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Publication Date

2026-09-10

Peer reviewed

Scaling Climate-Responsive Construction: A Framework for Designing Sustainable and Comfortable Homes Across Mexico's Climatic Regions

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Abstract. Housing development in the 21st century is impacted by two major challenges: the environmental impact of buildings, and a global housing crisis. In many parts of the world, unprecedented demand for new housing stock has led to construction of large numbers of standardized units that fail to perform well in energy efficiency and thermal comfort. To address both energy and climate challenges, housing solutions must be efficient, but also adaptable, scalable and centered on comfort. We present a methodology for design of climate-responsive housing at a national scale, using Mexico as a case study. Combining climate zone clustering, energy simulation, and thermal comfort evaluations, our framework revealed climate-responsive designs that provide an average 55% increase in yearly comfort hours, and energy savings of 2,127 kWh/year compared to the base-construction. These findings demonstrate that standardized units can be significantly improved (both in terms of occupant comfort and energy efficiency), offering scalable pathways towards more sustainable housing worldwide. Future work will expand this framework to integrate energy and construction costs, life-cycle assessment, and retrofit considerations to further support large-scale implementation of climate-responsive housing design.

Keywords: Building energy simulation, Occupant comfort evaluation, Climate analysis.

1 Introduction

The built environment is one of the largest consumers of energy globally, accounting for 30% of global energy consumption with residential buildings making up 70% of the total building energy demand [1]. Over half of residential energy use is attributed to heating and cooling systems; resulting energy consumption increases operational costs and contributes to carbon emissions [1]. These challenges are compounded by the ongoing housing crisis. In a 2024 report, the United Nations estimated that 2.8 billion people lack access to adequate housing. They estimate that 96,000 units must be built per day to meet the housing needs of 2030 [2].

Balancing sustainable design, and comfort with rapid construction, and cost minimization is difficult. Traditional approaches for design of sustainable and comfortable buildings rely either on generalized rules of thumb, which are too broad for varying climates and available materials, or hyper specific assessments, which are not feasible at scale [3]. Additionally, in scaling affordable housing, building quality and thermal comfort are often sacrificed in favor of cost minimization [4]. These challenges highlight the need for frameworks that bridge the gap between generic and localized design recommendations, quantifying the effect of design choices on residential resilience through thermal comfort and sustainability, while centering accessible, low-cost material solutions.

In Mexico, the federal government has pledged \$30 billion to construct over 1 million homes by 2030 [5]. The scale of construction necessitates a design strategy that can ensure both individual occupant comfort and overall building environmental sustainability, while also enabling national scalability. We propose a framework combining climate analysis, energy simulation, and sensitivity analysis to deliver region-specific, climate-adaptive construction recommendations. Such guidelines can support local builders in construction of climate-adaptive buildings, while accounting for regional constraints.

In this research, we propose a framework to balance sustainability, comfort, and affordability, focusing primarily on lowering operational carbon emissions of new constructions. Energy-efficiency and comfort are treated as complementary goals: energy modeling is integrated into the framework to maximize thermal comfort through passive design strategies rather than energy-intensive mechanical systems, lowering operational carbon and increasing occupant comfort. Affordability is addressed on two fronts: reducing planning costs and lowering long-term operational energy expenses. Small-scale developments and local building initiatives rarely have the resources to run complex energy simulations; this framework alleviates that burden by making climate-responsive design guidance accessible without specialized tools or expertise. Material and construction costs vary greatly by region, leaving this cost consideration out of scope for this research.

While this research focuses on single-family homes in Mexico, the framework is adaptable to any geographic region and building typology.

2 Background

2.1 Sustainable design

This research approaches sustainable design through passive thermal comfort, minimizing operational energy usage and associated carbon emissions while maximizing thermal comfort. Olgyay’s bioclimatic chart was an early systematic approach to passive-design, mapping strategies for maintaining comfort across climatic conditions [6]. Recent frameworks have extended these methods to incorporate energy simulation [3], [7]. Our method builds on simulation-based approaches, incorporating initial-stage climate analysis to guide sustainable building design across varying climates within a region.

Sustainable design practices have also inspired exploration of alternative building constructions. [8], [9], [10], [11] Our research analyzed three non-traditional facades: adobe, rammed earth, and a monolithic insulated masonry unit. Adobe and rammed earth offer low embodied carbon and strong thermal regulation [9], [10], [12], [13], while the insulated masonry unit replicates multi-layer facade performance in a single unit [14]. Approximate embodied carbon calculations are provided for reference [12], [13], [15], though accuracy remains limited by variability in material sourcing, transportation, and other location-specific factors.

2.2 Climate zones

Rather than relying on traditional climate zones classifications, our framework introduces an independent climate zoning method. Traditional classifications can oversimplify climatic conditions, complicating choice of appropriate sustainable design techniques. Additionally, some circumstances might require a simplified output of a specified number of design recommendations. Our method allows either an optimal number of climate zones to be determined (balancing cluster accuracy and overfitting) or a fixed number specified by the planner, making it adaptable to both high-accuracy and constrained-output situations.

2.3 Decision considerations

Building model performance is evaluated through thermal comfort analysis and climate-level sensitivity analysis. Thermal comfort is assessed using hourly operative temperature and predicted mean vote (PMV). We incorporate design variable sensitivity analysis to identify design interventions with the highest impact on thermal comfort. Combined, comfort and sensitivity analysis indicate not only what constructions perform the best, but how much each variable contributes to overall thermal comfort.

3 Methods

To optimize constructions of climate-responsive buildings we propose a methodology that combines climate analysis, energy simulation, and thermal comfort analysis (Fig. 1).

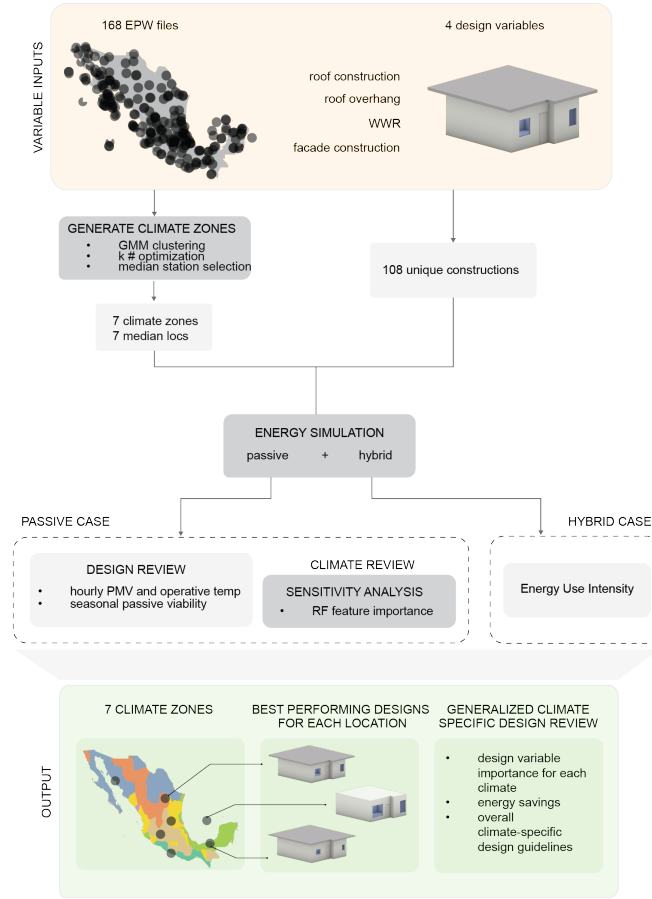


Fig. 1. Proposed methodology.

3.1 Climate zoning

EnergyPlus Weather (EPW) files [16] were used to generate custom climate zones within the geographic region. Hourly data from all 168 weather stations in Mexico were aggregated to monthly mean values. Clustering metrics included air temperature, diurnal temperature range, heating and cooling degree days, ventilation hours, precipitation, sky cover, and solar radiation. Features were normalized to ensure equal weighting across variables.

A Gaussian Mixture Model (GMM) grouped locations with similar meteorological characteristics; a method well suited for climate clustering where clusters differ in shape and size within feature space [17]. The clustering algorithm was performed for two to fifteen clusters. AIC, BIC, and Silhouette scores informed selection of an optimal seven climate zones for Mexico.

For each climate zone, a representative weather station was identified by selecting the location with minimum Euclidean distance to the cluster's mean vector.

3.2 Energy simulation

A single building (referenced from Fundación Vamos A Dar's single family, low-cost home [18]) was simulated across combinations of envelopes and geometric conditions for each representative location using Climate Studio [19]. Four design variables were explored: facade construction, roof construction, window-to-wall ratio, and roof-overhang (Fig. 2). A fully crossed experimental setup of three roof constructions, six facade constructions, three window-to-wall ratios, and two overhang conditions yielded 108 building models, benchmarked against the prototypical low-cost housing solution for Mexico [18].

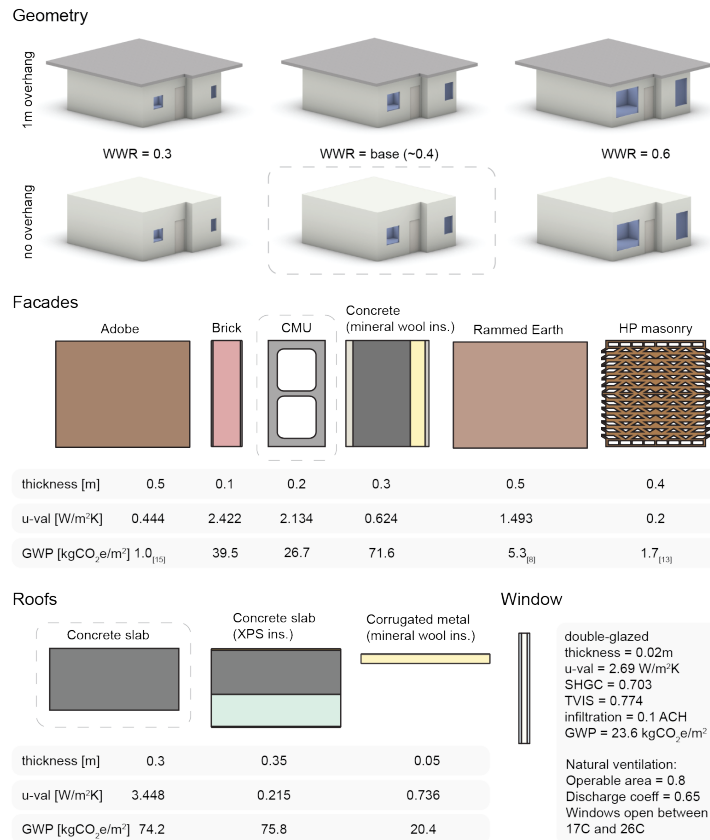


Fig. 2. Building model geometry and construction variables including overhangs, WWR, facade and roof construction types. Reference building is highlighted, with a WWR of 0.4, CMU facade, and concrete roof.

Our building envelopes represented a variety of constructions spanning from low-cost, low-tech solutions to state-of-the art highly insulated masonry units. Three typical facade constructions: brick, masonry (CMU), and insulated concrete were simulated as standard pre-set constructions [19]. Adobe and rammed earth blocks were each modeled with a thickness of 0.5 m and thermal properties from [9] and [10]. Performance of a novel, highly-insulated masonry unit [14] was represented using a low U-value mass construction from the ClimateStudio library [19]. Roof constructions included an uninsulated concrete slab, a concrete slab with XPS insulation, and corrugated metal with mineral wool insulation. Materials were defined by standard thermal characteristics (thermal transmittance (u-value), thermal capacitance, and density) without explicit configuration of hygrothermal properties. Window-to-wall ratios (WWR) of 0.3, ~0.4 (base), and 0.6 were modeled with double-pane glazing [20]. Embodied carbon for each construction (Fig. 2.) was calculated using Circular Ecology's ICE database unless otherwise noted [12], [13], [15]. Constructions were modeled with and without a 1-meter roof overhang and compared to the base model with CMU facade, uninsulated concrete roof, WWR of about 0.4, and no roof overhang.

Each construction was simulated for each representative location using Climate Studio. People density was calculated for five inhabitants (0.083 P/m^2), metabolic rate was set at 1.2 met. For each location, a unique natural ventilation schedule was determined by hourly ambient air conditions; when outdoor dry-bulb temperature was between 17°C and 26°C , windows were simulated as open. Windows were modeled with an operable area of 0.8 and discharge coefficient of 0.65. Building orientation was held fixed across simulations. Location-specific solar gains and prevailing winds were derived from representative location EPW files.

Two simulations were performed per construction: (1) a completely passive natural ventilation simulation, and (2) a hybrid simulation combining natural ventilation with mechanical strategies. Hybrid settings were 20°C (heating) and 26°C (cooling) with humidity control between 20-80% RH. Ideal air was simulated with heating COP of 0.8, and cooling COP of 3 with supply air between 12°C and 35°C . Heating used natural gas and cooling used electricity; hybrid simulation energy use intensity (EUI) captured energy use of both sources.

For each construction, recorded outputs included air temperature, mean radiant temperature, operative temperature, and yearly energy use intensity (EUI) for both simulation types.

3.3 Thermal comfort metrics

Constructions were evaluated using three comfort metrics: predicted mean vote (PMV), annual comfort hours, and number of passive-viable months.

Predicted mean vote: Hourly PMV was calculated using the `pythermalcomfort` package for Python [21]. Air velocity was approximated as 0.1 m/s [22], a highly conservative estimate given the presence of natural ventilation. Metabolic rate, and clothing insulation were held constant at 1.2 and 0.5, respectively.

PMV annual comfort hours: PMV range for thermal comfort is defined between -0.5 and +0.5 [22]. We also considered an “extended comfort range”, defined between -0.7 to +0.7.

Annual comfort hours: Thermal comfort range for operative temperature was defined as 19°C-28°C. Hours with operative temperatures within this range were defined as “operative temperature comfort hours”.

Passive-viable months: A month was considered passively viable if 90% of days have 90% of hours within the thermal comfort range (19°C -28°C). This metric accommodates high-seasonality climates, allowing models with 1–2 months of low performance to still be considered passively viable if they are comfortable for most of the year.

3.4 Design variable sensitivity analysis

A sensitivity analysis was performed for each location to determine impact of each design variable on overall thermal comfort performance. Using a Random Forest Regression model trained on four design variables, feature importance scores revealed the relative contribution of each variable to thermal comfort across climates.

4 Results

4.1 Climate zoning

Our zoning method indicated an optimal number of seven climate zones with representative locations: Acapulco, Palizada, Morelia, Guaymas, Rioverde, Saltillo, and Triangulos Reefs.

4.2 Passive thermal comfort

Passive thermal comfort performance of all 108 constructions for each location is shown in Figure 3. The base construction is highlighted in red. PMV hourly heat maps for five different cases further demonstrate the effect of passive design strategies on increasing yearly comfort hours. Across all seven climates, the highest-performing model for each climate delivered an average increase of 2,186 comfort hours, 55% more than the base construction. The most significant effects of climate-responsive interventions were observed in Morelia, Guaymas, Rioverde, and Saltillo. In Morelia the highest performing construction (Fig. 3c.) experienced 7,939 hours within the extended PMV comfort range, 3,383 hours more than the base construction (Fig. 3b.). Similarly, in Saltillo, the highest performing construction (Fig. 3e.) experienced 7,794 hours within the extended PMV comfort range, 4,756 hours more than the base construction (Fig. 3d.). In contrast, for Acapulco, Palizada, and Triangulos Reefs, construction interventions had very little impact on overall passive thermal comfort. For Acapulco, the difference between the highest and lowest performing structure (Fig. 3a.) was only 740 hours.

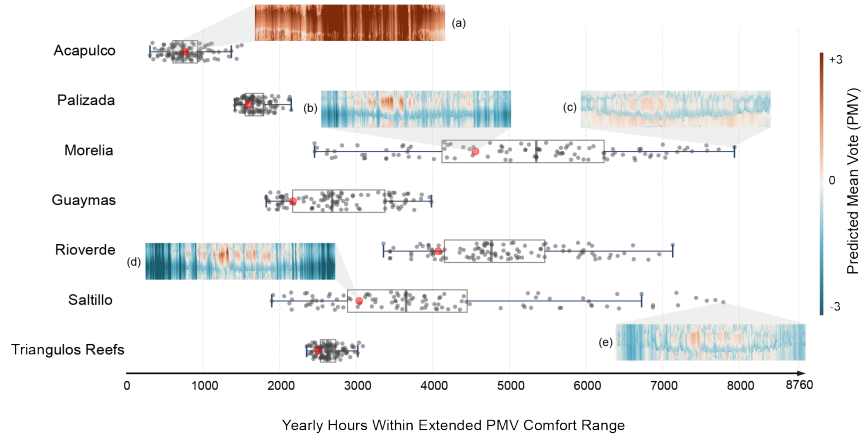


Fig. 3. Extended PMV comfort hours for all 108 constructions for each location with base construction highlighted in red. Yearly PMV heat maps for five unique constructions show the impact of high-performance constructions on yearly PMV comfort hours.

Overall passive viability of climate zones was evaluated using the passive-viable months metric. (Fig. 4.) Two out of seven zones (Saltillo, and Morelia) had constructions that were able to maintain passive viability for the entirety of the year. Only three of the seven zones (Acapulco, Palizada, and Triangulos Reefs) had fewer than six viable months.

4.3 High performance façade constructions

Top performing facades were the highly-insulated masonry unit and adobe; the top performing roof construction was the concrete slab with XPS insulation. In locations like Morelia and Saltillo, where days are warm and evenings are cold, low U-value constructions like adobe and the insulated masonry unit buffer daily temperature swings by retaining daytime heat and releasing it slowly overnight (Fig. 4a.).

On the other hand, high U-value, low insulation facade and roof constructions had the highest passive thermal performance in very hot, tropical climates of Acapulco and Palizada (Fig. 4b.). This is likely due to the night-time cooling potential in these locations where building envelopes with high thermal transmittance allow cooler outdoor conditions to quickly lower the daytime indoor temperatures.



Fig. 4. Passive-viable months for top-performing construction for each location. (a) high-performing construction in Saltillo and Morelia (façade: HP masonry unit, adobe; roof: concrete (insulated)), (b) high-performing construction in Acapulco and Palizada (façade: brick wall; roof: corrugated metal (insulated)).

4.4 Sensitivity analysis

Sensitivity analysis performed for each location revealed design interventions that had the greatest impact on thermal comfort for passive-mode simulations (Fig. 5). Façade and roof construction had the highest feature importance across most locations. Geometric design interventions had some impact on passive performance in Acapulco, Palizada, and Triangulos Reefs, consistent with their hot, coastal climates, where roof overhang (which regulates solar shading) and window-to-wall ratio (which influences natural ventilation exchange) are primary passive cooling mechanisms.

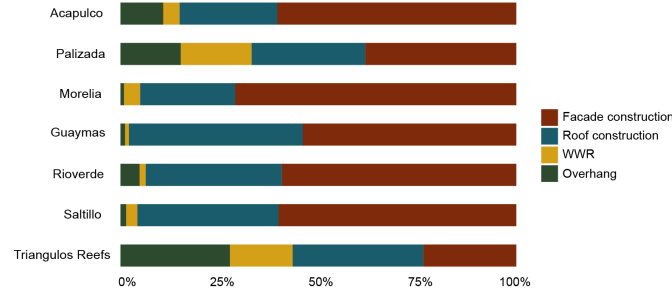


Fig. 5. Random forest sensitivity analysis with target of PMV comfort hours.

Sensitivity analysis was limited for Acapulco, Palizada, and Triangulos Reefs, where the difference between highest and lowest performing constructions was less than 1,000 PMV comfort hours (Fig. 3.), leaving the model with insufficient performance variation to accurately evaluate influence of individual variables.

4.5 Energy savings

Hybrid mode simulations revealed that prioritizing passive design strategies had a significant impact on lowering EUI across the board, even in climates where thermal

comfort is not fully achievable through passive means alone. Hybrid mode simulations revealed that prioritizing passive design strategies had a significant impact on lowering EUI across the board. Figure 6 shows EUI for three models in hybrid mode: (a) base model, (b) the model within each climate zone that achieved maximum number of comfort hours, and (c) the model within each climate zone that achieved the minimum EUI.

For locations without passive viability (Acapulco, Palizada, and Triangulos Reefs), optimizing climate-responsive designs cut energy use nearly in half with an average saving of 2,127 kWh/yr per structure. Across all climate zones, climate-optimized design resulted in increased comfort hours and significantly lower yearly EUI.

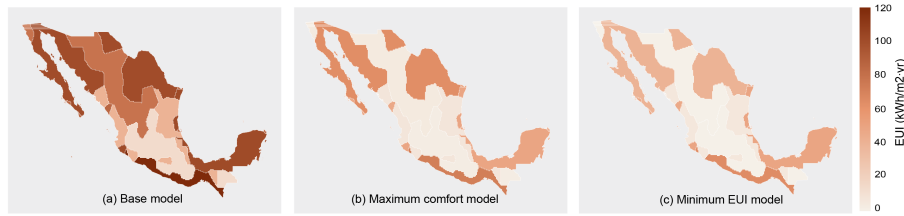


Fig. 6. EUI for three building models operating in hybrid-mode. (a) Base model. (b) Model with maximum comfort hours. (c) Model that achieved minimum EUI.

5 Conclusion

The results demonstrate the potential of our methodology in guiding climate-responsive design at a national scale. Passive models provided an average increase in 2,186 yearly comfort hours across all climate zones compared to the base model; in the three zones with over nine passive viable months, this rose to 3,733 hours. Sensitivity analysis identified which design interventions had the greatest impact on each climate, thus guiding localized designs and construction investments.

Prioritizing passive strategies also had a significant impact on lowering energy use when building models operated in hybrid mode. For places without passive viability, an investment in passive strategies is still worthwhile: top performing building models for Acapulco, Palizada, and Triangulos Reefs provided an average increase of 2,556 extended PMV comfort hours and decrease in 2,127 kWh/yr compared to the base building model operating in hybrid mode. Climate-adaptive construction dramatically reduces electricity demand now and improves long-term performance resilience: optimized buildings will remain functional as temperature rises and grid demand grows [23]. We demonstrate that these construction recommendations can be made for large areas with high climatic variance using a framework with low computational intensity.

The highest performing facades (Adobe, Rammed Earth, and the highly-insulated masonry unit), outperforming standard techniques on both energy savings and thermal comfort, are also estimated to be low-embodied carbon constructions. A complete

life-cycle-assessment is needed to confirm the embodied carbon of new construction techniques, and further exploration is required to establish viability of these new techniques.

Models were performed on a simplified geometry with baseline assumptions for ventilation strategy, material thermal properties, and HVAC performance, allowing the framework to give relative recommendations, not high-accuracy energy use predictions. Geometric variation was limited to WWR and roof-overhang and did not account for broader geometric adaptations such as shading depth, roof geometry, or greater variations in building typology. Nonetheless, our results capture some regional variability in climate-adapted geometries and illustrate the potential of parametric design for approaching climate-responsive construction. Further research should address different building typologies, scales and urban densities. Questions of construction cost, material availability, access to skilled labor, and embodied carbon and construction viability of novel building techniques must be investigated through full life-cycle assessment to provide more detailed design recommendations.

6 Outlook

This framework’s applicability extends beyond Mexico to guiding climate-responsive construction for other geographies, sustainability retrofits, and embodied carbon research.

Beyond informing construction of new stock, we see our framework being adaptable to guiding sustainability and energy efficiency retrofit recommendations for existing buildings. Recent research has emphasized the importance of tools, like sensitivity analysis, that can support regional, climate-responsive recommendations for building retrofits, lowering overall cost and increasing energy savings [24]. Our sensitivity analysis methods can guide what retrofits are needed and where to implement them to have the highest impact.

New research into embodied carbon and high-performance facade constructions have highlighted the sustainability of traditional earthen materials and thermal performance of highly-insulated constructions. Our research shows that novel highly-insulated masonry units outperform standard facade constructions across most climates. Novel high-performance, low-embodied carbon construction materials are promising [14], [25], but have yet to be established as scalable technologies. Realizing these constructions at scale requires linking regional material life-cycle analysis [26], [27], cost, availability, and construction viability, an integration this framework is positioned to support.

A central challenge of this framework is balancing sustainability, comfort, and affordability. The baseline construction, with a CMU facade, and concrete-slab roof was constructed for approximately \$30,000 USD in materials and labor [18]. This construction performed poorly in terms of sustainability (high operational and embodied carbon) and comfort, reflecting a broader pitfall in affordable housing development in which cost minimization is prioritized over building quality [4]. As this framework evolves, integrating regional material cost, availability, labor, and embod-

ied carbon, using a cost benchmark of \$30,000 USD would allow trade-offs to be explored in efforts to design homes that are simultaneously sustainable, comfortable, and affordable.

Our proposed methodology supports scalable design of climate-responsive buildings. Adaptable to different materials, design typologies, and geographic regions, this framework can help shape the future of sustainable construction globally.

Acknowledgments. The authors thank David Gottdiener for his support and providing the documentations for the initial baseline design. We thank Hitiksha Bansal and Daniel Dugatkin for initial research of alternative building materials and their visualization of geometry and constructions in Figure 2, and Paulina Alatorre for initial research on the baseline building.

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