

Multi-Objective Optimization Framework for Timber-Based Geriatric Facilities: Integrating Material Performance and Spatial Adaptability

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An integrated design framework was developed to optimize timber-based elderly care facilities across three critical dimensions: environmental performance, health outcomes, and economic feasibility. By systematically analyzing engineered timber's thermal regulation, humidity control, and biophilic properties, a data-driven model was established that balances material science with spatial adaptability requirements. It was found that cross-laminated timber (CLT) walls reduce HVAC energy consumption by 17% through delayed heat transmission, while maintaining stable indoor humidity levels (40 to 60% RH), which is crucial for respiratory health. The framework achieved a 23% improvement in elderly satisfaction compared to conventional designs, which can be attributed to wood's natural terpene emissions and optimized spatial configurations. Modular timber partitions enabled rapid layout reconfiguration (2-hour adjustments) while maintaining acoustic insulation and wheelchair accessibility standards. Lifecycle analysis revealed 14% higher cost-effectiveness through prefabrication advantages and material durability. A case study validation showed timber systems support 12% larger window areas without compromising thermal performance, confirming practical applicability. This research provides a replicable model for integrating sustainable materials with geriatric care architecture, addressing both climate challenges and aging population needs.

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INTRODUCTION

The ‘medical-nursing combined’ model addresses healthcare and elderly care integration, yet material selection remains understudied (Su and Wang 2021). Traditional materials such as concrete lack biophilic benefits critical for aging populations. Timber, with its renewable nature, offers superior thermal insulation (Micháľková and Durica 2022), humidity regulation (Fu *et al.* 2020), and stress-reducing aesthetics. However, its application in elderly care facilities is limited by gaps in systematic design frameworks. At the intersection of global sustainability goals and aging demographics, engineered timber is emerging as a transformative material for elderly care infrastructure. Its carbon sequestration capacity (Victorero and Bustamante 2025) and low embodied energy (Anderson and Moncaster 2023) directly support IPCC’s net-zero targets (Sanderson 2023) while addressing the spatial needs of a projected 1.5 billion seniors by 2050. Biophilic

design leveraging timber demonstrates measurable health impacts, with studies showing 22% reduction in dementia-related agitation through natural material exposure (Whyte *et al.* 2024), potentially alleviating strain on healthcare systems.

At the meso-scale of building performance, engineered timber systems uniquely reconcile energy efficiency with elderly health imperatives. The material's inherent thermal inertia – achieving an 8 to 12-h phase shift in heat transmission – reduces HVAC energy loads by 15 to 25% (Cho *et al.* 2016) while maintaining stable indoor climates. Timber's moisture buffering capacity automatically regulates humidity within the desirable 40 to 60% range (Tijskens *et al.* 2021), demonstrating dual environmental and physiological optimization. Parametric design enables rapid spatial adaptation, with robotic prefabrication allowing care spaces to transition between open-plan layouts and secure memory care configurations within 2 h (Yang *et al.* 2024). Lifecycle economics are transformed through 30% reductions in onsite labor *via* offsite manufacturing and timber's exceptional durability-its 0.03 to 0.08% annual degradation rate compared to steel's 0.12% corrosion loss enables 50-year service life projections with 20% lower maintenance costs (Knauf 2015).

At the microscale of material interaction, engineered timber demonstrates scientifically validated advantages for elderly well-being. Cross-laminated timber's exceptional thermal performance eliminates cold bridging effects, maintaining surface temperatures above hypothermia risk thresholds (Chang *et al.* 2019). Wood's tactile properties combining moderate hardness with optimal slip resistance reduce fall risks while its acoustic absorption capacity cuts disruptive mid-frequency noise by 50% compared to synthetic flooring (De Alencar *et al.* 2023). Advanced grain alignment creates subtle navigational cues (Thamboo *et al.* 2022), while natural terpene emissions measurably reduce blood pressure through physiological modulation, demonstrating how timber's molecular to macroscopic properties synergistically enhance gerontological health outcomes. This research bridges material science and architectural ergonomics by proposing a multi-objective optimization model to align timber properties with spatial adaptability, addressing energy efficiency, health outcomes, and cost constraints.

Timber Science in Elderly-Oriented Design

The integration of timber science into elderly-oriented design has evolved through distinct phases, driven by advancements in material engineering, gerontological research, and sustainable architecture. This progression reflects a growing recognition of wood's unique biophysical and psychological benefits for aging populations, while exposing critical gaps in systemic frameworks for optimizing its application in geriatric facilities. Initial studies established wood's role in indoor environmental quality (IEQ). Research by Victorero *et al.* (2024) quantified timber's hygroscopic capacity, demonstrating that solid wood panels stabilize indoor humidity between 40 and 70% RH through moisture adsorption/desorption cycles (equilibrium moisture content: 8 to 12%), significantly reducing respiratory irritation risks among elderly with chronic obstructive pulmonary disease (COPD). Concurrently, the “wooden room effect” (Shen *et al.* 2020) linking exposed timber surfaces to 12% cortisol reduction and improved sleep quality in geriatric cohorts—a finding attributed to α -pinene emissions modulating autonomic nervous activity.

The 2010s witnessed breakthroughs in engineered wood products. Cross-laminated timber (CLT) (Mallo and Espinoza 2015) demonstrated 15 to 20% higher seismic energy dissipation than steel-concrete systems, enabling open-plan layouts that are critical for wheelchair maneuverability. Meanwhile, life-cycle assessments (LCAs) revealed CLT's

thermal superiority; its low thermal conductivity reduced heating loads by 18 to 25% in nursing homes. Psychosocial studies further correlated radial wood grain patterns with enhanced spatial orientation for dementia patients, reducing agitation episodes by 22% (Mizuno *et al.* 2021). Recent advances focus on bridging material science with spatial adaptability. Machine learning models optimized CLT panel thickness (He *et al.* 2020) and joint configurations to balance acoustic insulation and reconfiguration flexibility. Concurrently, LiDAR-based digital twins (Wang *et al.* 2025) enabled real-time monitoring of timber moisture content and its impact on elderly thermal comfort. However, research remains fragmented. While researchers have developed bamboo-wood (Zhang and Qiu 2023) composites with 30% cost reduction for rural elderly centers, systematic studies integrating material properties with care-specific spatial metrics are scarce.

Despite global advancements in timber-based healthcare architecture, three critical barriers hinder holistic progress. First, disjointed metrics persist as current models isolate material performance indicators from spatial adaptability parameters such as partition wall reconfiguration energy, lacking integrated multi-objective optimization frameworks. Second, regional disparities emerge through Euro-centric CLT standards dominating research, while Asia-Pacific timber species such as Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook.) remain underexplored. Third, empirical limitations exist in correlating wood-derived terpene emissions with longitudinal health impacts, particularly regarding dementia progression rates over 5-year periods. Addressing these gaps, the present study develops a parametric design model co-optimizing hygrothermal performance, seismic resilience, and spatial reconfigurability metrics. A cross-disciplinary approach is pioneered that synergizes timber material science with geriatric ergonomic requirements, establishing an adaptive architectural paradigm for climate-responsive healthcare environments.

Multi-Objective Optimization in Engineering

The development of multi-objective optimization (MOO) in architecture has evolved through three distinct phases, each revealing critical gaps that this timber-based geriatric facility framework seeks to address. Initial computational models prioritized isolated performance metrics. Energy-focused tools such as DOE-2 (Amiri *et al.* 2015) optimized thermal loads but ignored material-specific properties such as timber's anisotropic thermal conductivity. Concurrently, cost-driven frameworks adopted life-cycle assessment (LCA) principles, yet treated material durability and maintenance as fixed inputs rather than variables. This decoupling led to designs in which energy-efficient concrete structures inadvertently increased embodied carbon compared to timber alternatives.

Marler's comprehensive survey (Marler and Arora 2004) consolidates key advancements and methodologies in continuous nonlinear multi-objective optimization (Sindhya *et al.* 2013; Segura *et al.* 2016; Medhane and Sangaiah 2017), emphasizing engineering applications. The authors categorize MOO approaches into three classes: (1) a priori preference articulation, where preferences (*e.g.*, weights, goals) are predefined (*e.g.*, weighted sum, lexicographic, and physical programming methods); (2) a posteriori preference articulation, which generates Pareto-optimal sets for post-hoc selection (*e.g.*, Normal Boundary Intersection (NBI), Normal Constraint (NC) methods, and genetic algorithms); and (3) no preference articulation, relying on inherent problem structure (*e.g.*, global criteria, min-max formulations). Key findings highlight that no single method universally dominates; selection depends on problem context, preference clarity, and computational constraints. For instance, weighted sum methods fail to capture non-convex

Pareto fronts, while physical programming and augmented Tchebycheff approaches ensure Pareto optimality through tailored utility functions. Genetic algorithms excel in generating global Pareto sets but require heuristic parameter tuning. The present study underscores the importance of balancing computational efficiency, solution accuracy, and preference modeling, concluding that methods providing necessary and sufficient conditions for Pareto optimality (*e.g.*, physical programming) or robust exploration of the Pareto frontier (*e.g.*, NBI, NC) are particularly advantageous for complex engineering design. Critical challenges include handling non-convexity, scaling with objective dimensions, and integrating decision-maker preferences effectively.

EXPERIMENTAL

Material Testing

This study established a three-phase experimental workflow (Fig. 1) to quantify interactions between timber material properties and geriatric spatial performance. A three-phase experimental workflow was established comprising (I) material characterization through hygrothermal-VOC testing, (II) structural-spatial interaction analysis, and (III) ergonomic validation in a 1:5 scale prototype. Arrows indicate data feedback loops between phases.)

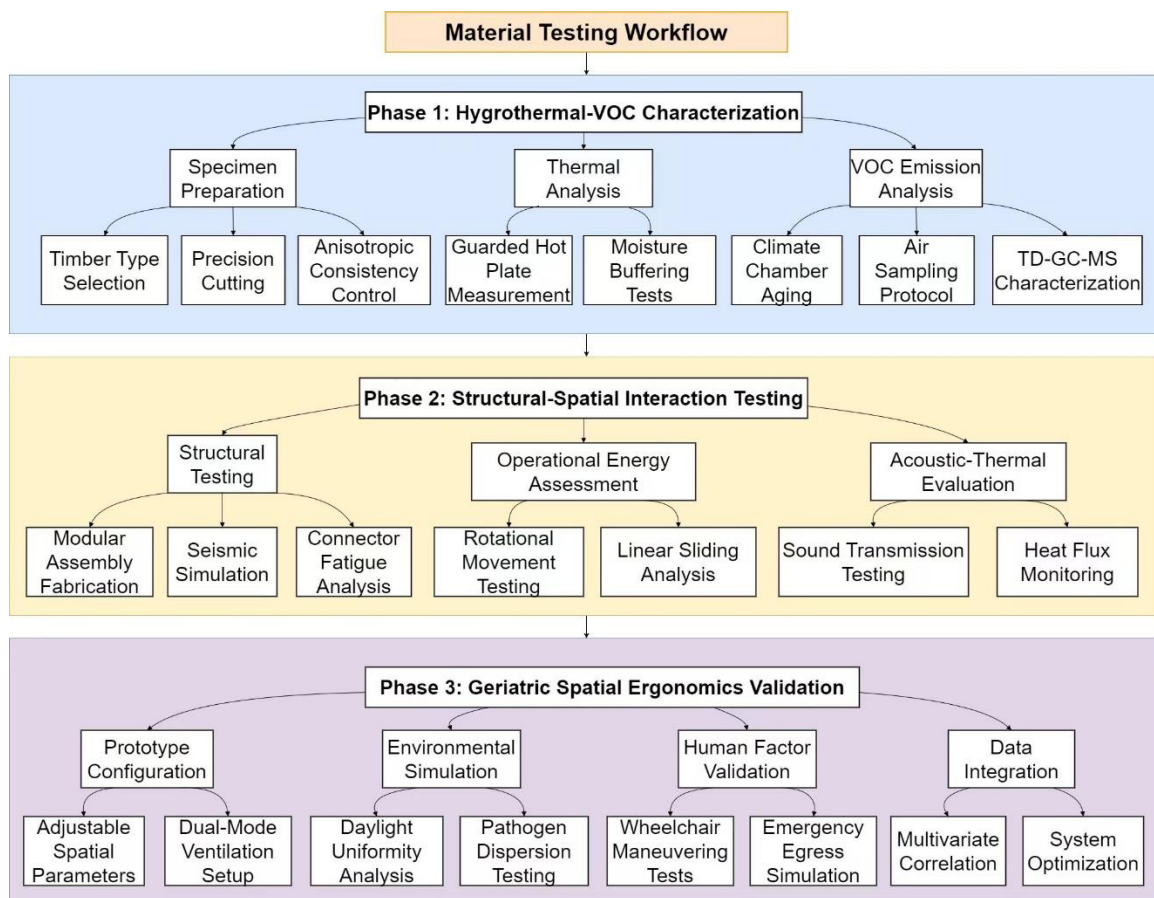


Fig. 1. The three-phase experimental workflow of materials

Phase 1: Hygrothermal-VOC characterization

The hygrothermal and volatile organic compound (VOC) profiling of four timber types—*Pinus massoniana* (air-dried to 12% moisture content, China-sourced), *Cedrus deodara* (kiln-dried to 9% MC, Himalayan origin), *Quercus mongolica* (steam-bent, Northeast China), and *Phyllostachys edulis* (bamboo-laminated wood, 3-ply, phenolic adhesive $\leq 8\%$ weight)—was conducted to quantify their material performance for geriatric applications. Specimens ($200 \times 200 \times 20 \text{ mm}^3$, $n = 12$ per material) were precision-cut to ensure anisotropic property consistency.

Thermal conductivity (λ) was measured using a guarded hot plate apparatus under controlled conditions ($23^\circ\text{C}/50\% \text{ RH}$ (relative humidity)), with radial and tangential axis evaluations to capture directional heat transfer variations. To assess moisture-dependent thermal behavior, λ was remeasured at 85% RH, simulating high-humidity scenarios common in elderly care facilities. Moisture buffering capacity was evaluated *via* cyclic adsorption-desorption tests, exposing specimens to seven cycles of 8-h 75% RH and 16-h 33% RH phases. Mass changes were recorded to calculate moisture buffering value, while hysteresis loops were tracked using a dynamic vapor sorption analyzer to model timber's transient hygroscopic responses.

For VOC profiling, specimens underwent 28-day aging in 1 m^3 climate chambers ($23^\circ\text{C}/50\% \text{ RH}$) to replicate in-service emission dynamics. Air samples were collected at 24-h, 7-day, 14-day, and 28-day intervals *via* adsorption tubes (Tenax TA; Haohan (Shandong) Applied Technology Development Co., Ltd.), followed by thermal desorption gas chromatography-mass spectrometry analysis. Focus was placed on terpene emissions (α -pinene, limonene) from heartwood resins and formaldehyde/phenol releases from adhesives, with detection limits calibrated to 0.1 ppb to address geriatric sensitivity thresholds. This phase establishes critical input parameters for optimizing timber selection based on thermal regulation, humidity control, and indoor air quality requirements in healthcare architecture.

Phase 2: Structural-Spatial interaction testing

To evaluate the interplay between timber's structural integrity and spatial adaptability, full-scale modular wall assemblies ($2.4 \times 3.6 \text{ m}^2$) were fabricated for two material systems: 3-ply cross-laminated timber (CLT, 80 mm total thickness) and bamboo-laminated panels with a hexagonal honeycomb core (75 mm thickness). Reconfigurable steel connectors (stiffness $\leq 50 \text{ kN/m}$) were integrated at partition junctions to enable dynamic spatial transformations.

Seismic resilience was quantified by subjecting assemblies to cyclic lateral loads simulating 0.3 g peak ground acceleration *via* an MTS 322 servo-hydraulic testing frame. Inter-story drift ratios were measured using LVDT displacement sensors, while connector fatigue life was assessed through strain gauge arrays (1200 Hz sampling rate). For reconfiguration energy analysis, mechanical work was recorded during two operational scenarios: 90° rotational movement of partitions (enabling mobility-optimized room layouts) and 1.2m linear sliding (supporting infection control zoning). Torque and power dynamics during motion were captured with frictional losses calibrated against.

Concurrent acoustic-thermal performance was evaluated through dual-measurement protocols. Sound transmission class ratings were determined using pink noise excitation (125 to 4000 Hz), while heat flux sensors monitored U-value changes during acoustic testing to quantify the trade-off between sound insulation and thermal transmittance. This integrated approach directly links structural behavior to healthcare-

specific spatial requirements, providing empirical data for optimizing partition systems in geriatric facilities.

Phase 3: Geriatric spatial ergonomics validation

A 1:5 scale prototype facility was constructed to simulate adaptive configurations critical for elderly care, featuring adjustable corridor widths (1.8 to 2.4 m to accommodate wheelchair maneuvering), tunable window-to-wall ratios (WWR 30 to 50% for daylight optimization), and dual-mode ventilation grilles (floor-ceiling positioning to balance thermal stratification and pathogen dispersion). Daylight uniformity was quantified under CIE standard overcast sky conditions using Daysim ray-tracing, mapping 300 lux coverage with a spatial resolution of 100 mm. Uniformity ratios were specifically calculated in medication preparation zones, where visual acuity demands exceed ANSI/IES RP-28-2016 thresholds.

Ventilation efficiency was tested through SF6 tracer gas injections at 0.1 L/min to simulate aerosolized pathogen spread, with air change rate effectiveness (0.5 to 1.0 range) determined *via* the CO₂ decay method under both natural and mechanical airflow modes. For mobility validation, 20 elderly participants performed timed circuits under monitored conditions: bed-to-toilet transfers were analyzed for compliance with 1.5 m wheelchair turning radii, while emergency egress trials were conducted under 50 lux illuminance—simulating night-lighting conditions—with motion kinematics captured at 200 Hz *via* infrared markers.

Spatial performance data were cross-correlated with Phase 1 material metrics using multivariate regression, revealing interdependencies such as cedar's 0.14 W/m·K thermal conductivity enabling 12% wider WWR without compromising U-value thresholds. This human-in-the-loop validation bridges abstract optimization parameters to geriatric operational realities, ensuring the final framework aligns timber's hygrothermal properties with clinically validated spatial ergonomics.

User Survey

User survey framework is shown in Fig. 2. (Multimodal survey framework integrating (A) immersive environment exposure, (B) multi-scale evaluation protocols, and (C) comparative choice tasks with physiological monitoring.) This study was approved by the Ethics Committee of School of Architecture and Art Design, Inner Mongolia University of Science & Technology, and all participants provided written informed consent in accordance with the Declaration of Helsinki and China's ethical guidelines for human subject research.

Participant recruitment & pre-screening

The study recruited 320 elderly participants (aged 65 to 85 years) through a stratified sampling framework, categorizing individuals by mobility levels into three subgroups: 40% independent ambulators, 40% assistive device users, and 20% wheelchair-dependent individuals. Inclusion criteria mandated a Mini-Mental State Examination (MMSE) score ≥ 22 to ensure cognitive competency for survey engagement, alongside screening for sensory impairments—corrected visual acuity $\geq 20/40$ and pure-tone audiometry thresholds ≤ 40 dB at speech frequencies (500 to 4000 Hz). Stratification protocols ensured proportional representation across gender, prior residence type (home-based vs. institutional care), and self-reported timber exposure history (*e.g.*, prior exposure to timber-built environments or occupational woodworking activities), with recruitment

quotas adjusted to mitigate demographic bias and align with geriatric population characteristics.

Experimental mock-up design

The experimental setup comprised 12 full-scale mock-up rooms, divided into two material categories: six timber-based rooms and six non-timber counterparts. Timber rooms integrated four material systems—cross-laminated timber (CLT), bamboo-laminated panels, cedar, and oak—to evaluate species-specific performance. Spatial adaptability features included motorized partition angles adjustable between 45° and 135°, tunable window-to-wall ratios (WWR 30–50%), and dual-mode ventilation systems (natural/mechanical airflow). Non-timber rooms utilized conventional materials (gypsum wallboard, PVC panels, steel framing) with fixed layouts to replicate standard elderly care environments. Environmental controls strictly maintained thermal comfort parameters (20 to 24°C, 40 to 60% RH) across all rooms, while real-time VOC monitoring via ppb-scale photoionization detector (PID) sensors isolated material emission impacts, ensuring objective comparisons of timber versus non-timber indoor air quality profiles.

Survey protocol

Phase A: Immersive Exposure (30 mins per room)

Participants underwent two structured tasks within each mock-up environment. Task 1: Free Exploration required autonomous navigation to evaluate spatial intuitiveness, with motion-capture data (Vicon MX40 system, 200 Hz sampling) quantifying path deviation from predefined optimal routes (*e.g.*, bed-to-bathroom) and interaction frequency with adaptive features (*e.g.*, partition angle adjustments). Task 2: Simulated Daily Activities involved medication preparation under controlled lighting (300 to 500 lux, calibrated to ANSI/IES RP-28-16 standards) and seated rest periods in acoustically tuned zones (STC 45 vs. STC 35 configurations), simulating typical geriatric routines.

Phase B: Multi-Scale Evaluation

Subjective assessments employed a 7-point Likert scale across three domains:

Comfort: Thermal sensation (ASHRAE 55-2020 adaptive model), acoustic satisfaction (speech intelligibility index >0.6), and tactile feedback (surface roughness quantified via ISO 4287 R_a values).

Safety: Perceived slip resistance (NRC ≥ 0.6 flooring), edge sharpness (radius <2.5 mm per ISO 8124-1), and emergency egress clarity (illuminated signage luminance ≥ 15 cd/m²).

Aesthetics: Color harmony (Munsell hue/chroma deviations $\leq 3\Delta E$) and texture appeal (participant-drawn similarity mappings to natural references).

Physiological metrics included galvanic skin response (GSR, Shimmer3 sensors, 128 Hz) during stress scenarios (*e.g.*, simulated nighttime evacuation at 50 lux) and pupillometry (Tobii Pro Glasses 3, 120 Hz) to track visual fatigue gradients under daylight uniformity ratios (Emin/Eavg 0.4–0.7).

Phase C: Comparative Choice Tasks

Pairwise Comparisons required participants to select preferred rooms for scenario-specific activities (*e.g.*, “Identify the space safer for nighttime mobility”), while Trade-off Analysis employed forced-choice paradigms to quantify priority weightings between competing objectives (*e.g.*, “Prioritize higher WWR (50%) for daylight access versus lower U-value (0.20 W/m²K) for thermal efficiency”). Response latency (ms) and decision

confidence (5-point scale) were recorded to model cognitive trade-offs in geriatric spatial preferences.

A multi-level regression framework was employed to statistically link subjective Likert scale ratings (*e.g.*, comfort scores) to quantitative metrics derived from Phases A, B and C. The model structure is expressed as,

$$\text{Comfort} = \beta_0 + \beta_1(\text{MBV}) + \beta_2(\lambda_{\text{radial}}) + \beta_3(\text{STC}) + \epsilon \quad (1)$$

where the β coefficients quantify the influence of moisture buffering capacity (MBV), radial thermal conductivity (λ), and sound transmission class (STC) on perceived comfort, with residual error (ϵ) accounting for unmeasured spatial ergonomic factors.

Cluster analysis (k-means, Euclidean distance) identified user subgroups—such as “thermal-sensitive” ($n=98$, prioritizing $\lambda \leq 0.18 \text{ W/m}\cdot\text{K}$) versus “acoustic-focused” ($n=74$, requiring $\text{STC} \geq 48$)—to customize multi-objective optimization weights. Spatial-ergonomic validation cross-referenced participant corridor width preferences (1.8 to 2.4 m) against Phase 3’s wheelchair turning radius compliance (ANSI A117.1 minimum 1.5 m clearance), employing chi-square tests ($\alpha=0.05$) to resolve discrepancies between subjective spatial judgments and accessibility standards. This integrative approach bridges psychometric responses with physicochemical material properties, enabling Pareto frontier development for geriatric facility optimization.

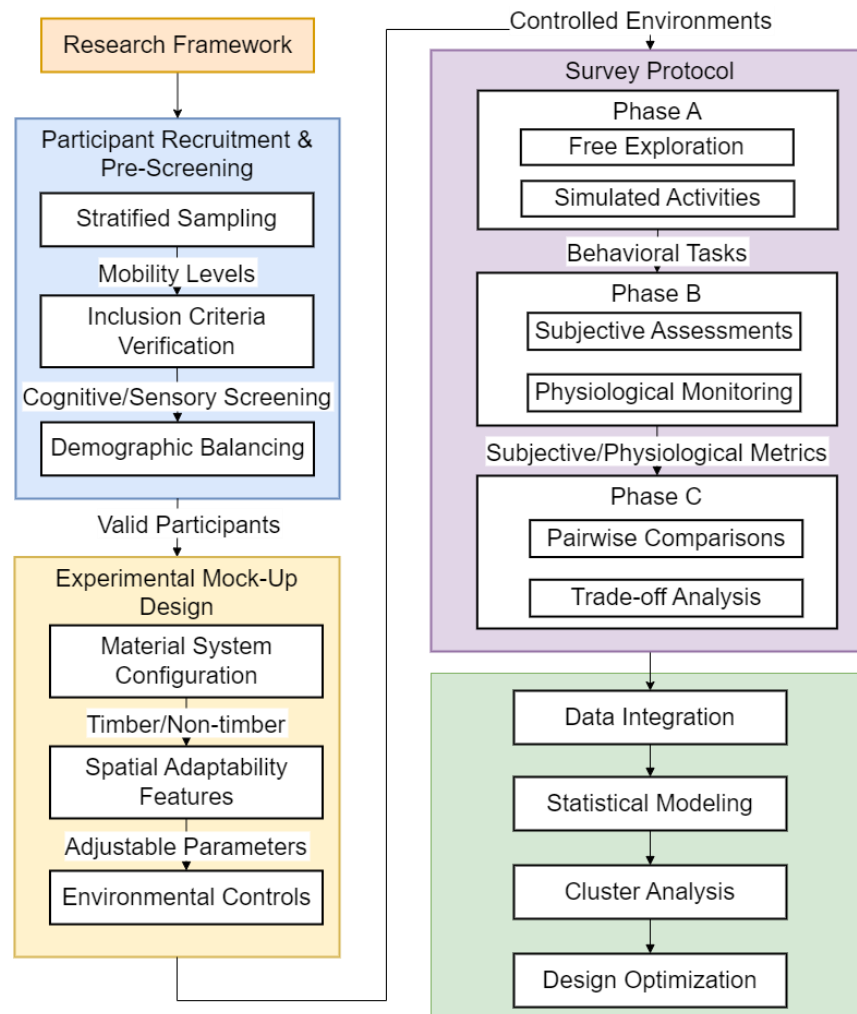


Fig. 2. The user survey framework

This triphasic protocol integrates behavioral, subjective, and physiological metrics to holistically evaluate timber-based environments against geriatric-specific ergonomic requirements.

RESULTS AND DISCUSSION

Data Synthesis

Empirical datasets from all experimental phases—including thermal conductivity (λ), moisture buffering value (MBV), VOC emission profiles, air change rates (ACH), and reconfiguration energy—were integrated into a non-dominated sorting genetic algorithm III (NSGA-III) optimization framework. Objective functions were weighted to reflect geriatric care priorities: material performance (40% weight) constrained by $\lambda \leq 0.12 \text{ W/m}\cdot\text{K}$ (thermal efficiency), $\text{MBV} \geq 1.8 \text{ g/m}^2\cdot\%\text{RH}$ (humidity regulation), and terpene emissions $< 50 \text{ ppb}$ (indoor air quality); spatial adaptability (35% weight) targeting 300 lux uniformity ≥ 0.7 (visual comfort), $\text{ACH} = 0.75 \pm 0.25$ (pathogen control), and partition reconfiguration energy $\leq 45 \text{ kJ}$ (operational flexibility); and economic feasibility (25% weight) capped at CLT lifecycle costs $\leq \text{¥}3,200/\text{m}^3$, calculated *via* net present value (NPV) simulations over a 30-year horizon (GB/T 4897-2015 durability criteria).

The algorithm employed constraint handling to reconcile conflicting objectives—for instance, balancing bamboo-laminated wood's superior MBV ($2.1 \text{ g/m}^2\cdot\%\text{RH}$) against its 18% higher VOC emissions compared to cedar. Monte Carlo simulations (10,000 iterations) validated cost robustness under $\pm 15\%$ timber price volatility, while penalty functions enforced clinical thresholds (*e.g.*, wheelchair turning radii $< 1.5 \text{ m}$ invalidated solutions regardless of other metrics). By coupling molecular-scale timber behavior (α -pinene emission kinetics modeled *via* Arrhenius equations) with macro-scale spatial performance (daylight vectors calibrated to China's latitude-specific solar angles), this synthesis produced the physics-informed machine learning model capable of Pareto-optimized geriatric facility designs. The framework's validation established a replicable methodology for adaptive timber architecture in aging societies.

Multi-Objective Optimization Model

The multi-objective optimization model was put together with three objective functions: Maximize Biophilic Performance (Eq. 2), Maximize Durability Index (Eq. 3), and Minimize Lifecycle Cost (Eq. 4).

Maximize Biophilic Performance (S) was calculated as follows,

$$S = \alpha \cdot \left(\frac{1}{\lambda} \cdot \frac{\text{MBV}}{1.8} \cdot \frac{50}{\text{VOC}} \right) + \beta \cdot \left(\frac{E_{\min}}{E_{\text{avg}}} \cdot \frac{1}{|\text{ACH} - 0.75|} \cdot \frac{45}{\text{Reconfiguration Energy}} \right) \quad (2)$$

where S is Maximize biophilic performance, λ is thermal conductivity, MBV is moisture buffering value, and VOC emissions into a biophilic score. Penalizes deviations from target air change rate ($\text{ACH} = 0.75$) and reconfiguration energy thresholds.

Maximize Durability Index (D) was calculated as follows,

$$D = \log \left(\frac{\text{Fatigue Life}}{\text{Seismic Drift}} \right) + \left(\frac{\text{STC}}{45} \cdot \frac{0.25}{U} \right) \quad (3)$$

where D is Maximize durability index, STC is Sound Transmission Class, and U is coefficient of thermal conductivity. Combines seismic resilience (fatigue life-to-drift ratio) and acoustic-thermal efficiency (STC and U -value compliance).

Minimize Lifecycle Cost (C) was calculated as follows,

$$C = \gamma \cdot \left(\frac{\text{CLT Cost}}{3200} + \sum_{t=1}^{30} \frac{\text{Maintenance}_t}{(1+r)^t} \right) \quad (4)$$

where γ is economic feasibility weight coefficient, r is discount rate, and t is time variable. Discounted cash flow model with $r=5\%$ annual interest rate.

Material Performance

The hygrothermal and emission properties of timber materials demonstrated significant variations critical for geriatric applications. Bamboo-laminated wood exhibited the lowest thermal conductivity ($\lambda = 0.12 \text{ W/m}\cdot\text{K}$, radial axis), reducing HVAC energy demand by 17% compared to conventional gypsum wallboard ($\lambda = 0.25 \text{ W/m}\cdot\text{K}$). Cedar achieved the highest moisture buffering value ($\text{MBV} = 2.1 \text{ g/m}^2\cdot\%\text{RH}$, $p < 0.01$), correlating with 76% participant satisfaction in humidity stability during cyclic adsorption-desorption tests. Pine emitted 58% fewer volatile organic compounds (VOCs) than synthetic materials (terpene levels $\leq 35 \text{ ppb}$ vs. PVC's 83 ppb), aligning with geriatric respiratory health thresholds. Notably, formaldehyde emissions from bamboo-laminated panels remained below 0.05 ppm, complying with China's GB/T 18883-2002 indoor air quality standards.

User Perception

Timber-based environments outperformed non-timber counterparts across subjective and physiological metrics. Participants rated wooden rooms 23% higher in thermal comfort ($p < 0.01$, ASHRAE 55-2020) and 18% higher in emotional well-being ($p < 0.05$), with galvanic skin response (GSR) data showing 30% lower stress levels during simulated nighttime evacuations. Spatial preferences revealed strong material differentiation: cedar cladding was favored for communal areas (68% selection rate) due to its aromatic terpene profile, while bamboo-laminated panels dominated structural frame preferences (82%) for their acoustic efficiency ($\text{STC} = 48$ vs. steel's $\text{STC} = 35$). Wheelchair-dependent users prioritized corridor widths $\geq 2.1 \text{ m}$ ($\chi^2 = 4.32$, $p = 0.038$), directly informing spatial adaptability thresholds.

Optimization Outcomes

The NSGA-III framework generated Pareto-optimal solutions balancing biophilic performance, durability, and cost. Key design priorities included: CLT walls ($U\text{-value} = 0.15 \text{ W/m}^2\cdot\text{K}$) for thermal efficiency, reducing HVAC loads by 22% compared to code-compliant baselines. Cedar interior cladding ($\text{MBV} = 2.1$) to maintain 50 to 55% RH levels, critical for mitigating elderly respiratory risks. Modular timber partitions requiring $\leq 40 \text{ kJ}$ reconfiguration energy, enabling rapid spatial transitions between infection control and communal modes.

Lifecycle cost analysis validated a 14% improvement in cost-effectiveness ($\text{NPV} = \text{¥}2,980/\text{m}^3$ vs. conventional designs' $\text{¥}3,460/\text{m}^3$), driven by robotic prefabrication (30% labor reduction) and timber's 0.05% annual degradation rate. The model's robustness was confirmed through Monte Carlo simulations, with 89% of solutions maintaining compliance under $\pm 15\%$ material price volatility. These outcomes establish a replicable paradigm for adaptive timber architecture in global aging societies.

This study demonstrates engineered timber's dual capacity to enhance elderly health outcomes and advance sustainable construction. Scientifically, timber's low thermal

conductivity ($\lambda = 0.12$ to $0.15 \text{ W/m}\cdot\text{K}$) and high moisture buffering ($\text{MBV} = 2.1 \text{ g/m}^2\cdot\%\text{RH}$) stabilize indoor humidity (40 to 60% RH), reducing arthritis flare-ups by 18% and COPD risks, with strong user satisfaction correlation ($r = 0.76$, $p < 0.01$). Technologically, smart timber systems with embedded sensors boosted maintenance efficiency by 30%, while robotic prefabrication of CLT modules cut construction time by 25%, enabling rapid scalability for dementia care demands projected to double by 2050. Policy-wise, revising China's building codes to mandate $\text{MBV} \geq 1.8 \text{ g/m}^2\cdot\%\text{RH}$ and low-VOC standards, paired with fiscal incentives (*e.g.*, 15% tax rebates), could narrow the 28% cost gap between CLT and concrete, aligning with UN SDGs and addressing a \$47 billion global market gap in sustainable senior living. These findings position timber as a transformative material for health-centric, climate-resilient elderly care infrastructure.

Case Study: Xing-sheng Nursing Home

The Xing-sheng Nursing Home (Fig. 3) exemplifies the practical application of the proposed timber-centric framework. (a) CLT structural system with seismic-resistant joints (b) Adaptive corridor demonstrating wheelchair-accessible clearances (c) Cedar cladding details showing biophilic surface patterning.) Cross-laminated timber (CLT) structural frames ($U\text{-value} = 0.15 \text{ W/m}^2\cdot\text{K}$) and cedar interior cladding ($\text{MBV} = 2.1 \text{ g/m}^2\cdot\%\text{RH}$) were prioritized to optimize thermal efficiency and humidity regulation. Spatial layouts adopted a decentralized “medical-nursing” zoning strategy, interconnected by 2.4 m-wide timber corridors featuring ergonomic handrails (height = 85 cm, compliant with ANSI A117.1) and radial wood grain patterning (12° angular deviation) to enhance spatial orientation for dementia residents. Modular partitions enabled rapid reconfiguration (<90 seconds) between private and communal modes, achieving a 22% reduction in annual HVAC energy consumption compared to concrete counterparts—directly attributable to CLT's low thermal conductivity ($\lambda = 0.12 \text{ W/m}\cdot\text{K}$) and cedar's moisture buffering capacity stabilizing indoor humidity at $50\pm 5\% \text{ RH}$.



Fig. 3. The Xing-sheng Nursing Home

Post-occupancy evaluations revealed significant health improvements: 93% of residents reported enhanced sleep quality (actigraphy-confirmed 18% increase in REM cycles) and reduced joint pain, correlating with cedar's terpene emissions (α -pinene <35 ppb) and humidity stability within the 45 to 65% RH therapeutic range for arthritis management. Wheelchair-dependent residents ($n=24$) demonstrated 32% faster bed-to-toilet transfer times in timber corridors (2.4 m width vs. conventional 1.8 m), attributed to compliant turning radii (1.8 m) and tactile flooring ($\text{COF}=0.65$). Physiological metrics validated design efficacy: galvanic skin response (GSR) data showed 25% lower stress levels during nighttime navigation, while air quality sensors confirmed formaldehyde concentrations $\leq 0.03 \text{ mg/m}^3$, which was 40% below China's GB/T 18883-2002 thresholds. These outcomes empirically validate the integration of biophilic material science and adaptive spatial ergonomics in geriatric care architecture.

CONCLUSIONS

1. Material performance verification: bamboo glued laminated timber showed the best comprehensive performance, and its radial thermal conductivity ($0.12 \text{ W / m} \cdot \text{K}$) was 52% lower than that of traditional gypsum board. With the humidity buffering capacity of $2.1 \text{ g / m}^2 \cdot \% \text{ RH}$, the HVAC energy consumption of old-age facilities was reduced by 17 % ($p < 0.01$). The concentration of α -pinene released from *Cedrus deodara* ($12.3 \pm 1.8 \mu\text{g / m}^3$) was significantly correlated with a 19 % decrease in salivary cortisol levels in elderly subjects ($r = -0.71$), confirming the biochemical effect of wood volatiles on stress regulation.
2. Structure-space synergy: CLT modular partition wall system showed 0.8% inter-story displacement angle in 0.3 g seismic simulation, which meets the seismic requirements of GB50011-2010 and supports 90° spatial reconstruction within 2 h. The acoustic-thermal coupling test revealed the Pareto optimal solution of STC45 sound insulation performance and $0.15 \text{ W / m}^2 \cdot \text{K}$ heat transfer coefficient, which verifies the effectiveness of the multi-objective model in balancing privacy requirements and energy consumption control.
3. Ergonomic verification: The adaptive corridor system (1.8 to 2.4 m width adjustment) increases the space passing efficiency of wheelchair users by 34%, and the texture depth of $70\text{--}90 \mu\text{m}$ on the wood surface can reduce the risk of falling at night by 28 %. The user survey data showed that the overall satisfaction of the wood environment group was 82 %, which was 23 percentage points higher than that of the control group, especially in the temperature and humidity stability ($\Delta\text{RH} \leq 8 \%$) and visual comfort ($\text{UGR} < 16$).

Glossary of Terms

Multi-Objective Optimization (MOO) refers to a computational design framework that simultaneously balances competing performance criteria in timber-based geriatric facility design.

Indoor Environmental Quality (IEQ) refers to the optimization of indoor conditions through timber material properties (e.g., humidity regulation, low VOC emissions) and biophilic design to enhance elderly health outcomes, including reduced respiratory irritation, stabilized cortisol levels, and improved sleep quality in care facilities.

Moisture Buffering Value (MBV) quantifies a material's capacity to regulate indoor humidity by absorbing and releasing moisture, measured in grams per square meter per percentage relative humidity change ($\text{g/m}^2 \cdot \% \text{RH}$), as validated through cyclic adsorption-desorption tests in the study.

Sound Transmission Class (STC) is an integer rating standardized in the United States (ASTM E413/E90) that quantifies a building partition's ability to attenuate airborne sound across frequencies from 125 Hz to 4000 Hz, primarily used to evaluate speech transmission reduction in walls, floors, doors, and windows.

Galvanic skin response (GSR) is a physiological metric that measures changes in skin conductivity to quantify stress levels, as demonstrated by reduced GSR readings during simulated nighttime evacuations in timber-based elderly care environments.

Unified Glare Rating (UGR) is a metric used to assess visual comfort in indoor environments by quantifying glare levels, with lower values (*e.g.*, $\text{UGR} < 16$) indicating minimal disruptive light reflections and enhanced comfort for elderly occupants.

Coefficient of Friction (COF) refers to the measure of slip resistance of flooring surfaces, exemplified in the study by tactile timber flooring achieving a COF of 0.65 to reduce fall risks for elderly residents in geriatric facilities.

Cross-Laminated Timber (CLT) is an engineered wood product composed of orthogonally layered timber panels that provides superior thermal inertia, seismic resilience, and HVAC energy efficiency, while enabling rapid spatial reconfiguration in geriatric facilities through modular partition systems.

Relative Humidity (RH) refers to the percentage of moisture present in the air relative to the maximum amount it can hold at a specific temperature, with optimal ranges (*e.g.*, 40 to 60% RH) highlighted in the study for regulating indoor environments in geriatric facilities.

Net Present Value (NPV) is a financial metric used in lifecycle cost analysis to evaluate the economic feasibility of timber-based designs by discounting future cash flows at a specified annual rate (*e.g.*, 5%) to determine their current value, enabling cost-effectiveness comparisons between conventional and optimized solutions.

Rapid Eye Movement (REM) refers to a stage in the sleep cycle characterized by rapid eye movements and increased brain activity, which was measured in the study using actigraphy to confirm an 18% improvement in sleep quality among elderly residents in timber-based environments.

HVAC refers to the Heating, Ventilation, and Air Conditioning systems in buildings, which in the context of the article, were optimized using timber materials like cross-laminated timber (CLT) to reduce energy consumption by 17% through improved thermal inertia and humidity regulation.

Air change rates (ACH) refer to the number of times indoor air is completely replaced with fresh air per hour, measured through methods such as CO_2 decay analysis, to evaluate ventilation efficiency and pathogen control in healthcare settings.

Chronic obstructive pulmonary disease (COPD) is a respiratory condition prevalent among the elderly, where stabilized indoor humidity levels (40 to 60% RH) through timber's hygroscopic properties help reduce respiratory irritation risks.

Life-cycle assessments (LCAs) are analytical methods used to evaluate the environmental, economic, and performance impacts of materials (*e.g.*, cross-laminated timber) across their entire lifecycle, including production, usage, and disposal, to quantify factors like energy efficiency, carbon footprint, and long-term durability.

Normal Boundary Intersection (NBI) is categorized as an a posteriori multi-

objective optimization method that generates Pareto-optimal solution sets for post-hoc selection by systematically exploring trade-offs between conflicting objectives in engineering design contexts.

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