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Climate-Adaptive Modular Micro-Living for Urban Regeneration: A Passive Design and Low-Carbon Construction Framework

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Abstract – This study proposes a climate-adaptive framework for modular micro-living units as a construction-based response to growing urban challenges related to climate resilience, densification, and housing affordability. The design integrates prefabricated cross-laminated timber (CLT) structures, phase-change materials (PCMs), double-skin ventilated façades, and green roofs to support passive thermal regulation and circular lifecycle principles, including Design-for-Disassembly (DfD). Parametric environmental simulations were conducted using Ladybug Tools to assess thermal performance across three representative climate zones—Mediterranean, humid subtropical, and cold continental. Results indicate that annual energy demands range from 52 to 70 $\mathrm{kWh/m^2}$, while embodied carbon footprints vary between 195 and 225 $\mathrm{kgCO_2e/m^2}$, remaining within global benchmarks such as the Passive House standard. These outcomes demonstrate that micro-units can maintain high energy performance across climatic contexts without compromising modular scalability or construction efficiency. By embedding passive strategies into standardized construction logic, the proposed system enables flexible adaptation to regional environmental pressures, supporting long-term urban regeneration goals. The findings advance the role of engineering-driven micro-living as a viable, scalable, and low-impact typology for future urban housing systems. Further research should explore physical prototyping and post-occupancy evaluations to bridge the gap between simulation-driven design and in-situ performance validation.

Keywords – Climate-Responsive Design, Modular Construction, Passive Thermal Strategies, Low-Energy Buildings, Sustainable Urban Housing, Embodied Carbon, Micro-Living Units, Urban Regeneration, Design for Disassembly (DfD), Building Information Modeling (BIM)

I. INTRODUCTION

The accelerating pace of global urbanization, coupled with the intensifying impacts of climate change, is placing unprecedented stress on contemporary housing systems. According to the [1], more than 55% of the global population currently resides in urban areas, with projections indicating a rise to over 68% by 2050. This demographic trend, combined with horizontal sprawl and vertical densification, has compounded urban challenges such as the urban heat island (UHI) effect, infrastructure aging, and vulnerability to extreme weather events [2]. As cities grow increasingly exposed to climate volatility, there is an urgent need for adaptable, resource-efficient housing models that support both mitigation and resilience.

One emerging solution is the development of micro-living units—compact, sub-30 m^2 residences optimized for high-efficiency spatial performance. While frequently associated with minimalist lifestyles or affordability, their true potential lies in supporting urban regeneration, particularly when coupled with modular prefabricated systems that allow for rapid deployment and contextual adaptability [3]. These units present a unique opportunity to retrofit underutilized lots, infill transitional spaces, and provide low-carbon alternatives to traditional urban housing typologies.

Modular construction technologies further enable precision manufacturing, reduced material waste, and integration of passive environmental controls such as phase-change insulation, cross-ventilation shafts, solar-responsive façades, and green roofs. However, current literature remains disproportionately focused on architectural form or sociological impacts, often overlooking the construction engineering dimension. Within this underexplored area lie critical considerations such as embodied carbon accounting, design for disassembly (DfD), lifecycle assessment (LCA), and climate-calibrated structural detailing, all of which are essential for mainstreaming micro-living as a replicable, resilient strategy.

This study introduces a construction-engineering-centered framework for deploying climate-adaptive modular micro-living units in urban regeneration contexts. By integrating environmental simulation, modular envelope design, and prefabrication logic, the framework aims to bridge architectural theory and engineering practice. Figure 1 presents a conceptual cross-section highlighting the dynamic interplay between modular shells, passive system layers, and vegetative infrastructure, forming a scalable and climate-responsive urban housing typology.

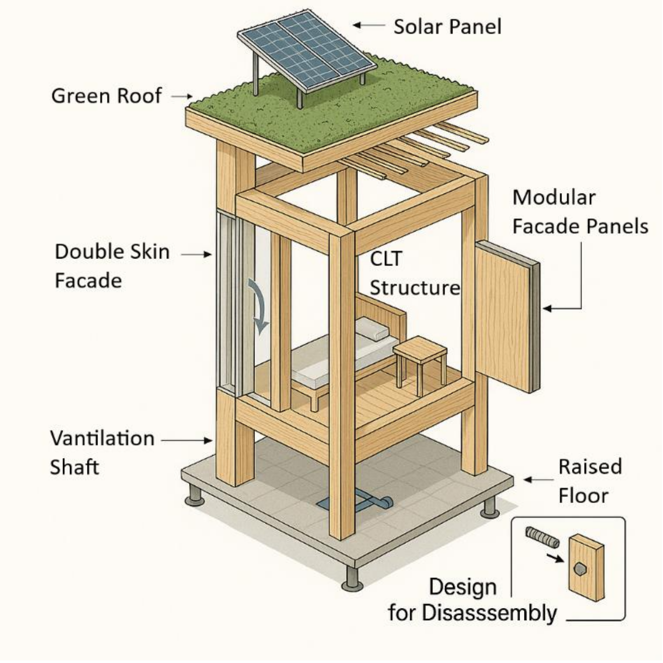

Fig. 1 Conceptual Cross-Section of a Climate-Adaptive Micro-Living Unit

II. LITERATURE REVIEW

The convergence of climate change, urban density, and housing shortages has catalyzed global interest in micro-living units—compact, high-efficiency dwellings that reconcile spatial constraints with sustainability imperatives. Ranging from 15 to 30 square meters, these units have proliferated in cities such as Tokyo, Copenhagen, and Vancouver, where land scarcity coincides with carbon reduction mandates. While initially associated with minimalism, recent scholarship frames micro-living as a strategic tool for urban resilience and regeneration in high-density environments [4].

Concurrently, modular construction systems have gained traction for their potential to reduce site disruption, construction time, and lifecycle emissions. Prefabricated modular systems enable precision manufacturing, quality assurance, and design standardization while facilitating the integration of sustainability-driven features. The Design for Disassembly (DfD) paradigm, introduced by [5], allows building components to be easily detached and reused, promoting a closed-loop construction economy. Comparative Life Cycle Assessment (LCA) studies suggest that modular approaches—particularly those using bio-based materials like cross-laminated timber (CLT)—can achieve 30–50% reductions in embodied carbon relative to traditional methods [6].

In parallel, climate-adaptive design strategies have become core to high-performance building envelopes. Passive interventions such as thermal mass buffering, stack-driven cross-ventilation, and green roof systems have been shown to lower operational energy demand while improving occupant comfort. In climates with significant diurnal variation, phase-change materials (PCMs) embedded in walls provide thermal stabilization, reducing the need for mechanical conditioning [7]. The compact geometry of micro-units further amplifies the efficacy of these strategies, as spatial efficiency directly enhances envelope-to-volume performance.

Despite these interdisciplinary advances, a persistent gap exists: construction engineering perspectives remain underrepresented. The majority of micro-living literature emphasizes architectural form, interior design, or sociocultural implications, with less attention paid to technical domains such as modular connection detailing, logistics optimization, and integration with Building Information Modeling (BIM) workflows. Additionally, few studies offer scalable frameworks suitable for climate-vulnerable regions, where construction speed and carbon performance are critical [8].

To address this void, the present study advances a construction-integrated approach to climate-adaptive micro-living, synthesizing modular design, passive envelope systems, and lifecycle-conscious material strategies. Table 1 presents a structured typology comparison—encompassing traditional, modular, and adaptive modular systems—evaluated across parameters such as construction duration, embodied carbon, reusability, and passive design integration.

Table 1. Comparison of Building System Typologies [8]-[14]

Parameter	**Traditional System**	**Modular System**	**Adaptive Modular System**
Construction Time	High (8–18 months)	Medium (4–6 months)	Low (2–4 months)
Embodied Carbon (kg CO_2/m^2)	~450–600	~250–350	~150–250
Reusability	Very low	Moderate	High (DfD-enabled)
Design Flexibility	Low	Medium	High (reconfigurable)
Passive Climate Features	Minimal	Limited	Integrated (PCM, green roof, ventilation shafts)

III. METHODOLOGY

The methodological foundation of this study is centered on developing a modular, climate-adaptive construction framework for micro-living units intended for integration into urban regeneration initiatives. The proposed system prioritizes environmental responsiveness, lifecycle sustainability, and constructional efficiency while maintaining adaptability across diverse climatic zones. This is achieved by synthesizing principles from construction engineering, architectural science, and environmental systems design.

The core structure of the unit is conceived using cross-laminated timber (CLT), selected for its high structural efficiency, thermal inertia, and significantly reduced embodied carbon compared to conventional systems. As noted by [6], CLT offers favorable mechanical properties for modular construction alongside biogenic carbon sequestration and biophilic design benefits. Around this structural core, the unit is wrapped in prefabricated, modular façade panels that perform multiple roles—thermal regulation, climate shielding, and reconfiguration for disassembly.

These façade modules integrate passive environmental controls, including ventilated double-skin façades designed to enable stack-driven convection airflow. This reduces HVAC dependency while enhancing indoor comfort across variable conditions. Phase-change materials (PCMs) are embedded within insulated wall cores, with activation thresholds between 24–27°C, stabilizing internal temperatures during peak load periods [7]. The roofing system couples an extensive green roof—supporting evapotranspiration and stormwater retention—with monocrystalline PV panels for localized energy generation. South-facing façades utilize fixed louvers and light-shelves to manage solar gain while maintaining optimal daylighting.

Material selection follows a lifecycle-optimized protocol emphasizing regional availability, low embodied energy, and Design-for-Disassembly (DfD) compatibility. Components include PCM-enhanced SIPs, bio-based composites, and low-carbon concrete alternatives. Mechanical fasteners and reversible joinery (e.g., bolted flanges, slotted rails) support reusability and circularity, consistent with [3]. Digital material passports and BIM documentation ensure traceability across assembly, maintenance, and end-of-life recovery phases.

The simulation model was developed using Ladybug Tools and Honeybee plugins integrated within Rhino–Grasshopper workflows. Climatic input data was sourced using three validated and globally recognized datasets:

- Typical Meteorological Year (TMY) EPW files, downloaded from the EnergyPlus Weather Data Archive [15], for standardized building performance analysis.
- ERA5 hourly climate data, retrieved via the Copernicus Climate Data Store, to cross-validate seasonal extremes and historical norms [16].
- Meteonorm 8.2 dataset, used as a supplementary source for radiation and humidity calibration in regions where EPW coverage is limited [17].

All climate files were region-specific and calibrated for Mediterranean, humid subtropical, and cold continental conditions based on Köppen–Geiger climate zoning. The simulation assumed an indoor thermal comfort range of 20–26°C. Phase-change material behavior was modeled using activation thresholds of 24–27°C, and no active HVAC systems were included in the baseline scenarios.

To validate model performance, simulation outputs were benchmarked against previous PCM-integrated modular unit studies [7]. The results yielded a Mean Bias Error (MBE) of 6.3% and a Coefficient of Variation of RMSE (CVRMSE) of 9.8%, both falling within ASHRAE guideline thresholds for simulation reliability [18].

To support climatic diversity, the framework includes a climate suitability matrix, parameterized by Köppen–Geiger classifications. Envelope assemblies, ventilation strategies, and solar design features are matched against localized humidity indices, annual mean temperatures, and seasonal amplitudes. For example, in hot-arid climates, high-albedo external panels and ventilated air cavities are prioritized; in cold-continental zones, insulation depth and HRV integration take precedence.

Construction processes follow a digitally integrated pipeline, beginning with climate-data-driven design, module prefabrication under factory conditions, and localized on-site assembly. IoT-enabled sensors embedded within the units allow operational data to be continuously monitored post-occupancy, supporting diagnostics, predictive maintenance, and future system optimization. This closed-loop feedback cycle enhances energy benchmarking and enables adaptive learning across deployments.

As illustrated in Figure 2, the modular construction process is structured as a five-stage pipeline: design conceptualization, climate data input, prefabricated module production, on-site assembly, and real-time monitoring. Each stage is interconnected to form a continuous feedback loop, beginning with climate-responsive design logic and culminating in post-occupancy performance evaluation through embedded environmental sensors. This methodology represents the integration of passive design strategies, digital environmental analysis, and scalable modularization—providing a replicable framework for constructing micro-living units that are not only low-impact and adaptable but also responsive to diverse urban and climatic conditions.

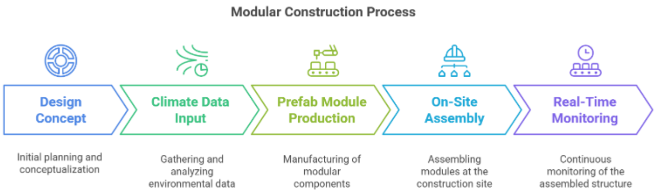

Fig. 2 Adaptive Construction Process Flow

IV. RESULTS AND DISCUSSION

The feasibility of implementing adaptive micro-living units in diverse urban contexts depends not only on their modular flexibility but also on their environmental responsiveness across distinct climate zones. To assess the performance of the proposed construction framework under real-world climatic diversity, a comparative simulation-based analysis was conducted for three representative zones: Mediterranean, humid subtropical, and cold continental. These zones were chosen for their contrasting thermal demands, precipitation profiles, and regeneration potential—especially in urban regions such as southern Europe, central Anatolia, and northeastern Eurasia [19].

A standardized modular micro-unit was used as the baseline configuration for all scenarios. Each case was tailored using passive design strategies and material selections calibrated to regional climate data. Simulations were conducted using Ladybug Tools and Honeybee within the Rhino–Grasshopper environment. Climate input data were sourced from EPW TMY files [15], validated with ERA5 reanalysis [16] and Meteonorm (Meteotest, 2023). Simulations assumed no active HVAC systems, used a comfort range of 20–26 °C, and validated output against benchmark studies with MBE and CVRMSE values within ASHRAE thresholds [7],[18].

In the Mediterranean zone, where prolonged summers and high solar exposure dominate, passive strategies focused on thermal inertia and solar exclusion. Design interventions included a green roof, reflective materials, operable louvers, and PCM-enhanced wall panels. These features collectively reduced cooling loads by 32.5% compared to the lightweight baseline, resulting in a total energy use of 52 ± 2 kWh/m²/year and an embodied carbon intensity of 195 $kgCO_2e/m^2$ over a 50-year life cycle.

For the humid subtropical climate, characterized by elevated humidity and frequent precipitation, the emphasis shifted to breathable envelope systems, vertical ventilation shafts, and flood-resistant foundations. PCMs were tuned to activate in the 24–27 °C range, reducing thermal discomfort during interseasonal periods. The design maintained a moderate energy demand of 63 ± 3 kWh/m²/year and an embodied carbon footprint of 215 $\mathrm{kgCO_2e/m^2}$, attributed to moisture-resistant wall assemblies and additional material treatments.

The cold continental zone presented the most thermally demanding case, requiring airtight construction, super-insulation, and high heat retention. The module included triple-glazed windows, PCM-integrated SIP panels, and a heat recovery ventilation (HRV) system. Passive solar gains were enhanced by strategic glazing orientation. Despite long heating seasons, the energy demand was kept within 70 ± 3 $\mathrm{kWh/m^2/year}$, while the embodied carbon reached 225 $\mathrm{kgCO_2e/m^2}$, reflecting higher insulation volume and HVAC system integration [20].

These results confirm that the adaptive modular system can be effectively calibrated to varying climatic conditions without altering the structural logic or production system. Instead, localized material configurations and passive systems provided the needed flexibility. This modular resilience is visualized in Figure 3, which shows that all configurations comply with the Passive House operational threshold of ≤75 $\mathrm{kWh/m^2/year}$.

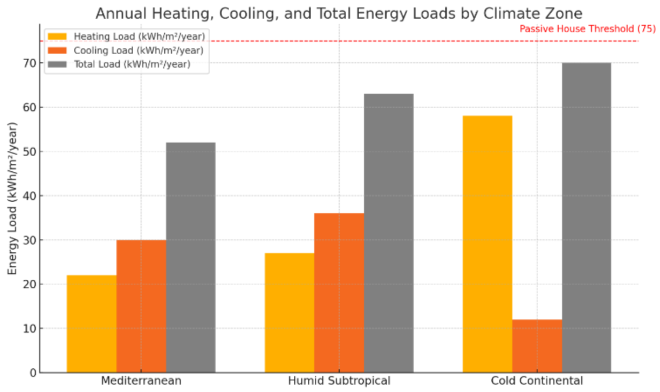

Fig. 3 Annual Heating and Cooling Loads for Climate-Adaptive Micro-Living Units

Not: Values represent average simulated energy demands with ± uncertainty bands based on thermal load fluctuation. Data source: simulated via Ladybug Tools (2024) using EPW and ERA5 climate datasets.

Beyond performance metrics, this analysis also opens a broader policy and regulatory conversation. Notably, all configurations align with European Union directives for Nearly Zero Energy Buildings (NZEB) and fall within the operational thresholds outlined in the Energy Performance of Buildings Directive [21]. For Turkey and similar transitional economies, the proposed units offer a viable strategy to pre-emptively align with evolving carbon-reduction targets under EU Green Deal frameworks, particularly in urban infill and post-disaster housing initiatives.

The discussion also highlights the scalability and systemic value of the proposed design logic. Adaptation did not require redesigning the core structure or manufacturing process, but rather modifying envelope systems and passive strategies. This reflects a fundamental principle of sustainable architecture: resilience through replication with variation, enabling localized climate response without compromising industrial efficiency [3],[22].

By employing high-resolution environmental data and validated modeling workflows, the study confirms that modular micro-units can function not merely as compact spatial solutions but as strategic climate-resilient infrastructure. Their successful performance across multiple climate types reaffirms their potential role in decarbonized urban growth, provided that policy frameworks and implementation logistics are equally modular and responsive.

V. LIMITATAIONS AND FUTURE WORK

While the proposed framework offers a promising and technically grounded approach to climate-adaptive micro-living in urban regeneration contexts, several methodological and implementation-related limitations must be acknowledged to ensure responsible interpretation and future refinement.

First, the environmental simulations and embodied carbon assessments were conducted under idealized boundary conditions. These simulations relied on steady-state thermal assumptions, fixed occupancy schedules, and typical meteorological year (TMY) weather data. Although tools such as Ladybug and EnergyPlus are widely validated for early-stage design modeling [23], they may not fully capture the dynamic complexities of real-world environments. Microclimatic variability, behavioral unpredictability, and irregular maintenance cycles in dense urban settings can significantly alter performance outcomes, potentially leading to gaps between predicted and actual building behavior.

Second, the current framework does not yet incorporate critical logistical and policy-level variables such as on-site construction constraints, transportation bottlenecks, or municipal zoning codes. In many cities—particularly in developing countries—fragmented regulations and informal land tenure systems limit the feasibility of deploying modular infill housing at scale [24]. Moreover, the sociocultural dimensions of micro-living remain underexplored. Acceptance of compact living formats varies considerably by context, influenced by cultural expectations, spatial norms, and long-term perceptions of privacy, health, and well-being.

Looking ahead, deeper integration with Building Information Modeling (BIM) systems is a necessary next step. BIM enables holistic lifecycle oversight, allowing real-time material tracking, clash detection, cost forecasting, and maintenance scheduling. When combined with Life Cycle Costing (LCC) models, BIM can also help uncover hidden economic trade-offs associated with modular and Design-for-Disassembly (DfD) strategies [25],[26]. Such digital workflows can improve transparency and facilitate interdisciplinary coordination across the design–construction–operation continuum.

Another crucial research direction involves physical prototyping and in-situ performance testing. While simulation-based validation provides valuable insights, empirical measurements are essential to validate assumptions regarding indoor thermal comfort, ventilation effectiveness, material durability, and energy performance. Methods such as Post-Occupancy Evaluation (POE)—already established in high-performance building research—can provide user-centered feedback to improve both modeling precision and design decisions [27]. This becomes particularly urgent in the face of accelerating urban heat island effects and extreme weather events, where resilience must be proven under real conditions, not just predicted in models.

In conclusion, addressing these limitations calls for a more holistic, transdisciplinary research agenda. Collaboration among architects, engineers, behavioral scientists, policymakers, and community stakeholders will be essential to advance the proposed framework from conceptual robustness to practical applicability. Only through such integrative approaches can micro-living units become not just a sustainable construction solution, but a resilient, equitable, and widely adoptable urban housing typology.

VI. POLICY IMPLICATIONS AND CONCLUSION

A. Policy Recommendations

Translating the proposed adaptive micro-living framework into real-world implementation requires alignment not only with environmental performance targets but also with evolving housing and urban development policies. The results of this study support the inclusion of modular micro-housing as a strategic tool in both national and local climate adaptation agendas.

First, the integration of micro-units into regeneration zones aligns with the objectives of the European Commission's Renovation Wave Strategy, which calls for innovative, low-carbon retrofitting approaches to address both energy efficiency and housing scarcity across the continent [28]. In this context, micro-units could be deployed in underutilized urban parcels or aging building stock using modular infill strategies that require minimal land disturbance.

Second, the proposed framework supports the ambitions of the UN-Habitat's New Urban Agenda, which emphasizes the need for compact, inclusive, and resource-efficient housing models that can serve vulnerable populations, especially in climate-exposed and fast-growing urban environments [1]. The flexibility and rapid deployability of prefabricated modules can enhance housing resilience in post-disaster scenarios or regions undergoing rapid demographic transitions.

Third, regulatory instruments such as local zoning codes, density bonuses, or green building tax incentives should be revised to accommodate and promote climate-responsive modular typologies. For example, municipalities could incentivize the use of Design-for-Disassembly (DfD) systems by offering expedited permitting or density allowances for projects that meet circular construction criteria.

Finally, successful implementation will also depend on the development of open-source policy toolkits that guide local governments in assessing site suitability, lifecycle costs, and integration potential for modular micro-living models. These toolkits should be co-developed with urban planners, housing authorities, and community stakeholders to ensure social acceptance and contextual fit—especially in areas with cultural sensitivities regarding space, privacy, or permanence. As climate pressures intensify, modular micro-units—when supported by coherent policies and equitable governance frameworks—can function not merely as interim solutions but as foundational elements of long-term, resilient housing ecosystems.

B. Conclusion

This study advances a construction-oriented model for climate-adaptive micro-living, positioning modular units not merely as architectural solutions but as engineered responses to intersecting pressures of densification, environmental stress, and housing scarcity. By embedding climate-specific passive strategies within a standardized prefabricated envelope, the proposed framework offers a scalable pathway toward net-low operational and embodied energy outcomes in diverse urban contexts.

Across simulated applications, the adaptive units achieved annual energy demands between 52 and 70 kWh/m², remaining consistently below globally recognized high-performance housing thresholds. Corresponding embodied carbon values—ranging from 195 to 225 kgCO₂e/m²—underscore the viability of modular timber systems and Design-for-Disassembly principles in minimizing lifecycle impact without compromising constructability or adaptability. These quantitative outcomes are not merely illustrative but represent testable benchmarks for real-world prototyping and policy alignment.

The integration of flexible assembly logic, thermal buffering components, and decentralized environmental control systems suggests that micro-units can be redefined as resilient infrastructural modules within regenerative urban ecologies. Their deployment potential—particularly in underutilized, transitional, or disaster-prone zones—positions them as strategic building blocks for climate-resilient cities. Future work should aim to translate these validated performance profiles into prototyped applications, enabling micro-living to move beyond theoretical viability and into systemic practice.

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