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Material Sufficiency, Energy Use, and Life-Cycle Carbon in Hot-Arid Residential Buildings: A Pareto-Informed Multi-Criteria Evaluation of Envelope Design Strategies

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Abstract

Hot-arid residential buildings experience persistent cooling demand and increasing material intensity, yet most building-performance studies prioritize operational energy while insufficiently integrating life-cycle carbon and material sufficiency into envelope evaluation. This limits the ability to distinguish between performance gains achieved through passive design efficiency and those dependent on increased material input. This study investigates the interaction between material sufficiency, energy use, and life-cycle carbon in residential buildings across three representative hot-arid climates: Riyadh, Abu Dhabi, and Doha. A Pareto-informed multi-criteria evaluation framework was applied using a standardized mid-rise residential prototype to assess predefined envelope design strategies under consistent operational conditions. Dynamic energy simulations were conducted in DesignBuilder/EnergyPlus, while embodied carbon was quantified through a consistent material inventory approach. Baseline energy use intensity (EUI) values reached 64.98, 83.13, and 93.67 kWh/m²·year for Riyadh, Abu Dhabi, and Doha, respectively, reflecting increasing cooling demand from inland dry to humid coastal conditions. Envelope optimization reduced EUI to 47.33–72.40 kWh/m²·year, while embodied carbon ranged from 40,761.2 to 57,146.2 kgCO$_2$-eq per configuration. Reduced window-to-wall ratio strategies consistently achieved the most balanced performance across all climates, whereas high-glazing configurations increased energy demand, carbon emissions, and material intensity. The study operationalizes a sufficiency-oriented evaluation perspective that supports climate-responsive envelope decision-making by integrating operational and material performance within a unified comparative framework.

Keywords: material sufficiency; energy use intensity; LCA; arid climate; envelope design; window-to-wall ratio; multi-criteria evaluation

1. Introduction

1.1. Energy Demand and Environmental Pressure in Arid Climate Buildings

The buildings and construction sector accounts for approximately 34% of global energy demand and 37% of energy- and process-related CO$_2$ emissions, while residential buildings represent nearly 70% of total building energy demand, highlighting the scale of the operational challenge addressed in this study [1–4]. In hot-arid regions, this burden is intensified by summer temperatures frequently exceeding 40 °C across the Middle East and North Africa (MENA), where cooling already represents nearly half of peak electricity demand and approximately one-quarter of annual electricity consumption [5,6]. Electricity demand in the region has tripled since 2000 and is projected to increase by a further 50% by 2035, with cooling expected to remain the primary driver of growth [2,6,7].

Despite improvements in energy-efficiency technologies, reducing operational energy demand remains a major challenge in cooling-dominated climates. This challenge is reinforced by the regional electricity mix, where natural gas and oil continue to supply more than 90% of electricity generation across MENA [6,8,9]. Consequently, improving residential performance in hot-arid climates requires a stronger understanding of how environmental conditions and envelope design influence cooling demand.

At the same time, building-related environmental impacts extend beyond operational energy. Embodied carbon, associated with material extraction, manufacturing, and construction, has become an increasingly important contributor to total building emissions, particularly in energy-efficient buildings where operational demand is reduced [8–10]. Because strategies that lower operational energy often require additional materials, trade-offs may emerge between operational and embodied impacts, reinforcing the need for integrated evaluation approaches that consider both dimensions simultaneously.

1.2. Envelope Design and Performance-Based Evaluation in Buildings

Building envelope design plays a critical role in thermal performance, particularly in cooling-dominated climates. Variables such as window-to-wall ratio, glazing type, insulation level, and shading systems directly influence heat transfer, solar gains, and indoor thermal conditions [5,11]. Because these variables interact in complex ways, building performance is increasingly evaluated through simulation-based approaches.

Performance-based design has therefore become central to contemporary architectural practice. Simulation environments such as EnergyPlus support detailed assessment of energy use, thermal comfort, and system behavior under realistic climatic conditions, while multi-objective and generative approaches increasingly assist decision-making through structured evaluation of competing design alternatives [12–15]. In particular, evolutionary methods such as NSGA-II and Pareto-informed frameworks enable simultaneous assessment of multiple objectives and identification of trade-offs among competing performance criteria [11,16].

However, most building-performance evaluation frameworks remain strongly focused on operational indicators, particularly energy demand and thermal comfort. Although these approaches improve performance outcomes, they often overlook the material implications of design decisions, potentially favoring solutions that reduce operational energy while increasing material intensity and embodied carbon. This limitation highlights the need for more integrated evaluation approaches capable of assessing both operational and material performance simultaneously.

1.3. Limitations of Efficiency-Driven Design and the Role of Material Sufficiency

Building-performance research is largely driven by efficiency-oriented objectives, where success is measured through reductions in energy demand or carbon emissions [17]. Although this approach has improved building performance, it often overlooks the relationship between environmental gains and resource input, particularly whether efficiency is achieved through optimized design or increased material use.

Recent studies show that interventions such as additional insulation or advanced shading may reduce operational energy demand while increasing embodied carbon [8,18]. In some cases, the environmental burden associated with extra materials may partially offset operational savings, revealing an important limitation of efficiency-driven design from a life-cycle perspective.

Material sufficiency offers an alternative perspective by evaluating the relationship between performance and the resources required to achieve it [10,19]. Rather than maximizing efficiency alone, sufficiency emphasizes balanced outcomes in which acceptable performance is achieved with restrained material input. This perspective is particularly relevant in hot-arid climates, where envelope decisions strongly influence cooling demand and material use. Strategies such as reducing glazing area or limiting solar exposure can substantially lower cooling loads without requiring

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additional materials, demonstrating how climate-responsive design restraint may provide effective performance improvements with lower environmental burden.

1.4. Research Questions

To address the limitations of single-objective building-performance assessment, this study comparatively evaluates the interaction between operational energy demand, life-cycle carbon, and material sufficiency across residential envelope configurations in hot-arid climates. The analysis is guided by the following research questions:

RQ1: How do envelope design strategies influence operational energy demand, life-cycle carbon, and material sufficiency across hot-arid climates?

RQ2: To what extent do geometry-driven and material-intensive strategies differ in environmental performance?

RQ3: Can a Pareto-informed multi-criteria evaluation framework support the identification of balanced design configurations under competing environmental priorities?

These research questions provide the analytical basis for evaluating trade-offs among envelope strategies and for assessing the suitability of sufficiency-oriented design approaches in cooling-dominated residential buildings

1.5. Research Gap and Study Objective

The literature reveals a persistent gap in the integration of operational performance, embodied carbon, and material sufficiency within a unified building-performance framework. Although simulation-based methods have advanced evaluation of energy performance, most studies remain focused on operational indicators, with embodied carbon and material-related impacts often treated separately or as secondary considerations. In addition, material sufficiency remains weakly operationalized in simulation-based envelope studies, particularly as a measurable relationship between performance improvement and resource input.

Another limitation concerns climatic representation. Existing studies commonly examine either single climatic contexts or broad cross-climate comparisons, with limited attention to variation within a specific climate category. In hot-arid regions, inland and coastal environments differ substantially in humidity, latent cooling demand, and thermal discomfort, yet these intra-climate differences remain insufficiently examined in comparative envelope studies.

To address these gaps, this study develops a simulation-based Pareto-informed multi-criteria evaluation framework integrating operational energy demand, life-cycle carbon, and material sufficiency within a consistent simulation environment. A standardized mid-rise residential prototype is comparatively evaluated across three representative hot-arid climates, Riyadh, Abu Dhabi, and Doha, to isolate the influence of envelope design under varying climatic conditions.

The study aims to examine how envelope design strategies influence energy demand, carbon emissions, and material sufficiency across hot-arid climates while identifying balanced configurations through multi-criteria evaluation. In doing so, the study provides a structured basis for climate-responsive residential envelope assessment through the combined lenses of operational performance, life-cycle carbon, and material sufficiency.

2. Theoretical Foundations

2.1. Performance-Based Design and Multi-Criteria Evaluation in Buildings

Performance-based design evaluates buildings according to measurable indicators such as energy use, thermal comfort, and environmental impact rather than prescriptive standards [11,20]. Advances in dynamic simulation tools have strengthened this approach by enabling assessment of building behavior under varying climatic and operational conditions.

In building-envelope design, improvements in one performance dimension frequently generate penalties in another. For example, strategies that reduce cooling demand through enhanced glazing or insulation may simultaneously increase embodied carbon because of additional material requirements, creating trade-offs that cannot be adequately captured through single-objective evaluation [12,16,21].

To address such complexity, evolutionary algorithms, particularly NSGA-II and other Pareto-based multi-objective approaches, are increasingly used in building-performance research to identify balanced solutions across competing objectives [15,16]. These methods support structured exploration of design alternatives and are widely integrated into simulation-based workflows for sustainable building design and early-stage decision-making [11,14].

Despite their methodological advantages, most optimization studies remain strongly focused on operational indicators, particularly annual energy demand and thermal comfort, while embodied impacts are frequently omitted or treated as secondary considerations [9,22]. This limitation is especially important in hot-arid regions, where cooling dominates annual building energy demand and places increasing pressure on electricity systems across the Middle East and North Africa (MENA) [2,6,23,24]. In high-performance envelopes, embodied carbon may account for 20–50% of total life-cycle emissions and, in some cases, exceed operational impacts [9,22].

Accordingly, the present study adopts a simplified evaluation-based framework to preserve interpretability and isolate the influence of discrete envelope variables while enabling comparative assessment of operational performance, life-cycle carbon, and material sufficiency under hot-arid conditions.

2.2. Envelope Design Variables and Thermal Performance in Arid Climates

Building-envelope design is a major determinant of energy performance in cooling-dominated climates, where variables such as window-to-wall ratio (WWR), glazing properties, insulation levels, and shading systems directly influence solar heat gains, conductive transfer, and indoor thermal behavior [5,7]. Their influence is particularly pronounced in hot-arid climates because of intense solar radiation and limited passive cooling potential.

Among these variables, sensitivity analyses consistently identify WWR as one of the strongest determinants of cooling demand [25]. Studies in hot-arid regions report that WWR values above 40–50% substantially increase cooling loads, whereas optimized residential configurations commonly converge toward 20–30%, depending on glazing and shading strategies [25,26]. Low-emissivity glazing systems further reduce cooling loads by approximately 17–22% relative to conventional glazing by limiting solar heat gain while maintaining acceptable daylight performance [27].

Insulation also affects thermal performance by reducing conductive heat transfer; however, studies report diminishing returns beyond moderate thickness levels, particularly under cooling-dominated conditions [18,28]. In hot-arid climates, operational improvements frequently become less significant beyond approximately 50–100 mm, although optimal values vary according to climate severity and envelope composition [18,28].

Shading systems, including overhangs and external devices, can effectively reduce solar gains and improve indoor thermal conditions. However, their effectiveness depends on climatic context, orientation, and depth, while additional material requirements may increase embodied carbon. This creates trade-offs between operational energy savings and material-related environmental impacts that are often overlooked in conventional performance assessment.

2.3. Passive Design Strategies and Demand Reduction

Passive design strategies reduce energy demand by aligning building performance with environmental conditions rather than relying primarily on mechanical systems. In hot-arid climates, these strategies commonly focus on minimizing solar gains and controlling heat transfer through measures such as orientation optimization, controlled solar exposure, thermal mass, and natural ventilation [26].

Vernacular architecture provides strong evidence of the effectiveness of passive design in arid regions. Traditional desert buildings frequently employ thick walls, compact geometry, small openings, and shading elements to reduce heat gain and improve indoor comfort. Field observations and simulation studies indicate that such strategies may reduce indoor temperatures by approximately 2–6 °C relative to exposed contemporary envelopes under similar climatic conditions [29], demonstrating that meaningful performance improvements can often be achieved through design simplicity rather than technological intensification.

Although passive strategies are increasingly evaluated through simulation-based methods, contemporary building-performance frameworks often prioritize material or technological interventions over demand reduction. This distinction is important because demand-reduction strategies lower energy needs through design decisions, whereas performance enhancement frequently depends on additional systems or materials. From a sustainability perspective, passive demand reduction is generally more resource-efficient, simultaneously reducing operational energy and material requirements. Recent climate mitigation assessments suggest that demand-side building strategies, including passive design, may reduce direct building emissions by approximately 51–85% by 2050 under systematic implementation scenarios [21].

2.4. Embodied Carbon and Life-Cycle Assessment in Buildings

Growing attention to embodied carbon has increased the use of life-cycle assessment (LCA) in building-performance research. Embodied carbon includes emissions associated with material extraction, manufacturing, transportation, and construction, and can represent a substantial share of total building-related emissions, particularly in energy-efficient buildings where operational demand is reduced [8,9].

LCA provides a structured framework for evaluating environmental impacts across different life-cycle stages. However, full life-cycle applications often require detailed datasets and substantial modeling effort, limiting their integration during early-stage architectural decision-making. Consequently, many performance-based studies adopt simplified approaches focused on key stages, particularly A1–A3 (material extraction, transportation, and manufacturing) [9].

An important challenge concerns the interaction between operational and embodied carbon. Recent studies emphasize that reductions in operational energy do not necessarily correspond to lower embodied impacts, particularly when performance improvements depend on additional materials or construction systems [18,22,30,31]. Strategies such as increased insulation or advanced glazing may reduce cooling demand while simultaneously increasing embodied emissions, creating trade-offs between operational and material performance [18].

Although embodied carbon is increasingly incorporated into building-performance frameworks, it is often treated as a complementary or secondary indicator rather than integrated alongside operational performance within comparative decision-support processes [22,30]. This can limit the ability to identify design strategies that achieve balanced environmental outcomes across both operational and material dimensions.

2.5. Material Sufficiency and Emerging Design Paradigms

Material sufficiency has emerged as an important sustainability paradigm that differs from efficiency-oriented approaches. Whereas efficiency seeks to maximize performance per unit of resource, sufficiency emphasizes achieving adequate performance with restrained material consumption and questions whether additional resource input is necessary [19,32]. This perspective is particularly relevant in construction, where carbon-intensive materials such as cement and steel collectively account for approximately 14–18% of global CO_2 emissions [4,33].

In building design, material sufficiency concerns whether performance improvements are achieved through optimized design or increased material input. This distinction is especially relevant in envelope design, where interventions such as additional insulation or shading may reduce operational energy demand while increasing material use and embodied carbon.

Recent studies have increasingly explored sufficiency-oriented approaches in the built environment, including reductions in floor area, material demand, and structural intensity [32].

However, the operationalization of material sufficiency within simulation-based building-performance evaluation remains comparatively limited, particularly through metrics capable of linking environmental performance with material input and design variables.

Quantitative indicators such as sufficiency indices provide one potential pathway for addressing this challenge by integrating material intensity with performance-related parameters. Such approaches enable evaluation of whether environmental improvements result from balanced design decisions or increased material intervention, aligning with broader sustainability paradigms that prioritize reduction and optimization over technological intensification.

In hot-arid residential envelopes, this perspective is especially relevant because operational improvements may often be achieved through climate-responsive geometry, glazing control, and passive solar management rather than material-intensive technological escalation. Material sufficiency therefore provides an additional interpretive lens for identifying balanced envelope strategies under cooling-dominated conditions.

3. Methodology

3.1. Research Framework and Analytical Approach

This study adopts a simulation-based, Pareto-informed multi-criteria evaluation framework to examine the interaction between material sufficiency, operational energy use, and carbon emissions in residential buildings under hot-arid climatic conditions. The framework integrates three analytical components: dynamic energy simulation, embodied carbon assessment, and comparative multi-criteria evaluation.

To capture trade-offs between operational efficiency, material-related impacts, and design sufficiency, eight predefined envelope configurations are comparatively assessed under consistent climatic and operational assumptions across Riyadh, Abu Dhabi, and Doha [11,16,34]. Performance is evaluated using three objectives: energy use intensity (EUI), life-cycle carbon, and material sufficiency.

Pareto dominance principles are applied to identify non-dominated configurations that achieve balanced performance across competing objectives. Unlike full evolutionary optimization workflows involving iterative population generation, crossover, mutation, and convergence tracking, the present study adopts a deterministic comparative assessment of predefined design scenarios [16]. This approach was selected to preserve interpretability, isolate the influence of discrete envelope variables, and support transparent comparison between material-based and geometry-driven interventions.

Accordingly, the Pareto-informed multi-criteria evaluation framework is implemented as a comparative decision-support mechanism rather than an optimization engine, supporting early-stage climate-responsive envelope assessment under competing environmental priorities.

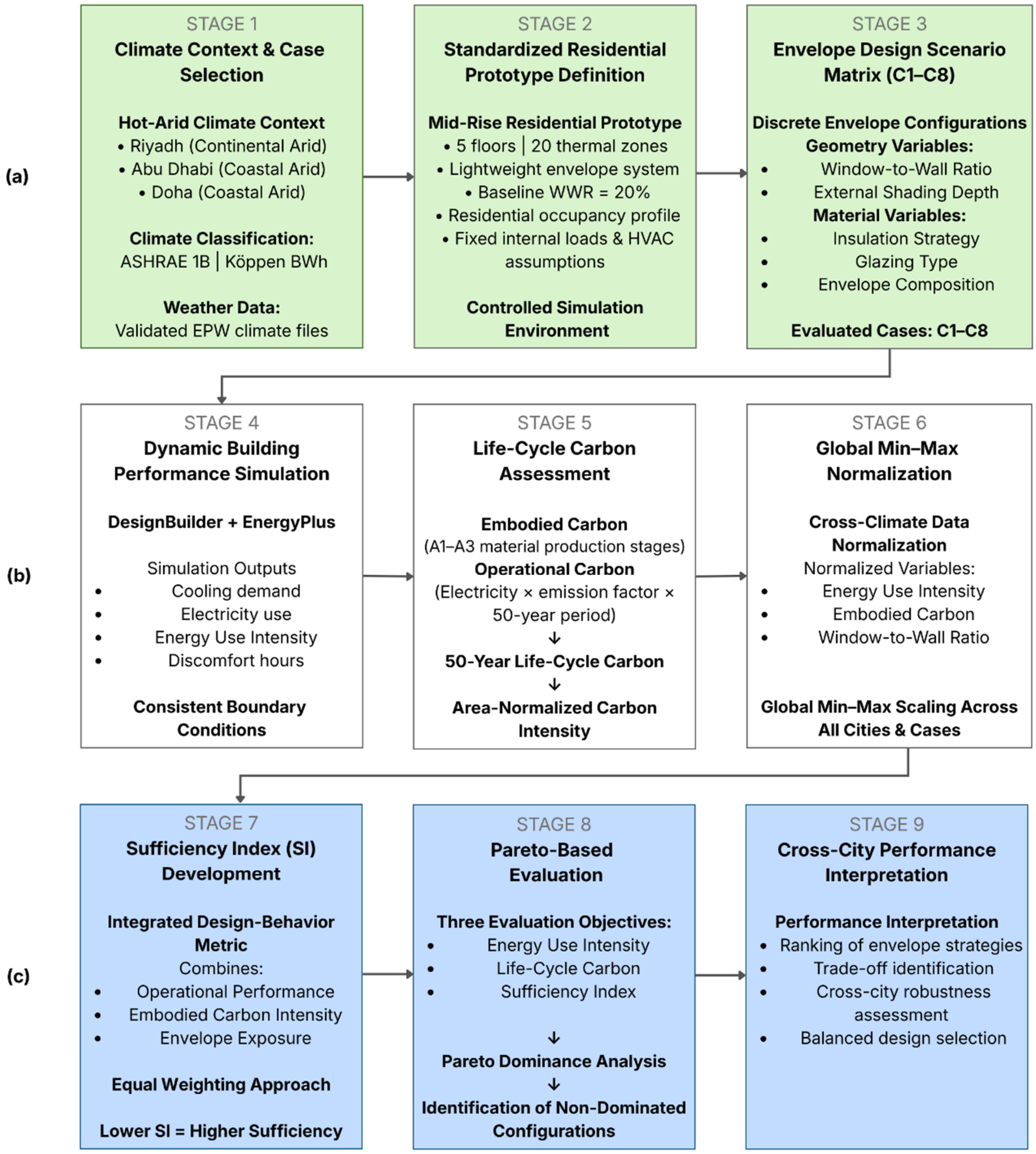

Figure 1. Methodological framework for Pareto-informed multi-criteria evaluation of envelope design strategies across hot-arid climates. (a) Study context and simulation setup, including climate selection, prototype definition, and envelope scenario matrix; (b) performance simulation and environmental assessment, including dynamic building simulation, life-cycle carbon calculation, and global normalization; (c) decision-support evaluation, including Sufficiency Index (SI) development, pareto-informed multi-criteria evaluation, and cross-city comparative interpretation.

3.2. Climate Context and Case Selection

The study focuses on hot-arid climates, where extreme temperatures and high solar radiation intensify cooling demand and increase the influence of envelope design on building performance. Three representative cities were selected: Riyadh (Saudi Arabia), Abu Dhabi (UAE), and Doha (Qatar).

All locations are classified as ASHRAE climate zone 1B and Köppen BWh, providing a consistent climatic basis for comparison. However, important intra-climate differences exist. Riyadh represents a continental hot-arid climate characterized by lower humidity, greater diurnal temperature variation, and predominantly sensible cooling loads. In contrast, Abu Dhabi and Doha represent coastal hot-arid climates, where elevated humidity increases latent cooling demand [5]. These differences are reflected in wet-bulb temperatures, which are higher in Abu Dhabi and Doha (approximately 23–24 °C) than in Riyadh (approximately 21 °C), while peak dry-bulb temperatures exceed 44 °C across all cities.

The selection of these cities enables a controlled intra-climate comparison within the hot-arid category, allowing investigation of humidity-driven cooling differences while maintaining consistency in climatic classification. This approach improves interpretation of how envelope strategies respond to varying latent cooling conditions under comparable hot-arid environments.

3.3. Climate Data and Simulation Inputs

Weather data for Riyadh, Abu Dhabi, and Doha were obtained in EnergyPlus Weather (EPW) format from validated international datasets, including IWEC and ASHRAE sources. These files represent typical meteorological year (TMY) conditions and are widely used in building-performance simulation studies [20]. Table 1 presents the climatic characteristics of the selected study locations, including temperature, humidity, and geographic parameters.

Table 1. Climatic characteristics of Riyadh, Abu Dhabi, and Doha, including temperature, humidity, and geographic parameters used for simulation.

Parameter	Riyadh	Abu Dhabi	Doha
Country	Saudi Arabia	UAE	Qatar
Climate Type	Hot-arid (Continental)	Hot-arid (Coastal-influenced)	Hot-arid (Coastal-influenced)
ASHRAE Zone	1B	1B	1B
Köppen Classification	BWh	BWh	BWh
Latitude (°N)	24.7	24.43	25.26
Longitude (°E)	46.73	54.65	51.57
Elevation (m)	620	27	10
Peak Dry-Bulb (°C)	44.7	46.2	45.2
Peak Wet-Bulb (°C)	21.2	23.6	23
Climate Character	Hot-arid (Low humidity)	Hot-arid (High humidity)	Hot-arid (High humidity)

Each climate file was applied separately to the same standardized building model to ensure that variations in simulation outcomes reflected climatic differences rather than changes in geometry or operational assumptions. This approach maintains methodological consistency and supports direct comparison across locations.

All simulations were conducted using DesignBuilder with the EnergyPlus simulation engine [20,35]. enabling detailed assessment of building thermal behavior, including heat transfer, solar gains, internal loads, and HVAC system performance. The use of present-day typical meteorological year data was intentionally selected to establish a controlled comparative baseline for evaluating envelope strategies under current climatic conditions. Future climate scenarios represent an important extension and are recommended for subsequent research examining long-term resilience under projected warming conditions.

3.4. Prototype Building and HVAC Configuration

A standardized mid-rise residential prototype was developed in DesignBuilder to provide a controlled reference model for comparative simulation across the selected hot-arid climates. The prototype consists of a compact five-story apartment building divided into four thermal zones per

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floor, resulting in twenty zones. This zoning arrangement was selected to balance thermal resolution with model simplicity while maintaining consistency across climate files and envelope scenarios.

The envelope includes lightweight concrete block external walls with an air gap and plasterboard finish, a lightweight flat roof, a reference ground floor slab, and 100 mm concrete internal floor slabs. Airtightness was represented by a constant infiltration rate of 0.7 ACH. External windows were modeled using double clear glazing (3 mm / 6 mm air gap). The baseline window-to-wall ratio (WWR) was fixed at 20%, with a window height of 1.50 m and sill height of 0.80 m. No external shading devices were included in the baseline case, enabling direct comparison with subsequent design interventions.

Internal conditions followed a residential activity template, with an occupancy density of 0.0188 people/m^2, lighting power density of 4 W/m^2 per 100 lux, and equipment loads of 5 W/m^2. These parameters were held constant across all simulations to isolate the influence of envelope and material variables on performance outcomes.

The HVAC system was modeled using a unitary cooling-based template with mechanical ventilation and outdoor air supplied according to the ASHRAE 62.1 fresh air method (L/s-person + L/s-m^2). Cooling was supplied through grid electricity with a seasonal coefficient of performance (COP) of 2.50. The cooling setpoint was fixed at 25 °C with a setback temperature of 28 °C. Heating, domestic hot water, humidification, dehumidification, and natural ventilation were deactivated to maintain focus on cooling-dominated energy behavior and isolate envelope-related effects under consistent boundary conditions.

3.5. Design Variables and Case Matrix

Eight predefined design configurations (C1–C8) were developed to evaluate the influence of envelope and material strategies on building performance. The configurations incorporate variations in:

- Window-to-wall ratio (WWR)
- Insulation characteristics
- Glazing systems
- External shading depth
- Envelope construction

The case matrix progresses from a baseline configuration (C1) to progressively modified scenarios, including both material-intensive and geometry-driven interventions. This structure enables controlled comparison of how discrete design decisions influence operational performance, life-cycle carbon, and material sufficiency across climatic contexts.

Detailed material assemblies, thermal properties, glazing specifications, embodied carbon assumptions, simulation inputs, and design configuration definitions are provided in the Supplementary Materials.

3.6. Life-Cycle Carbon Assessment

Life-cycle carbon was evaluated by integrating embodied carbon associated with material production and operational carbon resulting from building electricity consumption over a defined reference study period. The assessment adopted a simplified life-cycle framework focusing on dominant contributors to environmental impact in cooling-dominated residential buildings.

The total life-cycle carbon is defined as:

$$C_{LC} = C_{emb} + C_{op}$$

where:

- C_{LC}= total life-cycle carbon emissions (kgCO$_2$)
- C_{emb} = embodied carbon associated with building materials (kgCO$_2$)

- C_{op} = operational carbon over the reference study period ($kgCO_2$)

Operational carbon is calculated based on annual electricity consumption and location-specific grid emission factors over a defined reference study period:

$$C_{op} = E_{annual} \times EF \times L$$

where:

- E_{annual} = annual electricity consumption (kWh/year)
- EF = grid emission factor ($kgCO_2e/kWh$)
- RSP = reference study period (years)

The reference study period was fixed at 50 years, consistent with common building life-cycle assessment practice and widely used for comparative environmental evaluation of building design strategies [36].

Embodied carbon was calculated using a consistent material inventory approach applied across all configurations and focused on envelope-related materials, representing the principal source of variation between cases. Embodied carbon factors were obtained through the material life-cycle inventory database integrated within DesignBuilder, which primarily draws upon the Inventory of Carbon and Energy (ICE) database developed by the University of Bath. A consistent material database was applied across all envelope configurations to maintain methodological comparability during early-stage design evaluation.

To enable comparison across configurations, total life-cycle carbon was normalized by conditioned floor area:

$$C_{LC,norm} = \frac{C_{LC}}{A_f}$$

where:

- $C_{LC,norm}$= normalized life-cycle carbon ($kgCO_2$)
- A_f = total conditioned floor area (m^2)

The assessment scope focused on A1–A3 embodied carbon stages (material extraction, transportation, and manufacturing) together with operational electricity-related emissions. Construction processes (A4–A5), maintenance and replacement (B stages), and end-of-life impacts (C stages) were excluded to maintain methodological consistency and support transparent comparison between envelope configurations during early-stage design evaluation. This scope was selected because envelope-related material production represented the primary source of variation among predefined design strategies, whereas downstream life-cycle stages were assumed to remain comparatively consistent across scenarios.

3.7. Sufficiency Index as a Design-Behavior Metric

Material sufficiency in building design depends not only on resource use, but also on the relationship between resource input and performance outcomes. To evaluate this relationship, the present study develops a Sufficiency Index (SI) as a comparative design metric informed by material sufficiency principles and adapted for simulation-based envelope evaluation. The index integrates operational performance, material intensity, and envelope exposure within a unified framework.

Unlike conventional indicators such as energy use intensity (EUI) or life-cycle carbon, which evaluate environmental outcomes independently, the SI evaluates how efficiently those outcomes are achieved. It reflects the extent to which performance improvements depend on material intensification or increased façade exposure rather than balanced design strategies.

The index incorporates three normalized components representing operational demand, material input, and envelope exposure:

$$\mathrm{SI} = \frac{1}{3}\left(\mathrm{EUI_n} + \mathrm{C_{emb,int,n}} + \mathrm{WWR_n}\right)$$

To ensure comparability and dimensional consistency, each component is normalized using min–max scaling across the full set of design configurations:

$$EUI_n = \frac{EUI - EUI_{min}}{EUI_{max} - EUI_{min}}$$

$$C_{emb,int,n} = \frac{\frac{C_{emb}}{A_f} - C_{min}}{C_{max} - C_{min}}$$

$$WWR_n = \frac{WWR - WWR_{min}}{WWR_{max} - WWR_{min}}$$

where:

- SI= Sufficiency Index (dimensionless)
- EUI = energy use intensity (kWh/m²·year)
- C_{emb}= embodied carbon
- A_f = total conditioned floor area (m²)
- WWR= window-to-wall ratio (decimal)
- EUI_n = normalized operational energy demand
- $C_{emb,int,n}$= normalized embodied carbon intensity
- WWR_n = normalized envelope exposure

Embodied carbon intensity was included to capture material-related consequences of envelope decisions, while WWR was incorporated as a proxy for envelope exposure and solar gain potential in cooling-dominated climates. Global normalization limits were applied across all cities and configurations to maintain cross-climate comparability.

Equal weighting was assigned to all components:

$$w_1 = w_2 = w_3 = \frac{1}{3}$$

This weighting strategy was selected to maintain methodological neutrality and avoid privileging a single sustainability objective. Lower SI values indicate configurations achieving reduced energy demand with lower material intensity and controlled façade exposure, whereas higher values indicate greater reliance on material input or envelope exposure to achieve performance.

The proposed SI is intended as a comparative decision-support metric for early-stage envelope assessment rather than a standardized or absolute measure of sustainability. Its purpose is to support transparent comparison between competing envelope strategies under consistent environmental and operational conditions.

3.7.1. Sensitivity Analysis of Weighting Assumptions

To evaluate the robustness of the proposed Sufficiency Index (SI), a sensitivity analysis was conducted under alternative weighting assumptions emphasizing operational energy demand, embodied carbon intensity, and envelope exposure. The analysis assessed whether configuration ranking remained stable under differing sustainability priorities and therefore whether the proposed SI functions as a robust comparative decision-support metric rather than a weighting-sensitive construct.

The results demonstrated complete ranking stability across all tested weighting scenarios, with configuration C7 consistently remaining the highest-performing option and C8 remaining the least

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sufficient configuration regardless of weighting assumption. Although minor variations occurred in absolute SI values, no ranking changes were observed among configurations, indicating strong robustness of the proposed metric.

Detailed weighting formulations, equations, and sensitivity results are provided in the Supplementary Materials (Section S8.4, Table S23).

3.8. Pareto-Informed Multi-Criteria Evaluation Framework

The evaluation framework is structured as a three-objective comparative analysis problem, enabling simultaneous assessment of energy performance, life-cycle carbon impact, and material sufficiency across a discrete set of design configurations.

The multi-criteria evaluation is expressed as:

$$\min F\,(X) = [f_1(X), f_2(X), f_3(X)]$$

where the objective functions are defined as:

$$f_1(X) = EUI$$

$$f_2(X) = C_{LC,norm}$$

$$f_3(X) = SI$$

Although SI incorporates energy and material dimensions, it is retained as a separate objective to evaluate design efficiency rather than absolute environmental impact.

The design variable set is defined as:

$$X = \left[WWR, T_{ins}, G_{type}, S_{depth}\right]$$

where:

- WWR = window-to-wall ratio
- T_{ins} = insulation configuration (categorical: baseline, GRP, polyurethane
- G_{type} = glazing type (categorical: double clear, low-e)
- S_{depth} = external shading depth (m)

Unlike continuous optimization frameworks, the present study evaluates discrete predefined configurations rather than continuous search variables. Consequently, the analysis does not involve iterative population generation, crossover, mutation, or convergence procedures commonly associated with evolutionary algorithms.

A Pareto dominance approach is applied to identify non-dominated configurations, defined as solutions for which no alternative performs better across all objectives simultaneously. This enables identification of balanced envelope strategies that achieve favorable trade-offs among operational energy performance, life-cycle carbon, and material sufficiency.

The framework is therefore Pareto-informed but deterministically implemented, prioritizing interpretability and transparent attribution of performance outcomes to specific design decisions. Rather than identifying a single optimal solution, the approach defines a solution space of non-dominated configurations to support informed decision-making during early-stage envelope design.

3.9. Analysis Procedure

The analysis followed a structured workflow integrating building-performance simulation, carbon assessment, and Pareto-informed multi-criteria evaluation. First, all predefined envelope configurations (C1–C8) were simulated in DesignBuilder/EnergyPlus under standardized climatic and operational assumptions to obtain operational performance outputs [20].

Simulation results were then used to calculate operational carbon, based on annual electricity consumption and location-specific grid emission factors, together with embodied carbon, derived from the material composition of each configuration. Total life-cycle carbon was subsequently calculated over the defined reference study period and normalized by conditioned floor area to enable cross-configuration comparison.

In parallel, the Sufficiency Index (SI) was calculated for each configuration using normalized operational energy demand, embodied carbon intensity, and window-to-wall ratio, enabling comparative assessment of design efficiency in terms of material input and envelope exposure.

The resulting dataset was then evaluated using a Pareto-informed multi-criteria framework across three objectives: energy use intensity (EUI), normalized life-cycle carbon, and material sufficiency. Non-dominated configurations were identified according to Pareto dominance principles, representing envelope strategies that achieved balanced performance without being outperformed across all objectives simultaneously.

This workflow enabled systematic comparison of envelope strategies across climatic contexts and supported interpretation of trade-offs among operational performance, environmental impact, and material sufficiency in residential building design.

4. Results

4.1. Baseline Performance Across Arid Climate Contexts

To establish a consistent reference for comparative evaluation, baseline performance (C1) was assessed across Riyadh, Abu Dhabi, and Doha using identical geometry, envelope properties, operational schedules, and HVAC assumptions. Table 2 presents key performance indicators, including cooling demand, electricity consumption, energy use intensity (EUI), thermal comfort metrics, and carbon-related indicators. By maintaining constant building assumptions, the comparison isolates the influence of climatic variation within the hot-arid category.

Table 2. Baseline performance comparison (C1) across Riyadh, Abu Dhabi, and Doha under identical building conditions, showing cooling demand, electricity consumption, energy use intensity (EUI), thermal comfort indicators, and carbon metrics, highlighting the impact of climatic variation.

Metric	Riyadh	Abu Dhabi	Doha
Cooling demand (kWh)	137,159	189,907	220,527
Cooling electricity (kWh)	54,864	75,963	88,211
Total electricity (kWh)	75,526	96,625	108,873
EUI (kWh/m^2·year)	64.98	83.13	93.67
Unmet cooling hours	2	107	493
Not comfortable hours	1,534	2,615	2,722
Embodied carbon	51,595 kgCO$_2$	51,595 kgCO$_2$	51,595 kgCO$_2$
Equivalent CO$_2$	61,773 kgCO$_2$e	61,773 kgCO$_2$e	61,773 kgCO$_2$e

Despite all three cities belonging to hot-arid climates (ASHRAE 1B; Köppen BWh), substantial differences in operational performance are observed. Cooling demand increases from 137,159 kWh in Riyadh to 189,907 kWh in Abu Dhabi and 220,527 kWh in Doha, while EUI rises from 64.98 kWh/m^2·year to 83.13 kWh/m^2·year and 93.67 kWh/m^2·year, respectively, representing an increase of approximately 44% between Riyadh and Doha.

This pattern is primarily attributed to differences in humidity and latent cooling demand, which intensify cooling requirements in coastal environments [5,37]. Riyadh benefits from lower humidity and greater diurnal temperature variation, whereas Abu Dhabi and Doha experience elevated latent heat loads associated with humid coastal conditions, increasing cooling electricity demand and thermal discomfort.

Thermal comfort indicators reinforce this climatic gradient. Riyadh records only 2 unmet cooling hours and 1,534 discomfort hours, compared with 493 unmet cooling hours and 2,722 discomfort hours in Doha, while Abu Dhabi occupies an intermediate position.

Embodied carbon remains identical across baseline cases because material specifications were unchanged. Consequently, performance differences are driven primarily by operational energy demand rather than material variation. These findings confirm that humidity-driven cooling demand exerts a major influence on residential performance within hot-arid climates, emphasizing the importance of considering intra-climate variability in climate-responsive envelope evaluation and regional building policies [2,20].

4.2. Comparative Operational Performance of Envelope Design Strategies

Eight envelope configurations (C1–C8) were evaluated to examine the influence of material-based and geometry-driven interventions on residential performance across Riyadh, Abu Dhabi, and Doha. The strategies included insulation enhancement, glazing improvement, external shading, and modifications to window-to-wall ratio (WWR) under consistent building and operational assumptions.

Figure 2 presents the comparative energy use intensity (EUI) across all configurations and climatic contexts. Despite differences in climatic severity, a highly consistent performance pattern emerges. Geometry-driven interventions, particularly reduced WWR (C7), consistently achieve the largest reductions in operational energy demand, whereas increased façade exposure through higher glazing ratios (C8) systematically results in the highest energy consumption.

Across all cities, C7 delivers the strongest improvement relative to baseline conditions, reducing EUI from 64.98 to 47.33 kWh/m^2·year in Riyadh (−27%), 83.13 to 59.87 kWh/m^2·year in Abu Dhabi (−28%), and 93.67 to 72.40 kWh/m^2·year in Doha (−22.7%). The consistency of this pattern indicates that façade geometry exerts a stronger influence on cooling demand than intra-climate differences associated with humidity.

By contrast, C8 consistently performs worst, increasing operational energy demand because of elevated solar heat gains. This effect is particularly pronounced in Doha, where humid coastal conditions intensify latent cooling requirements. Intermediate strategies, including Low-E glazing (C4) and external shading (C5–C6), provide measurable energy reductions, although improvements vary according to climatic severity and intervention type.

Overall, the results indicate that geometry-driven demand reduction strategies outperform material-intensive interventions across all hot-arid contexts. Although absolute cooling demand increases substantially in coastal environments, the relative ranking of envelope strategies remains stable, suggesting strong transferability of climate-responsive design principles within the hot-arid category.

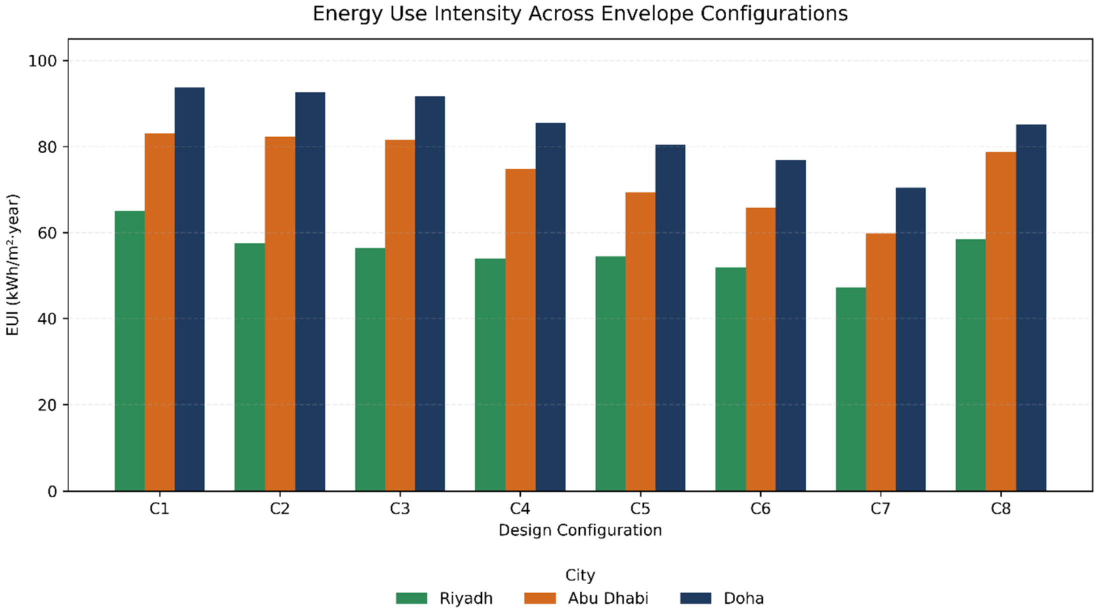

Figure 2. Energy use intensity (EUI) across envelope design configurations (C1–C8) in Riyadh, Abu Dhabi, and Doha, illustrating the influence of glazing ratio, shading depth, insulation strategy, and envelope composition on operational energy demand under different hot-arid climatic conditions.

4.2.1. Riyadh: Trade-Offs Between Energy, Carbon, and Thermal Comfort

Riyadh exhibits the strongest overall response to envelope optimization among the three climatic contexts, reflecting the sensitivity of inland hot-arid environments to envelope modifications. Across all configurations, energy use intensity (EUI) decreases from 64.98 kWh/m²·year in the baseline case (C1) to 47.33 kWh/m²·year in the reduced window-to-wall ratio configuration (C7), representing an overall reduction of approximately 27%. Cooling electricity closely follows EUI trends, confirming the dominance of cooling loads in Riyadh's operational energy profile.

Table 3 presents the comparative performance of all envelope configurations, including EUI, embodied carbon, thermal discomfort, and the Sufficiency Index (SI).

Table 3. Comparative performance of envelope design configurations (C1–C8) in Riyadh, showing energy use intensity (EUI), embodied carbon, integrated Sufficiency Index (SI), and thermal discomfort hours, highlighting trade-offs between operational efficiency, material intensity, and envelope exposure.

Case	Strategy	EUI (kWh/m²·yr)	Embodied Carbon ($kgCO_2$)	SI	Discomfort (h)
C1	Baseline	64.98	51,595.10	0.42	1,534
C2	GRP insulation	57.50	40,761.20	0.33	1,400
C3	UF foam insulation	56.50	42,580.70	0.32	1,331
C4	Low-e glazing	54.00	42,710.70	0.29	1,265
C5	0.5 m shading	54.45	52,000.20	0.29	1,229
C6	1.0 m shading	51.96	52,000.20	0.25	971
C7	Reduced WWR	47.33	46,854.30	0.01	1,018
C8	High WWR	58.50	57,146.20	0.52	1,229

Several performance patterns emerge. Material-based interventions, including GRP insulation (C2) and polyurethane insulation (C3), achieve moderate reductions in operational demand while lowering embodied carbon relative to baseline conditions. Low-E glazing (C4) further improves efficiency, reducing EUI to 54.00 kWh/m²·year with moderate material impacts.

Shading-based strategies (C5–C6) improve thermal comfort, particularly under high solar exposure, although additional façade materials increase embodied carbon. The deeper shading configuration (C6) achieves the lowest discomfort duration (971 h), corresponding to an approximate 37% reduction relative to baseline performance.

The reduced WWR configuration (C7) provides the strongest overall balance between performance objectives, achieving the lowest EUI, relatively low embodied carbon, and the lowest Sufficiency Index (SI = 0.01). This finding suggests that reducing façade exposure represents an effective passive strategy for minimizing solar gains without substantial material intensification.

By contrast, the high-glazing configuration (C8) performs least effectively, recording the highest embodied carbon (57,146 $kgCO_2$) and highest SI value (0.52), indicating poor alignment with cooling-dominated hot-arid conditions.

Overall, the Riyadh results indicate that geometry-driven passive demand reduction strategies outperform material-intensive interventions under inland hot-arid conditions, with façade exposure control providing the strongest balance between operational efficiency, thermal comfort, and material-related environmental impacts.

4.2.2. Abu Dhabi: Coastal Climate Influence on Envelope Performance

Abu Dhabi exhibits substantially higher operational demand than Riyadh because of elevated humidity and latent cooling requirements characteristic of coastal hot-arid environments. Despite this climatic penalty, envelope optimization remains effective, with energy use intensity (EUI) decreasing from 83.13 kWh/m²·year in the baseline case (C1) to 59.87 kWh/m²·year in the reduced window-to-wall ratio configuration (C7), representing an overall reduction of approximately 28%.

Table 4 presents the comparative performance of all envelope configurations in Abu Dhabi, including EUI, embodied carbon, thermal discomfort, and the Sufficiency Index (SI).

Table 4. Comparative performance of envelope design configurations (C1–C8) in Abu Dhabi, showing energy use intensity (EUI), embodied carbon, integrated Sufficiency Index (SI), and thermal discomfort hours, illustrating trade-offs between operational efficiency, material intensity, and envelope exposure.

Case	Strategy	EUI (kWh/m²·yr)	Embodied Carbon ($kgCO_2$)	SI	Discomfort (h)
C1	Baseline	83.13	51,595.10	0.55	2,615
C2	GRP insulation	82.36	40,761.20	0.54	2,600
C3	UF foam insulation	81.65	42,580.70	0.53	2,584
C4	Low-e glazing	74.77	42,710.70	0.45	2,272
C5	0.5 m shading	69.40	52,000.20	0.38	1,898
C6	1.0 m shading	65.80	52,000.20	0.34	1,761
C7	Reduced WWR	59.87	46,854.30	0.10	1,718
C8	High WWR	78.68	57,146.20	0.67	2,440

Compared with Riyadh, material-based interventions provide more limited operational benefits. Insulation-based configurations (C2–C3) produce only marginal reductions in EUI, suggesting that elevated latent cooling demand reduces the effectiveness of opaque-envelope insulation under humid coastal conditions. By contrast, Low-E glazing (C4) performs more effectively, reducing EUI to 74.77 kWh/m²·year, indicating the growing importance of solar heat gain control.

Shading strategies (C5–C6) achieve stronger relative benefits than in Riyadh, substantially reducing thermal discomfort while lowering cooling demand. The deeper shading configuration (C6) reduces discomfort duration from 2,615 h to 1,761 h, corresponding to an approximate 33% improvement, highlighting the importance of solar protection under humid coastal conditions.

The reduced WWR configuration (C7) again provides the strongest overall balance between operational efficiency and material intensity, achieving the lowest EUI (59.87 kWh/m²·year) and a substantially reduced SI (0.10). By contrast, the high-glazing configuration (C8) performs least effectively, recording the highest embodied carbon (57,146 $kgCO_2$) and highest SI value (0.67).

Overall, the Abu Dhabi results indicate that although humidity substantially increases cooling demand, the relative ranking of envelope strategies remains stable. Geometry-driven passive interventions continue to outperform material-intensive solutions, while shading becomes comparatively more valuable under coastal climatic conditions, suggesting that reductions in solar gains remain more influential than insulation enhancement when latent cooling loads are elevated.

4.2.3. Doha: Robustness of Envelope Performance Under Severe Coastal Conditions

Doha represents the most demanding climatic context among the three cities, exhibiting the highest cooling demand, electricity consumption, and thermal discomfort because of elevated humidity and persistent cooling requirements. Energy use intensity (EUI) decreases from 93.67 kWh/m²·year in the baseline configuration (C1) to 72.40 kWh/m²·year in the reduced window-to-wall ratio configuration (C7), corresponding to an overall reduction of approximately 25% despite severe cooling conditions.

Table 5 presents the comparative performance of all envelope configurations in Doha, including EUI, embodied carbon, thermal discomfort, and the Sufficiency Index (SI).

Table 5. Comparative performance of envelope design configurations (C1–C8) in Doha, showing energy use intensity (EUI), embodied carbon, integrated Sufficiency Index (SI), and thermal discomfort hours, highlighting the impact of humid coastal conditions on energy demand and design efficiency.

Case	Strategy	EUI (kWh/m²·yr)	Embodied Carbon ($kgCO_2$)	SI	Discomfort (h)
C1	Baseline	93.67	51,595	0.78	2,722
C2	GRP insulation	90.50	40,761	0.73	2,682
C3	UF foam insulation	88.90	42,581	0.71	2,665
C4	Low-e glazing	85.70	40,711	0.67	2,355
C5	0.5 m shading	80.90	52,000	0.61	2,244
C6	1.0 m shading	78.60	52,000	0.58	2,043
C7	Reduced WWR	72.40	46,854	0.33	1,874
C8	High WWR	98.20	57,146	1.00	2,522

Although absolute cooling demand increases substantially relative to Riyadh and Abu Dhabi, the relative ranking of envelope strategies remains highly consistent. Insulation-based interventions (C2–C3) again provide limited operational improvement, indicating reduced effectiveness when latent cooling demand becomes dominant. By contrast, Low-E glazing (C4) performs comparatively better, reducing EUI to 85.51 kWh/m²·year, highlighting the growing importance of solar heat gain control under severe cooling conditions.

Shading strategies (C5–C6) achieve meaningful reductions in thermal discomfort. The deeper shading configuration (C6) reduces discomfort duration from 2,722 h to 2,043 h, representing an improvement of approximately 25%, although these benefits are accompanied by additional material demand.

The reduced WWR configuration (C7) again demonstrates the strongest overall performance, recording the lowest EUI (72.40 kWh/m²·year) and lowest SI (0.33) despite severe climatic conditions. By contrast, the high-glazing configuration (C8) records the highest EUI value in Doha (98.20

kWh/m²·year) and the highest SI value (1.00), confirming the poor suitability of increased façade exposure under humid hot-arid conditions.

Overall, the Doha results reinforce the performance trends observed in Riyadh and Abu Dhabi. Although climatic severity substantially increases absolute cooling demand, the relative effectiveness of envelope strategies remains stable, confirming that geometry-driven passive interventions outperform material-intensive approaches across both inland and humid coastal hot-arid climates.

To further examine indoor environmental performance across climatic contexts, Figure 3 compares thermal discomfort duration for all configurations in Riyadh, Abu Dhabi, and Doha.

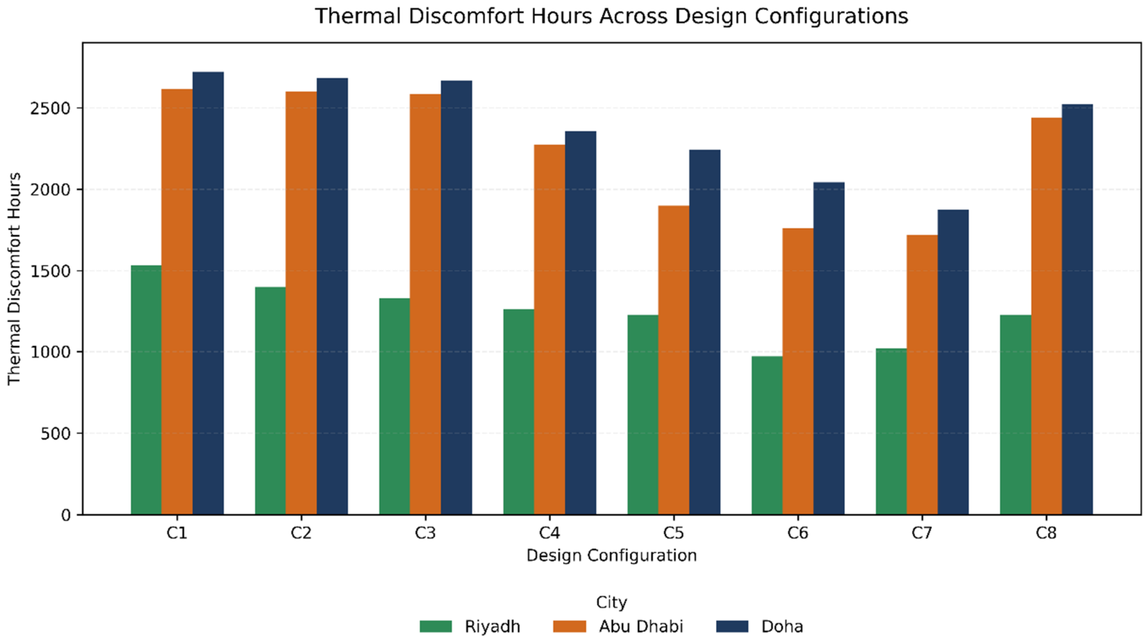

Figure 3. Thermal discomfort hours across envelope design configurations (C1–C8) in Riyadh, Abu Dhabi, and Doha, illustrating the influence of envelope strategies on indoor thermal conditions under varying hot-arid climatic contexts.

Figure 3 further confirms the influence of climatic humidity on indoor comfort, with discomfort duration remaining consistently highest in Doha. Nevertheless, reduced façade exposure (C7) and deeper shading (C6) consistently achieve the strongest reductions in discomfort, indicating that passive solar-control strategies remain effective despite elevated latent cooling loads.

4.3. Cross-City Comparison and Ranking

To evaluate the robustness of envelope performance across climatic contexts, Table 6 compares the Sufficiency Index (SI) values for all configurations in Riyadh, Abu Dhabi, and Doha, together with average SI and overall ranking. Although absolute SI values increase under more humid coastal conditions, the relative ranking of envelope strategies remains highly stable across all cities, indicating consistent design behavior despite climatic variation.

Minor variations are observed but do not affect the overall ranking structure.

Table 6. Cross-city comparison of Sufficiency Index (SI) values for all design configurations (C1–C8) in Riyadh, Abu Dhabi, and Doha, including average SI and overall ranking.

Case	Riyadh SI	Abu Dhabi SI	Doha SI	Average SI	Rank
C1	0.42	0.55	0.78	0.58	7
C2	0.33	0.54	0.73	0.53	6

C3	0.32	0.53	0.71	0.52	5
C4	0.29	0.45	0.67	0.47	4
C5	0.29	0.38	0.61	0.43	3
C6	0.25	0.34	0.58	0.39	2
C7	0.01	0.10	0.33	0.15	1 (Best)
C8	0.52	0.67	1.00	0.73	8 (Worst)

A highly consistent performance hierarchy emerges across all climatic contexts. The reduced window-to-wall ratio configuration (C7) consistently achieves the lowest SI values, ranging from 0.01 in Riyadh to 0.33 in Doha, with an average SI of 0.15, substantially outperforming all alternative strategies. By contrast, the high-glazing configuration (C8) consistently performs worst, increasing from 0.52 in Riyadh to 1.00 in Doha and recording an average SI approximately 4.9 times higher than C7. These findings confirm that geometry-driven demand reduction provides the strongest balance between operational performance, material efficiency, and façade exposure across both inland and humid coastal hot-arid environments.

Intermediate configurations reveal important trade-offs. Low-emissivity glazing (C4) and insulation-based interventions (C2–C3) achieve moderate reductions in operational demand with relatively lower material impacts, whereas shading strategies (C5–C6) provide stronger thermal benefits, particularly in coastal climates, but introduce additional embodied carbon through façade components.

To improve interpretability, Figure 4 visualizes SI values across climatic contexts using a heatmap representation, highlighting ranking stability despite climatic variation and identifying non-dominated configurations through Pareto comparison.

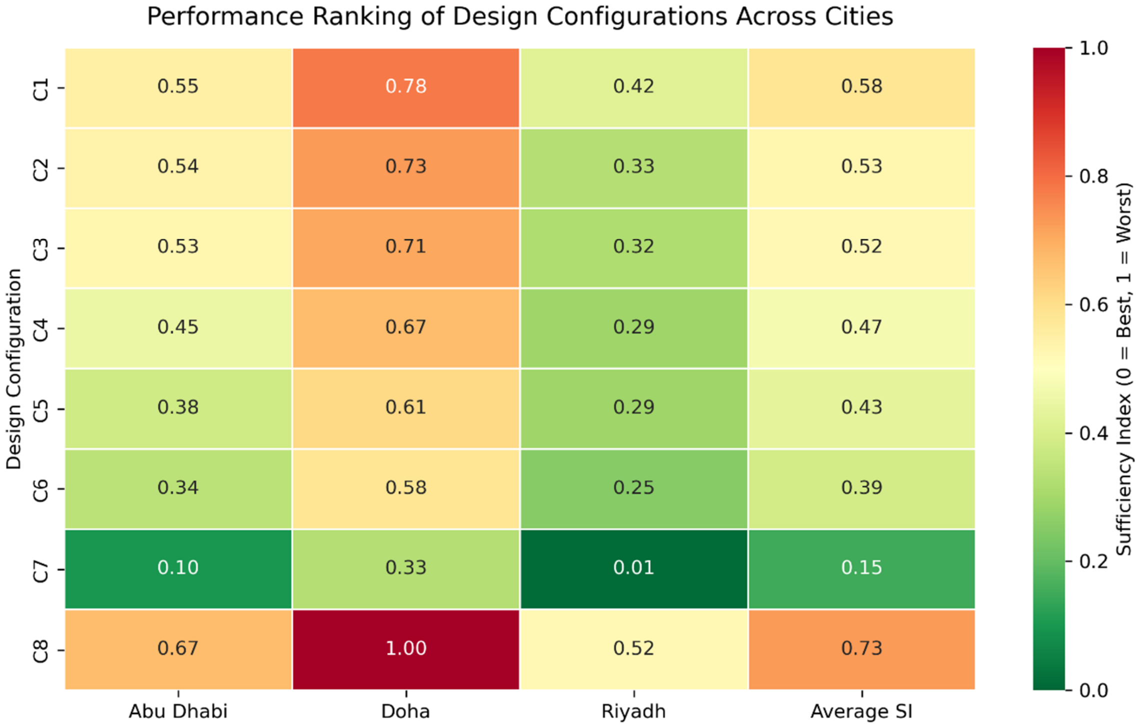

Figure 4. Cross-city comparison of Sufficiency Index (SI) values for envelope design configurations (C1–C8) in Riyadh, Abu Dhabi, and Doha, including average SI values, illustrating consistency of performance ranking across climatic contexts.

Figure 4 further confirms that while absolute SI values systematically increase in more humid coastal environments, the relative ordering of envelope strategies remains largely unchanged, indicating that climatic severity influences the magnitude of performance rather than the comparative effectiveness of design strategies.

To further examine trade-offs between operational performance and environmental impact, Figure 5 illustrates the relationship between energy use intensity (EUI) and normalized life-cycle carbon, with marker color representing the Sufficiency Index (SI).

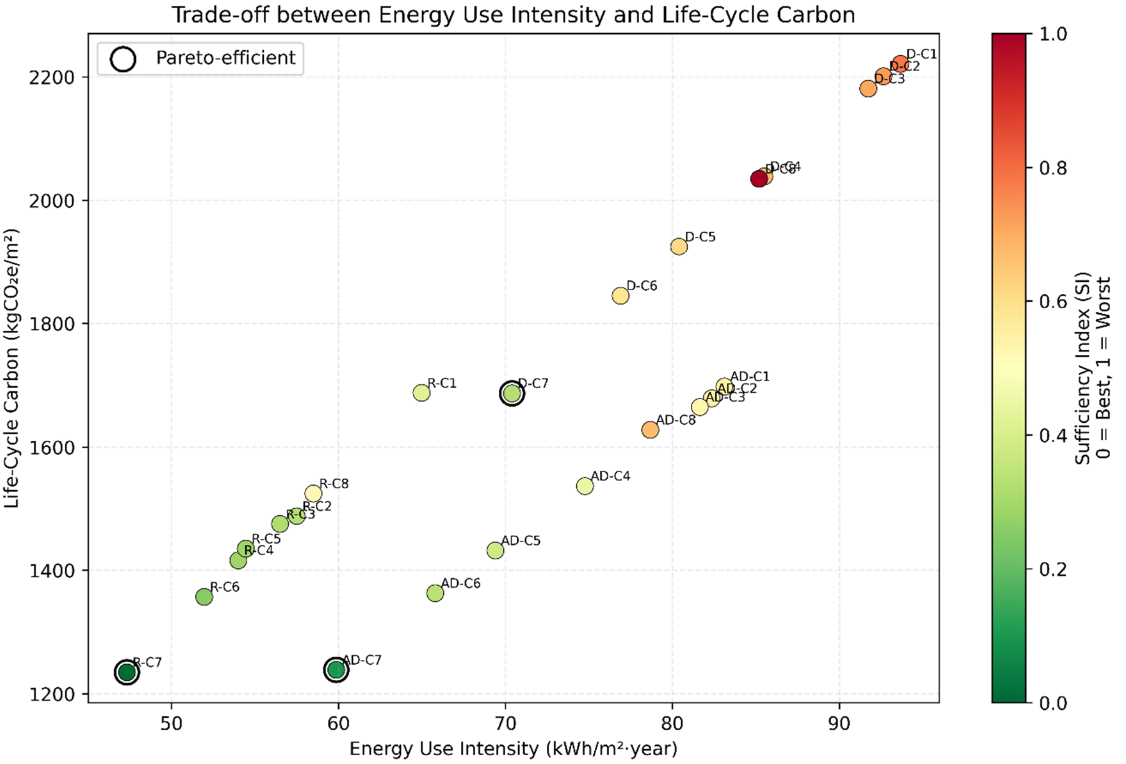

Figure 5. Trade-off between energy use intensity and life-cycle carbon across design configurations (C1–C8), with marker color representing the Sufficiency Index (SI) and highlighted points indicating non-dominated configurations.

The Pareto structure reveals a clear distinction between geometry-driven and material-intensive interventions. Configurations near the Pareto frontier, particularly C7, simultaneously achieve lower energy demand and reduced life-cycle carbon, whereas C8 consistently occupies the high-energy/high-carbon region of the solution space. Intermediate strategies, including shading and insulation interventions, occupy transitional positions, reflecting measurable performance gains moderated by additional material demand. Importantly, no material-intensive configuration outperformed geometry-driven interventions across all objectives, reinforcing the value of passive façade restraint over technological intensification in cooling-dominated hot-arid climates.

Overall, the consistency of ranking across Riyadh, Abu Dhabi, and Doha suggests that the effectiveness of envelope strategies is governed more strongly by façade geometry and material configuration than climatic variation alone, supporting the transferability of geometry-driven passive design principles across hot-arid climates.

4.4. Integrated Key Findings

Three consistent patterns emerge across all climatic contexts. First, geometry-driven envelope strategies outperform material-intensive interventions in reducing operational energy demand. Across Riyadh, Abu Dhabi, and Doha, the reduced window-to-wall ratio configuration (C7) consistently achieves the strongest performance, reducing energy use intensity (EUI) by approximately 23–28% relative to baseline conditions while maintaining comparatively low embodied carbon. This finding indicates that limiting façade exposure provides an effective passive strategy for reducing cooling demand across both inland and humid coastal hot-arid environments.

Second, the results reveal a clear trade-off between thermal performance and material intensity. While shading-based strategies (C5–C6) substantially improve thermal comfort—reducing discomfort duration by approximately 25–37%—these benefits are accompanied by additional material demand and embodied carbon. Similarly, insulation-based interventions provide moderate operational improvements but demonstrate diminishing returns under humid coastal conditions, where latent cooling demand reduces the effectiveness of opaque-envelope enhancement.

Third, the consistency of Sufficiency Index (SI) ranking across all cities demonstrates strong robustness and transferability of envelope design principles within the hot-arid climate category. Although absolute cooling demand increases substantially under humid coastal conditions, the relative effectiveness of design strategies remains highly stable. The consistently strong performance of C7 and persistently weak performance of high glazing (C8) indicate that façade geometry exerts a stronger influence on overall building sufficiency than climatic variation alone.

Importantly, the stability of configuration ranking across both climatic contexts and weighting scenarios suggests that the observed performance patterns are structurally robust rather than city-specific artifacts.

Figure 6 further illustrates the multi-objective performance relationships among envelope configurations through normalized performance fingerprints, where 0 represents the best observed performance and 1 represents the worst observed performance across each metric.

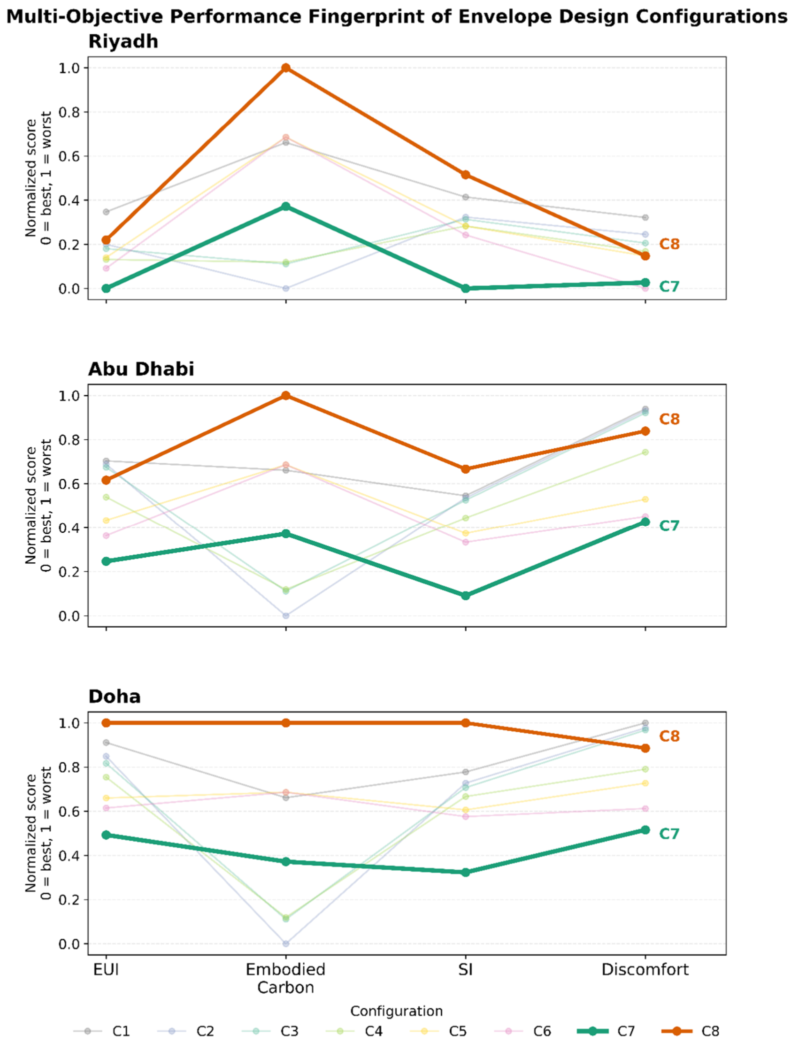

Figure 6. Multi-objective performance fingerprint of envelope design configurations across Riyadh, Abu Dhabi, and Doha. Values are normalized for each metric, where 0 represents the best observed performance and 1 represents the worst observed performance. The figure highlights the consistently strong multi-objective performance of reduced façade exposure (C7) and the weak performance of high glazing (C8) across operational energy demand, embodied carbon, Sufficiency Index, and thermal discomfort.

Collectively, the findings highlight the value of sufficiency-oriented envelope evaluation for climate-responsive residential design. Rather than maximizing isolated performance indicators, the results suggest that balanced design solutions emerge through passive demand reduction strategies that simultaneously reduce operational energy, material intensity, and environmental impact, particularly under cooling-dominated conditions.

5. Discussion

5.1. Reframing Building Performance: From Efficiency to Sufficiency

The findings indicate that conventional building-performance frameworks, which prioritize energy efficiency as the primary objective, are insufficient to capture the broader environmental implications of envelope design. Although reductions in energy use intensity (EUI) were achieved across most configurations, these improvements were not always accompanied by lower material use or reduced life-cycle carbon. This suggests that efficiency alone does not necessarily ensure balanced environmental performance, particularly when improvements depend on material-intensive interventions [8,18].

The proposed Sufficiency Index (SI) contributes an alternative perspective by enabling simultaneous evaluation of energy performance, material intensity, and envelope exposure within a unified comparative metric. Rather than emphasizing performance maximization alone, the sufficiency perspective evaluates how efficiently performance is achieved in relation to resource input. This distinction enables differentiation between strategies that improve performance through optimized design and those dependent on additional material intensification [22].

Accordingly, the shift from efficiency to sufficiency reframes design decision-making toward more resource-conscious and balanced building evaluation, particularly in cooling-dominated environments where operational and material trade-offs frequently interact.

5.2. Why Geometry Outperformed Material Intensification

One of the most consistent findings of this study is that geometry-driven interventions, particularly reduced window-to-wall ratio (WWR), outperformed material-intensive strategies across all climatic contexts. Configuration C7 consistently achieved the strongest balance between operational performance, material efficiency, and sufficiency, suggesting that in hot-arid residential buildings, façade geometry may exert greater influence on performance than material enhancement alone [12,13].

This outcome is closely linked to the dominant role of solar heat gains through transparent envelope components in cooling-dominated environments. By reducing façade glazing area, the building envelope limits transmitted solar radiation and internal heat accumulation, lowering cooling demand without requiring additional material input. The consistency of this effect across Riyadh, Abu Dhabi, and Doha indicates that passive control of façade exposure remains effective despite differences in humidity and climatic severity [13,25,38].

By contrast, insulation-based interventions (C2–C3) produced comparatively moderate improvements. This may reflect diminishing returns of additional insulation under cooling-dominated conditions, where solar gains through glazing frequently exceed conductive heat transfer through opaque envelope elements [12,13]. Similarly, shading-based strategies (C5–C6) improved thermal comfort and reduced cooling demand but introduced additional material requirements and embodied carbon burdens, illustrating the trade-off between operational gains and material intensity [8,22].

Taken together, the findings suggest that geometry-first passive strategies should be prioritized before material intensification, particularly in hot-arid residential buildings where operational gains may not justify additional material-related environmental burdens. From a sufficiency perspective, reducing thermal demand through design restraint may provide greater environmental benefit than relying primarily on increasingly complex material interventions [21].

5.3. Climatic Variation and the Role of Humidity

Although Riyadh, Abu Dhabi, and Doha share the same broad climatic classification (ASHRAE 1B; Köppen BWh), substantial differences emerged in operational performance. Doha consistently recorded the highest energy use intensity, thermal discomfort, and life-cycle environmental burden, followed by Abu Dhabi, whereas Riyadh generally exhibited lower operational demand and improved thermal conditions. These findings suggest that broad climatic classifications alone may not adequately explain performance variation within hot-arid regions.

A principal factor underlying this variation is atmospheric humidity and its influence on latent cooling demand. Compared with Riyadh's drier inland conditions, Abu Dhabi and Doha experience elevated coastal humidity, increasing cooling demand through additional dehumidification and moisture control requirements even when dry-bulb temperatures remain broadly comparable [37,39].

Consequently, envelope strategies that perform effectively in inland hot-arid climates may exhibit different magnitudes of benefit under humid coastal conditions.

These findings indicate that intra-climate variability, particularly humidity-related differences, should be more explicitly incorporated into climate-responsive envelope evaluation, especially in Gulf environments where coastal urbanization dominates residential development. Rather than relying solely on broad climate categories, envelope strategies may require adaptation according to local moisture conditions and latent cooling behavior.

5.4. Trade-Offs Between Energy, Carbon, and Material Use

The findings reveal a non-linear relationship between energy performance, life-cycle carbon, and material use, highlighting the limitations of single-objective building-performance evaluation. Although several envelope interventions reduced operational energy demand, these reductions were not always proportional to improvements in material efficiency or embodied environmental performance. This indicates that gains in one dimension do not necessarily translate into balanced sustainability outcomes across competing objectives.

The sensitivity analysis further reinforces this interpretation, showing that configuration ranking remained fully stable under alternative weighting assumptions. The persistent performance of reduced glazing configurations, particularly C7, suggests that observed relationships between energy demand, carbon burden, and material exposure represent stable interactions rather than weighting-dependent outcomes, supporting the robustness of the proposed Sufficiency Index (SI) as a comparative decision-support metric [12,13].

The evaluated strategies illustrate clear performance trade-offs. Shading-based interventions (C5–C6) improved thermal comfort and reduced solar gains but increased embodied carbon through additional material requirements [8,22]. Likewise, insulation-based strategies (C2–C3) produced only moderate operational improvements, indicating diminishing returns where glazing-related solar gains remain the dominant thermal driver. In cooling-dominated climates, additional insulation may not always generate proportional benefits and, in some circumstances, may contribute to heat retention or overheating effects, particularly when nocturnal heat dissipation becomes constrained. This reinforces the importance of evaluating material intensification in relation to climatic context rather than assuming universal performance gains [12,13].

By contrast, high-glazing configurations (C8) consistently increased cooling demand, life-cycle carbon burden, and material exposure, demonstrating poor environmental balance under hot-arid

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conditions. These findings confirm that maximizing façade transparency is incompatible with balanced environmental performance in cooling-dominated climates.

Overall, the findings underscore the importance of multi-criteria evaluation frameworks capable of simultaneously assessing operational performance, embodied impact, and material sufficiency. Rather than maximizing performance through additional intervention, the results suggest that balanced residential design in hot-arid climates may depend more strongly on restrained, climate-responsive envelope strategies that prioritize demand reduction before material intensification, particularly where diminishing returns may undermine broader sustainability outcomes [21].

5.5. Practical Design Implications for Hot-Arid Housing

The findings provide several practical implications for residential design in hot-arid and humid coastal climates, particularly in Gulf environments where cooling demand dominates building energy use. The consistent performance trends across Riyadh, Abu Dhabi, and Doha suggest that key envelope strategies remain robust despite climatic variation.

First, reducing window-to-wall ratio (WWR) should be prioritized during early-stage design. The strong performance of C7 indicates that limiting façade exposure can substantially reduce cooling demand while minimizing material intensity and embodied carbon, suggesting that façade geometry should be prioritized before advanced material intervention [12,13].

Second, shading systems should be implemented selectively. Although shading reduced thermal discomfort and cooling demand, these benefits were accompanied by additional material requirements and embodied carbon, suggesting context-specific rather than universal application [8,22].

Third, material intensification should be approached cautiously. Additional insulation and technologically enhanced envelope systems may produce diminishing returns where glazing-related solar gains remain the dominant thermal driver, reinforcing the need to evaluate interventions against broader life-cycle implications.

Finally, the proposed sufficiency-oriented framework offers a practical basis for early-stage architectural decision-making by enabling simultaneous evaluation of operational performance, life-cycle carbon, and material efficiency. Rather than promoting maximum technological intervention, the framework supports balanced and resource-conscious design strategies, particularly in rapidly urbanizing Gulf contexts [21].

5.6. Role of Pareto-Informed Multi-Criteria Evaluation

The Pareto-informed multi-criteria evaluation framework adopted in this study provides a structured mechanism for comparing envelope strategies across competing objectives, including operational energy demand, life-cycle carbon, and material sufficiency. Rather than functioning as an optimization engine, the framework supports transparent interpretation of trade-offs among predefined design alternatives under multiple environmental priorities [12,13].

A key strength of this approach lies in its interpretability and methodological transparency. By evaluating controlled envelope configurations rather than relying on stochastic optimization procedures, the framework enables direct interpretation of the influence of individual design variables while avoiding the complexity associated with iterative optimization workflows. This makes the approach particularly suitable for early-stage architectural decision-making, where clarity and transparent interpretation are essential.

The findings further demonstrate the usefulness of Pareto-informed evaluation for identifying balanced design relationships rather than prescribing singular solutions. Although C7 consistently emerged as the strongest-performing configuration, the framework highlights broader trade-offs among alternative interventions, particularly between operational improvement and material burden.

The integration of the Sufficiency Index (SI) further extends the framework by incorporating a design-oriented perspective on resource use. By simultaneously considering energy demand, embodied impact, and envelope exposure, the approach provides a more comprehensive basis for climate-responsive envelope evaluation in hot-arid residential buildings.

Overall, the framework provides a transferable basis for future climate-responsive building assessment, combining dynamic simulation, life-cycle carbon evaluation, and comparative decision-support within a unified analytical structure [12,13].

5.7. Contribution to Research and Design Practice

This study contributes to building-performance research and climate-responsive architectural design in several ways. First, it advances a sufficiency-oriented evaluation perspective that integrates operational energy demand, life-cycle carbon, and envelope exposure within a unified comparative framework. While these dimensions are often examined independently, the present study demonstrates the value of evaluating their interaction to identify more balanced and resource-conscious design strategies [21,22].

Second, the study develops and demonstrates a Sufficiency Index (SI) for envelope evaluation as a decision-support metric for assessing relationships between environmental performance and material intensity. By differentiating between strategies based on design restraint and those dependent on material intensification, the SI extends conventional building-performance assessment beyond isolated efficiency outcomes. The stability of ranking across alternative weighting scenarios further supports the robustness of the approach [12,13].

Third, the findings provide evidence that geometry-driven envelope strategies, particularly reduced window-to-wall ratio, may exert greater influence on performance than material intensification in cooling-dominated hot-arid climates, supporting the prioritization of passive-first design strategies during early-stage decision-making [25,38].

Finally, the study demonstrates the applicability of a Pareto-informed multi-criteria framework for interpreting trade-offs among competing environmental objectives. By combining dynamic simulation, life-cycle carbon assessment, and sufficiency-oriented evaluation, the framework provides a transparent basis for climate-responsive envelope assessment under multiple sustainability priorities [12,13].

5.8. Limitations and Future Research

Some limitations should be considered when interpreting the findings of this study. First, the analysis is based on a predefined set of envelope configurations rather than a continuous optimization process. While this improves transparency and interpretability, it does not explore the full design space that may emerge through stochastic or generative optimization techniques. Future studies may extend the framework through evolutionary optimization methods to evaluate larger combinations of envelope variables and operational conditions [12,13]. Although the Sufficiency Index (SI) demonstrated ranking robustness under alternative weighting scenarios, it remains a comparative decision-support metric and was not externally calibrated against empirical building-performance datasets.

Second, the study focuses primarily on operational energy demand, life-cycle carbon, and material sufficiency, without incorporating additional dimensions such as daylighting, glare, visual comfort, or occupant behavioral variability. Future research may integrate broader indoor environmental quality indicators within multi-criteria evaluation frameworks.

Third, the embodied carbon assessment is limited to major envelope-related material interventions and excludes a complete whole-life assessment across all life-cycle stages. Likewise, fixed assumptions regarding occupancy, internal gains, and HVAC operation were adopted to maintain comparability across climatic contexts. Real-world performance may therefore vary according to occupant behavior, adaptive comfort preferences, and building management practices.

Finally, the framework evaluates a single residential prototype geometry under static operational assumptions and does not incorporate adaptive or intelligent building-control systems. Future studies may explore the integration of digital twins, reinforcement learning, and predictive

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control systems together with sufficiency-oriented evaluation to support more adaptive climate-responsive buildings [40].

Despite these limitations, the findings remain valid because all configurations were evaluated under consistent climatic, operational, and methodological assumptions, enabling robust comparative assessment across Riyadh, Abu Dhabi, and Doha. The results directly address the research questions by demonstrating that (RQ1) envelope strategies significantly influence energy demand, life-cycle carbon, and material sufficiency; (RQ2) geometry-driven interventions outperform material-intensive approaches under cooling-dominated conditions; and (RQ3) a Pareto-informed multi-criteria framework can effectively support identification of balanced envelope configurations under competing environmental priorities.

6. Conclusions

6.1. Summary of Findings

This study evaluated the influence of envelope design strategies on operational energy demand, life-cycle carbon, and material sufficiency across Riyadh, Abu Dhabi, and Doha using a standardized residential prototype and eight predefined envelope configurations (C1–C8) assessed through dynamic simulation, life-cycle carbon evaluation, and Pareto-informed multi-criteria assessment.

The findings demonstrate that geometry-driven interventions consistently outperformed material-intensive strategies across all climatic contexts (RQ1–RQ2). In particular, the reduced window-to-wall ratio configuration (C7) achieved the strongest balance between operational performance and material efficiency, reducing energy use intensity (EUI) by approximately 23–28% relative to baseline conditions, while consistently recording the lowest Sufficiency Index (SI) values. By contrast, high-glazing configurations (C8) systematically produced the weakest outcomes, recording the highest SI values and environmental burden.

The analysis further revealed important intra-climate variation within hot-arid regions. Although all cities share broad climatic classifications, elevated humidity in Abu Dhabi and Doha increased latent cooling demand and thermal discomfort, confirming that humidity-related climatic variation should be explicitly considered during climate-responsive envelope evaluation.

The sensitivity analysis demonstrated stable ranking outcomes under alternative weighting assumptions, indicating that observed performance relationships are structurally robust rather than artifacts of subjective weighting selection. These findings directly support RQ3, showing that a Pareto-informed multi-criteria framework can effectively support identification of balanced envelope strategies under competing environmental priorities.

6.2. Final Contribution and Future Direction

This study contributes to climate-responsive architectural research by demonstrating the value of a sufficiency-oriented comparative perspective for evaluating residential envelope performance in hot-arid climates. Rather than examining energy demand, life-cycle carbon, and envelope exposure independently, the study illustrates the value of evaluating their interaction to support more balanced and resource-conscious design decisions.

The findings further suggest that passive geometric restraint may offer greater environmental benefit than progressive material intensification in cooling-dominated climates, particularly where additional envelope materials produce diminishing performance returns.

From a methodological perspective, the Pareto-informed comparative framework, combined with the Sufficiency Index (SI), provides a transparent basis for interpreting trade-offs among competing performance objectives during early-stage architectural design.

Future research may extend the framework through continuous optimization methods, broader whole-life carbon boundaries, life-cycle cost (LCC) assessment, adaptive comfort modelling, daylight integration, and intelligent operational control systems. Emerging approaches involving digital twins, reinforcement learning, and predictive building management may further strengthen climate-responsive residential performance under changing environmental conditions.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org, Table S1–S23 including envelope material specifications, embodied carbon assumptions, detailed case matrix, simulation inputs, sensitivity analysis of weighting assumptions, and supporting methodological calculations.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
EUI	Energy Use Intensity
SI	Sufficiency Index
HVAC	Heating, Ventilation, and Air Conditioning
WWR	Window-to-Wall Ratio
LCA	Life-Cycle Assessment
EPW	EnergyPlus Weather file
COP	Coefficient of Performance
GRP	Glass-Reinforced Polymer
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CO_2	Carbon dioxide

References

1. 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.
2. International Energy Agency (IEA) *Buildings Sector Energy Consumption and Emissions*; 2023;
3. International Energy Agency *Energy Efficiency 2025—Buildings*; International Energy Agency (IEA): Paris, 2025;
4. 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.
5. Bokhari, A.; Ali, K. *AI-Assisted Multi-Objective Optimization of Residential Buildings for Energy and Carbon Reduction Across Warm–Humid and Coastal Hot-Arid Climates.* Manuscript under review at *Buildings*, 2026.
6. International Energy Agency *The Future of Electricity in the Middle East and North Africa*; International Energy Agency (IEA): Paris, 2025;
7. Al-Sanea, S.A.; Zedan, M.F.; Al-Hussain, S.N. Effect of Thermal Mass on Performance of Insulated Building Walls and the Concept of Energy Savings Potential. *Applied Energy* **2012**, *89*, 430–442, doi:10.1016/j.apenergy.2011.08.009.
8. 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.
9. Cabeza, L.F.; Barreneche, C.; Miró, L.; Morera, J.M.; Bartolí, E.; Inés Fernández, A. Low Carbon and Low Embodied Energy Materials in Buildings: A Review. *Renewable and Sustainable Energy Reviews* **2013**, *23*, 536–542, doi:10.1016/j.rser.2013.03.017.
10. 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.
11. Attia, S.; Gratia, E.; De Herde, A.; Hensen, J.L.M. Simulation-Based Decision Support Tool for Early Stages of Zero-Energy Building Design. *Energy and Buildings* **2012**, *49*, 2–15, doi:10.1016/j.enbuild.2012.01.028.
12. Nguyen, A.-T.; Reiter, S.; Rigo, P. A Review on Simulation-Based Optimization Methods Applied to Building Performance Analysis. *Applied Energy* **2014**, *113*, 1043–1058, doi:10.1016/j.apenergy.2013.08.061.
13. Evins, R. A Review of Computational Optimisation Methods Applied to Sustainable Building Design. *Renewable and Sustainable Energy Reviews* **2013**, *22*, 230–245, doi:10.1016/j.rser.2013.02.004.
14. Suphavarophas, P.; Wongmahasiri, R.; Keonil, N.; Bunyarittikit, S. A Systematic Review of Applications of Generative Design Methods for Energy Efficiency in Buildings. *Buildings* **2024**, *14*, 1311, doi:10.3390/buildings14051311.
15. 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.
16. 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.
17. Hu, M.; Ghorbany, S. Building Stock Models for Embodied Carbon Emissions—A Review of a Nascent Field. *Sustainability* **2024**, *16*, 2089, doi:10.3390/su16052089.
18. 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.
19. Sandaruwan, I.P.T.; Allis, C.; Siriwardena, M. Building Green, Consuming Embodied Energy? Cradle-to-Gate Embodied Energy Assessment of Green Office Buildings for a Sustainable Built Environment in Sri Lanka. *Buildings* **2025**, *15*, 2819, doi:10.3390/buildings15162819.
20. 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.

21. Creutzig, F.; Niamir, L.; Bai, X.; Callaghan, M.; Cullen, J.; Díaz-José, J.; Figueroa, M.; Grubler, A.; Lamb, W.F.; Leip, A.; et al. Demand-Side Solutions to Climate Change Mitigation Consistent with High Levels of Well-Being. *Nat. Clim. Chang.* **2022**, *12*, 36–46, doi:10.1038/s41558-021-01219-y.
22. 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.
23. IEA Energy and AI—World Energy Outlook Special Report Available online: https://www.iea.org/data-and-statistics/data-product/energy-and-ai (accessed on 21 February 2026).
24. International Energy Agency *Space Cooling*; International Energy Agency (IEA), 2023;
25. 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.
26. Tzempelikos, A.; Athienitis, A.K. The Impact of Shading Design and Control on Building Cooling and Lighting Demand. *Solar Energy* **2007**, *81*, 369–382, doi:10.1016/j.solener.2006.06.015.
27. Kim, S.-C.; Yoon, J.-H.; Lee, H.-M. Comparative Experimental Study on Heating and Cooling Energy Performance of Spectrally Selective Glazing. *Solar Energy* **2017**, *145*, 78–89, doi:10.1016/j.solener.2016.11.028.
28. Al-Sanea, S.A.; Zedan, M.F. Optimum Insulation Thickness for Building Walls in a Hot-Dry Climate. *International Journal of Ambient Energy* **2002**, *23*, 115–126, doi:10.1080/01430750.2002.9674880.
29. Berghout, B.; Forgues, D. Passive Ambient Comfort and Correlation of Strategies and Vernacular Devices for Habitat Design in Arid Zones: The Case of Biskra, Algeria. *Buildings* **2019**, *9*, 87, doi:10.3390/buildings9040087.
30. 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.
31. 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.
32. Fouiteh, I.; Cabrera Santelices, J.D.; Susini, A.; Patel, M.K. Operationalising Building-Related Energy Sufficiency Measures in SMEs. *Buildings and Cities* **2024**, *5*, 368–387, doi:10.5334/bc.446.
33. Habert, G.; Miller, S.A.; John, V.M.; Provis, J.L.; Favier, A.; Horvath, A.; Scrivener, K.L. Environmental Impacts and Decarbonization Strategies in the Cement and Concrete Industries. *Nat Rev Earth Environ* **2020**, *1*, 559–573, doi:10.1038/s43017-020-0093-3.
34. Ostergård, T.; Jensen, R.L.; Maagaard, S.E. Building Simulations Supporting Decision Making in Early Design—A Review. *Renewable and Sustainable Energy Reviews* **2016**, *61*, 187–201, doi:10.1016/j.rser.2016.03.045.
35. DesignBuilder Simulation Software 2024.
36. Cabeza, L.F.; Rincón, L.; Vilariño, V.; Pérez, G.; Castell, A. Life Cycle Assessment (LCA) and Life Cycle Energy Analysis (LCEA) of Buildings and the Building Sector: A Review. *Renewable and Sustainable Energy Reviews* **2014**, *29*, 394–416, doi:10.1016/j.rser.2013.08.037.
37. 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;
38. 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.
39. Fanger, P.O. *Thermal Comfort: Analysis and Applications in Environmental Engineering*; Danish Technical Pr: Copenhagen, 1970; ISBN 978-87-571-0341-0.
40. Dai, X.; Chen, R.; Guan, S.; Li, W.-T.; Yuen, C. BuildingGym: An Open-Source Toolbox for AI-Based Building Energy Management Using Reinforcement Learning. *Build. Simul.* **2025**, *18*, 1909–1927, doi:10.1007/s12273-025-1306-y.

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