Climate-Responsive Saudi Architectural Design: Multi-Objective Optimisation of Thermal Comfort, Spatial Quality, and Life-Cycle Cost.

Abstract

Homes in Saudi Arabia use more than half of the nation's electricity, and most of that demand goes to cooling. Design guidance, however, usually treats energy, comfort, the quality of interior space and cost as separate questions, even though choices that improve one can harm another. This article develops a design-science framework, informed by a systematic integrative review, for optimising Saudi buildings against thermal comfort, spatial quality and life-cycle cost together. Thirty peer-reviewed studies dated 2020 to 2025 were synthesised; they cover the Saudi building stock and codes, passive cooling measures, courtyard and screen performance, spatial quality metrics, life-cycle costing and optimisation algorithms. The synthesis shows that envelope insulation, controlled glazing, shading and ventilated courtyards consistently lower cooling loads in Saudi and comparable climates, that life-cycle costing changes which measures appear best, and that spatial quality and occupant behaviour are rarely included in optimisation studies. On this basis, the article specifies a framework with three explicit objectives, seven groups of design variables, hard and soft constraints drawn from the national energy code and cultural requirements, and a solution process that combines surrogate modelling, evolutionary search, robustness testing and stakeholder selection. Four original design archetypes, from a reference villa to a compact courtyard house, are compared qualitatively using only findings reported in the cited studies. The archetypes are illustrative concepts; no simulation, cost or comfort values were produced. A validation protocol for future simulation, costing and post-occupancy work is provided.

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1. Introduction

Cooling dominates energy use in Saudi homes. Under the Kingdom's hot, arid conditions, more than half of all electricity is used in homes, and over 70% of that residential use goes to cooling (Rodrigues et al., 2025). The detached villa, now the usual dwelling type, has been described as inherently inefficient, and simulation of a typical villa showed that passive measures in

combination could cut its cooling energy use by 68% compared with the base case, although year-round passive operation remained unfeasible (Rodrigues et al., 2025). Rising temperatures will add to the pressure, and the stay-at-home period of 2020 showed how sensitive demand is to occupancy: a lasting move towards home-based living was projected to increase consumption across Saudi housing by 13.5% (Aldubyan & Krarti, 2022).

Energy is only part of the problem that designers face. Buildings must keep occupants comfortable, provide rooms that are well lit, private and suited to family life, and remain affordable over their lives, not just at the point of construction. These aims often conflict. Smaller windows reduce solar gain but may darken rooms and remove views; thicker insulation lowers cooling loads but adds cost and embodied impact; a courtyard can moderate the microclimate yet takes land. Multi-objective optimisation is designed for such trade-offs, and reviews show its rapid growth in building research (Al Mindeel et al., 2024; Manni & Nicolini, 2022). However, most optimisation studies focus on energy and comfort and treat space layout, spatial quality and the behaviour of occupants as secondary (Harshalatha et al., 2024).

Saudi research has accumulated many single-objective findings: which insulation thickness meets the code, which glazing reduces load, how a traditional screen affects temperature. What is missing is a framework that brings these findings together and states, for designers, which objectives to pursue, which variables to vary and which constraints to respect. This article addresses that gap. It combines a structured review of the evidence with the development of a design artefact, a multi-objective optimisation framework tailored to Saudi conditions, and a comparative set of original design archetypes that show how the framework could be applied.

2. Aim, Objectives and Research Questions

The article seeks to specify a climate-responsive, multi-objective design framework for Saudi buildings that treats thermal comfort, spatial quality and life-cycle cost as joint objectives, and to illustrate its use through comparative design archetypes. To achieve this, it pursues four objectives: (1) to synthesise evidence on passive design performance, spatial quality measurement and life-cycle costing relevant to Saudi climates; (2) to review the optimisation methods available for such problems and their limitations; (3) to define the objectives, variables, constraints and solution process of the framework; and (4) to outline original design archetypes and a protocol for validating the framework through simulation and occupancy studies.

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The research questions are as follows. RQ1: Which design measures does the evidence support for improving thermal comfort and reducing cooling demand in Saudi buildings, and how strong is that support? RQ2: How can spatial quality and life-cycle cost be incorporated alongside comfort in an optimisation problem, and which methods can solve it efficiently? RQ3: What framework and design archetypes follow from the evidence, and how should they be tested?

3. Methodology

A design-science approach was adopted because the intended outcome is a usable artefact rather than a description of practice. Design science develops artefacts from an established knowledge base, specifies them precisely and then evaluates them. In this article, the knowledge base is assembled through a systematic integrative review, the artefact is the optimisation framework together with its archetypes, and evaluation is defined as a protocol, since no new simulation, cost modelling or fieldwork was undertaken.

3.1 Evidence Base

Records were located in November 2026 through a freely available scholarly index, and each was checked against its registration metadata. Search strings paired climate and performance terms (thermal comfort, cooling load, passive design, building envelope, courtyard, mashrabiya, shading, daylight, life-cycle cost, life-cycle assessment) with method terms (multi-objective optimisation, genetic algorithm, surrogate model, machine learning, parametric design) and with location terms (Saudi Arabia, Riyadh, hot arid climate, hot dry climate, Gulf).

To be eligible, a study had to be an English-language article in a refereed journal, issued in a final volume from 2020 onwards and no later than 2025, and to report evidence or methods on building thermal performance, spatial quality, life-cycle cost or multi-objective design. Studies of mechanical systems alone, structural or seismic design and urban-scale energy planning were excluded, as were records without abstracts. Priority was given to Saudi studies, with studies from other hot climates or on transferable methods admitted where Saudi evidence was lacking. The study of passive cooling in Saudi residential buildings by Rodrigues et al. (2025) and the review of simulation-based optimisation of space layout parameters by Harshalatha et al. (2024) served as anchors. Table 1 shows the final set of 30 studies grouped by theme.

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Table 1. Distribution of the thirty studies across evidence themes

Theme	Studies	Representative studies	Use in the framework
Saudi stock, codes and occupancy	7	Krarti et al. (2020); Alardhi et al. (2022); Aldubyan and Krarti (2022)	Context, constraints, robustness scenarios
Passive measures in hot climates	9	Rodrigues et al. (2025); Al-Tamimi (2022); Khan et al. (2023)	Design variables and their evidence ratings
Spatial quality and daylight	3	Harshalatha et al. (2024); Wei and Li (2021); Sepúlveda et al. (2023)	Spatial quality objective
Life-cycle cost and impact	4	Alfalah et al. (2024); Alhazmi et al. (2021); Rabani et al. (2020)	Life-cycle cost objective
Optimisation methods	7	Manni and Nicolini (2022); Chaturvedi et al. (2020); Araújo et al. (2023)	Solution process

3.2 Framework Development and Appraisal

Each study was read in full and coded for climate, building type, design variables, performance indicators, method and reported findings. Each design measure then received an evidence rating: supportive where several hot-climate studies agreed on its direction of effect, mixed when results varied with context or metric, and limited when only one study or only indirect evidence was available. Framework elements were derived from the coded material: objectives from the indicators that studies used or recommended, variables from the measures they tested, constraints from codes and cultural requirements they reported, and the solution process from the methods they evaluated. Archetypes were then designed as distinct combinations of variables, and their likely performance was described only in qualitative terms supported by citations. Their status is that of illustrative concepts; none has been simulated or surveyed.

4. Evidence Synthesis

The synthesis is organised in five parts: the Saudi context of stock and codes, passive measures, spatial quality, life-cycle cost, and optimisation methods.

4.1 Building Stock, Codes and Occupancy

A bottom-up model of the Saudi residential stock, built from 54 prototypes by type, vintage and location and verified against reported consumption in four regions, found that a national retrofit programme could cut sector consumption by half, but only if measures were tailored to housing type, vintage and location (Krarti et al., 2020). Regional differences also appear in an assessment

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framework that combined operational energy, greenhouse gas emissions and cost through multi-criteria analysis for detached, attached and low-rise apartment buildings in five regions; demand was higher in the western, central and eastern regions than in the southern and northern ones (AlHashmi et al., 2021).

The Saudi energy conservation code, SBC-602, sets envelope requirements. Modelling in Riyadh, Hail and Abha showed that lowering wall U-values was the most effective way to reduce total electricity use, followed by roof U-values and higher cooling set points (Alardhi et al., 2022). Compliance with the wider Saudi Building Code adds cost, but a survey of developers, architects and citizens found these additional costs relatively small and outweighed by long-term benefits such as energy savings (Allahaim et al., 2024). Reaching zero energy in hot, dry Saudi conditions has been linked to a combination of thermal mass, daylight, natural ventilation, cavity walls, double glazing and solar panels, managed by a building management system (Alyami et al., 2021). Occupancy patterns matter as well, since the 2020 stay-at-home order raised daytime use of lighting, appliances and air conditioning (Aldubyan & Krarti, 2022).

4.2 Passive Design Measures

Envelope measures have the most consistent support. In the Rodrigues et al. (2025) villa study, ceiling insulation and smaller window-to-wall ratios each lowered cooling loads significantly, and the full combination of measures, which also included improved glazing, shading devices and natural ventilation assisted by wind towers, gave the 68% reduction noted earlier. In Sharurah, thermal insulation reduced annual energy consumption by up to 23.6%, followed by green roofs, while shading devices and glazing types had smaller effects; the best combination of strategies lowered total consumption by 35.4% against the reference building (Al-Tamimi, 2022). A Riyadh residential case tested floor, wall and roof proposals with simulation to compare energy use before and after passive changes (Al-Qahtani & Elgizawi, 2020). In Qassim, monitored villas facing the four cardinal directions were used to set the insulation thicknesses needed to achieve target indoor temperatures, together with material choices and their global warming potential, resulting in a performance-based selection flowchart (Alsaqabi et al., 2023).

Shading and screens have mixed but promising evidence. In a school building in a hot region, vertical shading systems were generally preferable for efficient shading (Alwetaishi et al., 2021). Simulation of a residence with a traditional mashrabiya reported that operative temperature fell

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by about 14%, peak solar gain by 77.8% and monthly cooling load by 5.7%, while the daylight factor rose by 35.5% (Taki & Kumari, 2023). A review of parametric second-skin facades found that simulation was the most accurate of the methods used to assess thermal comfort (Yazdi Bahri et al., 2022). Effects of shading thus depend on orientation, building type and metric, which is why the rating for this measure is mixed rather than supportive.

Courtyards and semi-outdoor spaces form a third group. Computational fluid dynamics simulations of courtyards in hot, dry regions showed that courtyard width strongly affects night ventilation and that additional shading such as galleries could improve thermal performance by 30% to 60% (Khan et al., 2023). Monitoring of two courtyards in Córdoba during summer and heatwave periods showed that indoor adaptive comfort models could be extended to such spaces, which can therefore be treated as potentially comfortable and habitable (Diz-Mellado et al., 2021). In a warm, humid climate, optimisation of a courtyard house found that replacing sandcrete block with rammed earth lowered cooling loads by 16% and embodied carbon by 12% (Addy et al., 2024). The Saudi evidence on courtyards in contemporary housing is still thin, so their rating is supportive for climate moderation but limited for Saudi-specific performance.

In answer to RQ1, the evidence is supportive for wall and roof insulation, controlled window-to-wall ratios and improved glazing; mixed for shading devices and screens, whose benefit varies with orientation and building type; and supportive in principle but limited in Saudi application for courtyards, night ventilation and wind towers. The evidence also shows that combinations of measures outperform single measures and that the best combination differs by region and dwelling type.

4.3 Spatial Quality as an Objective

Spatial quality is harder to quantify than energy, but several studies show that it can be measured and optimised. A review of space layout optimisation called for frameworks that combine layout with envelope parameters, giving more weight to cooling loads (Harshalatha et al., 2024). In nursing homes, a computational model used viewing distance, viewing angle and viewing field to measure privacy, accessibility, permeability and visibility in bedrooms, and then evaluated alternative layouts; it favoured layouts in which bathroom doors face into the bedroom and double rooms are generously wide (Wei & Li, 2021). For office facades, a solar-radiation-based prediction method balanced daylight provision against thermal comfort without full simulation

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and showed high rates of correct or conservative predictions in validation (Sepúlveda et al., 2023).

In the Saudi setting, spatial quality includes cultural requirements. The mashrabiya study combined thermal simulation with a survey of households and case studies of traditional and modern screens, and recommended preserving the identity of the element while improving its efficiency (Taki & Kumari, 2023). Privacy, the ability to receive guests separately from family and the use of outdoor space are therefore legitimate design objectives, not only constraints. Yet a review of 82 records found that optimisation studies of energy, comfort and indoor air quality often overlook occupant-related variables (Al Mindeel et al., 2024). Spatial quality, in short, can be represented by measurable proxies such as daylight sufficiency, view, visual privacy and functional fit, but these proxies remain rare in optimisation practice.

4.4 Life-Cycle Cost and Environmental Impact

Life-cycle costing changes which design appears best. For an office building in Al Khobar, a combined life-cycle cost and impact model identified reinforced concrete with insulated masonry units and triple glazing as the most cost-effective option, while insulated masonry with Nanogel glazing gave 22% annual energy savings (Alfalah et al., 2024). A cradle-to-grave assessment of a Saudi villa showed that a planned increase in renewable electricity would reduce carbon dioxide emissions from electricity by 53%, which would shift the balance between operational and embodied impacts (Alhazmi et al., 2021). In a Nordic office retrofit, coupling dynamic simulation with an optimisation engine reduced specific life-cycle cost by up to 11% while meeting passive house energy levels (Rabani et al., 2020). Early-stage environmental life-cycle costing of precast facade elements over 40 years exposed methodological dilemmas in applying such analysis (Zhang et al., 2021), and an optimisation of envelope, glazing and systems in a cooling-dominated climate showed the value of exploring trade-offs between investment cost and energy consumption from the earliest design phases (Le Gia et al., 2022). The common lesson is that cost objectives should cover construction, operation, maintenance and replacement over a defined period, with explicit assumptions about energy prices and discount rates.

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4.5 Optimisation Methods

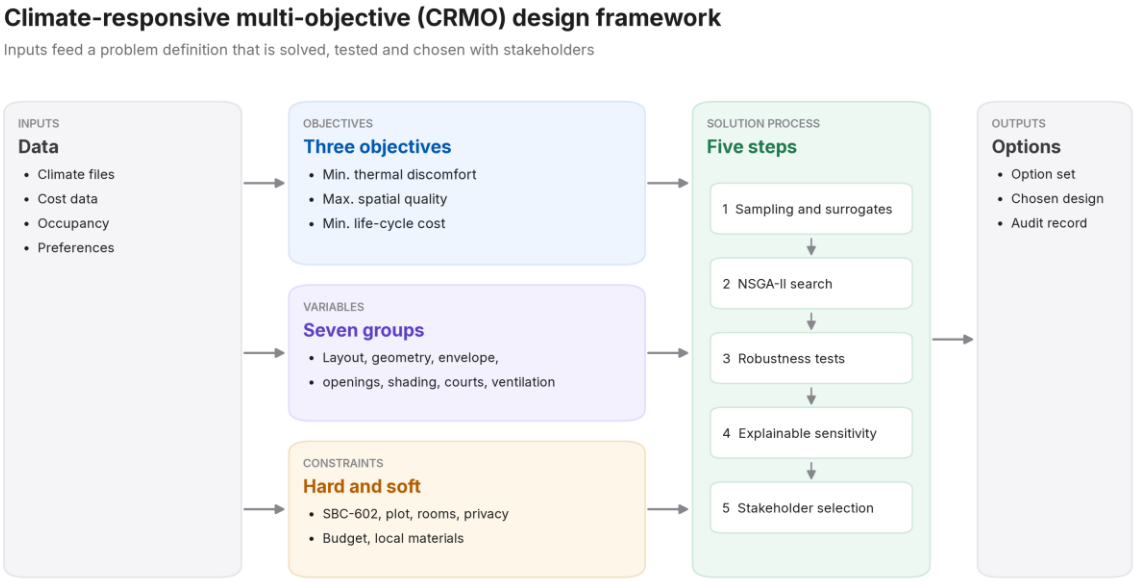
Methods for solving multi-objective building problems are mature but demanding. A synthetic review of around 140 articles found that optimisation workflows suit the exploration of envelope, systems and occupancy alternatives, but need to operate across temporal and spatial scales (Manni & Nicolini, 2022). Coupling simulation with genetic algorithms is the most common approach (Al Mindeel et al., 2024). An NSGA-II genetic algorithm was applied under operational uncertainty to a residential building in a hot, semi-arid climate, testing 13,122 combinations of measures; a robust decision function that included user preference and reliability selected a solution with 9.24% lower annual energy use and 45% fewer unmet cooling hours than the base case (Chaturvedi et al., 2020).

Because simulations are slow, surrogate models are increasingly used. One study reported cost reductions of up to 22% similar performance and computation up to a hundredfold quicker when a surrogate replaced direct simulation (Araújo et al., 2023). An active sampling strategy using a committee of surrogates found solutions within 1% of the best in the fewest simulations at early stages of optimisation (Bamdad et al., 2020). Explainable machine learning adds insight into which variables matter: in hot, arid climates, gradient boosting models identified the solar heat gain coefficient as dominant in raising cooling loads and served as a sensitivity tool to prioritise variables (Abdeyazdan et al., 2025). In answer to RQ2, spatial quality can enter the problem through measurable proxies of daylight, view and privacy, and cost through life-cycle cost over a defined period; the problem can be solved efficiently with evolutionary algorithms supported by surrogates, while robustness testing and explainable models make results more reliable and easier to interpret.

5. The Proposed Framework

The evidence leads to a climate-responsive multi-objective design framework, called CRMO in this article and summarised in Figure 1. It is defined by its objectives, variables, constraints and solution process, set out in Table 2.

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223 Figure 1. Structure of the climate-responsive multi-objective (CRMO) design framework.

224 **Table 2. Objectives, variables and constraints of the CRMO framework**

Element	Specification	Indicator or range	Main sources
Objective 1	Minimise thermal discomfort	Share of occupied hours outside adaptive band, indoors and in courts	Diz-Mellado et al. (2021); Al Mindeel et al. (2024)
Objective 2	Maximise spatial quality	Weighted index: daylight, view, visual privacy, functional fit	Wei and Li (2021); Sepúlveda et al. (2023)
Objective 3	Minimise life-cycle cost	Net present value of construction, energy, maintenance, replacement	Alfalah et al. (2024); Rabani et al. (2020)
Variables	Seven groups	Layout, geometry, envelope, openings, shading and screens, courtyards, ventilation	Rodrigues et al. (2025); Khan et al. (2023)
Hard constraints	Code and programme	SBC-602 envelope limits, plot and height limits, room areas, guest and family zones	Alardhi et al. (2022); Allahaim et al. (2024)
Soft constraints	Penalties	Budget ceiling, local materials, privacy of street openings	Taki and Kumari (2023); Alsaqabi et al. (2023)
Robustness	Scenario testing	Occupancy schedules and future weather files	Chaturvedi et al. (2020); Aldubyan and Krarti (2022)

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5.1 Objectives

CRMO has three objectives. The first is to minimise thermal discomfort, expressed as the share of occupied hours outside an adaptive comfort band in main rooms and, following Diz-Mellado et al. (2021), in courtyards and other semi-outdoor spaces. Cooling energy is computed as an intermediate result because it feeds the cost objective. The second objective is to maximise spatial quality, expressed as a weighted index of daylight sufficiency, outward view, visual privacy from streets and neighbours, and functional fit between rooms and family activities, measured with methods adapted from Wei and Li (2021) and Sepúlveda et al. (2023). Weights are set with users during the selection stage, not fixed in advance. The third objective is to minimise life-cycle cost, the net present value of construction, energy, maintenance and replacement over a defined period. Embodied carbon is reported alongside the three objectives as a secondary indicator, given the evidence that material choices affect it (Addy et al., 2024; Alhazmi et al., 2021).

5.2 Variables and Constraints

Variables fall into seven groups: plan layout and room adjacency; building geometry, including compactness and orientation; envelope construction, including wall and roof insulation and thermal mass; openings, including window-to-wall ratio by orientation and glazing properties; shading and screens, including vertical fins and mashrabiya-type panels; courtyards and semi-outdoor spaces, including proportion and galleries; and ventilation, including night purging and wind towers. These groups reflect the measures tested in the reviewed studies (Rodrigues et al., 2025; Al-Tamimi, 2022; Khan et al., 2023).

Constraints are divided into hard and soft. Hard constraints include SBC-602 envelope requirements (Alardhi et al., 2022), plot area, setbacks and height limits, required room areas, structural feasibility and the separation of guest and family zones. Soft constraints, applied as penalties, include a maximum construction budget, preferences for local materials and a minimum level of visual privacy for openings facing streets. Treating cultural requirements as explicit constraints prevents the optimiser from producing solutions that perform well numerically but would be rejected by families.

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5.3 Solution Process

The solution process has five steps. First, the design space is sampled to train surrogate models for comfort, energy and daylight, with active sampling to focus effort on promising regions (Bamdad et al., 2020). Second, NSGA-II searches the space using the surrogates and produces a set of non-dominated solutions, with selected solutions re-simulated in full to check accuracy (Araújo et al., 2023). Third, robustness is tested by evaluating solutions under alternative occupancy schedules, including daytime home occupancy (Aldubyan & Krarti, 2022), and under future weather files, following the scenario approach of Chaturvedi et al. (2020) and Rodrigues et al. (2025). Fourth, explainable models identify the variables with the greatest influence, so that designers understand why solutions differ (Abdeyazdan et al., 2025). Fifth, a small set of diverse solutions is presented to clients and designers, who set the weights for spatial quality and choose a preferred option through multi-criteria decision analysis, as AlHashmi et al. (2021) did for intervention strategies.

Three features distinguish CRMO from typical building optimisation workflows. It makes spatial quality a full objective rather than a check applied afterwards; it treats cultural requirements and the national energy code as explicit constraints; and it includes occupancy and climate robustness as standard steps. Each of these features responds directly to a gap identified in the reviews (Al Mindeel et al., 2024; Harshalatha et al., 2024).

5.4 Data Requirements and Use in Practice

Applying CRMO requires four kinds of input. Climate data are needed for each site, including current typical years and future scenarios, because measures that work today may become insufficient as temperatures rise (Rodrigues et al., 2025). Construction and cost data are needed for each variable option, including local prices for insulation, glazing, screens and masonry, maintenance intervals and replacement periods; the Al Khobar study shows how such data can be organised by structural and envelope system (Alfalah et al., 2024). Occupancy data are needed to set schedules for different household types, and the monitored data combined with stock modelling by Aldubyan and Krarti (2022) indicate how such schedules can be derived. Finally, preference data are needed to weight the components of spatial quality, which only residents can provide.

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In practice, the framework is intended for the concept and schematic stages, when form, orientation, layout and the proportion of openings are still open. A design team would define a few plot types, run the optimisation for each, and use the resulting set of non-dominated solutions as a menu of options rather than a single answer. The explainable models help the team decide where to spend design effort: if the solar heat gain coefficient of glazing dominates cooling loads, as Abdeyazdan et al. (2025) found for hot-arid cases, attention should go to glazing specification and window placement before secondary details. Later stages would refine the chosen option with full simulation and detailed costing. Because every run records its assumptions, results can be audited and repeated when prices, codes or climate data change.

6. Comparative Design Archetypes

Four original archetypes illustrate how CRMO could be applied to a typical suburban plot. They are compared in Figure 2 using qualitative judgements based only on the direction of effects reported in the cited studies. They are offered as illustrative concepts only, neither simulated nor surveyed, and no performance values are attributed to them.

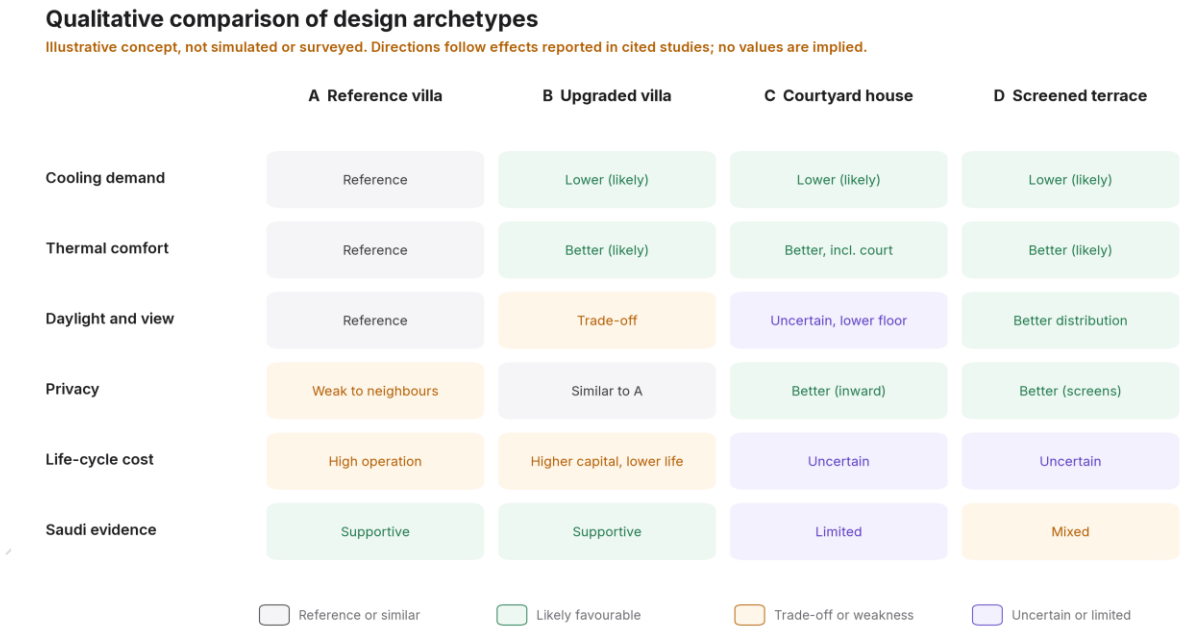


Figure 2. Qualitative comparison of four original design archetypes based on the direction of effects reported in the cited studies (illustrative concept, not simulated or surveyed).

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Archetype A is a reference detached villa of the kind that dominates contemporary Saudi suburbs, with a deep plan, large glazed openings on all sides and setbacks on every boundary. It serves as the baseline against which the others are judged. The cited evidence suggests that it carries high cooling demand (Rodrigues et al., 2025), that its spatial quality is mixed because generous rooms coexist with weak privacy towards neighbours, and that its construction cost is moderate while its operating cost is high.

Archetype B is an upgraded villa with the same form but an envelope that exceeds code requirements, reduced window-to-wall ratios on east and west faces, improved glazing and external shading. Evidence on insulation and glazing suggests a substantial reduction in cooling load (Al-Tamimi, 2022; Alardhi et al., 2022), while smaller windows may reduce daylight and view, a trade-off that the spatial quality objective is intended to reveal. Higher initial cost may be offset over the life cycle, as life-cycle studies of envelope upgrades indicate (Alfalah et al., 2024).

Archetype C is a compact courtyard house in which rooms face a shaded central court with galleries, external walls have few, deep openings, and a wind tower supports night ventilation. Studies of courtyards suggest improved microclimate and the possibility of comfortable semi-outdoor living (Khan et al., 2023; Diz-Mellado et al., 2021), and the inward orientation favours privacy. Its uncertainties are daylight in rooms on the lower floor, plot efficiency and construction cost, which are not established for contemporary Saudi housing.

Archetype D is a terrace of screened townhouses with shared party walls, mashrabiya-type screens on street faces and small rear courts. Shared walls reduce exposed envelope area, and the screen evidence suggests lower solar gain and better daylight distribution (Taki & Kumari, 2023), while screens also protect privacy. Its uncertainties are acceptance by families used to detached villas and the cost of high-quality screens.

In answer to RQ3, the archetypes show that CRMO is not intended to choose a single best house, but to make trade-offs visible: B tests how far the existing villa can be improved, C and D test whether different forms offer better balances, and the framework would quantify those balances once validated.

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7. Validation Protocol

Validation is left for future work and is planned in four stages. In the first stage, the archetypes would be modelled in a validated dynamic simulation tool for representative Saudi climate zones, such as those of Riyadh, Jeddah and Abha, using current and future weather files, and the surrogates would be checked against full simulation. In the second stage, life-cycle cost would be calculated using local construction prices, tariffs and stated discount rates, with sensitivity analysis on energy prices; embodied carbon would be assessed alongside. The third stage would test spatial quality proxies with residents, who would rank plans and visualisations, so that the weights and thresholds of the index reflect actual preferences rather than assumptions. Finally, built examples of the more promising archetypes would be monitored for indoor temperature and energy use, and their occupants would be interviewed after at least one cooling season. The framework would be revised at each stage, and results reported openly, including cases where the archetypes perform worse than expected.

8. Discussion, Implications and Limitations

The review confirms that the Saudi evidence on individual passive measures is substantial, especially for insulation and glazing, but fragmented. Studies use different base cases, climates and metrics, which makes direct comparison difficult and is one reason why the archetype comparison is qualitative. The proposed framework offers a common structure: by defining objectives, variables and constraints explicitly, it would allow future studies to report results that can be compared and combined.

Several implications follow. Designers can use the framework early, when changes to form and layout are cheap, rather than relying on late envelope upgrades. Developers of large housing programmes could apply it to a small set of plot types and reuse the results across many homes, consistent with the finding that measures should be tailored to housing type and location (Krarti et al., 2020). Regulators might consider whether performance requirements could be extended beyond envelope U-values to include comfort in semi-outdoor spaces and life-cycle cost, while the evidence of small additional compliance costs (Allahaim et al., 2024) suggests that stronger requirements need not be prohibitive. Researchers are invited to include spatial quality and occupant behaviour in optimisation studies, which reviews show remain under-represented.

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The archetype comparison also carries a design message. Traditional Saudi and regional forms, such as the courtyard and the mashrabiya, appear in the evidence not merely as cultural symbols but as performance devices whose benefits can be measured (Khan et al., 2023; Taki & Kumari, 2023). This supports a design culture in which climate response and identity are pursued together. At the same time, the evidence warns against assuming that traditional forms are always superior: their performance depends on proportion, orientation, materials and use, which is precisely why an optimisation framework is needed to test them under contemporary conditions.

The study has clear limitations. The review covers 30 journal articles, several of which come from outside Saudi Arabia, and it may have missed relevant reports, theses and conference papers. Numbers quoted in the synthesis come from different studies with different assumptions and should not be combined. The spatial quality index is proposed, not validated. The archetypes are conceptual, their comparison is qualitative, and none of them has been simulated, costed or occupied; claims about their likely behaviour are inferences from cited evidence and may not hold in practice. Coding and appraisal were done by one author. In addition, the framework has been specified for low-rise housing, and its extension to residential towers, schools or offices would require different variables and constraints.

9. Conclusion

Climate-responsive design in Saudi Arabia requires more than lower energy use; it must also keep people comfortable, provide good space and remain affordable over time. This article has synthesised evidence showing strong support for envelope and glazing measures, mixed support for shading, and promising but locally limited support for courtyards and natural ventilation, alongside methods that can solve multi-objective problems efficiently. It has proposed CRMO, a framework with explicit objectives for thermal comfort, spatial quality and life-cycle cost, seven groups of variables, code-based and cultural constraints, and a solution process that adds robustness testing and stakeholder choice. Four illustrative archetypes show how the framework could expose trade-offs. Simulation, costing and occupancy studies are the necessary next steps.

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