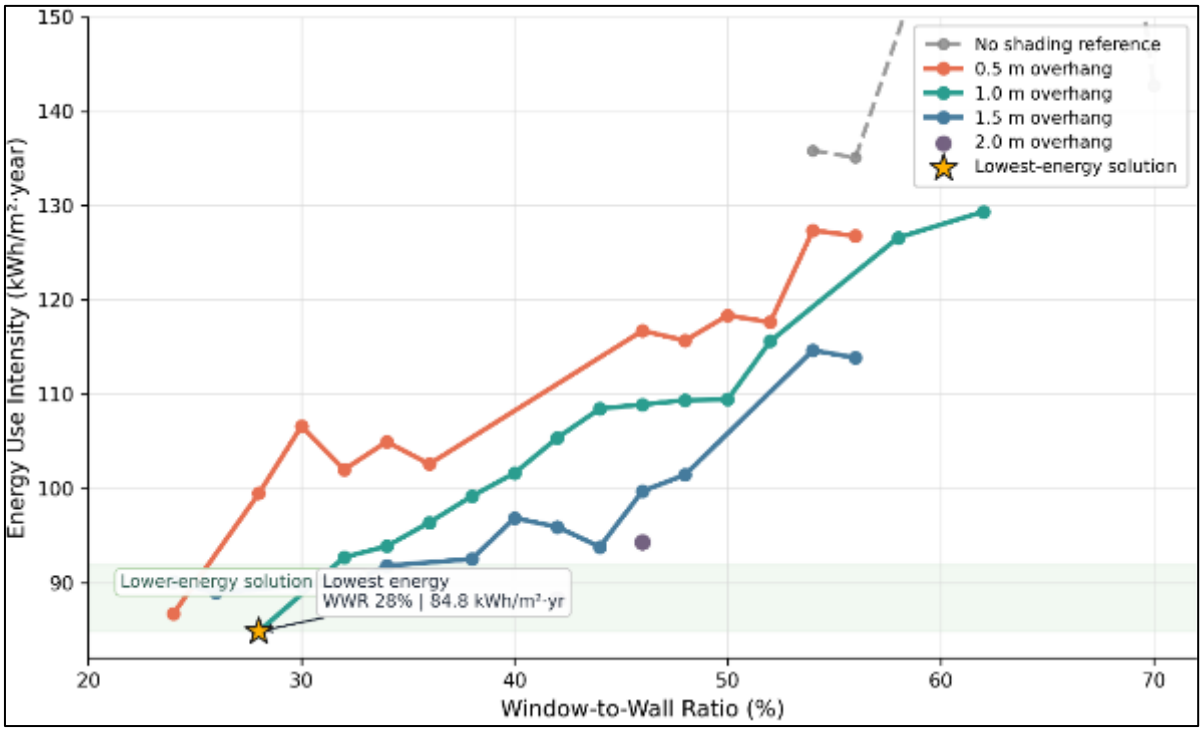

Figure 2 Relationship between window-to-wall ratio, shading depth, and energy use intensity for representative residential envelope configurations in Dubai. The figure illustrates how variations in window-to-wall ratio (WWR) and external shading depth influence residential energy use intensity (EUI) under Dubai climatic conditions. Colored lines represent alternative overhang depths, while the highlighted marker identifies the lowest-energy solution obtained through optimization. Results indicate that moderate glazing exposure combined with controlled solar shading consistently improves energy performance

Figure 2 shows that energy use intensity generally increases as WWR expands, particularly under unshaded or minimally shaded conditions. The lowest-energy configuration occurred at a moderate WWR of 28% with a 1.0 m overhang, indicating that façade openness and shading depth should be coordinated rather than selected independently.

3.3. Envelope Design Trade-Offs

Several recurring patterns emerged from the optimization results. First, moderate window-to-wall ratios consistently outperformed highly glazed façades, suggesting that excessive glazing increased solar heat gains beyond levels manageable through cooling alone. This finding is consistent with recent studies reporting diminishing energy benefits

at higher glazing percentages in hot climates [10,22]. Second, low-emissivity glazing systems appeared repeatedly among higher-performing solutions, indicating the importance of limiting solar heat transmission while maintaining daylight access.

Third, external shading systems contributed positively to cooling reduction, particularly when combined with moderate glazing areas. Envelope combinations incorporating horizontal overhangs consistently demonstrated improved energy performance compared with unshaded configurations, reinforcing the importance of passive solar-control strategies in hot-arid climates [17]. Finally, improved roof and wall thermal performance emerged as persistent features among favorable solutions, emphasizing the importance of conductive heat reduction under prolonged summer exposure.

To visualize trade-offs among competing performance objectives, Figure 3 illustrates the Pareto-optimal solution space generated through the multi-objective optimization process.

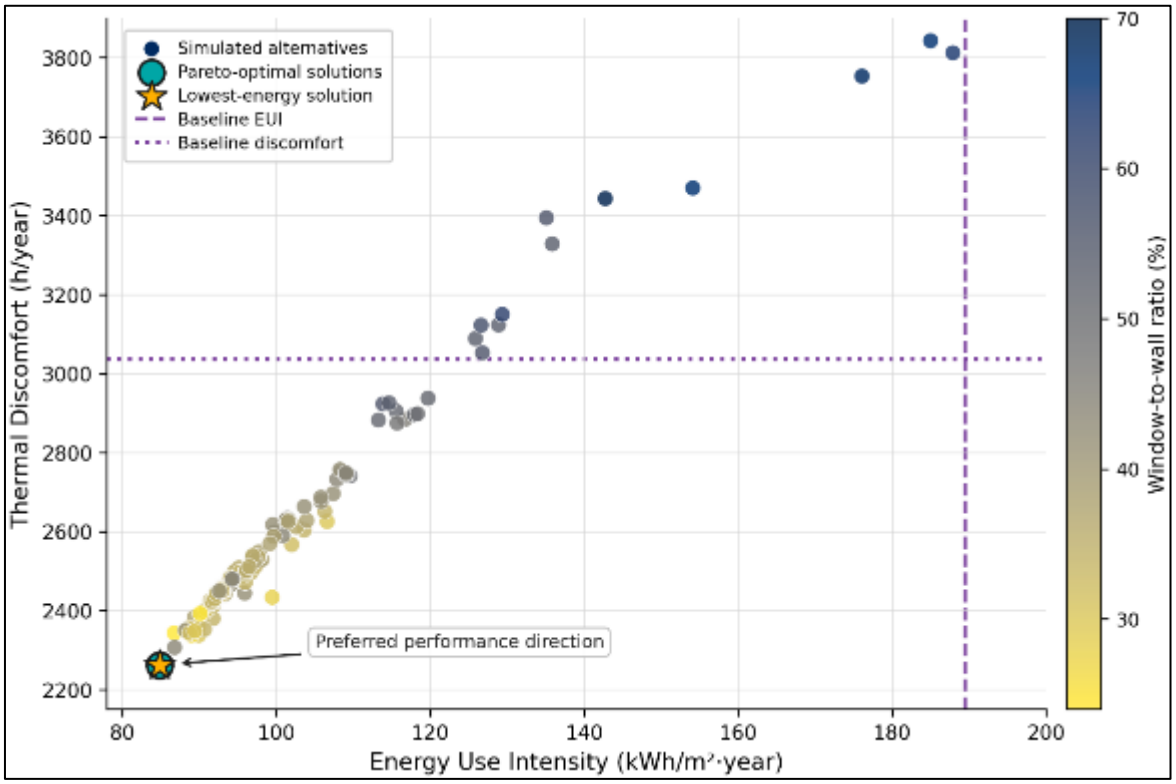

Figure 3 Pareto-optimal trade-off relationships between energy use intensity and thermal discomfort for residential envelope configurations in Dubai. The figure visualizes the Pareto-optimal solution space generated through the NSGA-II optimization framework, showing trade-offs between energy use intensity (EUI; kWh/m^2·year) and annual thermal discomfort (hours/year). Point color indicates window-to-wall ratio (WWR), while dashed lines represent baseline performance. The highlighted marker identifies the lowest-energy Pareto-optimal solution

Figure 3 demonstrates substantial environmental improvement relative to the baseline case, with optimized envelope configurations consistently achieving lower energy use intensity and reduced thermal discomfort. However, the distribution of Pareto-optimal alternatives indicates that minimizing energy demand does not always correspond to the lowest discomfort outcome, reinforcing the importance of balanced envelope decision-making.

To further examine recurring design tendencies among high-performing alternatives, Table 4 presents the top-performing Pareto-optimal envelope configurations identified during the optimization process. The selected solutions provide insight into the combinations of glazing, shading, thermal resistance, and façade openness associated with improved residential performance under Dubai climatic conditions.

Table 4 Top-performing Pareto-optimal residential envelope configurations identified through NSGA-II optimization

Rank	Annual site energy (kWh/year)	EUI (kWh/m²·year)	Thermal discomfort (h/year)	WWR (%)	Glazing type	Shading depth	Roof configuration	Wall configuration
1	18,107.08	84.85	2,261.38	28	Double clear 6 mm / 13 mm argon	1.0 m overhang	Asphalt–screed–wood wool insulated flat roof	Super-insulated brick/block wall
2	18,513.85	86.75	2,343.38	24	Double clear 6 mm / 13 mm argon	0.5 m overhang	Asphalt–screed–wood wool insulated flat roof	Super-insulated brick/block wall
3	18,521.00	86.79	2,306.63	44	Double low-E clear 3 mm / 13 mm air	1.5 m overhang	Asphalt–screed–wood wool insulated flat roof	Super-insulated brick/block wall
4	18,825.49	88.22	2,349.75	42	Double clear 6 mm / 13 mm air	2.0 m overhang	Asphalt–screed–wood wool insulated flat roof	Super-insulated brick/block wall
5	18,988.05	88.98	2,337.56	26	Double clear 6 mm / 13 mm air	1.5 m overhang	Asphalt–fibreboard insulated flat roof	Super-insulated brick/block wall

Note: Representative top-performing solutions extracted from the Pareto-optimal optimization set. Results reveal recurring design tendencies, including moderate window-to-wall ratios, insulated roof systems, external overhang shading, and super-insulated wall assemblies. The best-performing solution reduced annual site energy demand by approximately 55.2% relative to the baseline case (40,427.48 kWh/year).

Several recurring tendencies emerge from the solutions summarized in Table 4. Moderate glazing exposure, insulated roof systems, and external shading repeatedly appeared among higher-performing configurations, suggesting that coordinated envelope strategies produce stronger environmental outcomes than isolated interventions.

Taken together, the results indicate that low-carbon residential performance in Dubai cannot be attributed to isolated envelope interventions. Instead, performance improvements emerge from coordinated envelope strategies capable of simultaneously moderating solar heat gain, improving thermal resistance, and limiting material-related environmental impacts.

4. Discussion

4.1. Interpretation of Envelope Trade-Offs

The optimization results demonstrate that substantial reductions in residential energy demand can be achieved in Dubai through coordinated envelope strategies rather than isolated interventions. The optimized solutions reduced annual site energy consumption from 40,427.48 kWh/year to approximately 18,107 kWh/year, representing an improvement of nearly 55% relative to the baseline model. Such reductions highlight the strong influence of façade and roof performance in cooling-dominated environments where solar gains and conductive heat transfer dominate annual energy consumption. These findings support previous research indicating that envelope optimization remains among the most effective passive pathways for reducing cooling demand in hot climates [8,25].

However, the findings also indicate that the lowest-energy solution should not automatically be interpreted as the most suitable residential option. Multi-objective optimization revealed recurring trade-offs between operational performance, thermal comfort, and embodied carbon. While highly insulated envelopes and advanced glazing systems frequently reduced operational demand, some envelope improvements may involve additional material use, indicating the need to interpret operational savings alongside material-related impacts. This observation reinforces the importance of evaluating residential sustainability through combined operational and embodied perspectives rather than focusing exclusively on annual energy savings. More broadly, these findings support emerging sustainability discussions emphasizing structured decision-support approaches capable of balancing competing environmental objectives instead of privileging singular performance outcomes [6,31,32].

4.2. Influence of Key Envelope Variables

Several envelope variables emerged as dominant performance drivers. First, moderate window-to-wall ratios (WWR) consistently outperformed highly glazed alternatives. Although larger glazed areas may improve daylight penetration and architectural openness, excessive glazing substantially increased solar heat gain under Dubai's climatic conditions. This finding aligns with previous studies reporting that lower-to-moderate WWR values often provide stronger energy performance in hot climates due to reduced cooling loads [10,22].

Second, low-emissivity glazing systems appeared repeatedly among Pareto-optimal solutions, indicating their effectiveness in reducing solar heat transfer without eliminating visual connectivity or daylight access. Similarly, external shading depth emerged as an important design variable, particularly when combined with controlled glazing areas. Shaded configurations consistently reduced annual cooling demand compared with unshaded alternatives, supporting evidence from desert and coastal hot-climate studies emphasizing passive solar control as an essential cooling-reduction strategy [16,17].

Third, roof and wall assemblies with improved thermal resistance consistently demonstrated favorable performance outcomes. In Dubai's climate, where roof surfaces experience prolonged solar exposure and high peak temperatures, conductive heat transfer becomes a significant contributor to cooling demand. The repeated appearance of insulated roof and wall configurations among optimized solutions therefore reinforces the importance of thermal resistance in climate-responsive residential design [21,27].

4.3. Practical Implications and Study Limitations

The findings provide practical implications for residential architects, environmental designers, and sustainability consultants working in Dubai and comparable Gulf contexts. Rather than prioritizing singular design interventions, the results suggest that residential energy and carbon performance benefit most from integrated envelope strategies combining moderate glazing percentages, low-emissivity glazing, external shading, and improved roof and wall insulation. Importantly, the study demonstrates that substantial operational improvements may be achieved without relying exclusively on advanced mechanical systems or intensive active technologies.

Nevertheless, several limitations should be acknowledged. The study focuses on a single detached residential prototype, limiting direct generalization to apartments, towers, or mixed-use developments. Occupancy schedules, internal gains, HVAC efficiency, and ventilation assumptions were intentionally fixed to isolate envelope effects, meaning behavioral variability was not considered. In addition, although embodied carbon was included as a supporting environmental indicator, lifecycle stages beyond material production and construction were not explicitly modeled. Finally, the analysis focused exclusively on Dubai climatic conditions; therefore, findings should be interpreted cautiously when transferred to locations with different thermal or humidity characteristics. Future research may expand the framework to include economic assessment, adaptive occupant behavior, and broader Gulf climate comparisons.

Abbreviations

The following abbreviations are used in this manuscript:

- ACH: Air Changes per Hour;
- ASHRAE: American Society of Heating, Refrigerating and Air-Conditioning Engineers;
- BWh: Hot Desert Climate (Köppen Classification);
- CO_2: Carbon Dioxide;
- COP: Coefficient of Performance;
- EPW: EnergyPlus Weather File;
- EUI: Energy Use Intensity;
- HVAC: Heating, Ventilation, and Air Conditioning;
- MENA: Middle East and North Africa;
- NSGA-II: Non-Dominated Sorting Genetic Algorithm II;

5. Conclusion

This study investigated envelope design trade-offs for low-carbon residential buildings in Dubai through a simulation-based multi-objective optimization framework. Using a representative detached residential villa prototype modeled in DesignBuilder and evaluated under Dubai climatic conditions, the analysis examined how key envelope parameters influence annual energy demand, thermal comfort, and embodied carbon performance. The study focused specifically on five envelope-related variables: window-to-wall ratio, glazing specification, external shading depth, roof construction, and wall construction, while maintaining fixed operational assumptions to isolate envelope effects.

The baseline simulation confirmed the strong cooling dependency of residential buildings in Dubai. The reference case recorded an annual site energy consumption of 40,427.48 kWh/year, corresponding to 189.44 kWh/m^2·year, while cooling accounted for more than 88% of total annual energy use. Thermal performance assessment further indicated persistent indoor environmental challenges, with 3,036.50 annual discomfort hours despite mechanical cooling. These findings reinforce the importance of passive and envelope-related interventions in cooling-dominated climates where prolonged summer exposure and persistently elevated night-time temperatures intensify cooling dependency.

The optimization outcomes demonstrated that coordinated envelope improvements can substantially improve residential environmental performance. The best-performing solution reduced annual site energy consumption to approximately 18,107 kWh/year, representing an improvement of approximately 55% relative to the baseline case. However, the results also demonstrated that the lowest-energy configuration did not necessarily correspond to the lowest-discomfort alternative, and material-related implications should be considered when selecting envelope strategies. Instead, Pareto-based evaluation revealed the importance of balancing competing objectives through integrated decision-making rather than prioritizing a single performance metric.

Several consistent design tendencies emerged from the optimization process. Moderate window-to-wall ratios, low-emissivity glazing systems, external shading devices, and improved roof and wall insulation repeatedly appeared among higher-performing alternatives. These findings indicate that low-carbon residential performance in Dubai depends less on singular technological interventions and more on coordinated envelope strategies capable of reducing solar heat gain and conductive heat transfer while maintaining acceptable indoor thermal conditions.

From a practical perspective, the study offers a simplified decision-support framework for architects and environmental designers seeking climate-responsive residential solutions in Dubai and comparable Gulf environments. Rather than relying exclusively on active cooling technologies, envelope optimization may provide meaningful operational improvements with comparatively straightforward architectural interventions. Future studies may extend this

framework by incorporating lifecycle costing, adaptive occupant behavior, renewable integration, and comparative assessments across multiple Gulf cities to strengthen transferability and decision relevance

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare no conflicts of interest.

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Data Availability Statement

No new datasets were generated or analyzed in this study. All materials used are cited in the reference list and presented within the article.

References

[1] International Energy Agency (IEA) Buildings Sector Energy Consumption and Emissions; 2023;

[2] United Nations Environment Programme; Global Alliance for Buildings and Construction (GlobalABC) Global Status Report for Buildings and Construction - Beyond Foundations: Mainstreaming Sustainable Solutions to Cut Emissions from the Buildings Sector; United Nations Environment Programme, 2024; ISBN 978-92-807-4131-5.

[3] Ürge-Vorsatz, D.; Cabeza, L.F.; Serrano, S.; Barreneche, C.; Petrichenko, K. Heating and Cooling Energy Trends and Drivers in Buildings. Renewable and Sustainable Energy Reviews 2015, 41, 85–98, doi:10.1016/j.rser.2014.08.039.

[4] Ali, K.; Tintawi, G.; Bassma, M.K. AI-Guided Evolutionary Optimization of Passive Solar Design for Residential Heating Across Distinct Climate Zones. Solar 2026, 6, 13, doi:10.3390/solar6020013.

[5] Bokhari, A.; Ali, K. Simulation-Based Evolutionary Optimization of Residential Buildings for Energy and Carbon Reduction Across Warm–Humid and Coastal Hot–Arid Climates. Buildings 2026, 16, 2157, doi:10.3390/buildings16112157.

[6] Ali, K.; Tintawi, G. Algorithmic Sustainability: Ethics, Governance, and Global Policies for AI-Driven Environmental Decision-Making. 2026, Preprint doi:10.20944/preprints202602.0733.v1.

[7] Ali, K.; Tintawi, G. AI-Driven Multi-City Optimization of Glazing and Shading Systems for Building Energy Use and Operational Carbon Reduction Across Global Climate Zones. Preprint 2026, doi:10.20944/preprints202605.1646.v1.

[8] Alwetaishi, M.; Benjeddou, O. Impact of Window to Wall Ratio on Energy Loads in Hot Regions: A Study of Building Energy Performance. Energies 2021, 14, 1080, doi:10.3390/en14041080.

[9] Resende, J.; Corvacho, H. Optimisation of Nearly Zero Energy Building Envelope for Passive Thermal Comfort in Southern Europe. Buildings 2024, 14, 2757, doi:10.3390/buildings14092757.

[10] Gigasari, A.R.; Cañada-Soriano, M.; Aparicio-Fernández, C.; Vivancos, J.-L. Impact of Window-to-Wall Ratio (WWR) and Shading on Energy Demand in a Residential Building across Five Distinct Climates. Results in Engineering 2025, 28, 107518, doi:10.1016/j.rineng.2025.107518.

[11] Pomponi, F.; Moncaster, A. Embodied Carbon Mitigation and Reduction in the Built Environment – What Does the Evidence Say? Journal of Environmental Management 2016, 181, 687–700, doi:10.1016/j.jenvman.2016.08.036.

[12] Röck, M.; Saade, M.R.M.; Balouktsi, M.; Rasmussen, F.N.; Birgisdottir, H.; Frischknecht, R.; Habert, G.; Lützkendorf, T.; Passer, A. Embodied GHG Emissions of Buildings – The Hidden Challenge for Effective Climate Change Mitigation. Applied Energy 2020, 258, 114107, doi:10.1016/j.apenergy.2019.114107.

[13] Tintawi, G.; Ali, K.; Monteiro, L.; Bassma, M.K.; Rosse Caldas, L. Material Sufficiency, Energy Use, and Life-Cycle Carbon in Hot-Arid Residential Buildings: A Pareto-Informed Multi-Criteria Evaluation of Envelope Design Strategies. Preprint 2026, doi:10.20944/preprints202605.1583.v1.

[14] Fu, Y.; Wang, C. Optimisation of Embodied Carbon and Thermal Performance of Roof Material Selections for Australian Residential Housing. Buildings 2025, 15, 268, doi:10.3390/buildings15020268.

[15] Bacheva, T.S.; Raposo Grau, J.F. Embodied Impacts in Buildings: A Systematic Review of Life Cycle Gaps and Sectoral Integration Strategies. Buildings 2025, 15, 1661, doi:10.3390/buildings15101661.

[16] Wingrove, K.; Heffernan, E.; Daly, D.; Ambrose, M. Passive-Solar Design: Evidence of the Disconnect between Theory, Policy and Practice in the Glazing Design of Contemporary Australian Homes. Energy and Buildings 2025, 345, 116104, doi:10.1016/j.enbuild.2025.116104.

[17] Edbais, A.; Hossain, M. Analysis of Window Parameters and Shading Strategies in Buildings in Hyper-Arid Desert Coastal Climates: A Case Study for Kuwait. Discov Sustain 2025, 6, 534, doi:10.1007/s43621-025-01305-7.

[18] Ali, K.; Vasconcellos, V. Os Mega Projetos Imobiliários e Seus Impactos Sociais. O Caso Da Ilha Palm Jumeirah. In Proceedings of the 18a Conferência Internacional da LARES; Latin American Real Estate Society: São Paulo, 2018.

[19] Deb, K.; Pratap, A.; Agarwal, S.; Meyarivan, T. A Fast and Elitist Multiobjective Genetic Algorithm: NSGA-II. IEEE Trans. Evol. Computat. 2002, 6, 182–197, doi:10.1109/4235.996017.

[20] Xue, Q.; Wang, Z.; Chen, Q. Multi-Objective Optimization of Building Design for Life Cycle Cost and CO2 Emissions: A Case Study of a Low-Energy Residential Building in a Severe Cold Climate. Build. Simul. 2022, 15, 83–98, doi:10.1007/s12273-021-0796-5.

[21] Ayoobi, A.W.; Inceoğlu, M. Developing an Optimized Energy-Efficient Sustainable Building Design Model in an Arid and Semi-Arid Region: A Genetic Algorithm Approach. Energies 2024, 17, 6095, doi:10.3390/en17236095.

[22] Tawfeeq, H.; Qaradaghi, A.M.A. Optimising Window-to-Wall Ratio for Enhanced Energy Efficiency and Building Intelligence in Hot Summer Mediterranean Climates. Sustainability 2024, 16, 7342, doi:10.3390/su16177342.

[23] Magnier, L.; Haghighat, F. Multiobjective Optimization of Building Design Using TRNSYS Simulations, Genetic Algorithm, and Artificial Neural Network. Building and Environment 2010, 45, 739–746, doi:10.1016/j.buildenv.2009.08.016.

[24] Ali, K. Caminhos indicativos para o atendimento aos Objetivos de Desenvolvimento Sustentável – Agenda 2030: a sustentabilidade sociocultural na Ilha Palm Jumeirah, Dubai, Emirados Árabes, Zenodo, 2021.

[25] Pajek, L.; Potočnik, J.; Košir, M. The Effect of a Warming Climate on the Relevance of Passive Design Measures for Heating and Cooling of European Single-Family Detached Buildings. Energy and Buildings 2022, 261, 111947, doi:10.1016/j.enbuild.2022.111947.

[26] Lu, Y.; Ma, N.; Arsano, A.Y.; Brown, N.; Chung, J.; Dilsiz, A.D.; Dong, B.; Franconi, E.; Han, X.; Jiang, Z.; et al. Towards High-Performance Buildings for Thermal Resilience and Health. Energy and Buildings 2025, 347, 116367, doi:10.1016/j.enbuild.2025.116367.

[27] Toroxel, J.L.; Silva, S.M. A Review of Passive Solar Heating and Cooling Technologies Based on Bioclimatic and Vernacular Architecture. Energies 2024, 17, 1006, doi:10.3390/en17051006.

[28] American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) ANSI/ASHRAE Standard 55-2023: Thermal Environmental Conditions for Human Occupancy; Atlanta, GA, USA, 2023;

[29] Crawley, D.B.; Lawrie, L.K.; Winkelmann, F.C.; Buhl, W.F.; Huang, Y.J.; Pedersen, C.O.; Strand, R.K.; Liesen, R.J.; Fisher, D.E.; Witte, M.J.; et al. EnergyPlus: Creating a New-Generation Building Energy Simulation Program. Energy and Buildings 2001, 33, 319–331, doi:10.1016/S0378-7788(00)00114-6.

[30] Alexakis, K.; Benekis, V.; Kokkinakos, P.; Askounis, D. Genetic Algorithm-Based Multi-Objective Optimisation for Energy-Efficient Building Retrofitting: A Systematic Review. Energy and Buildings 2025, 328, 115216, doi:10.1016/j.enbuild.2024.115216.

[31] Abouhamad, M.; Abu-Hamd, M. Life Cycle Assessment Framework for Embodied Environmental Impacts of Building Construction Systems. Sustainability 2021, 13, 461, doi:10.3390/su13020461.

[32] Chen, Y.; Chen, Z.; Wang, D.; Liu, Y.; Zhang, Y.; Liu, Y.; Zhao, Y.; Gao, M.; Fan, J. Co-Optimization of Passive Building and Active Solar Heating System Based on the Objective of Minimum Carbon Emissions. Energy 2023, 275, 127401, doi:10.1016/j.energy.2023.127401