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Towards sustainable social housing: An integrative life cycle and multi-criteria approach

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ABSTRACT

Structural systems for social housing must address pressing challenges of affordability, rapid execution, and long-term sustainability. However, choosing the most appropriate alternative requires balancing economic, environmental, social, and technical dimensions under uncertainty. This study applies a hybrid multi-criteria decision-making (MCDM) framework that combines the Best–Worst Method (BWM), fuzzy Decision-Making Trial and Evaluation Laboratory (DEMATEL), and the Measurement of Alternatives and Ranking according to COmpromise Solution (MARCOS) to evaluate five construction systems: Light Steel Frame (LSF), bolt-connected sandwich panels (LBSPS), reinforced concrete walls (RCW), monolithic reinforced concrete (RCF-M), and cast-in-place reinforced concrete (RCF-CP). The framework combines life cycle-based assessments—LCA, LCC, and SLCA—with causal analysis to capture interdependencies among criteria and generate transparent sustainability rankings. Results consistently position LSF as the top performing alternative, reflecting its balance between efficiency, durability, and reduced maintenance. Social aspects collectively accounted for nearly 40% of the total weight, surpassing economic and environmental dimensions, highlighting the central role of labor conditions, community impacts, and functionality in sustainable housing. Sensitivity analyses demonstrated stable rankings and validated the hybrid framework under alternative MCDM methods and diverse scenario perturbations. The findings provide actionable insights for housing policy in developing contexts, where industrialized systems and participatory evaluation processes can jointly advance resource efficiency, affordability, and social well-being.

1. Introduction

The housing crisis in developing countries remains one of the most pressing global urban challenges. According to UN-Habitat, more than 1.6 billion people live in inadequate housing. By 2030, nearly 96,000 housing units must be built daily to meet worldwide demand (United Nations & Economic Commission for Europe, 2021). Beyond the quantitative gap, the deficit includes quality, safety, and habitability issues disproportionately affecting low-income populations. Therefore, the development of social housing emerges as a critical strategy to ensure access to dignified living conditions, social inclusion, and economic improvement. This challenge requires efficient resource use and long-term sustainability, moving away from temporary or purely cost-driven solutions (Gomide et al., 2024b). Christoforatos et al. (2025) further emphasize that sustainability in residential buildings ensure both environmental efficiency and social adequacy in large-scale housing programs.

The construction sector accounts for nearly 37% of global energy-related CO_2 emissions and consumes vast raw materials (Kaneko et al., 2024). This dilemma is especially acute in social housing, where economic constraints must align with sustainability and technical performance. Structural design decisions directly shape construction and maintenance costs, seismic safety, and environmental footprint (Tighnavard Balasbaneh et al., 2022). As demonstrated by Kufner et al. (2025), alternative structural materials can significantly reduce environmental impacts while maintaining performance, highlighting the importance of material selection in sustainable housing design. Addressing social housing from a life cycle and circular economy perspective enhances understanding of the interdependencies among resources, impacts, and performance. In this regard, applying circular economy concepts to the built environment requires optimizing resources during construction, operation, maintenance, and end-of-life processes (Gomide et al., 2024a).

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Glossary

SDG	Sustainable Development Goals
LCSA	Life Cycle Sustainability Assessment
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
S-LCA	Social Life Cycle Assessment
MCDM	Multi-Criteria Decision-Making
BWM	Best-Worst Method
S-BWM	Stratified - Best Worst Method
DEMATEL	Decision-Making Trial and Evaluation Laboratory
MARCOS	Measurement of Alternatives and Ranking according to COmpromise Solution
MSHP	Mass Social Housing Projects
EoL	End-Of-Life
RCF-M	Reinforced Concrete Frame + Confined Masonry
RCW	Reinforced Concrete Monolithic Walls
LSF	Light Steel Frame
RCF-CP	RC Frame + Concrete Panels
LBSPS	Light Bolt-connected Sandwich Panels
MRH	Medium Risk Hours

Sustainability in social housing requires a perspective that goes beyond initial construction costs. While affordability remains fundamental, focusing exclusively on this aspect often leads to short-term, inefficient, or unsustainable solutions. Studies such as Leichter & Piccardo (2024), Mazzucco et al. (2023) and Tokede (2025) emphasize the need for a comprehensive understanding of sustainability based on the triple bottom line approach—economic, environmental, and social—which enables the simultaneous assessment of resource efficiency, environmental impact mitigation, and the generation of social benefits. This holistic vision is reinforced by Maaze & Shrivastava (2023), who highlight the need to integrate technical, economic, and social feasibility in selecting eco-friendly materials for housing construction. Such a framework aligns with Sustainable Development Goals (SDGs), particularly SDG 11 (sustainable cities and communities) and SDG 12 (responsible consumption and production) (Salas & Yepes, 2018; Tayefi Nasrabadi et al., 2024).

To achieve this comprehensive evaluation, methodologies such as Life Cycle Costing (LCC), Environmental Life Cycle Assessment (LCA), and Social Life Cycle Assessment (S-LCA) are essential (Balasbaneh et al., 2018; Younis et al., 2018). Considering these tools alongside structural alternatives provides a more robust decision-making framework. Recent studies show that evaluating construction costs in isolation may lead to suboptimal conclusions (Lu et al., 2021). In contrast, life cycle approaches assess durability, maintenance, environmental performance, and social implications, offering a holistic perspective (Amini Toosi et al., 2022). The need for integrated sustainability and resilience analysis has also been stressed by de Paula Salgado et al. (2025), who argue for combining environmental and hazard-resilience dimensions in infrastructure evaluation.

Although many structural solutions for social housing exist, there is no consensus on the most sustainable option under different contexts (Dong et al., 2023). Most previous studies have focused on partial comparisons, such as initial construction (Filho et al., 2022), cost or embodied carbon emissions (Ge et al., 2020; Houlihan Wiberg et al., 2014), neglecting the integration of multiple dimensions of sustainability. Theilig et al. (2024) and Safarzadeh & Jafari (2025) highlight that recent methodological advances increasingly combine life cycle assessment with MCDM techniques to better represent these multidimensional trade-offs, particularly at the component level. This methodological gap persists given the long-term economic, technical, environmental, and social effects of structural decisions (Huang et al., 2024). However, although this holistic perspective is widely acknowledged, existing studies rarely operationalize it through analytical frameworks capable of capturing the causal relationships and interdependencies among sustainability dimensions. Table 1 synthesizes representative review studies on sustainability-oriented LCA–MCDM frameworks relevant to built environment decision-making, outlining their scope, methodological focus, and principal findings.

The complexity of construction systems and the multiple criteria involved call for using Multi-Criteria Decision-Making (MCDM) methods that can integrate quantitative and qualitative indicators into a coherent framework (Aghazadeh et al., 2022; Khorasani Nejad et al., 2025). Approaches such as Analytic Hierarchy Process (AHP) (Oyefusi et al., 2024), Analytic Network Process (ANP) (Fathy, 2025), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Swathi & Vidjeapriya, 2024; Zhao & Guo, 2025), VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) (Mali et al., 2024), and ÉLimination et Choix Traduisant la REalité (ELECTRE) (Hadjar et al., 2025), have been applied in construction evaluations. However, these methods show limitations when handling interdependencies or reducing the cognitive load in pairwise comparisons (Puviarasu et al., 2023; Yazdani et al., 2020). Systematic review by Villalba et al. (2025) and Safarzadeh & Jafari (2025) confirms the growing use of MCDM methods but also persistent gaps: interdependencies are rarely modeled, weighting procedures are often simplified, and uncertainty in expert judgments is seldom addressed. Hence, hybrid MCDM frameworks capable of integrating stakeholder-driven weights, causal relationships, and uncertainty are needed—an aspect addressed here through BWM, fuzzy DEMATEL, and MARCOS.

To overcome these limitations, this study proposes an integrative methodological approach combining the Best-Worst Method (BWM), fuzzy Decision-Making Trial and Evaluation Laboratory (fuzzy DEMATEL), and the Measurement of Alternatives and Ranking according to COmpromise Solution (MARCOS). Each method contributes complementary strengths: BWM elicits weights with fewer comparisons (Darzi, 2025); fuzzy DEMATEL identifies causal relationships among criteria, capturing how some factors act as drivers and others as receivers in the system (Yu & Ma, 2025); and MARCOS provides a robust evaluation and ranking framework, ensuring transparency and comparability of results (Celik & Gul, 2021). Their integration ensures methodological robustness by incorporating hierarchization, interdependencies, and uncertainty (Baykasoǧlu & Gölcük, 2015).

Recent literature on sustainable housing shows advances in using MCDM and life cycle assessment tools (Davis et al., 2025; Kaneko et al., 2024). Nonetheless, most research has addressed either environmental, mainly carbon emissions, or economic aspects, usually focused on upfront costs. This partial approach restricts the ability to capture the full scope of sustainability by excluding social dimensions and long-term performance, including maintenance and end-of-life processes. Only a limited number of studies have included social aspects (Hosseinijou et al., 2014; Zimdars et al., 2018), and even fewer have explored causal interrelationships, which are essential for understanding trade-offs. Moreover, criteria weights are often arbitrarily defined, introducing methodological bias.

This conceptual fragmentation in previous research translates into concrete methodological limitations that restrict comprehensive sustainability assessments in the built environment. Consequently, three main research gaps can be identified: (i) integrated frameworks combining LCA, LCC, and S-LCA in social housing (Di Domênico et al., 2024; Kumar et al., 2025), (ii) explicit modeling of causal links among criteria (H. Li et al., 2025), and (iii) robust MCDM methods capable of addressing structural system complexity (Cinelli et al., 2014).

This article evaluates and compare alternative structural systems for social housing through a comprehensive sustainability framework. It integrates LCA, LCC, and S-LCA with advanced MCDM techniques to capture long-term impacts, interdependencies, and trade-offs, ensuring result stability through sensitivity analyses.

Table 1
Summary of representative review studies on sustainability-oriented LCA–MCDM frameworks.

Reference	Review Scope	Methodological Focus	Key Findings
Cinelli et al. (2014)	Review of MCDA in sustainability assessment	MCDA–LCA integration	MCDA improves interpretation of LCA results for sustainability decisions
Zanghelini et al. (2018)	Review of MCDA integrated with LCA	MCDA–LCA across LCA phases	MCDA supports trade-off analysis; growing use of AHP, WSA, and outranking methods
Navarro et al. (2019)	Review of MCDA in sustainable infrastructure design	MCDA-based sustainability assessment	MCDA enables structured evaluation of environmental, economic, and social criteria
Kandakoglu et al. (2019)	Systematic review of MCDA for sustainable development	MCDA sustainability frameworks	MCDA widely applied to manage multidimensional sustainability trade-offs
Theilig et al. (2024)	Systematic review of LCA–MCDA in building components	LCA–MCDA hybrid frameworks	Hybrid methods enhance comparability and transparency
Safarzadeh & Jafari (2025)	Review of MCDA in environmental and construction domains	Trends in MCDA–LCA integration	Rapid growth of MCDA-based sustainability applications
de Paula Salgado et al. (2025)	Review of sustainability and resilience integration	LCA–MCDA–resilience frameworks	Emphasizes need for integrated sustainability–resilience assessment

Despite the growing application of LCA, LCC, S-LCA and MCDM tools in sustainable construction, most studies treat these dimensions separately, evaluated only environmental or upfront economic indicators, or relied on single-method approaches that overlook interdependencies and uncertainty. Existing research has seldom integrated life cycle–based sustainability with hybrid MCDM frameworks, and even fewer works have examined structural systems for social housing through a unified environmental–economic–social–technical perspective. Additionally, expert competence and causal relationships are rarely incorporated, limiting systemic insight. This study addresses these gaps by combining LCA, LCC, and S-LCA within a hybrid BWM–fuzzy DEMATEL–MARCOS approach, capturing interdependencies, uncertainty, and long-term trade-offs.

This study makes four main contributions:

I. An integrative methodological framework combining life cycle approaches with BWM, fuzzy DEMATEL, and MARCOS.
II. Application to a real social housing case with empirical evidence of sustainability performance.
III. Identification of the structural system with the best balance across sustainability dimensions.
IV. Validation of model robustness through sensitivity analyses.

By addressing these methodological gaps and applying the framework to a practical case study, this research contributes theoretically and empirically to sustainable construction. On the one hand, it advances methodological integration for life cycle and multi-criteria analysis. On the other hand, it generates evidence to inform decision-making in designing and implementing social housing policies and projects, particularly in contexts of rapid urbanization and resource constraints.

The article is structured as follows: Section 2 describes the materials and methods, integrating life cycle tools and MCDM. Section 3 presents results, including criteria weighting, interrelationships, and ranking. Section 4 discusses the findings and provides sensitivity analyses. Section 5 outlines conclusions, implications, and limitations.

2. Materials and methods

The methodological design aims to identify the most sustainable structural system for mass social housing projects (MSHP). A hybrid multi-criteria framework was applied, integrating life cycle–based evaluation tools (LCA, LCC, and S-LCA) with advanced MCDM techniques. This combination allows simultaneous assessment of economic, environmental, and social impacts, capturing interrelationships among criteria and incorporating uncertainty in expert judgments.

2.1. Research framework

The research process was structured in four phases (Fig. 1):

Phase 1. Criteria definition and case study: Evaluation criteria were defined within economic, environmental, and social dimensions. The case study comprised five structural alternatives for MSHP. LCA and LCC data were extracted from Luque Castillo and Yepes (2025).

Phase 2. Weighting and interrelationships: Criteria weights were obtained using BWM, reducing expert workload through fewer comparisons. Fuzzy DEMATEL was then applied to model the causal structure among criteria under uncertainty.

Phase 3. Ranking of alternatives: The MARCOS method integrated the weighted criteria to establish the final ranking, comparing performance against ideal and anti-ideal solutions for transparent aggregation.

Phase 4. Validation and discussion: Robustness was tested through sensitivity analyses under multiple scenarios, followed by discussion, conclusions, and limitations.

- **Functional Unit**

The functional unit is one square meter (1 m^2) of constructed housing over a 50-year service life, enabling consistent comparison across the five structural alternatives (Llantoy et al., 2020). The cradle-to-grave boundary covers manufacturing, construction, use, and end-of-life (EoL) stages consistent with international LCA guidelines (Arvanitoyannis, 2008) and the methodological framework of Luque Castillo and Yepes (2025).

The manufacturing stage includes raw material extraction, industrial processing, and the production of concrete, steel, brick, aggregates, and prefabricated elements, as well as their transport to the construction site. The analysis is contextualized in Carabayllo (Lima), where transport distances correspond to actual supplier locations (T2, Supplementary Material S2). The construction stage includes assembly processes, labor intensity, machinery use, and construction logic of each alternative (cast-in-place, prefabricated, or hybrid).

The use phase covers only preventive maintenance —such as anti-corrosion and anti-carbonation painting—which vary according to the structural systems. Following Luque Castillo and Yepes (2025), operational energy consumption was excluded, since all alternatives share the same geometry, occupancy patterns, and climate exposure. Its inclusion would introduce non-structural variability unrelated to the systems being compared (Soust-Verdaguer et al., 2016).

The EoL stage accounts for demolition activities, waste transport, and recovery or disposal. A 7 km distance was assumed for final disposal in accordance with local practice, while recovery and recycling processes were prioritized whenever feasible to reduce environmental burdens.

- **Description of construction alternatives**

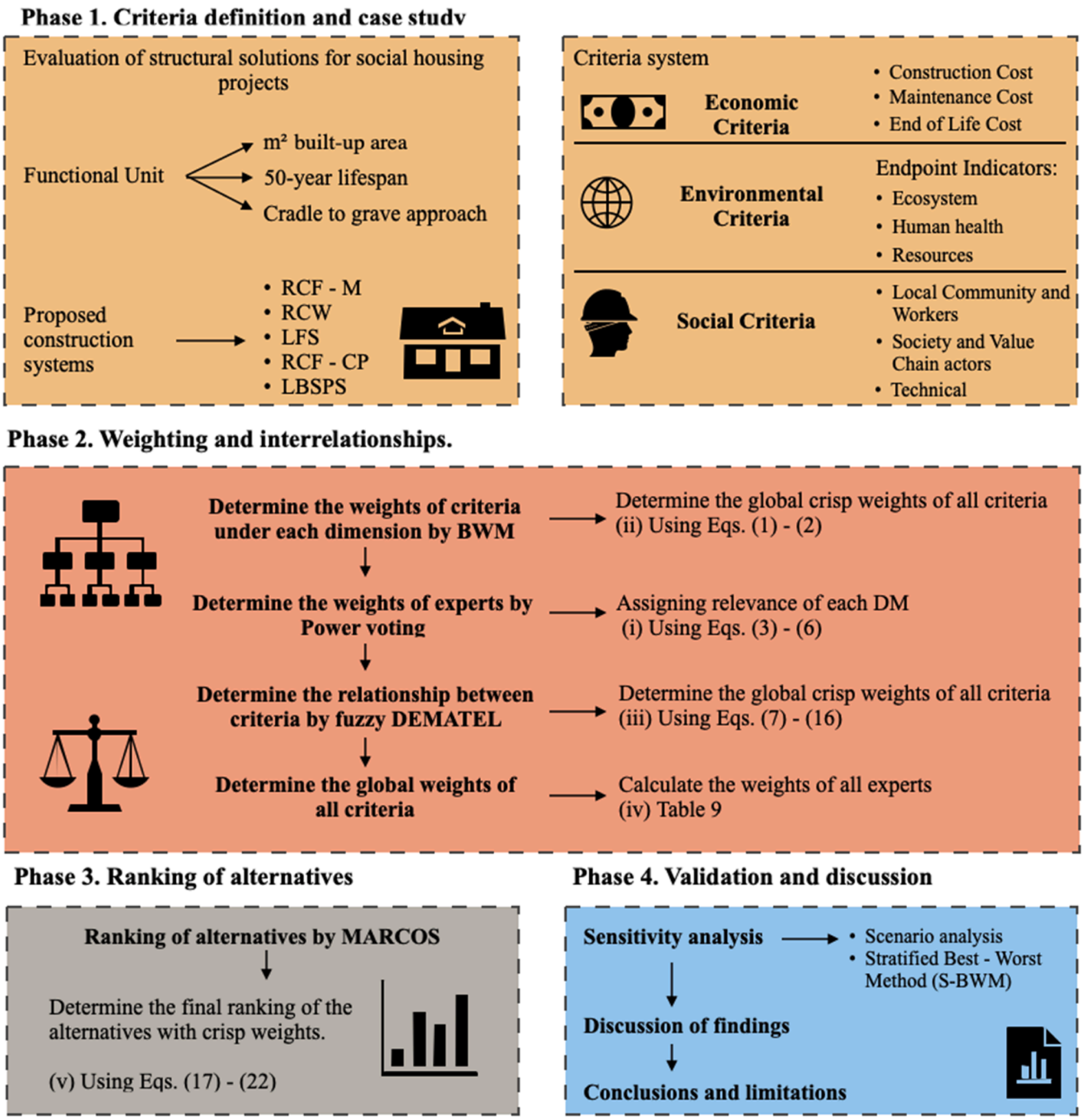

Fig. 1. Methodology of the study.

Five construction alternatives from Luque Castillo and Yepes (2025) were evaluated, adapted to the realities of social housing in a rapidly urbanizing district in northern Lima, Peru. They include conventional and industrialized systems (Table 2), each defined by structural configuration, construction logic, and degree of industrialization.

Regulatory compliance with Peru's National Building Regulations (RNE) ensures comparable seismic safety E.030. (Ministerio de Vivienda, 2019), thermal performance EM.110. (Ministerio de Vivienda, 2014), and sustainability criteria (Código Técnico de Construcción Sostenible, 2024). The detailed constructive characteristics of each alternative—including structural components, finishes, construction

Table 2
Structural definition of alternatives.

Code	System	Description	Type	Construction logic	References
RCF-M	Reinforced Concrete Frame + Confined Masonry	RC columns/beams, clay brick infill, ribbed slab	Conventional	Cast-in-place, labor intensive	(Gulkan et al., 2002)
RCW	Reinforced Concrete Monolithic Walls	Cast-in-place RC walls with solid slab	Conventional	High seismic resistance	(Loa et al., 2022)
LSF	Light Steel Frame	Galvanized steel frame, gypsum board, lightweight roof	Industrialized	Dry construction	(Alibazi et al., 2025)
RCF-CP	RC Frame + Concrete Panels	EPS core panels, welded mesh, shotcrete	Innovative	Hybrid (wet + precast panels)	(Dissanayake et al., 2017; Pawar et al., 2022)
LBSPS	Light Bolt-connected Sandwich Panels	Precast wall/slab panels for enclosure	Semi-industrial	Modular, rapid construction	(Wang et al., 2024; Zhao et al., 2023)

speed, and labor intensity—are provided in Table S1 (Supplementary Material 1).

Despite this common regulatory framework, the systems differ substantially in construction methods, material requirements, labor intensity, and life cycle implications. These contrasts provide a diverse set of structural solutions suitable for a multi-criteria sustainability assessment.

2.2. Life cycle sustainability assessment (LCSA)

A LCSA integrating LCA, LCC, and S-LCA was implemented, following Klöpffer (2008) three-pillar approach and recent developments in sustainability assessment (Cucurachi & Rocha, 2018; van der Giesen et al., 2020). Environmental and economic assessments are consistent with previous modelling work (Luque Castillo & Yepes, 2025), while the social dimension is newly incorporated following UNEP/SETAC guidelines. The cradle-to-grave boundary and modelling assumptions remained consistent across the three pillars. All modelling assumptions—including functional unit, lifespan, and maintenance scenarios.

LCA: Environmental impacts were modelled in OpenLCA using the ReCiPe 2008 Endpoint (H) methodology. Three endpoint indicators—Ecosystems, Human Health, and Resources—were selected as environmental criteria for the multicriteria decision-making phase due to their interpretability and relevance for structural design decisions (Goedkoop et al., 2009). The assessment covered material extraction, processing, transport, construction, preventive maintenance, and EoL activities. Detailed results appear in Tables S3–S4 (Supplementary Material 2).

LCC: Economic impacts were quantified using a Life Cycle Costing approach consistent with international LCC practice and adapted to the Peruvian construction context. Cost data came from the CYPE database supplemented with local prices. LCC included construction, maintenance, and demolition/EoL costs, aligned with LCA boundaries to ensure cross-pillar comparability.

S-LCA: The social pillar followed UNEP/SETAC guidelines (Ciroth & Finkbeiner, 2011) and contemporary S-LCA applications in the construction sector (Arcese et al., 2018; UNEP, 2024). A stakeholder-based assessment using SOCA v2 ensured compatibility with Ecoinvent datasets. Social indicators were quantified for five stakeholder groups and aggregated following the SOCA v2 characterization scheme. Complete results and indicator performance for all alternatives are presented in Tables S8–S9 (Supplementary Material 3).

2.3. Multi-criteria decision-making (MCDM) procedure

- **Criteria selection and structure**

Nine criteria (C1–C9) were defined and structured into three dimensions (D1–D3). Their formulation was grounded in the outputs of the LCA, LCC, and S-LCA analyses (Section 2.2), complemented by relevant literature and expert consultation. To ensure internal consistency with the updated sensitivity analyses, the criteria set remained fixed across all scenarios, while variations were introduced exclusively through the weighting structure. To maintain methodological consistency, the criteria were aligned with a consolidated LCA, LCC and S-LCA frameworks. This continuity ensures that all criteria share a common scope and functional unity, strengthening the comparability and internal consistency of the assessment.

Economic perspective (C1–C3): Construction cost (C1), maintenance cost (C2), and EoL (C3) were quantified through LCC, following the same cost structures and regional adjustments applied in Luque Castillo and Yepes (2025).

Environmental perspective: (C4–C6): Ecosystem quality (C4, Pt), human health (C5, DALYs), and resource scarcity (C6, USD) were calculated using the ReCiPe endpoints and normalized with World ReCiPe H/H. The selection of these indicators was also consistent with the previous study (Luque Castillo & Yepes, 2025).

Social perspective (C7–C9): Following recent applications in the literature (Erauskin-Tolosa et al., 2021; Navarro et al., 2024), the method covers four stakeholder groups—Workers, Local Community, Society, and Value Chain Actors—from which the original 55 indicators were aggregated to three criteria:

C7: Workers and Local Community (Medium Risk Hours, MRH), addressing labor conditions, occupational safety, and local employment.

C8: Society and Value Chain Actors (MRH), assessing equity, social inclusion, and responsible supply chain practices.

C9: Functionality (qualitative), capturing constructability, execution time, and skilled labor requirements. Execution time scale was informed by published data and field observations (Correia Lopes et al., 2018; Martins et al., 2023; Pawar et al., 2022; Tavares et al., 2021). Skilled labor was evaluated through an AHP-based approach (Luque Castillo & Yepes, 2025). This criterion was included to ensure that technical and operational attributes—often underrepresented in S-LCA—were explicitly reflected in the decision-making process.

These criteria provide a comprehensive basis for comparing alternatives within the sustainability framework.

- **Weighting and interrelationship análisis**

The MCDM analysis was structured sequentially to ensure a coherent and transparent evaluation of the construction alternatives. First, the Best–Worst Method (BWM) was used to obtain consistent criteria weights through a reduced number of pairwise comparisons, offering high reliability and low cognitive burden (Rezaei, 2015, 2016). These initial weights were subsequently refined using a competence-based Power Voting scheme, which adjusts individual influence according to expert expertise and judgment consistency, thereby reducing aggregation bias in group decision-making contexts (Chen & Li, 2010; Sánchez-Garrido et al., 2022).

Next, fuzzy DEMATEL was applied to identify causal and dependent relationships among the criteria. DEMATEL is well established for modeling structural interdependencies (Gabus & Fontela, 1972; Li, 1999), and its fuzzy extension enables a more accurate representation of uncertainty in expert inputs—particularly relevant in sustainability assessments (Govindan et al., 2022; Tseng et al., 2013). This step contextualizes the BWM-derived weights by situating them within a broader causal structure.

Finally, the MARCOS method was employed to integrate the weighted performance scores and derive the final sustainability ranking. MARCOS benchmarks alternatives against both ideal and anti-ideal reference points, offering high discrimination and stability under different weighting schemes (Birkocak et al., 2023; Puška et al., 2020).

Overall, the sequential integration of BWM, Power Voting, fuzzy DEMATEL, and MARCOS yields a methodologically robust and interpretably coherent MCDM framework. BWM provides reliable weights, fuzzy DEMATEL reveals the causal architecture among criteria, and MARCOS synthesizes these inputs into a transparent and stable ranking—an approach aligned with contemporary recommendations for integrated MCDM applications (Sánchez-Garrido et al., 2024). A summary of the methods is provided in Table 3, and full mathematical derivations are available in Supplementary Material S4.

Consistency checks

Three consistency procedures ensured robustness before sensitivity analysis:

±15% perturbation of criteria weights: Nineteen scenarios evaluated the impact of weight variation. In 18 scenarios, each criterion was individually increased or decreased by ±15%, with the remaining weights proportionally adjusted to maintain normalization; the nineteenth applied equal weights. This procedure identifies criteria with the strongest leverage and reveals possible ranking instabilities (Mulliner

Table 3
Summary of the MCDM methods used in the study.

Method	Type	Main Purpose	Key Features	References
BWM	Weighting	Derive criteria weights from limited pairwise comparisons	High consistency; low cognitive demand; reliable weight estimates	Rezaei (2015, 2016)
Power Voting (Competence-Based Aggregation)	Weighting	Aggregate expert judgments considering expertise and consistency	Adjusts influence based on competence; reduces aggregation bias	Sánchez-Garrido et al. (2022,)
Fuzzy DEMATEL	Weighting / Interdependency	Identify causal and dependent relationships among criteria under uncertainty	Influence matrices; cause–effect diagrams; fuzzy modeling of expert uncertainty	Gabus & Fontela (1972); Li (1999); Govindan et al. (2022)
MARCOS	Ranking	Rank alternatives using ideal, anti-ideal, and actual performance	High discrimination; stable under different weights; robust reference-based evaluation	Stević et al. (2020)

et al., 2016; Pombo et al., 2016).

±15% variation of causal-effect intensities in fuzzy DEMATEL: A structural stress test was performed using the causal map (Ebrahimi, 2023). Three scenarios were assessed: (i) –15% reduction in causal criteria, (ii) +15% increase in effect criteria, and (iii) combined –15%/+15%. These perturbations emulate strategic shifts and test the resilience of rankings under structural modifications in the influence network (Deveci et al., 2021).

Multi-method verification: Additional MCDM techniques were applied to further validate the stability of the MARCOS results. TOPSIS evaluates alternatives through their distance to ideal and anti-ideal solutions (Hwang & Yoon, 1981), WASPAS combines additive and multiplicative aggregation (Zavadskas et al., 2012), and MABAC and MAIRCA rely on linear normalization—contrasting with the additive normalization used in MARCOS and WASPAS.

3. Results

3.1. Life cycle costing (LCC) results

The economic evaluation followed the framework of Luque Castillo and Yepes (2025), considering construction, use, and EoL phases. Results were expressed per square meter and adjusted to November 2024 prices.

The outcomes, summarized in Table 4, indicate that the construction phase dominated total costs for all systems, as reported in previous residential LCC studies (Tighnavard Balasbaneh et al., 2022). LBSPS registered the highest construction cost, approximately 20% above the baseline RCF-M system, while LSF achieved a 15% reduction, confirming its advantage in upfront investment.

In the use phase, RCW and RCF-CP incurred the highest costs, averaging 77% above RCF-M, primarily due to the need for recurrent preventive treatments. By contrast, LSF recorded the lowest use expenditures, 42% below the reference, benefiting from its reduced demand for surface treatments. The EoL phase also revealed marked differences: RCW and RCF-CP had elevated demolition costs due to waste volume and complexity, while RCF-M remained the most expensive overall, driven by the low recyclability of clay bricks (Coelho & De Brito, 2011). LSF achieved the most favorable outcome, with EoL costs 77% lower than RCF-M.

Overall, the results stress the relevance of evaluating life cycle costs beyond initial investments. While heavy systems such as LBSPS and RCF-based typologies impose high upfront and downstream burdens, lightweight systems like LSF emerge as the most cost-effective strategy across the full life cycle. These insights are particularly valuable for designing and promoting sustainable and affordable social housing.

3.2. Life cycle assessment (LCA) results

Environmental performance was evaluated using the ReCiPe endpoint method (Luque Castillo & Yepes, 2025), which aggregates midpoint categories into three damage dimensions: Human Health, Ecosystems, and Resources. This approach enables a more policy-relevant interpretation of the environmental burdens.

The results in Table 5 show that the manufacturing phase constitutes the highest contribution across all systems and impact categories, primarily due to intensive energy consumption, pollutant emissions, and raw material extraction, consistent with prior building-sector studies (Negrin et al., 2025).

Among the alternatives, LBSPS exhibits the highest overall impact (71.74 Pt), mainly driven by resource depletion, followed by RCF-M and RCF-CP. RCW records a slightly lower burden, while LSF achieves the lowest total impact. These differences highlight the significant role of structural typology and material composition in shaping environmental performance.

Specifically, RCF-based systems (masonry and concrete panels) exhibit higher burdens due to the embodied impacts of concrete and clay bricks, widely recognized materials for their energy- and resource-intensive production (Joglekar et al., 2018; Vitorio Junior et al., 2022). By contrast, LSF demonstrates a more favorable profile across all three damage dimensions, particularly regarding resource use and human health, reflecting its lower material intensity and efficient use of steel. This finding aligns with prior comparative LCA studies on lightweight construction systems (Aghazadeh et al., 2022; Martins et al., 2019).

Table 5
LCA results of construction systems (endpoint level).

Criteria		RCF - M	RCW	LSF	RCF - CP	LBSPS
C4	**Ecosystem quality (Points)**	3.30	2.44	3.18	2.52	2.82
C5	**Human health (Points)**	15.36	13.40	10.81	14.12	16.99
C6	**Resources (Points)**	41.54	36.26	30.18	38.17	51.92
	Total impact (Points)	60.20	52.10	44.18	54.80	71.74

Table 4
LCC results of construction systems (USD/m²).

Criteria		RCF - M	RCW	LSF	RCF - CP	LBSPS
C1	**Construction Cost (USD)**	15,196.86	14,300.79	12,904.25	15,039.53	18,347.01
C2	**Use Cost (USD)**	3968.36	6989.78	2307.40	7048.77	4360.33
C3	**EoL Cost (USD)**	4581.73	3096.34	1060.65	3026.71	1705.32
	Total impact (USD)	23,746.95	24,386.91	16,272.31	25,115.01	24,412.67

3.3. Social life cycle assessment (S-LCA) results

The social dimension was assessed through Workers + Local Community (C7), Society + Value Chain actors (C8), and Functionality (C9) (Table 6). Indicators for C7 and C8 represent MRH, aligned with UNEP/SETAC guidelines (Sonnemann & Valdivia, 2014). The functionality criterion (C9) integrates two dimensions: the execution schedule, derived from literature and expert judgment, and the need for skilled labor, weighted through the AHP method.

As shown in Fig. 2, lower values consistently indicate better social performance, as they reflect reduced exposure to medium-risk hours (C7, C8) and fewer functional challenges (C9). RCF-M achieved the best results across the three indicators, followed by RCW and RCF-CP.

By contrast, the LSF alternative registers the highest impact across all three social criteria, reflecting greater exposure of workers and local communities and higher functional demands, as previously noted by Sierra et al. (2017) and Wang et al. (2023), who observed that higher modularization can increase labor complexity. LBSPS showed moderate MRH values but the highest functionality impact, indicating increased execution complexity, in line with Liu et al. (2022). Overall, the findings indicate that traditional reinforced concrete-based alternatives (RCF-M, RCW, RCF-CP) tend to be socially less demanding, particularly regarding worker/community exposure and execution feasibility. In contrast, more industrialized systems such as LSF and LBSPS appear to transfer part of the burden toward functional challenges and skilled labor needs, as previously highlighted in Kwon et al. (2025).

These indicators were normalized and integrated into the decision-making framework to ensure balanced consideration of social, environmental, and economic dimensions.

3.4. BWM group weights

Five experts in civil engineering and architecture were selected to ensure reliable group judgments (Clemen & Winkler, 1985). Their 10–35 years of experience in structural engineering, construction, and sustainability provided the multidisciplinary perspective required for this assessment. As summarized in Table 7, the group-weighting procedure not only characterizes expert profiles but also determines their relative influence in the aggregation process. Experts with stronger specialization and more consistent BWM judgments received higher influence, enhancing aggregation coherence and minimizing bias (Vidal et al. (2024).

The individual BWM weights for each criterion were first obtained independently for the five decision-makers. These were then integrated using the group-weighting (Table 6), ensuring that expert influence corresponded to their credibility and domain specialization. Table 8 reports the final aggregated weights, while the complete BWM matrices and consistency ratios for all experts are presented in Tables S10–S11 of Supplementary Material 5.

Construction Cost (C1) emerged as the most influential criterion (22.16%), underscoring the central role of economic feasibility in housing sustainability assessments. Conversely, EoL Cost (C3) received the lowest weight (5.37%), indicating that long-term disposal and recyclability—though acknowledged—remain secondary considerations. This contrast illustrates how short- and medium-term financial constraints still outweigh circularity-oriented concerns.

Social aspects accounted for nearly 40% of the total weight, surpassing both economic and environmental dimensions. Within this block, the highest importance was assigned to Local Community and Workers (C7: 13.49%), followed by Functionality (C9: 12.80%) and Society + Value Chain (C8: 12.64%). These results show that stakeholders prioritize occupational safety, labor conditions, and community-level impacts, reflecting an understanding that construction systems affect both material performance and human well-being. The weight of functionality highlights concerns about usability, adaptability, and long-term suitability of housing solutions (Golubchikov & Badyina, 2012). Overall, this distribution evidences a shift in priorities where social sustainability becomes a structural component rather than a secondary consideration (Dong & Ng, 2016). The prominence of social criteria aligns with the causal patterns later identified through fuzzy DEMATEL, where several social attributes act as influential drivers rather than passive outcomes. These weighting results also foreshadow the causal maps, in which environmental criteria appear mainly as effect attributes shaped by economic and social factors. Thus, the BWM prioritization provides the analytical basis for examining causality and interdependencies among the sustainability attributes.

Table 6
S-LCA results of construction systems.

Criteria		RCF - M	RCW	LSF	RCF - CP	LBSPS
C7	**Workers + Local Community (MRH x 10^4)**	135.66	139.58	167.20	145.92	144.21
C8	**Society + Value Chain actors (MRH x 10^4)**	91.35	93.05	111.01	97.11	96.13
C9	**Functionality (Scale)**	0.194	0.167	0.223	0.175	0.240

3.5. Cause-effect relationships among criteria (Fuzzy DEMATEL)

Fuzzy DEMATEL was applied to identify interdependencies among the criteria and distinguish those that operate as causal drivers from those that behave as dependent effects. Elements exceeding the threshold value (0.161) are highlighted in Table 9. Based on this matrix, network relationship maps (NRMs) were developed to visualize the causal structure within each sustainability dimension. The direction of the arrows in the NRMs indicates the influence exerted by causal criteria on the corresponding effect criteria. Fig. 3a–c illustrates these relationships for the economic, environmental, and social dimensions.

As shown in Fig. 3, the NRMs provide a visual representation of the causal structure identified through the Fuzzy DEMATEL analysis. In the economic dimension (Fig. 3a), Construction Cost (C1) acts as the primary causal driver, exerting direct influence on Maintenance Cost (C2) and EoL Cost (C3), confirming its dominant role in shaping downstream cost-related impacts. In the environmental dimension (Fig. 3b), Resources (C6) shows a causal influence on Ecosystems (C4) and Human Health (C5), illustrating that resource management decisions are central to the environmental performance of construction systems. Finally, in the social dimension (Fig. 3c), Functionality (C9) and Society and Value Chain Actors (C8) emerge as key causal criteria, driving Local Community and Workers (C7). This pattern suggests that socially desirable outcomes depend on effective coordination across the value chain and adequate functional design. Altogether, these results establish the directional hierarchy of cause–effect relationships across dimensions.

Fig. 4 integrates Tables 9 and 10, providing an overall visualization of the interdependencies among the nine sustainability criteria derived from the Fuzzy DEMATEL analysis. This map combines the total relationship matrix (Table 9) with the causal strength indicators (D–R) and prominence values (D+R) reported in Table 10, allowing a comprehensive interpretation of the system's structure.

Construction Cost (C1) emerged as the main causal driver, exerting a strong influence on the entire system. Within the social dimension, Society and Value Chain Actors (C8) and Functionality (C9) also acted as causal factors, indicating that stakeholder coordination and design adequacy tend to propagate their effects across dimensions. Conversely, Local Community and Workers (C7) behaved as a dependent criterion, showing that labor well-being and community conditions are strongly influenced by economic and resource-related decisions. Despite its dependent role, C7 ranked second in overall importance, highlighting its relevance for housing sustainability. Similarly, Human Health (C5) was identified as a dependent factor with a low aggregated weight,

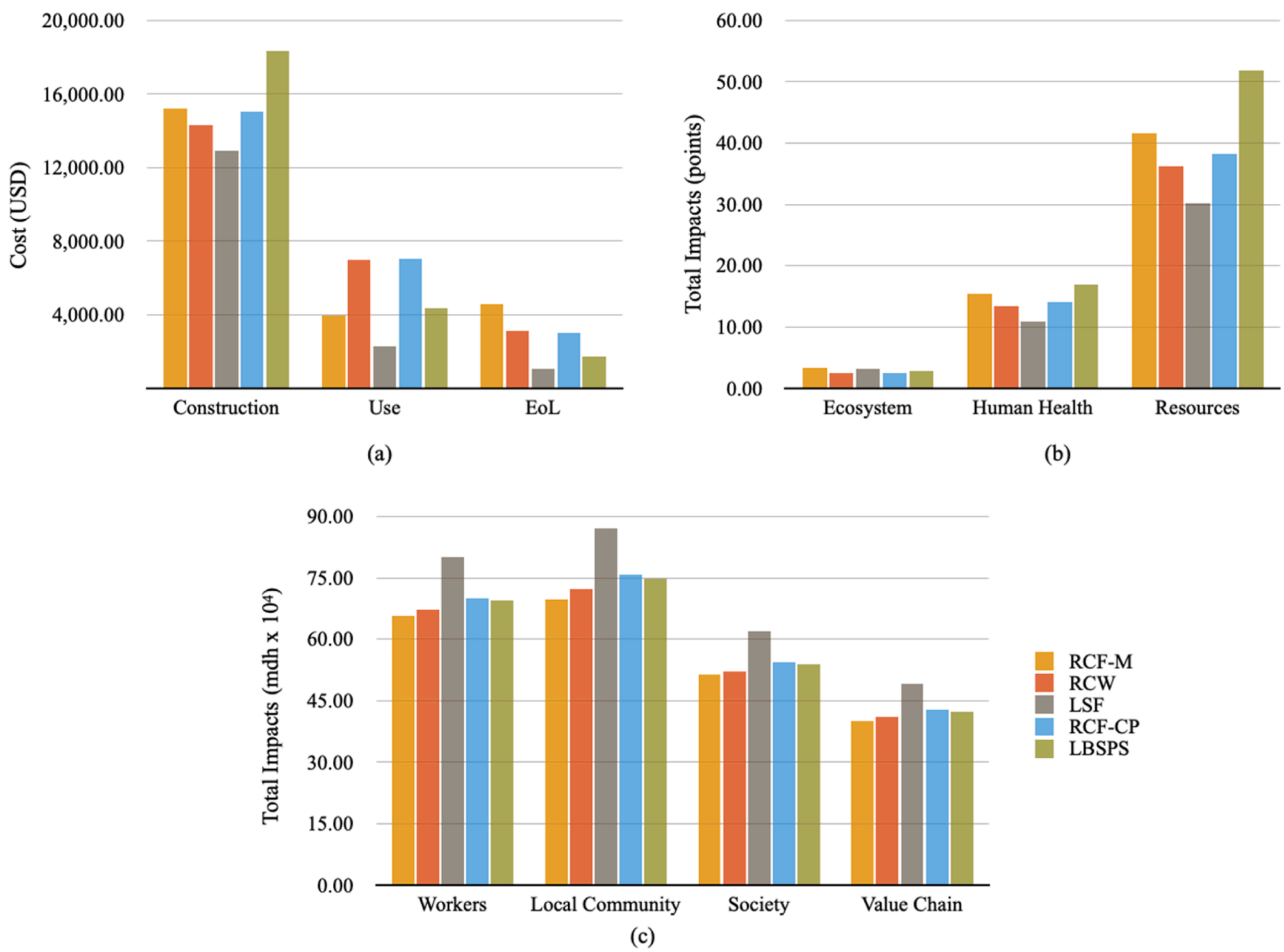

Fig. 2. Outcomes of the life cycle analyses. (a) LCC. (b) LCA. (c) S-LCA.

Table 7
Relevance of BWM group experts.

Definition of the experts' profile	Parameter	D1	D2	D3	D4	D5
Expertise						
Years of professional experience	PAk	21	10	20	35	10
Years of specialization of the expert	SEk	4	8	3	18	3
Research						
Lead author JCR	LAk	1	4	3	15	2
Conference papers	CPk	3	2	2	77	1
Specific knowledge						
Construction Engineering	Kc1	5	5	4	5	4
Structural design	Kc2	4	4	4	4	2
Budgeting	Kc3	2	3	3	3	3
Enviromental assessment	Kc4	3	3	3	3	1
Social assessment	Kc5	4	4	2	4	1
Expert's inconsistency (BWM)	ε_k	0.391	0.347	0.553	0.507	0.390
Expert's credibility	δ_k	0.525	0.558	0.480	0.856	0.324
Expert's voting influence	φ_k	0.338	0.364	0.267	0.488	0.276

suggesting that improvements in this area depend on systemic drivers such as cost management, resource efficiency, and functional performance rather than isolated interventions.

Table 8
Criteria weights derived from BWM combined with Power Voting.

Criteria	DM1	DM2	DM3	DM4	DM5	BWM - G
C1	0.066	0.095	0.053	0.112	0.059	22.16%
C2	0.029	0.038	0.018	0.031	0.016	7.59%
C3	0.015	0.028	0.007	0.031	0.012	5.37%
Subtotal Economic Dimension D1						**35.12%**
C4	0.044	0.019	0.035	0.024	0.016	7.95%
C5	0.044	0.023	0.035	0.031	0.027	9.19%
C6	0.022	0.028	0.032	0.031	0.040	8.82%
Subtotal Environmental Dimension D2						**25.95%**
C7	0.044	0.038	0.035	0.077	0.040	13.49%
C8	0.029	0.038	0.035	0.077	0.040	12.64%
C9	0.044	0.057	0.018	0.077	0.027	12.80%
Subtotal Social Dimension D3						**38.93%**

The inclusion of integrated weights provides a more comprehensive perspective. As shown in Table 9, three sets of values were considered: (i) baseline weights (w) obtained following the methodology of Vidal et al. (2024); (ii) weights derived from the BWM combined with the power voting approach; and (iii) aggregated weights, calculated as the synthesis of both. This integration enhances robustness by combining the relative importance suggested by the literature with the judgments of domain experts. The aggregated ranking (Table 9) therefore underscores a dual emphasis: while economic feasibility (C1) continues to dominate, social aspects (C7–C9) occupy leading positions, evidencing that decision-makers recognize the long-term importance of labor conditions, supply chain interactions, and functionality in shaping the sustainability of construction alternatives.

Table 9
Total relationship matrix for criteria.

	C1	C2	C3	C4	C5	C6	C7	C8	C9
Construction Cost – C1	**0.234**	**0.351**	**0.225**	**0.216**	**0.220**	**0.357**	**0.335**	**0.291**	**0.217**
Maintenance Cost – C2	0.128	0.084	0.127	0.101	0.094	0.136	**0.190**	0.156	0.115
EoL Cost – C3	0.081	0.061	0.040	0.043	0.061	0.089	0.132	0.125	0.037
Ecosystems – C4	0.130	0.083	0.068	0.053	**0.283**	**0.214**	0.138	0.122	0.049
Human health – C5	0.057	0.044	0.038	0.032	0.032	0.046	0.087	0.082	0.029
Resources – C6	**0.253**	**0.181**	0.139	**0.164**	**0.311**	0.134	**0.218**	**0.234**	0.080
Local Community and workers – C7	**0.308**	**0.207**	0.160	0.123	**0.208**	**0.225**	0.152	**0.228**	0.099
Society and Value Chain Actors – C8	**0.349**	**0.252**	**0.200**	0.137	**0.201**	**0.248**	**0.316**	0.156	0.123
Functionality – C9	**0.410**	**0.288**	**0.208**	0.133	0.125	**0.193**	**0.187**	**0.167**	0.093

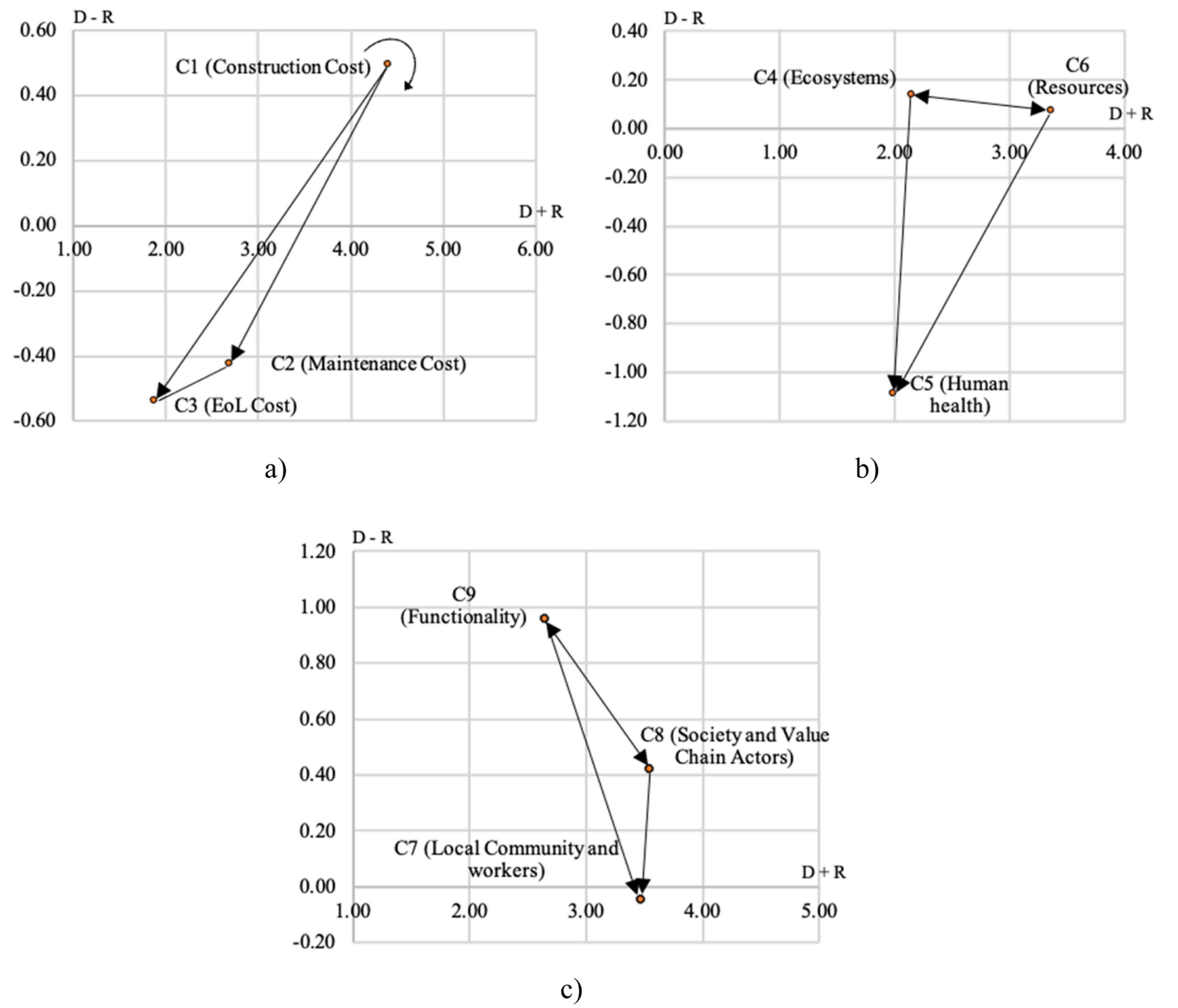

Fig. 3. NRM derived from the Fuzzy DEMATEL analysis: a) Economic, b) Environmental, c) Social dimensions.

3.6. *Sustainability ranking of construction systems (MARCOS)*

Table 11 presents the decision matrix with the criteria and indicators grouped into the economic, environmental, and social dimensions. The normalization of heterogeneous data ensured comparability across construction systems, allowing for an integrated application of the MARCOS method. Intermediate MARCOS calculations are presented in Table S12 (Supplementary Material 6).

The aggregated scores (Table 12) positioned the LSF system as the most sustainable alternative, followed by RCW and RCF-M. Conversely, RCF-CP and LBSPS occupied the last two positions. This outcome reflects the capacity of lightweight and industrialized approaches to balance cost, resource efficiency, and functional performance more effectively than conventional masonry-based systems.

However, social results add nuance. LSF and LBSPS scored highest in functionality (C9) but showed greater social exposure (C7, C8). Masonry-based systems performed more moderately in functionality yet exhibited lower social exposure. Fig. 5 illustrates these trade-offs,

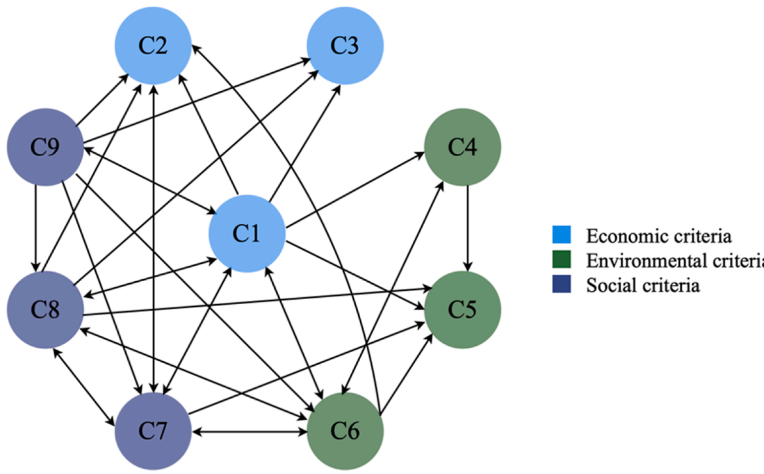

Fig. 4. Overall network relationship map.

Table 10
Direct effect, indirect effect, weights and ranking of criteria.

Criteria	D	R	D+R	D-R	Attribute	w	BWM - G	Aggregated Weigth	Ranking
C1	2.446	1.950	4.395	0.496	Cause	0.166	0.222	0.302	1
C2	1.129	1.551	2.681	-0.422	Effect	0.102	0.076	0.063	7
C3	0.669	1.205	1.874	-0.536	Effect	0.073	0.054	0.032	9
C4	1.141	1.001	2.142	0.140	Cause	0.080	0.079	0.053	8
C5	0.447	1.536	1.983	-1.088	Effect	0.085	0.092	0.064	6
C6	1.713	1.643	3.356	0.071	Cause	0.126	0.088	0.091	5
C7	1.711	1.756	3.468	-0.045	Effect	0.130	0.135	0.144	2
C8	1.983	1.560	3.544	0.423	Cause	0.134	0.126	0.139	3
C9	1.803	0.842	2.645	0.961	Cause	0.105	0.128	0.111	4

Table 11
Decision matrix.

Criteria	Unit	RCF - M	RCW	LSF	RCF - CP	LBSPS
C1	USD/m^2	15,196.86	14,300.79	12,904.25	15,039.53	18,347.01
C2	USD/m^2	3,968.36	6,989.78	2,307.40	7,048.77	4,360.33
C3	USD/m^2	4,581.73	3,096.34	1,060.65	3,026.71	1,705.32
C4	Points	3.30	2.44	3.18	2.52	2.82
C5	Points	15.36	13.40	10.81	14.12	16.99
C6	Points	41.54	36.26	30.18	38.17	51.92
C7	MRH x10^4	135.66	139.58	167.20	145.92	144.21
C8	MRH x10^4	91.35	93.05	111.01	97.11	96.13
C9	Scale	0.194	0.167	0.223	0.175	0.240

Table 12
Ranking of the alternatives.

Alternative	Ranking
RCF - M	3
RCW	2
LSF	1
RCF - CP	4
LBSPS	5

emphasizing that sustainability requires balancing economic efficiency with long-term social and environmental commitments.

3.7. Consistency checks

The internal consistency checks confirmed that the decision framework is highly robust. The first set of tests perturbed all criteria weights by ±15% across nineteen scenarios (Fig. 6a). Even under equal weighting, only one minor shift was observed—an exchange between RCF-M and LBSPS in the lower ranks—indicating that the hierarchy is resilient to moderate uncertainty in expert judgments. Across the remaining scenarios, no changes were detected in the ordering of alternatives, and variations in normalized performance scores remained within narrow margins.

A second group of consistency checks examined the causal–effect structure obtained through fuzzy DEMATEL (Fig. 6b). Three scenarios were evaluated: (i) −15% applied to causal criteria, (ii) +15% applied to effect criteria, and (iii) a combined perturbation. In all cases the MARCOS rankings were preserved, and the driver–receiver configuration remained stable, with only marginal variations in centrality scores. This confirms the framework's capacity to withstand systematic changes in the balance between driving and dependent criteria—a dimension rarely addressed but essential for assessing the resilience of MCDM models (Backes & Traverso, 2021; Ho et al., 2010).

The third verification consisted of a multi-method cross-check using WASPAS, MAIRCA, MABAC, and TOPSIS (Table 13). Although minor variations appeared among intermediate positions, the overall ranking structure remained strongly consistent. All methods placed LBSPS last

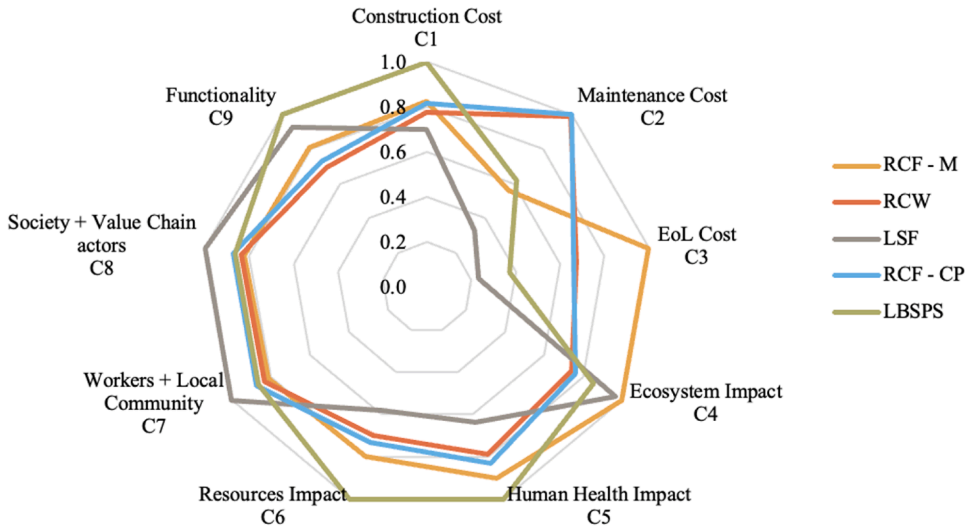

Fig. 5. Comparison of criteria between alternatives.

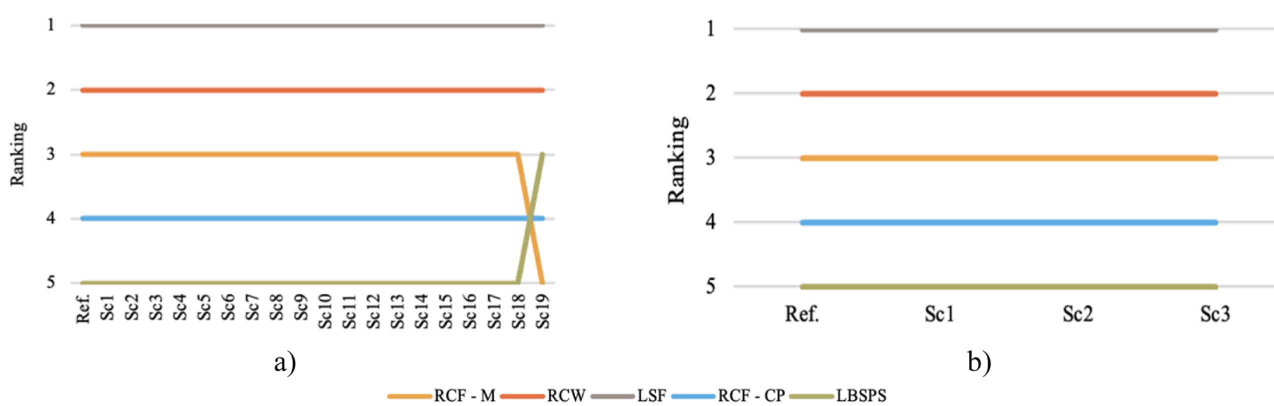

Fig. 6. Sensitivity analysis: a) Weight change. b) Perturbation of causal-effect weights.

Table 13
Comparison of the ranking orders.

Alternative	MARCOS	WASPAS	MAIRCA	MABAC	TOPSIS
RCF - M	3	3	4	4	3
RCW	2	2	1	1	2
LSF	1	1	2	2	1
RCF - CP	4	4	3	3	4
LBSPS	5	5	5	5	5

and positioned LSF, RCW, and RCF-M within the top tier in closely aligned orders. LSF ranked first in MARCOS, WASPAS, and TOPSIS, while MAIRCA and MABAC placed it second—still within the leading group. Likewise, RCW consistently appeared among the top two positions and ranked first in MAIRCA and MABAC. These convergent patterns, despite differing aggregation principles, indicate that the prioritisation is not method-dependent and reduce concerns about algorithmic bias (Zavadskas et al., 2018). Prior studies similarly show that hybrid methods such as MARCOS and WASPAS offer strong discriminatory capacity in construction decision-making (Nabavi et al., 2023).

3.8. Sensitivity analysis

- **Scenario analysis of Transport Distances (A and B)**

Two alternative transport-distance scenarios were evaluated (details in Supplementary Material 2). As noted in previous LCA studies, transport modelling can meaningfully affect life-cycle outcomes depending on supply-chain configuration (Blengini & Garbarino, 2010). Scenario A represents the district of Chancay (Lima)—a rapidly expanding coastal logistics hub where construction activity has intensified due to the new deep-water port. Scenario B corresponds to Cerro Colorado (Arequipa), a high-growth district shaped by accelerated residential expansion and increasing material demand. Both scenarios were selected because, like Carabayllo (baseline), they represent peri-urban expansion zones with active low-income housing development, making the three locations operationally comparable in terms of supply-chain structure and construction market dynamics.

Across both scenarios, transport distances for all construction materials were recalibrated to reflect realistic geographic conditions. As expected, changes in total endpoint impacts were moderate, given the dominant contribution of manufacturing processes —a trend consistent with envelope-focused residential LCAs in which production stages typically dominate impacts (Soust-Verdaguer et al., 2018). However, sensitivity was heterogeneous across alternatives. Prefabricated systems—especially LBSPS—showed the largest percentage variations, consistent with their reliance on industrialised components and longer logistical chains, while monolithic and in-situ concrete systems exhibited minimal changes.

The detailed percentage variations for each sustainability domain are presented in Table 14 (Scenario A) and Table 15 (Scenario B). Despite these fluctuations, the overall sustainability hierarchy remained unchanged. As shown in Table 16, LSF preserved the highest performance under the baseline and both transport scenarios, followed by RCW and the two reinforced-concrete systems, with LBSPS consistently ranking last. This convergence confirms that the MARCOS-based sustainability ranking is robust even under substantial perturbations in transport-related assumptions. Full scenario-specific LCA outputs are provided in TS5 – TS7 (Supplementary Material S2).

- **Stratified Best–Worst Method (S-BWM)**

The S-BWM builds upon the stratified multi-criteria decision-making framework originally proposed by Asadabadi (2018) and its formal extension to the Best–Worst Method introduced by Torkayesh et al. (2021). This approach allows expert heterogeneity to be explicitly accounted for by segmenting decision-makers into homogeneous groups prior to aggregation, thereby reducing aggregation bias and improving the interpretability of group decision outcomes. Recent applications further confirm that disaggregating expert groups before re-aggregation enhances the robustness and stability of sustainability-oriented MCDM results Asadabadi et al. (2023).

Within the S-BWM framework, the event corresponds to the elicitation of criteria weights under heterogeneous expert judgment, while the states are represented by distinct expert strata. The relative influence of each state is reflected through the aggregation scheme, rather than through explicit probabilistic assignment.

To examine the influence of expert heterogeneity in this study, the expert panel was divided into two groups based on professional experience:

- Senior experts (>15 years): D1, D3, D4

Tabla 14
Percentage variation under Scenario A.

Alternative	Δ Ecosystems (%)	Δ Human Health (%)	Δ Resources (%)
RCF-M	-2.05	4.95	-5.47
RCW	14.30	2.32	0.22
LSF	8.08	-12.77	1.41
RCF-CP	3.64	-5.71	-2.71
LBSPS	-11.40	-9.04	-4.22
Average	**2.52**	**-4.05**	**-2.15**

Tabla 15
Percentage variation under Scenario B.

Alternative	Δ Ecosystems (%)	Δ Human Health (%)	Δ Resources (%)
RCF-M	9.48	-1.75	-5.80
RCW	20.04	1.68	-3.62
LSF	7.46	-3.78	0.98
RCF-CP	-2.71	-3.82	0.96
LBSPS	-17.32	-5.86	-2.43
Average	**3.39**	**-2.70**	**-1.98**

- Junior experts (≤15 years): D2, D5

Each stratum produced its own BWM weight vector, which was subsequently aggregated using Power Voting following the same procedure as in the baseline model.

S-BWM revealed systematic differences in priorities: senior experts assigned higher weight to environmental and human-health dimensions, whereas junior experts emphasised construction cost and functional performance. Despite these shifts, the MARCOS rankings generated with each stratum-specific weight set remained identical (Table 17). In all cases, LSF was consistently the top-ranked alternative, followed by RCW and the two reinforced-concrete systems, with LBSPS invariably in last place. This alignment demonstrates that the sustainability hierarchy is robust to plausible variations in expert composition and weighting behaviour. S-BWM comparative weight sets are provided in Supplementary Material S7.

Overall, the two sensitivity analyses collectively demonstrate a high degree of robustness in the sustainability ranking. Despite variations in the life cycle scenarios, the hierarchy of alternatives—led consistently by LSF—remained largely unchanged. This stability is particularly relevant for social housing decision-making, where stakeholders frequently operate under uncertainty regarding the relative importance of economic, environmental, and social criteria. A framework capable of preserving the same ranking under diverse weighting perspectives reduces the risk of misaligned or volatile decisions during participatory or policy-driven processes. Accordingly, the results provide decision-makers with a reliable and resilient basis for prioritizing construction systems, even when preference structures or contextual priorities fluctuate. These findings underscore the relevance of integrative sustainability assessment frameworks, echoing trends identified in recent studies (Akintayo et al., 2024; W. Li et al., 2023; Seddiki & Bennadji, 2025).

4. Discussion of results

Integrating Life Cycle methods (LCA, LCC, and S-LCA) with advanced multi-criteria techniques (BWM, fuzzy DEMATEL, and MARCOS) enabled a comprehensive evaluation of the five construction alternatives. As highlighted in previous sustainability assessments by Kim (2025), such hybrid frameworks are essential to capture the complexity of construction decision-making and the trade-offs inherent to sustainability evaluation. Similar interdependencies were also identified by Safarzadeh & Jafari (2025), who noted that MCDM approaches enhance the understanding of cause–effect dynamics within environmental systems, further reinforcing the methodological validity of this approach. This methodological design clarified the interdependencies among criteria and ensured a robust sustainability ranking. Moreover, the consistency of the outcomes was reinforced through cross-method validation using WASPAS, TOPSIS, MAIRCA, and MABAC, which provided further confidence in the reliability of the results (Govindan et al., 2015).

The fuzzy DEMATEL results underscore the decisive role of causal criteria in shaping sustainability outcomes. Construction cost (C1) emerged as the most influential driver, exhibiting both high prominence and a positive causal relation, consistent with studies identifying

Table 16
Comparison of the ranking orders.

Alternative	MARCOS (baseline)	Rank (baseline)	Scenario A	Rank A	Scenario B	Rank B
RCF-M	0.657	3	0.66	3	0.66	3
RCW	0.672	2	0.66	2	0.67	2
LSF	0.712	1	0.71	1	0.71	1
RCF-CP	0.644	4	0.64	4	0.64	4
LBSPS	0.611	5	0.62	5	0.62	5

Table 17
Comparison of the ranking orders.

Alternative	MARCOS (baseline)	Rank (baseline)	MARCOS-S (Senior)	Rank-S (Senior)	MARCOS-J (Junior)	Rank-J (Junior)
RCF-M	0.657	3	0.836	3	0.83	3
RCW	0.672	2	0.86	2	0.848	2
LSF	0.712	1	0.912	1	0.918	1
RCF-CP	0.644	4	0.827	4	0.816	4
LBSPS	0.611	5	0.785	5	0.777	5

economic feasibility as a central determinant in housing projects (Dara et al., 2019). In social housing, where affordability constraints are pronounced, cost considerations naturally act as the primary trigger for evaluating alternatives (Tam, 2011).

Beyond the economic dimension, social criteria such as Functionality (C9) and Society and Value Chain actors (C8) also exhibited causal behavior, exerting substantial influence despite their comparatively lower weights. This pattern reflects a growing shift in sustainable construction, where labor conditions, feasibility, and community well-being are increasingly recognized as structural drivers (Karatas & El-Rayes, 2014; Mármol et al., 2023; Valdes-Vasquez & Klotz, 2012). Functionality—understood through execution time, skilled labor needs, and adaptability—operates not only as a technical parameter but also as a determinant of downstream economic and social outcomes (Lizana et al., 2016; Zhong & Wu, 2015). Delays or excessive reliance on specialized labor, for instance, affect affordability and long-term community acceptance.

Interestingly, environmental indicators such as Human Health (C5) and Ecosystems (C4) were classified as effect criteria. Although they reflect the long-term ecological consequences of material and design choices, their influence appears to be largely conditioned by economic and social drivers, rather than exerting a direct causal role in the decision system (Luthin et al., 2021). This hierarchical interaction, clearly depicted in the NRMs (Figs. 3 and 4), visually confirms that sustainability performance emerges from a cascade of cause–effect links, where economic and social levers trigger downstream environmental effects. This asymmetry highlights a persistent challenge in sustainability assessment: while environmental performance remains central to the discourse, in practice it often depends on cost feasibility and implementation-related factors (Zabalza Bribián et al., 2011). Hence, the DEMATEL-based maps reinforce the systemic character of housing sustainability, illustrating that addressing upstream causal drivers (C1, C8, C9) may indirectly improve dependent criteria (C4, C5, C7), suggesting that housing policies should explicitly strengthen these enabling conditions (Kedir & Hall, 2021).

From a methodological perspective, identifying causal criteria through DEMATEL enriches the interpretation of MCDM results by clarifying which indicators act as drivers of decision dynamics (Braga et al., 2021; Mehregan et al., 2014). In this study, construction cost (C1), functionality (C9), and societal impacts (C8) emerged as structural levers that shape the trajectory of sustainability assessments, while other indicators responded to these dynamics (Wu et al., 2024). This finding is consistent with the causal hierarchy visualized in Fig. 4, where the integration of all dimensions highlights the propagation of influence from economic to social and environmental outcomes. This causal structure reinforces the importance of targeting the most influential criteria when designing policies or strategies for sustainable housing, since improvements in these drivers can cascade into broader economic, social, and environmental benefits (Goubran & Cucuzzella, 2019). Enhancing functionality—for example, through efficient design or workforce training—can reduce delays, maintenance needs, and improve social acceptance (Stroebele & Kiessling, 2017).

The radar chart of the normalized decision matrix (Fig. 5) illustrates intrinsic trade-offs across the construction systems. No alternative excels in all dimensions, confirming that sustainability requires balancing competing priorities. LSF showed advantages in environmental dimensions such as resource efficiency (C6) and ecosystem impact (C4), while its construction cost (C1) was less competitive than concrete-based systems. RCW and RCF-M performed strongly in economic indicators but exhibited higher environmental burdens. RCF-CP benefited from relatively low EoL costs (C3), though its performance in functionality (C9) and labor intensity (C7) was weaker. Meanwhile, the LBSPS system displays promising results in functionality and community-related criteria (C7, C8) but falls significantly short in cost indicators, reducing its utility value.

These patterns reflect the multidimensional nature of sustainability, where improvements in one dimension often come at the expense of others (Cabeza et al., 2014). Such trade-offs are consistent with prior research, emphasizing that sustainable construction decision-making requires navigating inherent tensions between environmental, economic, and social pillars (Diaz-Sarachaga et al., 2018; Mardani et al., 2015). Importantly, these findings suggest that policymakers and practitioners in social housing must prioritize criteria according to contextual needs—affordability, environmental protection, or community well-being—rather than expecting a single "best" solution. The integration of LCA, LCC, S-LCA, and MCDM proves valuable in structuring these trade-offs and offering a transparent decision basis.

At the aggregated level, the BWM results adjusted by voting power revealed that social aspects concentrated almost 40% of the total weight, surpassing economic (28%) and environmental (26%) dimensions. This outcome indicates that stakeholders prioritize labor well-being, community impacts, and functionality, reflecting a growing recognition of social sustainability in construction decision-making (Ezeokoli et al., 2023; Hosseini et al., 2020; Sánchez-Garrido et al., 2022).

The MARCOS ranking identified LSF as the most sustainable alternative, driven by reduced material consumption, shorter construction times, and lower labor requirements. Its modularity and adaptability further strengthened functionality (Kamali & Hewage, 2016). This pattern is consistent with the findings of Kufner et al. (2025), who demonstrated that substituting traditional reinforced concrete with textile-reinforced systems significantly decreases embodied impacts while preserving structural integrity. Similar advantages of innovative lightweight construction were also highlighted by Moghayedi et al. (2024), who showed that emerging technologies such as 3D-printed housing can achieve substantial environmental gains and accelerated construction, despite higher initial costs. Collectively, these results align with international studies emphasizing industrialized lightweight systems as effective strategies to enhance resource efficiency and affordability in social housing (Alibazi et al., 2025; Ramadhan et al., 2022). Conversely, reinforced concrete systems (RCW and RCF-M) ranked in intermediate positions: environmentally burdensome but economically robust and feasible in contexts with limited industrial capacity (Tarque & Pancca-Calsin, 2022).

The combined sensitivity analyses further validate the stability and practical relevance of the proposed decision-making framework. The transport-distance scenarios showed that while logistical variations alter the magnitude of environmental and economic impacts, they do not change the relative sustainability hierarchy, indicating that stakeholders would reach consistent decisions even under fluctuating supply-chain conditions. Similarly, the S-BWM analysis—designed to emulate shifts in expert perspectives caused by policy changes, evolving stakeholder priorities, or differences in professional experience—revealed that alternative weighting structures lead to rankings fully aligned with the main model. Despite the differing emphasis placed by Senior and Junior experts on economic, environmental, and social dimensions, LSF consistently emerged as the preferred option. This convergence across scenario-based and preference-based perturbations suggests that the framework is resilient to contextual variability and that its conclusions are not dependent on a particular expert profile. Although contextual factors may vary across developing regions, the mechanisms tested here—supply-chain uncertainty and heterogeneous stakeholder perspectives—are common across such settings, supporting the potential transferability of the results while still allowing local adaptation. Overall, the robustness of the rankings reinforces the applicability of LSF as a sustainable solution for social housing decisions under uncertainty.

By contrast, LBSPS obtained the lowest score. Although prefabricated solutions can provide environmental advantages (Haque et al., 2022), their higher costs, demand for specialized labor, and weak local supply chains limit their overall evaluation (Amede et al., 2025; Li et al., 2022). The integrated results also reveal concrete opportunities to enhance the performance of each structural system throughout the life cycle. Linking the LCA findings with the weighted criteria shows how specific indicators influence each alternative in particular stages. For example, although LSF ranks highest overall, its environmental burden is concentrated in the manufacturing stage due to steel production; thus, improving supplier selection, increasing recycled steel content, or adopting low-emission industrial processes could meaningfully strengthen its profile. In contrast, monolithic reinforced concrete systems show low maintenance needs but high upfront impacts in materials and construction; optimization strategies—such as reducing on-site concrete waste or improving formwork efficiency—become central for enhancing their performance. These differentiated pathways illustrate that the most influential drivers generate system-wide effects, and that improvements depend heavily on technological maturity and local supply-chain constraints. Introducing innovative technologies requires not only technical validation but also supportive institutional frameworks (Ferdous et al., 2022), as otherwise such alternatives risk becoming economically unfeasible (Nadeetharu & Kulatunga, 2022).

By merging life-cycle methods with MCDM, this study captured the multidimensional nature of housing decisions, while causal analysis clarified which criteria exert structural influence on outcomes (Karamoozian et al., 2023). The results indicate that targeting cost efficiency, functionality, and social well-being provides most significant leverage in promoting sustainable construction. At the same time, strengthening institutional and market conditions is essential to enable the diffusion of innovative solutions—such as prefabricated systems—that continue to face structural and cultural barriers in many contexts (Ogunmakinde et al., 2024).

From a policy perspective, the results provide actionable insights for housing programs in developing contexts, echoing evidence that underscores the central role of governance and institutional support in advancing sustainable housing agendas (Galster & Lee, 2021; Wang et al., 2023). Prioritizing industrialized systems like LSF while reinforcing training schemes and local supply chains can increase affordability and sustainability in large-scale housing initiatives (Gao & Tian, 2020; Ziaesaeidi & Noroozinejad Farsangi, 2024). Moreover, focusing on influential drivers such as construction cost and functionality can generate cascading benefits, ensuring that environmental efficiency and community well-being progress together.

Ultimately, this study contributes to bridging the gap between methodological innovation and practical decision-making, a challenge widely acknowledged in sustainability research (Sánchez-Garrido et al., 2022). Consistent with recent works advocating the need for integrated, transparent, and context-sensitive frameworks for evaluating built-environment sustainability (de Paula Salgado et al., 2025; Raut et al., 2025), the integration of BWM, fuzzy DEMATEL, and MARCOS within a life-cycle framework, and its validation through multiple sensitivity analyses—offers a replicable pathway for evaluating construction sustainability (Kaswan & Rathi, 2021). This is particularly relevant for social housing, where aligning economic, social, and environmental objectives remains a pressing challenge (Abdelaal et al., 2024; Escorcia Hernández et al., 2024; Gomide et al., 2024a).

5. Conclusion and limitations

This study compared five structural alternatives for social housing by integrating environmental, economic, technical, and social criteria through a multi-criteria decision-making framework. The results show that the Light Steel Frame (LSF) system consistently achieved the highest ranking across all methods and sensitivity analyses, confirming its balance between sustainability and technical feasibility. The superior performance of LSF reflects a clear trend toward the industrialization of social housing construction, which aligns with recent studies emphasizing the opportunities and challenges of modular and prefabricated systems for resource efficiency, affordability, and adaptability to household needs. Reinforced concrete walls (RCW) obtained the second position, mainly driven by favorable cost and durability performance, while monolithic reinforced concrete (RCF-M) and cast-in-place reinforced concrete (RCF-CP) occupied intermediate positions with slight variations depending on the weighting scenarios. Lightweight bolt-connected concrete sandwich panels (LBSPS) were systematically the least preferred option.

Social aspects collectively accounted for the highest weight (39%) at the dimension level, surpassing economic and environmental dimensions. Within this block, occupational safety, labor conditions, community well-being, and functionality emerged as decisive criteria. These findings underscore that stakeholders perceive housing systems as technical solutions and vehicles for safeguarding workers, strengthening local communities, and ensuring long-term usability for families. In this sense, integrating social sustainability was a key factor that shaped the prioritization of alternatives, adding relevance to a dimension often underrepresented in conventional assessments.

The causal analysis revealed that cost and environmental impacts acted as system drivers. At the same time, social and functional criteria largely appeared as receivers, meaning that improvements in these areas stemmed from strategic decisions in other domains. This structure helps to explain the trade-offs observed between sustainability dimensions. It emphasizes the need to design interventions where leverage is most significant, without losing sight of the social outcomes that ultimately define housing quality and acceptability. These causal patterns also help identify where the main opportunities for enhancing structural alternatives emerge across the life cycle. Because cost and environmental indicators operate as influential drivers, interventions aimed at improving material efficiency, construction times, supply-chain reliability, or workforce training can generate positive ripple effects on social and functional performance. Likewise, systems such as LSF, which already exhibit strong environmental outcomes, may further benefit from targeted material optimization or industrialized assembly processes. However, the extent to which each alternative can improve remains context-dependent, as technological maturity, regulatory support, and market conditions shape the feasibility of these enhancements This contextual dependence explains why improvement trajectories in social housing may diverge from those observed in other building types.

Methodologically, the main contribution of this research lies in integrating the BWM, fuzzy DEMATEL, and MARCOS within a single decision-making framework. This combination offers clear advantages: BWM reduced the cognitive burden on experts while ensuring consistency in weights, fuzzy DEMATEL explicitly captured causal interrelations among criteria, and MARCOS provided transparent and validated rankings that were further cross-checked with alternative MCDM methods. This framework fulfills key conditions of robustness in MCDM—hierarchical clarity, consideration of interdependence, and management of uncertainty—thus strengthening methodological rigor while enhancing its practical usability.

The findings have direct implications for housing policy in developing contexts. No structural system is universally optimal; the most suitable choice depends on the balance of sustainability dimensions established by decision-makers. The framework applied here makes such priorities explicit, showing that structural alternatives can shift in ranking when different weights are assigned. However, the overall robustness of results was confirmed through sensitivity analysis. This reinforces the value of adopting transparent and participatory processes, where stakeholders—including policymakers, housing agencies, and community representatives—can negotiate and calibrate evaluation criteria in line with local objectives. By doing so, the decision-making process ensures methodological rigor and enhances the legitimacy and social acceptance of housing strategies.

Regarding transferability, it is important to note that the results obtained in this study are closely tied to the specific characteristics of the national social housing context—particularly labor skills, supply-chain maturity, cost structures, and technological readiness. Therefore, while the integrated MCDM–life-cycle framework is fully generalizable and can be applied in other developing contexts, the ranking of the alternatives should not be assumed to hold universally. Instead, applying this framework elsewhere would require recalibrating the criteria weights and causal relationships to reflect local priorities and constraints. This distinction clarifies that although the methodological structure is transferable, the hierarchy of alternatives remains inherently context-dependent.

This study has limitations that also open avenues for future research. First, the analysis relied on a limited group of experts, which may restrict the generalizability of the findings; expanding the panel of stakeholders could provide a broader perspective and more robust prioritization of criteria. Second, the evaluation focused on a single national social housing case, meaning that the weighting structures and causal patterns identified here are context-specific and may differ in other building typologies, where stakeholder priorities and technical conditions vary; applying the framework to commercial, educational, or high-rise residential projects would help assess its transferability. Third, the accuracy of environmental and social indicators depended on secondary databases, highlighting the need for primary data collection from real projects to improve reliability. Finally, although fuzzy DEMATEL structured interdependencies, uncertainty inherent in expert-based methods remains; integrating more advanced approaches—such as dynamic LCA or coupling the MCDM framework with BIM platforms—could enhance predictive capacity and support real-time decision-making in sustainable housing design.

CRediT authorship contribution statement

Ximena Luque Castillo: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lorena Yepes-Bellver:** Writing – review & editing, Validation, Supervision, Software, Investigation. **Victor Yepes:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2026.107164.

Data availability

Data will be made available on request.

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