

Balancing Energy Performance, Thermal Comfort, and Embodied Carbon in Residential Buildings: A Tri-Objective Pareto Optimization Study of Riyadh and Dubai

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Abstract

Buildings account for a substantial share of global energy consumption and greenhouse gas emissions, creating an urgent need for design strategies that simultaneously address operational performance, occupant comfort, and life-cycle environmental impacts. While simulation-based optimization has become increasingly common in building performance research, relatively few studies evaluate energy use, thermal comfort, and embodied carbon within a unified tri-objective framework. This study presents a simulation-based tri-objective Pareto optimization of residential buildings in Riyadh, Saudi Arabia, and Dubai, United Arab Emirates, using DesignBuilder, EnergyPlus, and the Non-Dominated Sorting Genetic Algorithm II (NSGA-II). A standardized four-story residential apartment prototype comprising 16 thermal zones and 2239.82 m² of conditioned floor area was developed and simulated under identical geometric, operational, and HVAC assumptions. Window-to-wall ratio, glazing type, external shading depth, and cooling setpoint temperature were optimized to minimize annual site energy consumption, ASHRAE 55 thermal discomfort hours, and embodied carbon emissions. Baseline simulations revealed substantially higher operational demand in Dubai, with annual energy consumption reaching 272,077 kWh compared with 196,478 kWh in Riyadh, while discomfort hours increased from 2,530 h/year to 3,262 h/year. Optimization reduced annual energy demand by 72.9% in Riyadh and 74.5% in Dubai, while thermal discomfort was reduced to 776 h/year in the best-performing comfort solution. Pareto-optimal solutions consistently favored low window-to-wall ratios (10–16%), high-performance glazing, and external overhangs between 1.5 and 2.0 m. The findings demonstrate the effectiveness of tri-objective optimization for balancing operational efficiency, occupant comfort, and embodied carbon while providing climate-responsive façade design guidance for residential buildings in hot-arid Gulf environments.

Keywords: Building performance simulation; NSGA-II; Multi-objective optimization; Thermal comfort; Embodied carbon; Energy efficiency; climate-responsive design.

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1. INTRODUCTION

The building sector remains one of the largest consumers of energy and one of the most significant contributors to global greenhouse gas emissions. According to the Global Status Report for Buildings and Construction, buildings account for approximately 34% of global final energy demand and 37% of energy- and process-related carbon dioxide emissions, emphasizing the urgency of improving building performance and reducing environmental impacts throughout the building life cycle (Global Alliance for Buildings and

Construction & United Nations Environment Programme, 2024). As climate change intensifies and urban populations continue to grow, improving the sustainability of residential buildings has become a major priority for governments, researchers, and practitioners worldwide.

In hot-climate regions, building energy consumption is dominated by cooling demand. Residential buildings in Gulf countries are particularly dependent on mechanical cooling systems because of

prolonged periods of high outdoor temperatures, intense solar radiation, and increasing urban heat island effects. These conditions create substantial operational energy demands and contribute significantly to electricity consumption and associated carbon emissions (Calvin *et al.*, 2023). Consequently, improving the thermal performance of residential buildings through climate-responsive design strategies has emerged as an important pathway toward reducing environmental impacts while maintaining acceptable indoor comfort conditions.

Building envelopes play a critical role in regulating heat transfer between indoor and outdoor environments. Elements such as glazing systems, window-to-wall ratio (WWR), insulation levels, and external shading devices directly influence solar heat gains, cooling loads, and thermal comfort outcomes. Previous studies have demonstrated that façade-related design decisions can significantly affect building energy performance, particularly in cooling-dominated climates (Albatayneh, 2021; Alwetaishi & Benjeddou, 2021). However, the effectiveness of these strategies often varies according to local climatic conditions, building characteristics, and occupant requirements.

Recent simulation-based studies further confirm that envelope-related variables, including glazing, WWR, shading, and passive solar design, produce strongly climate-dependent performance outcomes across residential buildings (Ali *et al.*, 2026; Bassma & Tintawi, 2026; Bokhari & Ali, 2026).

Recent advances in building performance simulation have enabled researchers to evaluate large numbers of design alternatives before construction. Simulation engines such as EnergyPlus have become widely adopted for investigating the interactions between climate, building systems, occupant behavior, and envelope characteristics (Crawley *et al.*, 2001). These tools allow designers to assess performance outcomes under realistic operating conditions and support evidence-based decision-making during early design stages.

Simultaneously, computational optimization techniques have become increasingly important for identifying high-performing design solutions within large and complex design spaces. Traditional trial-and-error approaches often evaluate only a limited number of alternatives and may fail to identify globally optimal solutions. In contrast, optimization algorithms can systematically explore thousands of possible design combinations and identify solutions that balance multiple competing objectives (Evins, 2013; Nguyen *et al.*, 2014).

Building design problems frequently involve competing objectives. Reducing energy consumption may require design interventions that increase construction materials or costs. Similarly, improving thermal comfort may increase cooling demand if not

carefully managed. As a result, optimization studies increasingly adopt multi-objective approaches that evaluate trade-offs between multiple performance criteria rather than focusing on a single outcome.

Among available optimization methods, the Non-Dominated Sorting Genetic Algorithm II (NSGA-II) has become one of the most widely applied algorithms in building performance research (Deb *et al.*, 2002). NSGA-II is particularly suitable for architectural optimization because it generates a set of Pareto-optimal solutions rather than a single optimum, allowing designers to understand trade-offs among competing objectives. Previous studies have successfully applied NSGA-II to optimize building envelopes, glazing systems, insulation levels, and renewable energy integration strategies (Alexakis *et al.*, 2025; Hamdy *et al.*, 2013; Magnier & Haghighat, 2010).

More recent work has extended this approach to AI-guided and simulation-based optimization across multiple climates, showing that evolutionary search can reveal climate-specific envelope rules rather than universal design prescriptions (Ali *et al.*, 2026; Bokhari & Ali, 2026).

Most existing optimization studies focus primarily on operational energy consumption and operational carbon emissions. While these indicators are important, increasing attention is being directed toward embodied carbon because construction materials contribute substantially to the total environmental impact of buildings over their life cycle. Materials such as concrete, insulation products, and glazing systems contain embedded greenhouse gas emissions associated with extraction, manufacturing, transportation, and installation processes (Bolattürk, 2008; Ozel, 2011).

Consequently, optimizing building performance solely from an operational perspective may inadvertently increase embodied carbon burdens. High-performance glazing systems, thicker insulation layers, and additional façade components may reduce annual energy demand while simultaneously increasing material-related emissions. Understanding these trade-offs is therefore essential for achieving genuinely sustainable building design solutions.

Despite the growing literature on building performance optimization, several research gaps remain evident. First, many studies investigate energy performance and thermal comfort without explicitly considering embodied carbon as a simultaneous optimization objective. Second, comparative studies examining hot-arid Gulf climates often focus on individual cities rather than evaluating how optimization outcomes differ between distinct climatic contexts within the region. Third, relatively few studies investigate the interactions among energy use, thermal comfort, and

embodied carbon using a unified tri-objective optimization framework.

However, previous related studies have generally focused on heating-demand optimization, operational energy and carbon reduction, or deterministic envelope sufficiency assessment, rather than combining energy, thermal comfort, and embodied carbon into a tri-objective NSGA-II framework for Riyadh and Dubai (Ali *et al.*, 2026; Bassma & Tintawi, 2026; Bokhari & Ali, 2026; Tintawi *et al.*, 2026).

To address these gaps, this study develops a simulation-based tri-objective optimization framework for residential buildings in Riyadh and Dubai. The study employs Design Builder and Energy Plus simulations coupled with the NSGA-II optimization algorithm to evaluate trade-offs among annual energy consumption, thermal comfort performance, and embodied carbon emissions.

The specific objectives of the study are:

- a) To establish baseline energy, comfort, and embodied carbon performance for a representative Gulf residential apartment building.
- b) To optimize façade-related design variables using NSGA-II.
- c) To identify Pareto-optimal solutions that balance energy efficiency, thermal comfort, and embodied carbon.
- d) To compare optimization outcomes between Riyadh and Dubai.
- e) To derive climate-responsive design recommendations for residential buildings in hot-arid Gulf environments.

Through this approach, the study contributes a practical framework for evaluating competing sustainability objectives and supports evidence-based architectural decision-making in rapidly urbanizing and climate-sensitive regions.

2. MATERIALS AND METHODS

This study employed a simulation-based multi-objective optimization framework to investigate trade-offs between energy performance, thermal comfort, and

embodied carbon in residential buildings located in two representative Gulf cities: Riyadh, Saudi Arabia, and Dubai, United Arab Emirates. The methodological workflow combined dynamic building energy simulation with evolutionary optimization using the Non-Dominated Sorting Genetic Algorithm II (NSGA-II).

Riyadh and Dubai were selected not to represent the entire Gulf region, but to establish a controlled comparison between two influential Gulf urban contexts with contrasting hot-arid sub-conditions: an inland dry climate and a coastal humid climate.

This selection also builds on earlier Gulf-focused research on Dubai, hot-arid envelope performance, and socio-environmental urban development in the region (Ali & Nogueira de Vasconcellos, 2018; Bassma & Tintawi, 2026; Tintawi *et al.*, 2026).

The research consisted of five sequential stages. First, a representative residential building prototype was developed and standardized across both climatic locations. Second, baseline simulations were conducted to establish reference performance metrics for energy consumption, thermal comfort, and embodied carbon. Third, a set of design variables related to façade performance and operational control were defined. Fourth, NSGA-II optimization was performed to identify Pareto-optimal design solutions. Finally, the resulting trade-offs were analyzed and compared between the two climatic contexts.

The methodology was designed to isolate the effects of climate and design decisions by maintaining identical building geometry, occupancy schedules, internal loads, construction assemblies, and HVAC configurations across both locations. Consequently, differences observed between Riyadh and Dubai can be attributed primarily to climatic influences and optimization outcomes rather than variations in building characteristics. Figure 1 summarizes the methodological workflow adopted in this study, illustrating the integration of building performance simulation, NSGA-II optimization, and Pareto-based interpretation to evaluate energy, thermal comfort, and embodied carbon trade-offs in residential buildings located in Riyadh and Dubai.

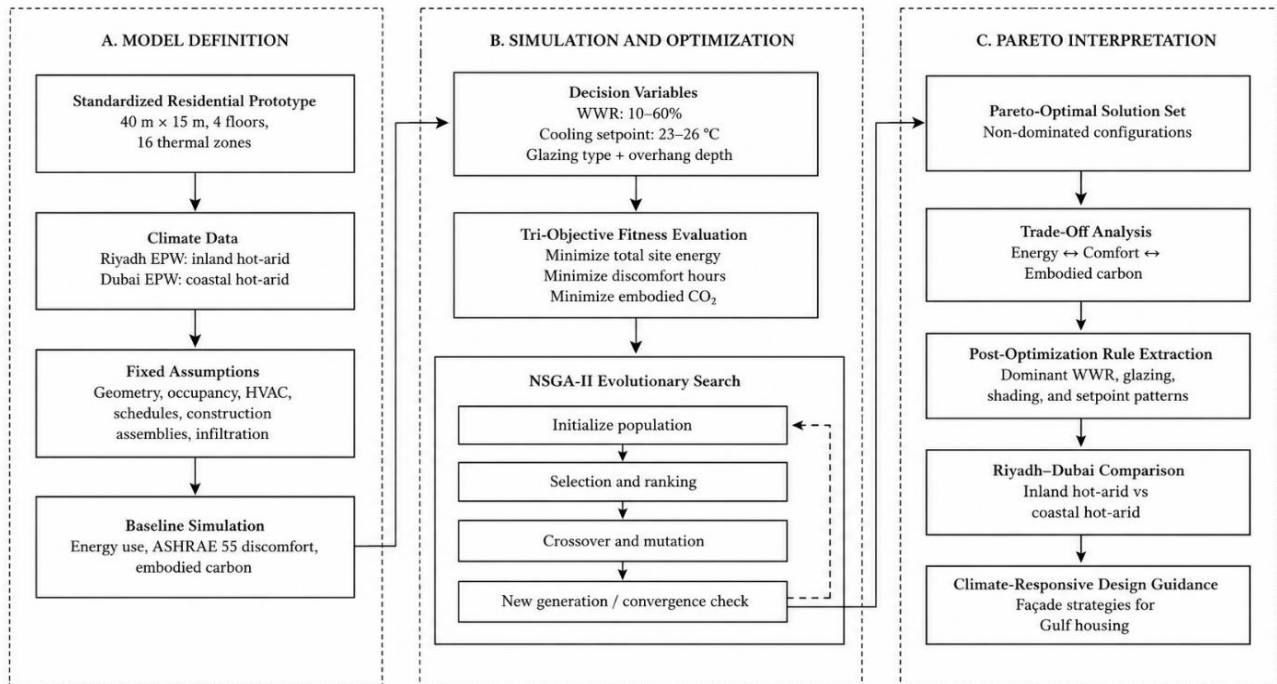


Figure 1: Simulation-based tri-objective Pareto optimization workflow adopted in this study. The framework integrates Design Builder/Energy Plus simulations with NSGA-II optimization to evaluate trade-offs among annual site energy consumption, thermal discomfort hours, and embodied carbon emissions for residential buildings in Riyadh and Dubai

All simulations were performed using Design Builder, which employs the Energy Plus simulation engine for dynamic thermal and energy calculations. Energy Plus has been extensively validated and remains one of the most widely adopted simulation engines for building performance assessment (Crawley *et al.*, 2001).

The optimization process utilized the integrated NSGA-II algorithm available within Design Builder. NSGA-II is recognized as one of the most effective evolutionary algorithms for solving building optimization problems involving competing objectives because it generates a set of non-dominated solutions rather than a single optimum (Deb *et al.*, 2002; Evins, 2013).

Typical Meteorological Year (TMY) weather files were used for both locations. Riyadh represents an inland hot-arid climate characterized by high solar radiation and low humidity, whereas Dubai represents a coastal hot-arid climate influenced by elevated humidity levels and maritime conditions.

Although both cities are classified as hot-arid environments (Köppen BWh), important climatic differences exist between them. Riyadh is characterized by lower annual humidity, larger diurnal temperature variations, and predominantly dry atmospheric conditions, whereas Dubai experiences higher relative humidity due to its coastal location along the Arabian Gulf. These climatic differences influence cooling demand, thermal comfort performance, and the

effectiveness of passive envelope strategies, making the comparison between the two cities particularly relevant for climate-responsive building design (Crawley *et al.*, 2001; *EnergyPlus*, n.d.; Machard *et al.*, 2024).

A simplified low- to mid-rise residential apartment building was developed as the reference prototype. The building was intentionally designed to balance thermal realism and computational efficiency during optimization. The prototype consists of a rectangular building measuring 40 m × 15 m, resulting in a footprint area of 600 m². The building contains four floors, producing a total gross floor area of approximately 2400 m² and a conditioned floor area of 2239.82 m².

Each floor contains four residential apartments, and each apartment was represented as an individual thermal zone. This zoning strategy resulted in a total of sixteen thermal zones and enabled efficient simulation of a large number of optimization iterations while preserving the principal thermal characteristics of residential occupancy. A floor-to-floor height of 3.0 m was adopted throughout the building, and simulations were performed over a full annual cycle.

To ensure comparability between climatic contexts, building geometry, orientation, occupancy schedules, internal gains, HVAC configuration, and construction assemblies were maintained identical in both cities.

The baseline building envelope represents a contemporary Gulf residential construction employing medium-weight construction and moderate insulation levels. External walls consisted of insulated brick/block assemblies, while the roof employed an insulated flat-roof system with a thermal transmittance of approximately 0.25 W/m²K. Internal partitions were modeled using lightweight gypsum board assemblies, and air infiltration was fixed at 0.30 air changes per hour (ACH).

The baseline façade configuration employed single clear 6 mm glazing with an initial window-to-wall ratio of approximately 20% and no external shading devices. These characteristics intentionally represent a simplified baseline condition from which performance improvements could be evaluated through optimization.

Operational assumptions were maintained constant throughout the study. Occupancy density was fixed at 0.0188 persons/m², corresponding to

approximately three occupants per apartment. Mechanical ventilation was enabled using the ASHRAE outdoor-air methodology, while dehumidification remained active to reflect realistic operation in Gulf climates. Natural ventilation was disabled to ensure consistent cooling-dominated operation.

The HVAC system was modeled using a Unitary Heat Cool configuration operating with a cooling coefficient of performance (COP) of 2.5 and a heating COP of 2.0. The baseline cooling setpoint was maintained at 25°C with a setback temperature of 28°C, while the heating setpoint remained fixed at 21°C.

Four design variables were selected based on their demonstrated influence on building thermal performance and cooling demand in hot climates (Albatayneh, 2021; Alwetaishi & Benjeddou, 2021; Tawfeeq & Qaradaghi, 2024). These variables include window-to-wall ratio, cooling setpoint temperature, glazing type, and external overhang depth.

Table 1: Optimization variables and corresponding search ranges used in the NSGA-II framework. Continuous variables were explored within predefined numerical bounds, while discrete variables represented alternative façade design options evaluated during the optimization process

| Variable | Type | Range / Options |
|------------------------------|------------|---|
| Window-to-Wall Ratio (WWR) | Continuous | 10–60% |
| Cooling Setpoint Temperature | Continuous | 23–26°C |
| Glazing Type | Discrete | Double Green, Double Low-E, Double Low-E Electrochromic |
| Overhang Depth | Discrete | 0.0 m, 0.5 m, 1.0 m, 1.5 m, 2.0 m |

The optimization framework simultaneously minimized three competing objectives representing operational performance, occupant comfort, and environmental impact.

This treatment is consistent with recent sufficiency-oriented envelope research, where operational energy and material-related carbon are evaluated together to avoid shifting impacts from operation to construction (Tintawi *et al.*, 2026).

Annual energy performance was evaluated using total site energy consumption extracted directly

from EnergyPlus simulations. Thermal comfort performance was assessed using ASHRAE Standard 55 discomfort hours, representing the number of annual hours during which indoor conditions fall outside acceptable comfort limits (American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), 2023). Environmental performance was quantified through embodied carbon emissions calculated using DesignBuilder's integrated material carbon database derived from Bath ICE inventories and reported as equivalent carbon dioxide emissions (kgCO₂e).

Table 2: Performance objectives adopted in the tri-objective optimization framework. Energy use, thermal comfort, and embodied carbon were simultaneously minimized to identify Pareto-optimal solutions that balance operational performance and environmental impact

| Objective Dimension | Performance Indicator | Unit | Optimization Goal |
|------------------------------|---|---------------------|-------------------|
| Energy Efficiency | Total Site Energy | kWh/year | Minimize |
| Occupant Comfort | ASHRAE 55 Discomfort Hours | h/year | Minimize |
| Environmental Sustainability | Embodied Carbon (Equivalent CO ₂) | kgCO ₂ e | Minimize |

Optimization was performed using the Non-Dominated Sorting Genetic Algorithm II. The algorithm iteratively evolved candidate design solutions through crossover and mutation operations while preserving non-dominated solutions throughout successive generations. The final configuration employed a population size of 50

individuals, a convergence threshold of 20 generations, a maximum of 120 generations, a crossover probability of 0.90, and a mutation rate of 0.20. The optimization process was limited to a maximum of 10,000 evaluations.

The resulting Pareto-optimal solutions represent alternative trade-offs among energy consumption, thermal comfort, and embodied carbon. These solutions form the basis for the comparative analysis presented in the following sections.

3. RESULTS

Baseline simulations were first conducted to establish a common reference for comparing the performance of the residential prototype under the climatic conditions of Riyadh and Dubai. The building geometry, construction materials, HVAC configuration, occupancy schedules, internal loads, and operational assumptions were maintained identical in both locations. Consequently, differences in performance are attributable exclusively to climatic variations.

The baseline results reveal substantial differences between the two cities. Dubai exhibited higher annual energy consumption and greater thermal discomfort than Riyadh despite the use of the same building configuration. Annual site energy consumption reached 272,077 kWh in Dubai compared with 196,478 kWh in Riyadh, representing a 38.5% increase. Similarly, thermal discomfort hours increased from 2,530 h/year in Riyadh to 3,262 h/year in Dubai.

The observed differences can be attributed primarily to the combined influence of elevated ambient temperatures and higher humidity levels in Dubai, which increase cooling demand and reduce passive cooling opportunities. In contrast, Riyadh's drier climate permits slightly improved thermal performance despite similar solar exposure conditions.

Table 3: Baseline Performance Comparison Between Riyadh and Dubai

| Indicator | Unit | Riyadh | Dubai |
|----------------------------|------------------------|----------|----------|
| Total Site Energy | kWh/year | 196,478 | 272,077 |
| Total Source Energy | kWh/year | 252,415 | 330,375 |
| Energy Use Intensity (EUI) | kWh/m ² .yr | 87.72 | 121.47 |
| Source EUI | kWh/m ² .yr | 112.69 | 147.50 |
| ASHRAE 55 Discomfort Hours | h/year | 2,530 | 3,262 |
| Cooling Setpoint Not Met | h/year | 71.5 | 123.0 |
| Embodied Carbon | kgCO ₂ | 143,394 | 143,394 |
| Conditioned Floor Area | m ² | 2,239.82 | 2,239.82 |

As expected, embodied carbon remained identical in both locations because the same construction materials and quantities were used in the prototype. The

baseline energy and thermal comfort results for both cities are summarized in Figure 2.

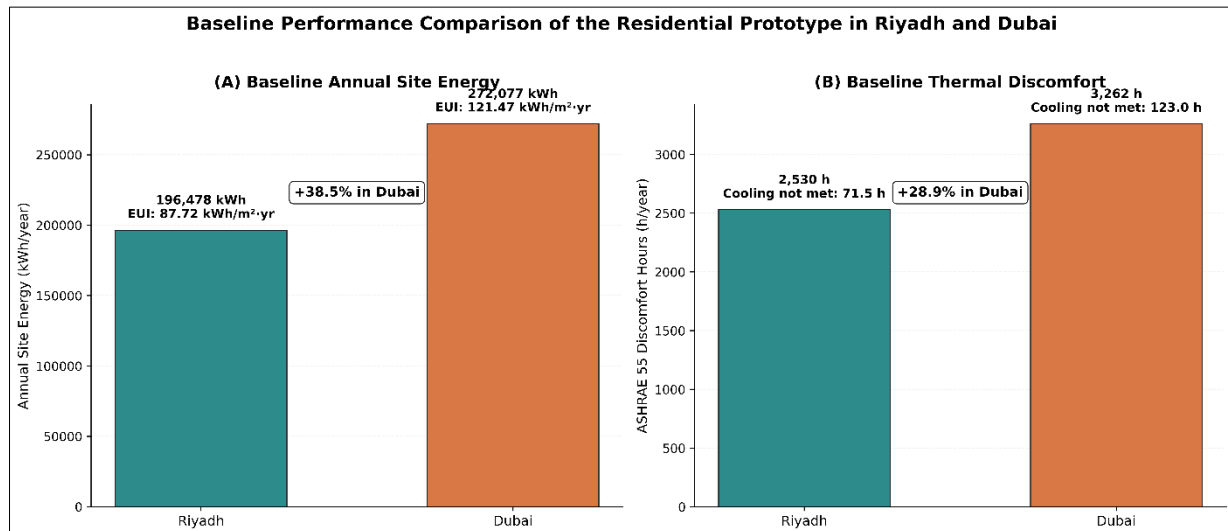


Figure 2: Baseline performance comparison of the standardized residential prototype in Riyadh and Dubai. Panel (A) presents annual site energy consumption and energy use intensity (EUI), while Panel (B) compares thermal comfort performance based on ASHRAE 55 discomfort hours. Despite identical building geometry, envelope characteristics, HVAC systems, occupancy schedules, and operational assumptions, Dubai exhibited higher energy demand and greater thermal discomfort than Riyadh, highlighting the influence of coastal hot-arid climatic conditions on residential building performance

Overall, the baseline simulations establish Dubai as the more demanding climatic environment from

an operational perspective, exhibiting both higher cooling-related energy demand and greater thermal

discomfort. These findings provide a clear benchmark against which the effectiveness of the subsequent optimization process can be evaluated.

The NSGA-II optimization process generated multiple Pareto-optimal solutions representing alternative trade-offs between energy consumption, thermal comfort, and embodied carbon.

The best-performing energy solution reduced annual energy demand from 196,478 kWh to 53,152

kWh, corresponding to a reduction of approximately 72.9%. This solution employed a low window-to-wall ratio, a high cooling setpoint, deep external shading, and high-performance glazing.

The best thermal comfort solution achieved a reduction in discomfort hours from 2,530 h/year to 776 h/year. This result demonstrates that substantial comfort improvements can be achieved through façade optimization without requiring major modifications to building geometry or HVAC systems.

Table 4: Representative Pareto-optimal solutions identified for Riyadh. The table presents baseline performance and selected non-dominated solutions that prioritize energy efficiency, thermal comfort, and embodied carbon reduction within the tri-objective optimization framework

| Solution Type | Energy (kWh/year) | Discomfort (h/year) | Embodied CO ₂ (kgCO ₂) | WWR (%) | Setpoint (°C) | Overhang (m) |
|---------------|-------------------|---------------------|---|---------|---------------|--------------|
| Baseline | 196,478 | 2,530 | 143,394 | 20 | 25.0 | 0.0 |
| Best Energy | 53,152 | 1,407 | 159,962 | 10 | 25.6 | 2.0 |
| Best Comfort | 68,578 | 776 | 159,962 | 10 | 23.5 | 0.0 |
| Best Carbon | 55,395 | 1,467 | 159,860 | 10 | 25.5 | 1.5 |

The optimization results consistently favored reduced glazing areas and increased solar protection. Most Pareto-optimal solutions converged toward window-to-wall ratios between 10% and 15%, indicating the strong influence of solar gains on cooling-dominated residential buildings in Riyadh.

Optimization results for Dubai revealed similar but more pronounced trends. Because of the additional influence of humidity and higher cooling demand, the

optimization algorithm consistently selected façade configurations with aggressive solar control measures.

The best energy solution reduced annual energy demand from 272,077 kWh to 69,427 kWh, corresponding to a reduction of approximately 74.5%. Thermal discomfort was also substantially reduced, although improvements were generally smaller than those observed in Riyadh due to the more demanding climatic conditions.

Table 5: Representative Pareto-optimal solutions identified for Dubai. The table summarizes baseline performance and selected non-dominated solutions that prioritize energy efficiency, thermal comfort, and embodied carbon reduction under coastal hot-arid climatic conditions

| Solution Type | Energy (kWh/year) | Discomfort (h/year) | Embodied CO ₂ (kgCO ₂) | WWR (%) | Setpoint (°C) | Overhang (m) |
|---------------|-------------------|---------------------|---|---------|---------------|--------------|
| Baseline | 272,077 | 3,262 | 143,394 | 20 | 25.0 | 0.0 |
| Best Energy | 69,427 | 2,203 | 159,860 | 10 | 25.7 | 2.0 |
| Best Comfort | 94,898 | 1,452 | 161,947 | 16 | 23.1 | 2.0 |
| Best Carbon | 89,539 | 1,471 | 159,860 | 10 | 25.2 | 1.0 |

The results indicate that low-glazing configurations combined with high-performance glazing systems and substantial external shading provide the most effective strategy for reducing cooling demand in Dubai.

Comparison of the optimized solutions reveals notable similarities between the two cities. In both locations, the optimization process consistently selected low window-to-wall ratios and improved glazing

systems. Deep external overhangs emerged as a recurring characteristic of energy-efficient solutions.

Despite these similarities, Dubai generally required more aggressive solar control measures and achieved higher final energy consumption values than Riyadh. This finding confirms that humidity and maritime climatic influences introduce additional cooling burdens beyond those associated with dry hot-arid conditions.

Table 6: Comparison of the best energy-performing Pareto-optimal solutions identified for Riyadh and Dubai. The results highlight differences in baseline performance, optimized energy demand, thermal comfort outcomes, and preferred façade design characteristics under inland and coastal hot-arid climatic conditions.

| Indicator | Riyadh | Dubai |
|--------------------------------------|---------|---------|
| Baseline Energy (kWh/year) | 196,478 | 272,077 |
| Optimized Energy (kWh/year) | 53,152 | 69,427 |
| Energy Reduction (%) | 72.9 | 74.5 |
| Baseline Discomfort (h/year) | 2,530 | 3,262 |
| Optimized Discomfort (h/year) | 1,407 | 2,203 |
| Embodied Carbon (kgCO ₂) | 159,962 | 159,860 |
| Optimal WWR (%) | 10 | 10 |
| Optimal Overhang (m) | 2.0 | 2.0 |

The convergence of optimal solutions toward similar façade configurations suggests that low glazing ratios and strong solar control constitute robust design strategies for hot-arid Gulf climates. However, differences in comfort outcomes indicate that local climatic characteristics remain important when selecting final design solutions.

The representative Pareto-optimal solutions provide insight into the competing relationships among energy performance, thermal comfort, and embodied

carbon. Unlike single-objective optimization, the tri-objective framework generates multiple non-dominated solutions, each representing a different balance between sustainability objectives. Examining these solutions helps identify the performance implications of prioritizing energy efficiency, thermal comfort, or embodied carbon reduction. Figure 3 visualizes the trade-offs between annual site energy consumption and thermal discomfort for selected Pareto-optimal solutions in Riyadh and Dubai.

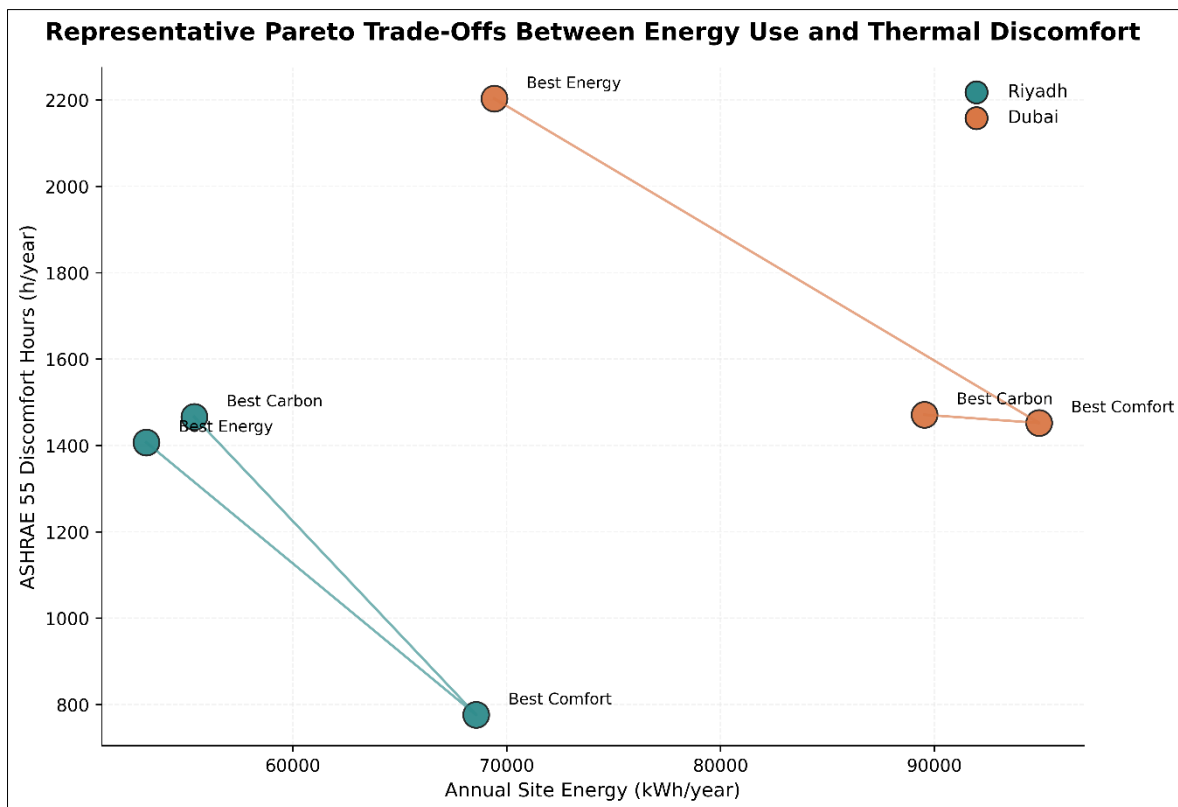


Figure 3: Representative Pareto-optimal trade-offs between annual site energy consumption and ASHRAE 55 discomfort hours for Riyadh and Dubai. The plotted solutions illustrate how different non-dominated configurations prioritize energy efficiency, thermal comfort, or embodied carbon within the tri-objective optimization framework.

Figure 3 illustrates the inherent trade-offs among the optimization objectives. In both cities, solutions that achieved the lowest energy consumption

did not necessarily provide the lowest thermal discomfort, demonstrating the competing nature of energy efficiency and occupant comfort. The best

comfort solutions achieved substantial reductions in ASHRAE 55 discomfort hours but required moderately higher energy consumption than the best energy solutions.

The figure also highlights climatic differences between Riyadh and Dubai. Although both cities converged toward similar façade strategies, the Dubai solutions remained associated with higher discomfort levels and higher energy consumption, reflecting the additional cooling burden imposed by coastal humidity. Riyadh, by contrast, achieved lower final discomfort levels and lower optimized energy demand under comparable design conditions.

Overall, the Pareto distributions confirm that no single configuration simultaneously minimizes all objectives. Instead, designers must select among alternative non-dominated solutions according to project priorities, whether emphasizing operational energy

reduction, occupant comfort, or embodied carbon performance. The results demonstrate the value of multi-objective optimization for revealing these trade-offs and supporting evidence-based design decisions in hot-arid residential buildings.

The Pareto fronts demonstrate the inherent trade-offs among energy consumption, thermal comfort, and embodied carbon. Solutions that minimized energy demand generally required additional façade elements and higher-performance glazing systems, leading to moderate increases in embodied carbon. Conversely, solutions that prioritized minimum embodied carbon often exhibited slightly higher energy consumption.

The optimization process therefore confirms that no single design solution simultaneously minimizes all objectives. Instead, decision-makers must select among alternative Pareto-optimal solutions according to project priorities and sustainability targets.

Table 7: Representative Pareto-optimal solutions identified by the NSGA-II optimization process. The solutions illustrate alternative trade-offs among annual energy consumption, thermal comfort, and embodied carbon for Riyadh and Dubai

| City | Energy (kWh/year) | Discomfort (h/year) | Embodied Carbon (kgCO ₂ e) | WWR (%) | Setpoint (°C) | Shading | Glazing |
|-----------|-------------------|---------------------|---------------------------------------|---------|---------------|----------------|-----------------------------|
| Riyadh R1 | 59,558 | 1,052 | 159,962 | 10 | 24.3 | 1.0 m Overhang | Double Low-E Electrochromic |
| Riyadh R2 | 68,578 | 776 | 159,962 | 10 | 23.5 | None | Double Low-E |
| Riyadh R3 | 66,864 | 778 | 160,678 | 12 | 23.4 | 0.5 m Overhang | Double Low-E Electrochromic |
| Riyadh R4 | 62,975 | 905 | 159,962 | 10 | 23.6 | 1.0 m Overhang | Double Low-E Electrochromic |
| Riyadh R5 | 53,152 | 1,407 | 159,962 | 10 | 25.6 | 2.0 m Overhang | Double Low-E Electrochromic |
| Dubai D1 | 94,898 | 1,452 | 161,947 | 16 | 23.1 | 2.0 m Overhang | Double Green |
| Dubai D2 | 89,539 | 1,471 | 159,860 | 10 | 23.2 | 1.0 m Overhang | Double Green |
| Dubai D3 | 84,331 | 1,652 | 162,112 | 16 | 24.5 | 1.5 m Overhang | Double Low-E |
| Dubai D4 | 74,611 | 1,859 | 160,678 | 12 | 25.2 | 1.0 m Overhang | Double Low-E Electrochromic |
| Dubai D5 | 69,427 | 2,203 | 159,860 | 10 | 25.7 | 2.0 m Overhang | Double Green |

The Pareto frontier reveals a range of alternative design strategies rather than a single optimal solution. In Riyadh, the non-dominated solutions converged toward low window-to-wall ratios of 10–12%, cooling setpoints between 23.4°C and 25.6°C, and predominantly high-performance low-E glazing systems. In Dubai, the frontier similarly favored reduced glazing areas and external shading but exhibited greater variability in cooling setpoints and glazing selection. The results demonstrate that improvements in thermal comfort were generally associated with higher energy consumption, whereas the lowest-energy solutions were obtained at higher cooling setpoints and with more aggressive solar

control measures. Embodied carbon varied only moderately across the frontier, suggesting that operational performance was the dominant driver of optimization outcomes.

Overall, the optimization framework successfully identified design configurations capable of substantially improving building performance relative to baseline conditions while maintaining reasonable embodied carbon levels. These findings provide a foundation for the broader interpretation and practical implications discussed in the following section.

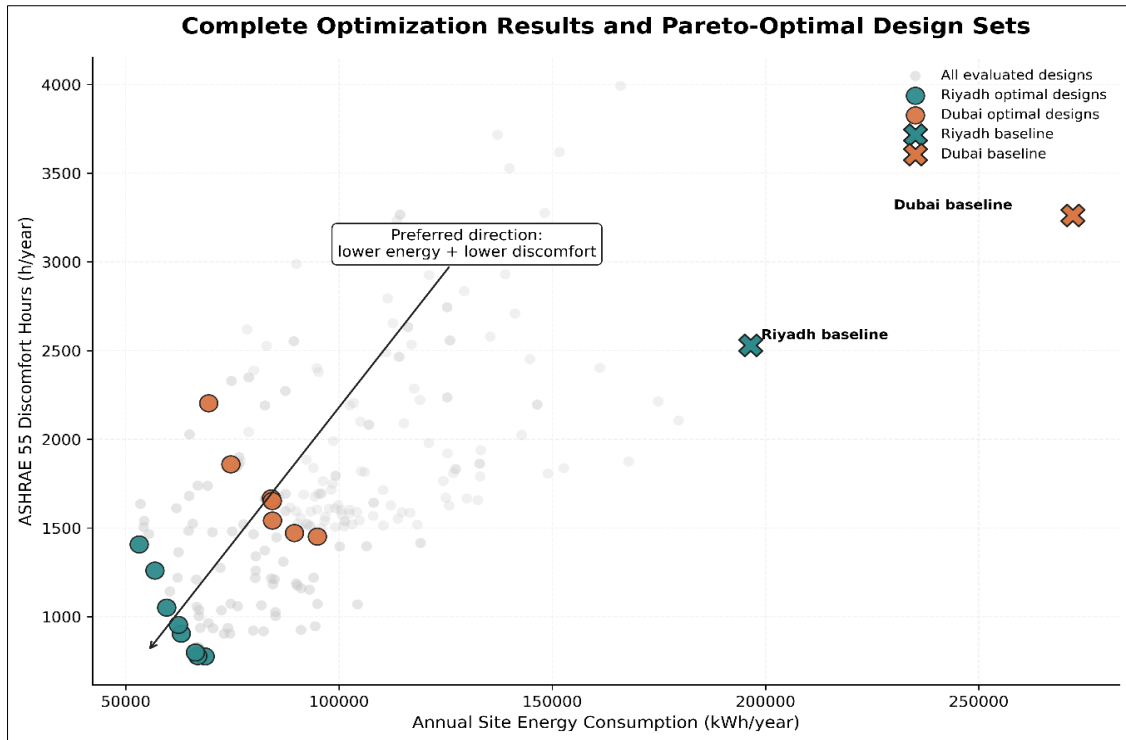


Figure 4: Complete optimization results for Riyadh and Dubai showing all evaluated design alternatives, Design Builder-identified optimal solutions, and baseline reference cases. The figure illustrates the distribution of energy–comfort trade-offs and highlights the movement from baseline conditions toward lower-energy and lower-discomfort Pareto-optimal configurations

The optimization process generated multiple Pareto-optimal solutions representing different trade-offs among energy consumption, thermal comfort, and embodied carbon. To facilitate interpretation of the optimization results, a post-optimization rule extraction procedure was conducted by examining recurring characteristics across the non-dominated solution set. The analysis focused on identifying common ranges of WWR, cooling setpoint temperature, glazing type, and

shading depth associated with high-performing solutions. Rather than focusing on individual solutions, the analysis examined recurring patterns across the non-dominated solution set to identify common design characteristics associated with improved building performance. Figure 5 summarizes the dominant design rules extracted from the optimization results for Riyadh and Dubai.

| Post-Optimization AI-Assisted Rule Extraction from Pareto-Optimal Solutions | | | |
|---|-----------------------|-----------------------|--|
| Extracted Design Rule | Riyadh Pattern | Dubai Pattern | Architectural Interpretation |
| Reduced glazing ratio | WWR: 10-15% | WWR: 10-16% | Lower solar gains in both climates. |
| External solar control | 1.5-2.0 m overhangs | 1.0-2.0 m overhangs | Deep shading reduced cooling demand. |
| Comfort-dependent cooling setpoint | 23.5-25.6°C | 23.1-25.7°C | Comfort–energy trade-off identified. |
| Solar-control glazing | Low-E / green glazing | Green / Low-E glazing | High-performance glazing improved performance. |

Figure 5: Post-optimization rule extraction matrix derived from Pareto-optimal solutions for Riyadh and Dubai. The figure summarizes recurring design patterns identified across the non-dominated solution set and translates numerical optimization outcomes into climate-responsive façade design guidance

The extracted rules reveal a high degree of consistency between the two climatic contexts. In both Riyadh and Dubai, Pareto-optimal solutions converged toward reduced glazing ratios, indicating that limiting solar heat gains is a primary strategy for improving performance in cooling-dominated residential buildings. Similarly, external overhangs emerged as a recurring feature among high-performing solutions, demonstrating the importance of passive solar control in reducing cooling demand.

The analysis also highlights the role of cooling setpoint selection in balancing energy efficiency and occupant comfort. Lower setpoints generally improved thermal comfort, whereas higher setpoints contributed to reduced energy consumption. In addition, high-performance glazing systems were consistently associated with superior overall performance, confirming their effectiveness in mitigating solar heat gains while maintaining indoor environmental quality.

Overall, the rule extraction process transforms complex optimization outputs into practical design guidance that can support early-stage decision-making. The resulting recommendations provide architects and designers with a concise set of climate-responsive façade strategies for residential buildings in hot-arid Gulf environments.

4. DISCUSSION

The optimization results demonstrate the substantial influence of climate-responsive façade design on residential building performance in hot-arid environments. Although Riyadh and Dubai are commonly classified within the same broad climatic category, the baseline simulations revealed considerable differences in operational performance. Dubai exhibited significantly higher annual energy consumption and thermal discomfort than Riyadh despite identical building geometry, construction assemblies, occupancy schedules, and HVAC configurations. This finding highlights the importance of considering local climatic characteristics rather than relying solely on generalized climate classifications.

The higher cooling demand observed in Dubai can be attributed to the combined effects of elevated temperatures and higher humidity levels. While Riyadh experiences extreme summer temperatures, its lower humidity enables more effective heat dissipation and slightly improved indoor thermal conditions. In contrast, Dubai's coastal climate increases latent cooling requirements and prolongs periods of thermal discomfort. Similar observations have been reported in previous studies examining cooling-dominated climates, where humidity was identified as a critical factor influencing annual energy demand and occupant comfort (Pajek *et al.*, 2022; Sayadi *et al.*, 2022).

The optimization process achieved substantial reductions in annual energy use in both cities. Energy consumption decreased by approximately 72.9% in Riyadh and 74.5% in Dubai relative to baseline conditions. These reductions are comparable to or exceed improvements reported in previous simulation-based optimization studies of residential building envelopes (Albatayneh, 2021; Ayoobi & Inceoğlu, 2024). The magnitude of these reductions confirms that façade-related design decisions remain among the most influential variables affecting cooling-dominated building performance.

The results also reinforce the importance of passive design strategies. Across both locations, the optimization algorithm consistently favored solutions that minimized solar heat gains through reduced glazing areas and enhanced external shading. These findings align with research emphasizing the effectiveness of passive solar control measures in hot climates (Gigasari *et al.*, 2025; Toroxel & Silva, 2024).

One of the principal motivations for applying multi-objective optimization is the recognition that building design objectives are often conflicting. The Pareto-optimal solutions identified in this study clearly illustrate the trade-offs between energy performance and thermal comfort.

Solutions that minimized annual energy consumption generally employed higher cooling setpoints combined with aggressive solar control measures. While these strategies substantially reduced cooling loads, they did not always produce the lowest discomfort-hour values. Conversely, solutions optimized primarily for thermal comfort tended to employ lower cooling setpoints, resulting in increased energy demand.

This behavior is consistent with previous multi-objective building optimization research, which has repeatedly shown that energy efficiency and thermal comfort cannot be optimized independently (Hamdy *et al.*, 2013; Magnier & Haghghat, 2010). The findings also support the principles underlying adaptive thermal comfort frameworks, which recognize that occupant comfort depends not only on indoor temperatures but also on climatic adaptation and acceptable comfort ranges (American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), 2023; de Dear & Brager, 1998).

The results therefore emphasize the importance of evaluating comfort and energy simultaneously rather than prioritizing a single performance indicator. From a design perspective, Pareto-optimal solutions provide architects and engineers with multiple alternatives rather than a single recommended design, allowing decisions to be aligned with project-specific priorities and stakeholder objectives.

A major contribution of this study is the explicit inclusion of embodied carbon as an optimization objective. Although operational energy remains the dominant focus of many building optimization studies, growing attention is being directed toward life-cycle environmental impacts. High-performance envelope systems often reduce operational energy consumption but may simultaneously increase emissions associated with material production and construction processes.

The results demonstrate this relationship clearly. Several of the highest-performing energy solutions incorporated advanced glazing systems and additional shading components, which increased embodied carbon relative to the baseline building. Consequently, the solutions with the lowest energy demand were not necessarily those with the lowest environmental impact when material-related emissions were considered.

This finding supports previous research indicating that operational and embodied impacts must be evaluated simultaneously to avoid unintended environmental trade-offs (Chen *et al.*, 2023; D'Agostino *et al.*, 2021). As operational energy demand decreases through improvements in building efficiency, embodied carbon is expected to represent an increasingly significant proportion of total life-cycle emissions. Therefore, optimization frameworks that neglect embodied impacts may fail to identify genuinely sustainable solutions.

The relatively narrow range of embodied carbon values observed in the present study suggests that glazing quantity and shading systems were the primary drivers of carbon variation. Future research may reveal stronger embodied-carbon trade-offs through the inclusion of additional variables such as insulation thickness, structural systems, or alternative construction materials.

Several practical design recommendations emerge from the optimization results. First, window-to-wall ratio proved to be one of the most influential design variables. Nearly all high-performing solutions converged toward values between 10% and 16%, substantially lower than those frequently observed in contemporary residential developments throughout the Gulf region. Excessive glazing remains a common architectural feature despite its negative implications for cooling-dominated climates.

Second, external shading consistently improved building performance. Deep overhangs between 1.5 m and 2.0 m were repeatedly selected by the optimization algorithm, confirming the importance of solar control in reducing cooling demand. These findings are consistent with previous investigations highlighting the effectiveness of shading systems in hot climates (Gigasari *et al.*, 2025; Tawfeeq & Qaradaghi, 2024).

Third, glazing performance emerged as a critical factor influencing both energy use and comfort. High-performance glazing systems provided measurable reductions in cooling demand while contributing to improved thermal comfort conditions. The optimization results therefore support the continued adoption of advanced glazing technologies in Gulf residential projects.

Earlier studies on Dubai also indicate that urban development, vegetation, and large-scale real-estate transformation influence environmental comfort and sustainability outcomes, reinforcing the need to connect envelope-level optimization with broader regional design conditions (Ali & Nogueira de Vasconcellos, 2018; Ali & Nogueira De Vasconcellos, 2020; O'Donoghue *et al.*, 2021).

Finally, the similarity of optimal solutions across both cities suggests the existence of robust design principles applicable to hot-arid residential environments. Reduced glazing, enhanced shading, and improved glazing performance consistently emerged as favorable strategies regardless of climatic differences. However, the greater cooling demand and thermal discomfort observed in Dubai indicate that local climatic conditions should still be considered when refining final design decisions.

Overall, the findings demonstrate that substantial performance improvements can be achieved through relatively conventional design interventions. Rather than relying exclusively on advanced technologies or complex mechanical systems, architects can realize significant benefits through careful optimization of fundamental façade parameters. This reinforces the continuing importance of climate-responsive design as a cornerstone of sustainable residential architecture in the Gulf region.

This study has several limitations that should be acknowledged. First, the analysis was based on a standardized residential prototype intended to facilitate controlled comparison between Riyadh and Dubai. While this approach improves methodological consistency, actual residential buildings may exhibit different geometries, occupancy patterns, operational schedules, and construction characteristics.

Second, the optimization framework focused on four design variables: window-to-wall ratio, glazing type, external shading depth, and cooling setpoint temperature. Other influential design parameters, including insulation thickness, building orientation, natural ventilation strategies, thermal mass, and renewable energy integration, were not considered and may influence optimization outcomes.

Third, thermal comfort was evaluated using ASHRAE 55 discomfort hours, while visual comfort,

daylight availability, indoor air quality, and acoustic performance were not included within the optimization objectives. Future multi-objective studies could incorporate these additional performance dimensions to provide a more comprehensive assessment of building sustainability.

Fourth, embodied carbon calculations were derived from the material database available within DesignBuilder and associated ICE datasets. Although suitable for comparative analysis, embodied carbon estimates may vary depending on regional material sourcing, transportation assumptions, construction practices, and life-cycle assessment methodologies.

Finally, occupant behavior was represented through standardized schedules and operational assumptions. Real-world variations in occupancy, thermostat settings, equipment use, and adaptive comfort behavior may affect actual building performance. Future research could integrate stochastic occupancy models, climate change weather scenarios, economic assessment, and additional envelope variables to further improve the robustness and applicability of optimization-based design guidance.

This study developed and applied a simulation-based tri-objective optimization framework to evaluate the interactions among energy performance, thermal comfort, and embodied carbon in residential buildings located in two representative Gulf cities: Riyadh and Dubai. Using DesignBuilder, EnergyPlus, and the Non-Dominated Sorting Genetic Algorithm II (NSGA-II), the research investigated how façade-related design variables influence building sustainability outcomes under hot-arid climatic conditions.

Baseline simulations demonstrated that identical residential buildings can exhibit substantially different operational performance when exposed to different climatic contexts. Dubai recorded higher annual energy consumption and greater thermal discomfort than Riyadh, highlighting the importance of local climate conditions in shaping building performance. These

differences establish the need for climate-responsive design strategies rather than universal design solutions.

The optimization process successfully identified Pareto-optimal solutions capable of significantly improving building performance. Energy consumption reductions exceeded 70% in both cities, while thermal discomfort was simultaneously reduced through combinations of lower window-to-wall ratios, improved glazing systems, and enhanced solar shading. The results confirmed that façade design remains one of the most influential factors affecting cooling-dominated residential buildings in Gulf environments.

The study further demonstrated that embodied carbon introduces important trade-offs within optimization processes. Solutions that minimized operational energy demand often required additional façade components or higher-performance glazing systems, resulting in moderate increases in material-related emissions. Consequently, the findings emphasize the importance of evaluating operational and embodied impacts simultaneously when pursuing sustainable building design.

Across both climatic contexts, the optimization consistently favored reduced glazing areas, high-performance glazing systems, and substantial external shading. These recurring characteristics suggest that robust design principles exist for hot-arid residential environments, although local climatic conditions continue to influence final performance outcomes.

Overall, the proposed framework demonstrates the value of multi-objective optimization as a decision-support tool for climate-responsive architecture. By simultaneously considering energy use, thermal comfort, and embodied carbon, the methodology provides architects, engineers, and policymakers with a more comprehensive basis for evaluating residential building performance and advancing sustainability objectives in rapidly urbanizing Gulf regions.

Abbreviations: The following abbreviations are used in this manuscript:

| | |
|--------------------------|---|
| ACH | Air Changes per Hour |
| ASHRAE | American Society of Heating, Refrigerating and Air-Conditioning Engineers |
| CO₂ | Carbon Dioxide |
| COP | Coefficient of Performance |
| EUI | Energy Use Intensity |
| EPW | EnergyPlus Weather File |
| HVAC | Heating, Ventilation, and Air Conditioning |
| ICE | Inventory of Carbon and Energy |
| kgCO_{2e} | Kilograms of Carbon Dioxide Equivalent |
| NSGA-II | Non-Dominated Sorting Genetic Algorithm II |
| TMY | Typical Meteorological Year |
| WWR | Window-to-Wall Ratio |

REFERENCES

- Albatayneh, A. (2021). Sensitivity analysis optimisation of building envelope parameters in a sub-humid Mediterranean climate zone. *Energy Exploration & Exploitation*, 39(6), 2080–2102. <https://doi.org/10.1177/01445987211020432>
- Alexakis, K., Benekis, V., Kokkinakos, P., & Askounis, D. (2025). Genetic algorithm-based multi-objective optimisation for energy-efficient building retrofitting: A systematic review. *Energy and Buildings*, 328, 115216. <https://doi.org/10.1016/j.enbuild.2024.115216>
- Ali, K., & Nogueira de Vasconcellos, V. M. (2018). *Ilhas artificiais, impactos ambientais e estratégias sustentáveis: A Ilha Palm Jumeirah, Dubai*. <https://doi.org/10.5281/ZENODO.17497710>
- Ali, K., & Nogueira De Vasconcellos, V. M. (2020). Vizinhança Sustentável: Avaliação da Sustentabilidade da Ilha Palm Jumeirah em Dubai. *Paranoá: Cadernos de Arquitetura e Urbanismo*, (27), 146–170. <https://doi.org/10.18830/issn.1679-0944.n27.2020.09>
- Ali, K., Tintawi, G., & Bassma, M. K. (2026). AI-Guided Evolutionary Optimization of Passive Solar Design for Residential Heating Across Distinct Climate Zones. *Solar*, 6(2), 13. <https://doi.org/10.3390/solar6020013>
- Alwetaishi, M., & Benjeddou, O. (2021). Impact of Window to Wall Ratio on Energy Loads in Hot Regions: A Study of Building Energy Performance. *Energies*, 14(4), 1080. <https://doi.org/10.3390/en14041080>
- American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). (2023). *ANSI/ASHRAE Standard 55-2023: Thermal Environmental Conditions for Human Occupancy* (ANSI/ASHRAE Standard 55-2023). <https://www.ashrae.org>
- Ayoobi, A. W., & Inceoğlu, M. (2024). Developing an Optimized Energy-Efficient Sustainable Building Design Model in an Arid and Semi-Arid Region: A Genetic Algorithm Approach. *Energies*, 17(23), 6095. <https://doi.org/10.3390/en17236095>
- Bassma, M. K., & Tintawi, G. (2026). Envelope Design Trade-offs for Low-carbon Residential Buildings in Dubai: A Simulation-based Multi-objective Optimization Study. *International Journal of Science and Research Archive*, 19(3), 157–170. <https://doi.org/10.30574/ijrsra.2026.19.3.1228>
- Bokhari, A., & Ali, K. (2026). Simulation-Based Evolutionary Optimization of Residential Buildings for Energy and Carbon Reduction Across Warm-Humid and Coastal Hot-Arid Climates. *Buildings*, 16(11), 2157. <https://doi.org/10.3390/buildings16112157>
- Bolattürk, A. (2008). Optimum insulation thicknesses for building walls with respect to cooling and heating degree-hours in the warmest zone of Turkey. *Building and Environment*, 43(6), 1055–1064. <https://doi.org/10.1016/j.buildenv.2007.02.014>
- Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P. W., Trisos, C., Romero, J., Aldunce, P., Barrett, K., Blanco, G., Cheung, W. W. L., Connors, S., Denton, F., Diongue-Niang, A., Dodman, D., Garschagen, M., Geden, O., Hayward, B., Jones, C., ... Péan, C. (with Lee, H.). (2023). *IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]*. IPCC, Geneva, Switzerland. (First). Intergovernmental Panel on Climate Change (IPCC). <https://doi.org/10.59327/IPCC/AR6-9789291691647>
- Chen, Y., Chen, Z., Wang, D., Liu, Y., Zhang, Y., Liu, Y., Zhao, Y., Gao, M., & Fan, J. (2023). Co-optimization of passive building and active solar heating system based on the objective of minimum carbon emissions. *Energy*, 275, 127401. <https://doi.org/10.1016/j.energy.2023.127401>
- 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., & Glazer, J. (2001). EnergyPlus: Creating a new-generation building energy simulation program. *Energy and Buildings*, 33(4), 319–331. [https://doi.org/10.1016/S0378-7788\(00\)00114-6](https://doi.org/10.1016/S0378-7788(00)00114-6)
- D'Agostino, D., D'Agostino, P., Minelli, F., & Minichiello, F. (2021). Proposal of a new automated workflow for the computational performance-driven design optimization of building energy need and construction cost. *Energy and Buildings*, 239, 110857. <https://doi.org/10.1016/j.enbuild.2021.110857>
- de Dear, R., & Brager, G. S. (1998). Developing an adaptive model of thermal comfort and preference. *ASHRAE Transactions*, 104, 145–167.
- Deb, K., Pratap, A., Agarwal, S., & Meyarivan, T. (2002). A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE Transactions on Evolutionary Computation*, 6(2), 182–197. <https://doi.org/10.1109/4235.996017>
- EnergyPlus*. (n.d.). Retrieved March 14, 2026, from <https://energyplus.net/>
- Evins, R. (2013). A review of computational optimisation methods applied to sustainable building design. *Renewable and Sustainable Energy Reviews*, 22, 230–245. <https://doi.org/10.1016/j.rser.2013.02.004>
- Gigasari, A. R., Cañada-Soriano, M., Aparicio-Fernández, C., & Vivancos, J.-L. (2025). Impact of Window-to-Wall Ratio (WWR) and shading on energy demand in a residential building across five distinct climates. *Results in Engineering*, 28, 107518. <https://doi.org/10.1016/j.rineng.2025.107518>

- Global Alliance for Buildings and Construction & United Nations Environment Programme. (2024). *Global Status Report for Buildings and Construction—Beyond foundations: Mainstreaming sustainable solutions to cut emissions from the buildings sector* (I. Hamilton, H. Kennard, O. Rapf, J. Amoroch, S. Steuwer, J. Kockat, & Z. Toth, Trans.; Nos. 978-92-807-4131-5). <https://doi.org/10.59117/20.500.11822/45095>
- Hamdy, M., Hasan, A., & Siren, K. (2013). A multi-stage optimization method for cost-optimal and nearly-zero-energy building solutions in line with the EPBD-recast 2010. *Energy and Buildings*, 56, 189–203. <https://doi.org/10.1016/j.enbuild.2012.08.023>
- Machard, A., Salvati, A., P. Tootkaboni, M., Gaur, A., Zou, J., Wang, L. L., Baba, F., Ge, H., Bre, F., Bozonnet, E., Corrado, V., Luo, X., Levinson, R., Lee, S. H., Hong, T., Salles Olinger, M., Machado, R. M. E. S., Da Guarda, E. L. A., Veiga, R. K., ... Holzer, P. (2024). Typical and extreme weather datasets for studying the resilience of buildings to climate change and heatwaves. *Scientific Data*, 11(1), 531. <https://doi.org/10.1038/s41597-024-03319-8>
- Magnier, L., & Haghghat, F. (2010). Multiobjective optimization of building design using TRNSYS simulations, genetic algorithm, and Artificial Neural Network. *Building and Environment*, 45(3), 739–746. <https://doi.org/10.1016/j.buildenv.2009.08.016>
- Nguyen, A.-T., Reiter, S., & Rigo, P. (2014). A review on simulation-based optimization methods applied to building performance analysis. *Applied Energy*, 113, 1043–1058. <https://doi.org/10.1016/j.apenergy.2013.08.061>
- O'Donoghue, S., Lehmann, M., Major, D., Major-Ex, G., Sutherland, C., Motau, A., Haddaden, N., Kibria, A. Smg., Costanza, R., Groves, C., Behie, A., & Johnson, K. (2021). Adaptation to climate change in small coastal cities: The influence of development status on adaptation response. *Ocean & Coastal Management*, 211, 105788. <https://doi.org/10.1016/j.ocecoaman.2021.105788>
- Ozel, M. (2011). Thermal performance and optimum insulation thickness of building walls with different structure materials. *Applied Thermal Engineering*, 31(17–18), 3854–3863. <https://doi.org/10.1016/j.applthermaleng.2011.07.033>
- Pajek, L., Potočnik, J., & Košir, M. (2022). 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*, 261, 111947. <https://doi.org/10.1016/j.enbuild.2022.111947>
- Sayadi, S., Akander, J., Hayati, A., & Cehlin, M. (2022). Analyzing the climate-driven energy demand and carbon emission for a prototype residential nZEB in central Sweden. *Energy and Buildings*, 261, 111960. <https://doi.org/10.1016/j.enbuild.2022.111960>
- Tawfeeq, H., & Qaradaghi, A. M. A. (2024). Optimising Window-to-Wall Ratio for Enhanced Energy Efficiency and Building Intelligence in Hot Summer Mediterranean Climates. *Sustainability*, 16(17), 7342. <https://doi.org/10.3390/su16177342>
- Tintawi, G., Ali, K., Monteiro, L., Bassma, M. K., & Rosse Caldas, L. (2026). *Material Sufficiency, Energy Use, and Life-Cycle Carbon in Hot-Arid Residential Buildings: A Pareto-Informed Multi-Criteria Evaluation of Envelope Design Strategies*. <https://doi.org/10.20944/preprints202605.1583.v1>
- Toroxel, J. L., & Silva, S. M. (2024). A Review of Passive Solar Heating and Cooling Technologies Based on Bioclimatic and Vernacular Architecture. *Energies*, 17(5), 1006. <https://doi.org/10.3390/en17051006>