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Life cycle assessment of social housing construction: A multicriteria approach

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ABSTRACT

Social housing construction is crucial in providing cost-effective and sustainable solutions, especially in developing contexts. This study applies Life Cycle Analysis to assess the environmental, economic, and technical impacts of five construction methods: (1) reinforced concrete frames with brick masonry, (2) cast-in-place concrete walls with metal formwork, (3) Light Steel Frame systems with gypsum panels, (4) sandwich panels, and (5) precast concrete walls. Using a comprehensive cradle-to-grave approach, the study evaluates the economic, environmental, and technical performance of each alternative. Five multicriteria decision-making methods were applied, structuring a hierarchy of 12 key indicators that integrate cost, sustainability, and construction efficiency. The Light Steel Frame system emerged as the most favorable due to its balance between low cost, reduced environmental impact, and fast execution time. The cast-in-place concrete wall alternative ranked second, followed closely by the sandwich panel option. Despite their advantages in execution time, precast concrete walls ranked the lowest due to higher costs and environmental burdens. These findings contribute to developing sustainable social housing strategies by offering a holistic evaluation framework that integrates multiple perspectives.

1. Introduction

The United Nations 2030 Agenda for Sustainable Development highlights the urgent need to ensure access to adequate and affordable housing, particularly in informal settlements [57]. Addressing this challenge requires not only expanding housing supply but also adopting sustainable construction methods that reduce environmental impact while maintaining cost efficiency [50,75]. In recent decades, the housing sector has seen a growing emphasis on innovation, driven by the increasing recognition of its role in urban equity and sustainability ([40, 52,89]). Social housing initiatives are particularly relevant, as they not only help reduce housing deficits but also promote community development, strengthen social ties, and enhance resource efficiency ([29,64, [78]). Beyond offering affordable housing solutions, social housing projects foster community development [29], strengthen social ties [56], and enhance urban sustainability through resource optimization [51], and cleaner construction technologies [25,37].

Social housing is crucial in Peru to meet the growing demand, particularly in rapidly expanding urban areas. Programs such as Techo Propio and Fondo Mi Vivienda aim to facilitate access to decent housing for vulnerable populations by promoting Mass Social Housing Projects (MSHP) [80]. While these initiatives have contributed to reducing the housing deficit, they also underscore the urgent need for more efficient, cost-effective, and environmentally sustainable construction methods. In recent years, interest in the environmental impacts of public housing has increased, particularly in developing countries, due to the scale at which these projects are being implemented. In the case of Peru, the potential for significant environmental burdens is considerable given the large number of housing units promoted under Techo Propio and Fondo Mi Vivienda. Additionally, migration exacerbates pressure on urban infrastructure, intensifying the demand for social housing. Internal migration, driven by job opportunities, and external migration, fueled by regional crises, have significantly increased urban populations in Peru [66]. This underscores the importance of developing MSHPs capable of absorbing demographic growth.

At the same time, urban population growth drives housing demand, creating market opportunities for the construction sector [27]. Adopting Modern Methods of Construction (MMC) could be pivotal in addressing this challenge. These techniques enable faster, more efficient, and environmentally responsible construction, optimizing resources while

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aligning with MSHP needs. However, a Life Cycle Sustainability Assessment (LCSA) is essential for these innovations to be truly effective. LCSA is gaining importance in the building sector due to its comprehensive assessment of environmental, economic, and social impacts ([15]). It integrates Life Cycle Assessment (LCA), Life Cycle Cost Analysis (LCC), and Social Life Cycle Assessment (SLCA) ([14,42]). Increasingly applied in engineering—especially civil engineering [4,45,77]—these tools evaluate construction alternatives across their entire life cycle, from design and material selection to implementation, operation, and maintenance.

Numerous studies have compared construction alternatives using LCA, employing different evaluation approaches. However, few have conducted a complete cradle-to-grave analysis, which considers all life cycle phases, from raw material extraction to demolition and disposal [11,32]. Other approaches include cradle-to-gate analyses [5], which assess impacts only up to material production, and gate-to-grave assessments, which focus on construction and end-of-life stages [12]. Cradle-to-use assessments incorporate the building's operation phase but exclude final disposal [33]. In developing countries like Peru, where building materials are often locally sourced and manufactured with variable efficiencies, cradle-to-grave assessments provide a more realistic view of environmental performance. Selecting the appropriate scope is crucial to ensuring representative results. Overall, the potential environmental impacts of Peruvian residential buildings—including material production, construction, and final disposal—remain insufficiently explored and deserve further study.

From an economic perspective, LCC has historically been a key factor in project decision-making. LCC goes beyond initial investment costs by incorporating operational, maintenance, and end-of-life expenses [81]. This long-term perspective enables the selection of the most cost-effective alternative, offering a more complete view of each construction option's economic performance. In parallel, multi-criteria decision-making (MCDM) methods have gained prominence in civil engineering, allowing the comparison and prioritization of construction alternatives based on multiple factors such as cost, time, environmental impact, and energy efficiency [76,86]. However, the application of MCDM in social housing faces the challenge of the great variety of techniques available, since not all are equally suitable for every context. Currently, no single method is capable of addressing all the complexities of decision-making in the construction sector [79]. While each tool—LCA, LCC, and MCDM—provides valuable insights on its own, their integrated application allows for a more robust and comprehensive assessment of housing solutions. Moreover, applying multiple MCDM methods enables a comparative analysis across different decision-making paradigms, reinforcing the transparency and reproducibility of results. This is particularly important in public housing projects, where decisions must balance technical, economic, and environmental priorities in a defensible and evidence-based manner.

Despite their potential, few studies have integrated MCDM with LCA (cradle-to-grave) and LCC for social housing assessments [22,48]. While many researchers have applied these techniques separately to analyze materials and construction systems, combining them comprehensively remains underexplored. This study aims to fill this gap by evaluating five structural social housing solutions in Lima, Peru, integrating LCA and LCC within a cradle-to-grave framework. Subsequently, an MCDM approach is applied to rank the alternatives, facilitating a holistic assessment of their environmental, economic, and technical impacts. This integration provides valuable insights for decision-making, encouraging the adoption of more sustainable construction methods in large-scale projects.

The article is organized as follows: Section 2 defines the problem and describes the materials and methods used, covering life cycle impact analysis from an economic and environmental perspective. It presents a methodology using economic, environmental, and technical indicators from the MCDM. Section 3 presents and evaluates the results of the study. Section 4 provides an in-depth discussion. Finally, Section 5 presents the main conclusions of the study.

2. Materials and methods

2.1. Definition of the goal and scope

2.1.1. Goal of the study

This study conducts a comparative evaluation of structural solutions for MSHP, assessing their economic, environmental, and technical performance throughout their life cycle. The research aims to support evidence-based decision-making in social housing development by identifying the most sustainable and efficient alternative. To achieve this, a LCA is applied to quantify environmental impacts, while MCDM will evaluate the overall performance of each alternative. Data on materials, construction processes, and maintenance requirements, ensuring a comprehensive and representative assessment.

The study is based on a hypothetical site in Carabayllo, a rapidly urbanizing district in northern Lima, Peru, where affordable housing demand has surged due to internal migration and population growth [36]. Carabayllo is characterized by high land availability and diverse socio-economic conditions, making it a relevant case for exploring construction alternatives that optimize costs, reduce environmental impact, and improve housing quality for low-income families.

2.1.2. Definition of alternatives

Five structural solutions were selected to evaluate the different construction approaches based on their relevance in the Peruvian context and their potential to contribute to sustainable development. Two of them - reinforced concrete frames with masonry (RCF-M) and reinforced concrete walls (RCW) - represent conventional systems widely used in current social housing projects, valued for their cost-effectiveness, availability of local materials, and familiarity among the workforce. RCF-M, in particular, is widely adopted in low-income housing due to these factors, as 71.2 % of urban dwellings have exterior walls made primarily of brick, underscoring the predominance of masonry and cement-based construction in the country [36]. The other three—light steel frame (LSF), reinforced concrete frames with precast panels (RCF-CP), and lightweight bolt-connected concrete sandwich panel systems (LBSPS)—are considered emerging technologies. These alternatives are being tested in pilot projects because they can reduce material consumption, shorten construction times, and lower environmental impact.

The selected typology corresponds to a single-floor social housing unit of 40.3 m^2, comprising a kitchen, living room, bedrooms, and bathroom (see Fig. 1). Table 1 summarizes the main structural components and construction logic of each alternative. The Supplementary Material (S1) provides additional technical and procedural details. Fig. 2 provides visual references for the five construction alternatives, illustrating each system's characteristic configuration or typical components.

2.1.3. Functional unit

In this study, the Functional Unit (FU) is defined as one square meter (1 m^2) of total built-up area in a residential building, with an assumed service life of 50 years. This standardized reference enables consistent comparison of environmental and economic results across construction alternatives, in line with ISO 14,040 [35]. Although several FU definitions are available in the literature [41], total built-up area was selected due to its alignment with architectural practice in Peru, applicability to whole-building assessments, and consistency across the alternatives analyzed. As [53] demonstrated, different FU definitions can influence ranking outcomes, reinforcing the importance of selecting a comparable unit based on function, size, and lifespan. Material quantities were divided by the total built-up area to obtain values per FU. Machinery use was assessed at the project level and proportionally allocated across dwellings. This approach ensures a fair distribution of environmental

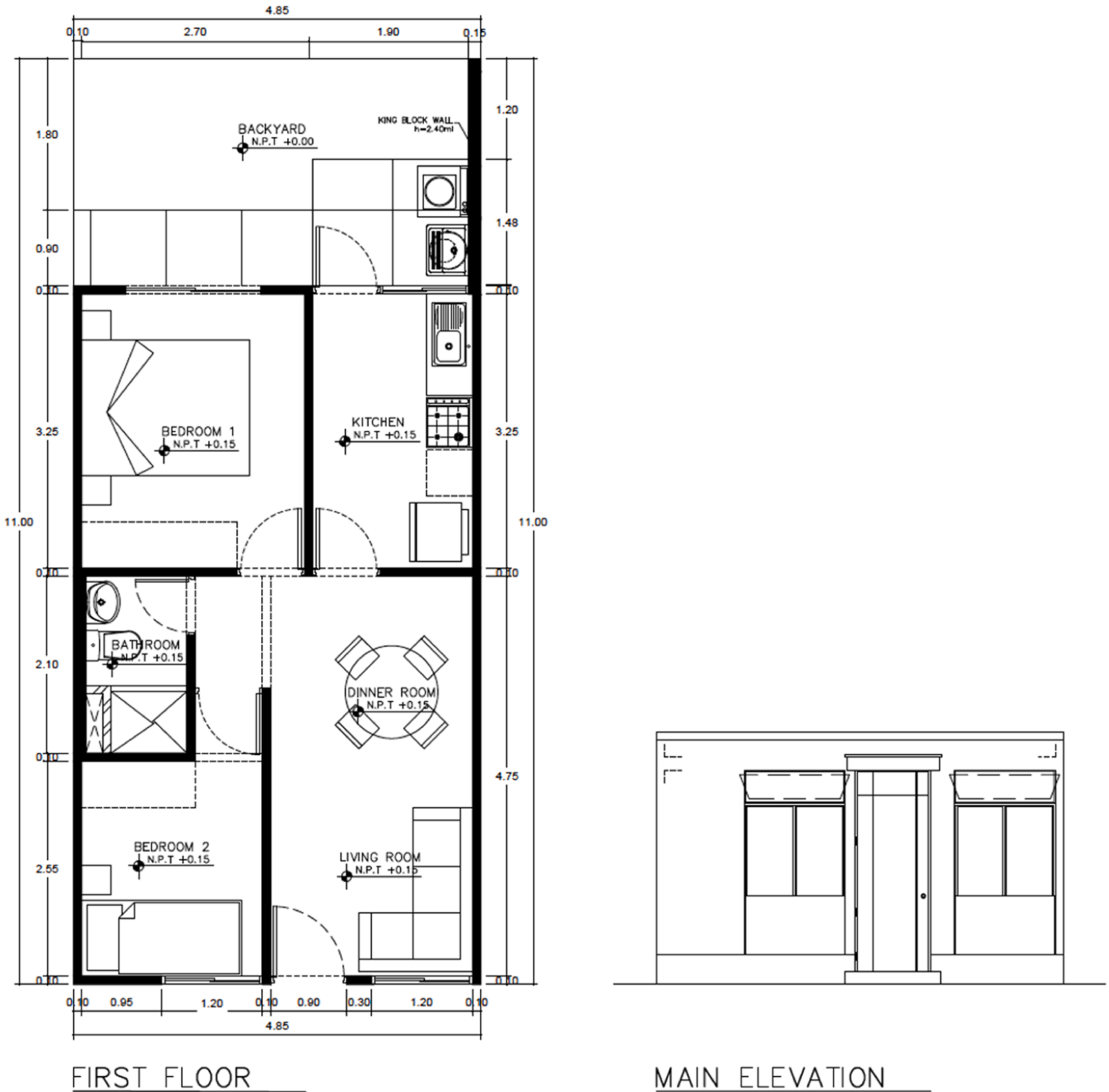

Fig. 1. Floor plan and main elevation of the prototype house for MSHP (dimensions in meters).

Table 1
Structural definition of alternatives.

Code	System name	Description	Type	Construction logic	References
RCF-M	Reinforced Concrete Frame + Masonry	RC frames + clay brick masonry walls + ribbed slab	Conventional	Cast-in-place, labor-intensive	Polat Gulkan et al. [61]
RCW	Reinforced Concrete Walls	Cast-in-place monolithic concrete walls + solid slab	Conventional	High seismic resistance	Loa et al. [44]
LSF	Light Steel Frame	Galvanized steel frame + gypsum board walls + lightweight roof	Industrialized	Dry construction	Alibazi et al. [2]
RCF-CP	RC Frame + Concrete Panels	RC frame with precast concrete sandwich wall panels	Semi-industrial	Hybrid (wet + prefabricated panels)	Dissanayake et al. [13], Pawar et al. [60]
LBSPS	Bolt-connected Sandwich Panel Structure	Lightweight bolt-connected concrete sandwich panels (walls and slab)	Innovative	Modular, rapid assembly	Wang et al. [82], Zhao et al. [88]

burdens and economic costs, avoiding distortions between systems with differing construction processes. All calculated material quantities per FU are presented in Table 2. The selected housing alternatives were designed by Peru's National Building Regulations (RNE), incorporating the Technical Standard E.030 [18] for seismic resistance—which assesses structural performance based on the seismic risk zoning of the study area—and ensuring that all five construction systems meet the minimum seismic safety requirements. Similarly, compliance with Technical Standard EM.110 [19] for thermal performance guarantees comparable R-values across alternatives. These considerations confirm that the dwellings align with the RNE and the Technical Code for Sustainable Construction [49], ensuring alignment with current environmental and energy performance standards. Although the analysis primarily focuses on the structural system, finishes are also included, as their material requirements and maintenance need directly influence the building's life cycle performance.

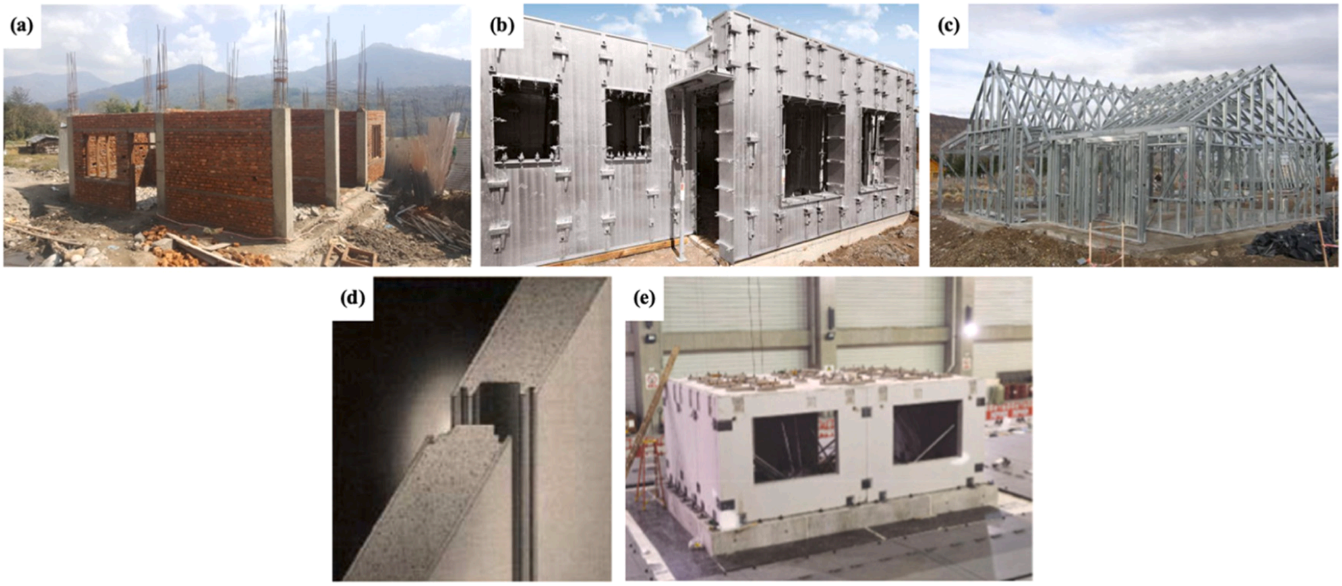

Fig. 2. Structural alternatives in MSHP, a) RCF-M, b) RCW, c) LSF, d) RCF-CP, e) LBSPS.

Table 2
Inventory data with material quantities and energy used by FU.

Description	Unity	RCF-M	RCW	LSF	RCF-CP	LBSPS
Manufacturing						
Concrete 20MPa	m^3	0.39	0.60	0.24	0.42	0.59
Reinforcing steel	kg	29.35	27.60	12.57	32.65	25.65
Cold - Formed Steel (CFS)	kg	–	–	6.05	–	–
XPS	kg	–	–	–	–	5.13
Hot rolling steel	kg	–	–	–	–	14.56
Hard fibreboard	m^3	–	–	0.02	–	–
Rigid PVC coating	kg	–	–	1.34	–	–
Clay brick	kg	318.51	–	–	–	–
Concrete brick	kg	33.45	33.45	33.45	33.45	33.45
Gypsum plasterboard	kg	–	–	62.38	–	–
Fiberglass wool	kg	–	–	3.07	–	–
Cement mortar	kg	1.23	1.13	–	1.13	1.13
Brick veneer roof	kg	36.22	36.22	–	36.22	36.22
Ceramic tile	kg	20.36	20.36	20.36	20.36	20.36
Lime mortar	kg	–	0.05	–	0.05	0.05
Cement plaster	kg	0.16	–	–	–	–
Joint compound	kg	–	–	4.47	–	–
Latex paint	kg	1.44	1.44	1.44	1.44	1.44
Aluminum window/door frame	kg	0.01	0.01	0.01	0.01	0.01
Glass	kg	3.21	3.21	3.21	3.21	3.21
Wood door frame	m^2	0.20	0.20	0.20	0.20	0.20
Water (excluding concrete mix)	kg	102.93	216.33	3.84	3.84	3.84
Primers, resins and release agents	kg	0.07	0.13	0.01	0.00	0.11
Construction						
Preliminary	MJ	117.43	117.43	117.43	117.43	117.43
Foundation slab	MJ	26.04	26.04	26.04	26.04	–
Columns	MJ	7.42	–	–	7.42	–
Concrete walls in situ	MJ	–	40.51	–	–	–
Floor slab	MJ	9.54	11.69	–	11.69	–
Module building	MJ	–	–	–	91.42	327.15
Assembly (5t)	MJ	–	–	–	–	255.40
Masonry	MJ	0.06	0.06	0.06	0.06	0.06
Concrete Floor	MJ	–	–	–	–	13.61
Use						
Anti-carbonation paint	kg	0.77	2.24	–	2.24	2.24
Anti-corrosion paint	kg	–	–	0.38	–	0.11
End of life						
Structure overthrow	MJ	241.37	268.99	164.22	253.91	258.79
On-site crushing	kg	895.86	1375.14	45.81	1245.41	1244.64

2.2. Life cycle assessment LCA

LCA is a technique used to analyze the potential environmental impacts in all phases of a product's life cycle, ranging from raw material procurement, production, and processing to its use and final disposal. This study follows the ISO 14,040:2006 framework, which defines four methodological phases: (1) goal and scope definition, (2) life cycle inventory, (3) life cycle impact assessment, and (4) interpretation [35].

2.2.1. Definition of the objective and scope

The primary objective of this LCA is to provide a comparative assessment of the environmental impacts associated with the five structural alternatives under study. The analysis adopts a 'cradle-to-grave' approach, evaluating key impact categories such as carbon footprint, energy consumption, and material depletion.

The scope of the study focuses on the structural elements of the dwellings, including foundations, columns, slabs, and structural walls, as they represent the largest contributors to environmental impact. Additionally, finishing materials are incorporated into the assessment due to their influence on energy consumption, resource use, and long-term maintenance requirements.

2.2.2. Phases of the analysis

The LCA of social housing involves a structured assessment of environmental impacts through different life cycle phases. This section describes the key stages of manufacturing, construction, use, and End of Life (EoL) analysis. Fig. 3 visually represents these stages, providing an overview of the life cycle approach applied in this study.

2.2.2.1. Manufacturing. The manufacturing stage encompasses the extraction of raw materials, their processing, and the manufacture of the materials necessary for the construction of the house. This phase includes the consumption of natural resources, the use of energy in the production processes, and the emissions generated, considering key materials such as concrete, steel, brick, and aggregates. Concrete production involves manufacturing cement, obtaining aggregates, and consuming water; steel requires extraction, smelting, and shaping processes; brick involves clay extraction, molding, and firing at high temperatures; and aggregates come from quarries, which are crushed and classified. The project is located in Carabayllo, an area with industrial infrastructure and access to main transport routes, influencing transport emissions and logistical efficiency. The transportation distances considered in the analysis are 41.4 km to the precast plant, 31.2 km to the steel plant, and 10.7 km to the concrete plant. These distances were determined based on a market analysis of suppliers operating in Lima. Specifically, the companies currently serving North Lima were selected, and the distances reflect the actual routes between these facilities and the hypothetical Carabayllo site. The transport distances are detailed in Supplementary Material S3. Additionally, the mobilization of heavy equipment and machinery required for the on-site execution of the structural systems is considered.

2.2.2.2. Construction. The construction phase comprises all activities related to the assembly of materials and the construction of the house on-site, including the use of machinery, labor, energy consumption, and waste generation. Each construction method has its particularities:

- RCF-M: Formwork erection, steel reinforcement, concrete pouring, curing, stripping, and masonry work.
- RCW: Reusable metal formwork, reduced waste in concrete pouring and stripping.
- LSF: Pre-cut steel components, rapid panel installation with insulation.
- RCF-CP: On-site concrete pouring, prefabricated polystyrene panels.
- LBSPS: Fully prefabricated modules, transported and assembled on-site.

For RCF-M, RCW, LSF, and RCF-CP, a 15 cm thick reinforced concrete foundation slab was used to meet one-story housing structural requirements. In LBSPS, precast foundations were chosen to align with its modular assembly approach. Each system's construction stage was modeled using the total energy demand (MJ) for typical activities (e.g., excavation, compaction, casting, factory work). This modeling reflected each technology's specific sequence of tasks, equipment, and mechanization levels. Using a consistent energy-based indicator across systems ensured a fair comparison, with normalized values reflecting the relative

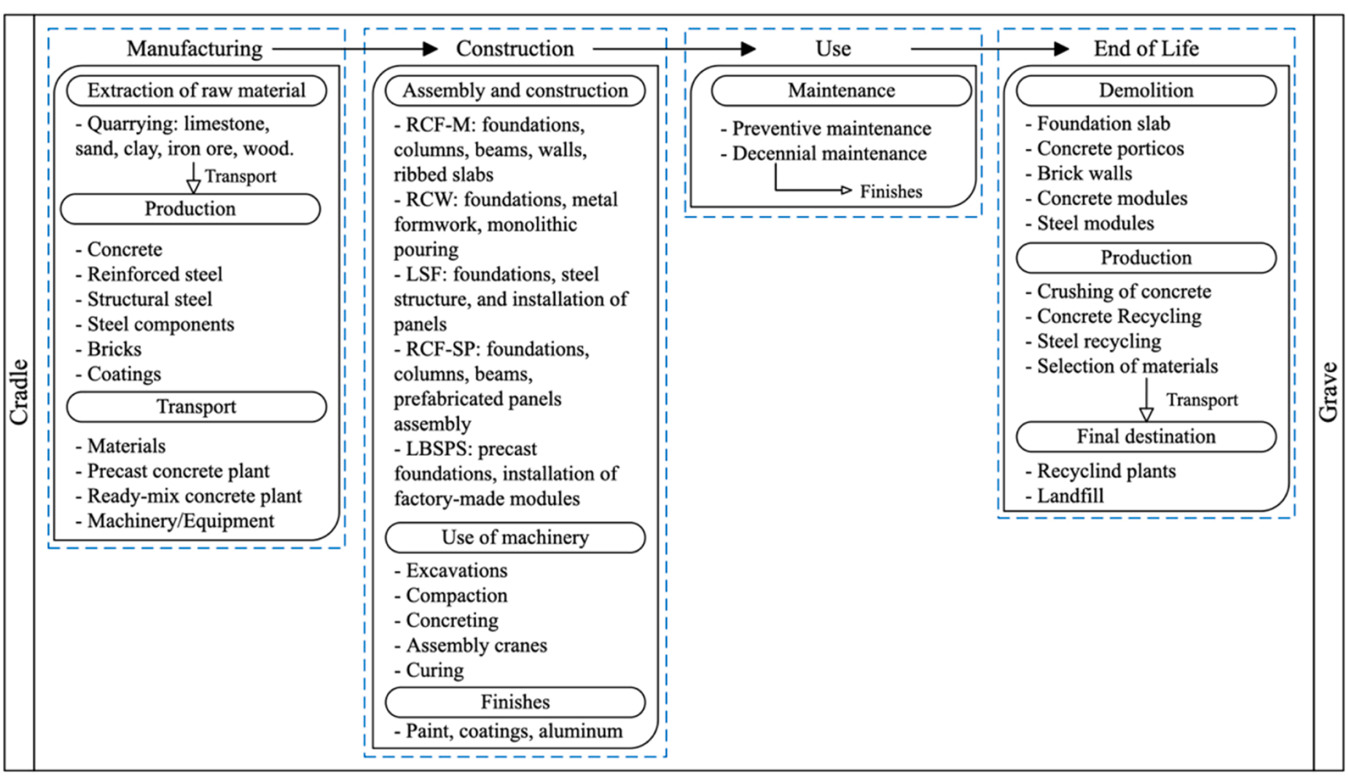

Fig. 3. System boundaries of environmental life cycle analysis.

energy intensity of each construction method.

2.2.2.3. Use and end-of-life. The use phase includes preventive maintenance to extend the service life of the structure. The study considers protective coatings such as anti-carbonation acrylic resin paints and epoxy-based anti-corrosion treatments, whose application frequency varies by construction method. All systems were modeled to receive appropriate protection to ensure equivalent performance over time, following standard maintenance practices used in social housing. This means that, while the same coating material was used across alternatives for consistency, the amount and treated surfaces varied depending on the building system's design and exposure conditions. All protective coating quantities were estimated according to each system's exposed surfaces requiring treatment. However, operational energy consumption is not included, as it largely depends on user behavior, climatic conditions, and occupancy patterns, which are not directly influenced by the construction system. This approach is consistent with other studies in the field, which highlight the high variability and uncertainty associated with modeling the operational energy use [71].

In the EoL phase, demolition processes, waste management, and options for recycling or reusing materials are evaluated to minimize environmental impacts. Although this stage occurs after the service life of the housing unit, it is included due to its relevance in the total environmental burden and the institutional responsibility of public authorities for final waste treatment. Non-recoverable waste is assumed to be disposed of in a landfill located 7 km away, but material recovery will be prioritized in each alternative to reduce the amount of waste sent to disposal.

2.2.3. Life cycle inventory analysis

The Life Cycle Inventory (LCI) analysis focuses on collecting and quantifying material and energy consumption data to accurately model the life cycle processes of the five structural alternatives under study. Table 2 presents the inventory of all alternatives in the case study. It includes key construction materials such as concrete with a compressive strength of 20 MPa for all structural elements, ASTM A706 Gr.60 reinforcing steel, and fired clay bricks, among others. Additionally, auxiliary materials such as adhesives, primers, resins, and release agents are considered. Different routes have been evaluated according to the nature of the inputs to analyze the transport of materials. For cement, its transportation from the production plant to the construction site and the concrete production plant is analyzed, considering real distances based on the suppliers' locations. In the case of ready-mix concrete, the route from the batching plant to the construction site is included, considering the use of mixer trucks. Similarly, for precast elements, transportation from the factory to the construction site is evaluated, while finishing materials are considered from the supplier's store. In the case of the LSF system, distances have been determined through a specialized distributor, optimizing transportation logistics. These variations in the supply chain directly influence the overall environmental impact of each alternative, resulting in a key factor for the sustainability assessment.

The study was developed using OpenLCA, a widely recognized open-source software for LCA [58]. The Ecoinvent database v3.7.1 was used for process modeling, ensuring global comparability of results [16]. To address data uncertainty, the pedigree matrix approach was applied, evaluating reliability, temporal coverage, and technological adequacy [21]. This method enhances result robustness by quantifying variability in input data [85]. Energy consumption was estimated using the BEDEC database, which provides detailed values for construction processes [7]. For prefabricated elements, energy estimates followed Liu & Gambatese [43], adopting an automation level four classification. Lastly, assembly process efficiency was refined using empirical data from Wang et al. [82] and Zhao et al. [88], ensuring alignment with real-world construction scenarios.

2.2.4. Life cycle impact assessment

The ReCiPe 2008 method was used for environmental impact assessment, considering both midpoint and endpoint approaches. The midpoint approach evaluates 18 specific environmental impact categories, such as global warming potential (GWP), fossil depletion (FD), human toxicity (HTP), and ozone depletion (ODP), among others. This level of detail allows for identifying processes with the most significant environmental burdens. On the other hand, the endpoint approach groups these impacts into three more general damage categories: ecosystem impact, human health impact, and resource impact. The units of these categories are species/year (species.year), disability-adjusted life years (DALYs), and US dollars (USD), respectively, which facilitates the interpretation of the results for decision-making [46]. The complete list of categories, acronyms, and units for both approaches is provided in Table 3.

The H (Hierarchical) perspective was chosen because it reflects a scientific consensus on impact models and their long-term effects, providing standardized and comparable results in LCA studies [28]. The results were normalized using the H/H (person/year) option.

2.2.5. Interpretation of analysis

In the interpretation stage of the analysis, the results obtained for the midpoint and endpoint approaches will be presented, evaluating the 18 impact categories throughout the different phases of the life cycle. However, a specific analysis of the GWP by phase will be carried out to identify which phase contributes the most to the total environmental impact. In the endpoint approach, the three damage categories and the total points obtained in each life cycle phase will be examined, providing an overall view of the aggregate impact of each construction alternative.

2.3. Life cycle cost

Economic costs were analyzed for the construction, use, and EoL stages using data from the CYPE Ingenieros S.A. cost database, adapted to the Peruvian context by selecting locally available materials, adjusting labor costs to national standards, and ensuring compliance with the RNE. Data from Peruvian social housing projects were also used to prepare the inventory. All costs are referenced to November 2024 and presented in USD. For each alternative, the analysis included materials, labor, machinery, and equipment costs for construction and transportation. In the use phase, preventive maintenance was considered, including anti-corrosion, anti-carbonation paint, and decennial maintenance to ensure durability. The EoL stage included demolition

Table 3
Environmental indicators in the study.

Approach	Acronym	Impact Category	Unit
Midpoint	ALO	Agricultural land occupation	m^2a
	GWP	Global warming potential	kg CO_2 eq
	FD	Fossil depletion	kg oil eq
	FEPT	Freshwater ecotoxicity	kg 1,4-DB eq
	FEP	Freshwater eutrophication	kg P eq
	HTP	Human toxicity	kg 1,4-DB eq
	IRP	Ionizing radiation	kBq U-235 eq
	MEPT	Marine ecotoxicity	kg 1,4-DB eq
	MEP	Marine eutrophication	kg N eq
	MD	Metal depletion	kg Fe eq
	NLT	Natural land transformation	m^2
	ODP	Ozone depletion	kg CFC-11 eq
	PMF	Particulate matter formation	kg PM_{10} eq
	POFP	Photochemical oxidant formation	kg NMVOC eq
	TAP	Terrestrial acidification	kg SO_2 eq
	TEPT	Terrestrial ecotoxicity	kg 1,4-DB eq
	ULO	Urban land occupation	m^2a
	WD	Water depletion	m^3
Endpoint	—	Ecosystem damage	species·year
	—	Human health damage	DALYs
	—	Resource scarcity	USD

machinery and transportation to final disposal, considering recycling or landfill options. Further LCC data can be found in Supplementary Material S2.

A 2 % discount rate was applied for maintenance and EoL costs, as these are future expenses distributed over the project's 50-year life. This low rate is justified because long-term infrastructure and sustainability projects recommend lower values to accurately reflect future costs' relevance [3,68]. The equation to convert future to present costs is as follows:

$$LCC = \sum_{t_0}^{t_{SL}} \frac{C_t}{(1+d)^t} \quad (1)$$

where LCC is the Life Cycle Cost of the structure, C_t is the cost incurred at time t, t_0 is the initial year of the evaluation period (in our case $t_0 = 0$), t_{SL} is the service life of the structure (in years), and d is the value of the discount rate.

2.4. Multi-criteria decision making

At this study stage, MCDM methods are applied to evaluate the construction alternatives considered in the analysis. These methods enable a structured and objective evaluation by considering multiple, and potentially conflicting, criteria simultaneously [54]. The MCDM process was divided into two main stages: (i) weighting and identification of interdependencies among the evaluation criteria, and (ii) ranking of the construction alternatives. This dual-stage structure enhances analytical clarity and supports a robust evaluation framework. This combination of techniques will provide a comprehensive view of the performance of each option according to the defined criteria. To strengthen the analysis and ensure result consistency, a combination of traditional and recent MCDM methods was applied. The selected methods differ in terms of their theoretical underpinnings, computational approaches, and treatment of uncertainty. Table 4 summarizes the main characteristics and purposes of each method.

2.4.1. Selection of criteria

The selection of economic, environmental, and technical perspectives was based on their widespread use in LCA in the construction sector and their fundamental importance in evaluating housing projects; [1,9,65]. Each perspective includes specific criteria (8 in total) and indicators (12 in total) selected.

- Economic criteria (C1, C2 and C3): Covers construction, maintenance, and EoL costs measured in dollars. These criteria evaluate affordability and long-term financial performance, which align with LCC.
- Environmental criteria (C4, C5 and C6): Covers impacts on ecosystems, human health, and resource use across the life cycle. Based on LCA methods, these impacts can be quantified in points, reflecting the need to minimize burdens from cradle to grave.
- Technical criteria (C7 and C8): Focuses on constructability aspects such as execution time and technical necessity, which are key to assessing feasibility, efficiency, and project suitability for users and contractors. To define scales, C7 was informed by scientific literature [10,47,60,74] and field observations, using RCF-M as baseline. For C8, an AHP was applied to assess the need for skill labor.

3. Analysis of results and interpretation

3.1. Environmental life cycle assessment

3.1.1. Midpoint

This study quantifies the midpoint environmental impacts of social housing across various impact categories. The ReCiPe method was selected for its broad coverage of impact categories and its applicability to construction. Midpoint indicators provide a detailed characterization of specific environmental mechanisms and are located closer to the inventory results, which makes them more suitable for tracking the origins of environmental burdens. Moreover, they are typically associated with lower uncertainty compared to endpoint indicators, as their calculation involves fewer modeling assumptions [73]. Fig. 4 shows the environmental impacts of social housing throughout the manufacturing, construction, use, and EoL phases. These results are shown in relation to the alternative with the greatest impacts in each category.

In the manufacturing phase (Fig. 4a), most housing alternatives show high impacts across most categories. RCF-M presents the highest values, followed by RCF-CP and LBSPS, primarily due to the use of cement and steel in precast components, which are energy- and resource-intensive. In particular, RCF-M's elevated impact is linked to brick masonry, which requires significant energy and emits pollutants during production. In contrast, LSF exhibits the lowest impact in most categories.

During construction (Fig. 4b), LBSPS shows the highest impact, which generates 5.5 times more impact than LSF due to increased energy demand for precasting and on-site assembly machinery. RCW shows a lower impact than the precast options; despite monolithic concrete's logistical and timing challenges, its in-situ monolithic casting reduces factory-related burdens. LSF remains the least impactful option during construction, reinforcing its overall sustainability. Since the same energy-based indicator was used across all systems, the normalized values show consistent percentage distributions across midpoint categories, reflecting the relative energy intensity of each technology.

Fig. 4c, corresponding to the use phase, shows a similar ranking. While all systems used epoxy resin-based coatings for protection (anti-

Table 4
MCDM methods applied in the study.

Method	Type	Main Purpose	Key Features	Reference
AHP (Analytic Hierarchy Process)	Weighting	Derive weights from pairwise comparisons	Hierarchical structure; consistency ratio; expert judgment	Saaty [63]
Group Aggregation (AHP-based)	Weighting	Combine expert judgments with competence weighting	Weighted consensus based on expertise level	Sánchez-Garrido et al. [68]
DEMATEL	Weighting / Interdependency	Identify interdependencies and causal relationships among criteria	Influence matrices; cause-effect diagrams	Yazdi et al. [84]; Si et al. [69]
TOPSIS	Ranking	Select alternative closest to the ideal solution	Geometric distance from ideal and anti-ideal	Hwang & Yoon [34]
WASPAS	Ranking	Hybrid ranking based on additive and multiplicative utility	Combines WSM and WPM for robust performance	Zavadskas et al. [87]
EDAS	Ranking	Evaluate alternatives based on deviation from average	Positive/negative distance from average; outlier-resistant	Ghorabaee et al. [26]
MABAC	Ranking	Rank alternatives using border approximation	Incorporates uncertainty and decision-maker subjectivity	Pamučar et al. [59]
MARCOS	Ranking	Rank alternatives using compromise solution and reference points	Considers ideal, anti-ideal, and actual performance	Stević et al. [72]

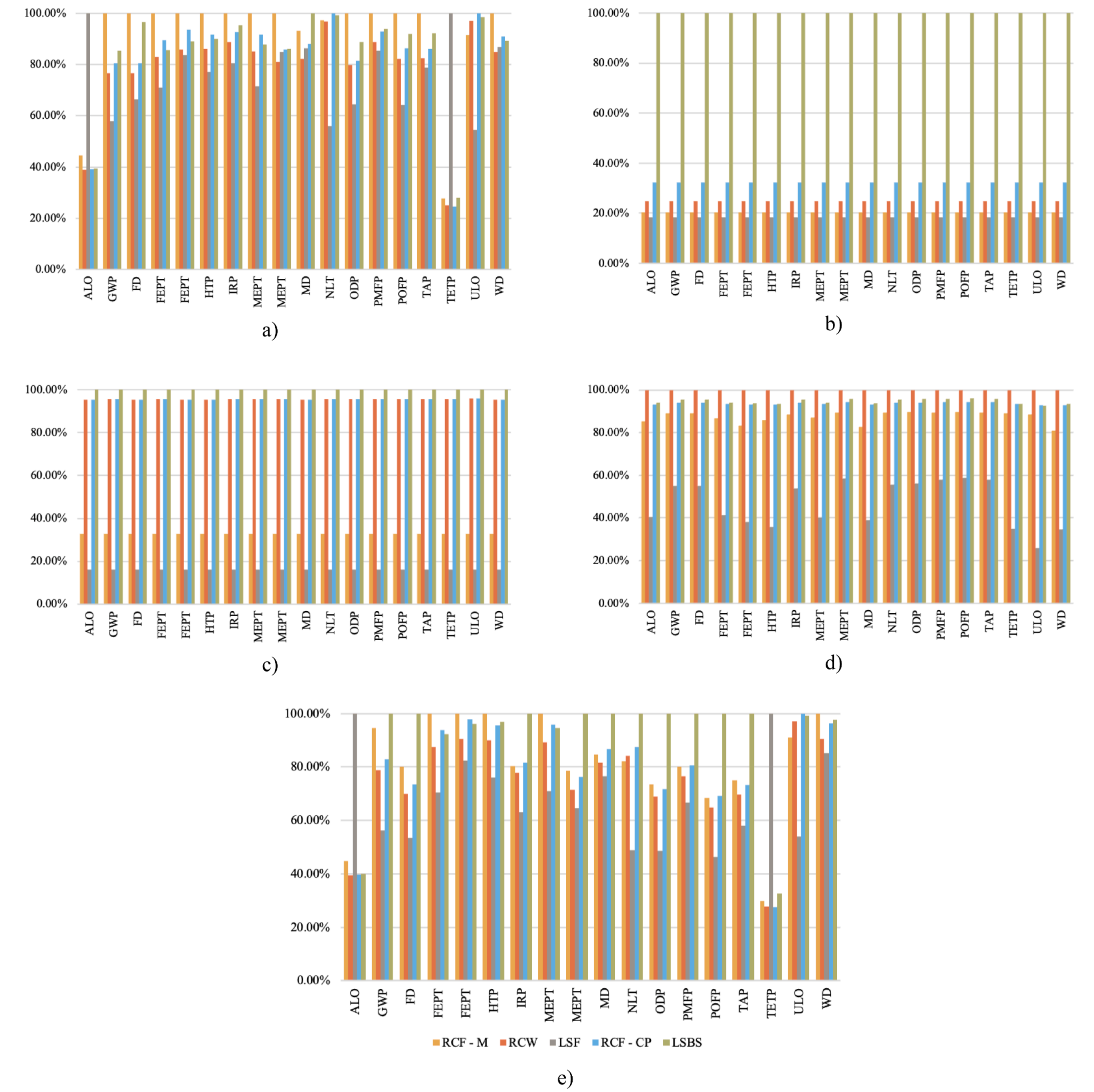

Fig. 4. Environmental impacts with midpoint: a) Manufacturing, b) Construction, c) Use, d) EoL and e) Total. [Agricultural Land Occupation (ALO), Global Warming Potential (GWP), Fossil Depletion (FD), Freshwater Ecotoxicity (FEPT), Freshwater Eutrophication (FEP), Human Toxicity (HTP), Ionizing Radiation (IRP), Marine Ecotoxicity (MEPT), Marine Eutrophication (MEP), Metal Depletion (MD), Natural Soil Transformation (NLT), Ozone Depletion (ODP), Particulate Matter Formation (PMF), Photochemical Oxidant Formation (POFP), Terrestrial Acidification (TAP), Terrestrial Ecotoxicity (TEPT), Urban Land Occupation (ULO) and Water Depletion (WD)].

carbonation or anti-corrosion), the amount and application areas varied according to the materials and exposure of each alternative. RCW and RCF-CP required full-envelope coating due to their exposed reinforced concrete surfaces. RCF-M applied coatings only to structural elements (e. g., columns, slabs), resulting in lower impacts. LSF required minimal treatment limited to steel profiles, while LBSPS combined both anti-corrosion (for steel joints) and anti-carbonation (for concrete panels) treatments, leading to the highest impact in this phase. This classification reflects the material requirements of each system, as all systems were modeled to provide comparable long-term performance through standardized maintenance practices.

In the EoL phase (Fig. 4d), RCW presents the most significant impacts, followed by LBSPS and RCF-CP. Since this phase involves dismantling and final disposal of materials, concrete structures produce significant waste volumes that must be managed. RCF-M has a 10 % lower impact than the concrete options, as its combination with brick masonry reduces total volumetric waste. LSF has 40 % fewer impacts than RCW, as light steel structures generate far less waste at the end of their life.

The midpoint analysis in this LCA identifies LBSPS as the least favorable option environmentally, as shown in Fig. 4e. In contrast, LSF, despite its galvanized steel structure, is the alternative with the lowest environmental impact in most categories. Additionally, there is a 23 % total impact difference between LBSPS and LSF. The most significant midpoint category is GWP due to its weight in environmental and political contexts [24]. Fig. 5 shows each LCA phase's emissions per stage and total emissions per m². In the manufacturing phase, RCF-M has the highest impact, exceeding LSF by 42 %, indicating a greater environmental burden.

In contrast, RCF-M has the lowest impact during construction, while LBSPS stands out for high fuel consumption during assembly. In the use phase, RCW, RCF-CP, and LBSPS show similar impacts due to equivalent preventive treatments, while RCF-M and LSF show minimal impacts. In the EoL phase, impacts are relatively similar, although LSF has the lowest, generating only 56 % of the maximum impact.

In analyzing the main contributors to the midpoint impact categories, concrete production is a significant environmental contributor in nearly all alternatives. Concrete represents 31 % of the total impact in RCW, exceeding reinforcing steel (19 %), the second-largest contributor across all options. In RCF-M, clay brick production stands out due to its manufacturing process and high presence in this alternative. As a result, in RCF-M, impacts from concrete, reinforcing steel, and clay bricks differ by only 5 %. Diesel use is also a significant contributor in RCW, RCF-CP, and LBSPS, driven by the need for specialized production, transport, and assembly machinery. Additional data are provided in Supplementary Material (S3).

3.1.2. Endpoint

The endpoint assessment measures the environmental impact in terms of damage to resource consumption and pollutant emissions, affecting human health, ecosystems and natural resources. This higher level of aggregation facilitates comparison across impact categories and supports decision-making by offering more intuitive results for stakeholders, including those without technical expertise in LCA. Fig. 6 displays the endpoint results for each alternative. The analysis highlights that the manufacturing phase contributes the most to all three damage categories, primarily due to high energy consumption, emissions, and raw material extraction. In contrast, the construction, use, and EoL phases show comparatively lower and more localized impacts. However, in the construction phase, LBSPS shows significantly higher impacts in all three categories evaluated.

These endpoint indicators are derived from aggregating various midpoint categories modeled in ReCiPe. For example, GWP, presented in Fig. 5, is a midpoint category that contributes to both the Human Health and Ecosystems damage endpoints due to the wide-ranging consequences of climate change. Therefore, the endpoint results in Fig. 6 offer a broader perspective that integrates GWP and other midpoint impacts such as acidification, eutrophication, human toxicity, and resource depletion. The consistency between midpoint and endpoint results

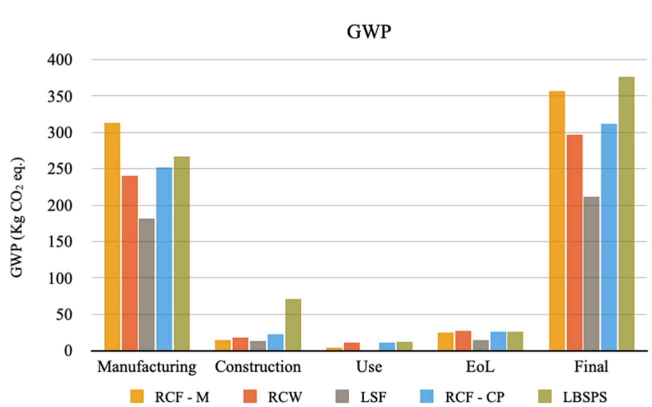

Fig. 5. Global Warming Potential in all the stages.

reinforces the reliability and transparency of the overall impact assessment.

In the manufacturing phase, the RCF-M and LSF alternatives have the greatest environmental impact. In contrast, during the use phase, RCW, LSF, RCF-CP and LBSPS triple the impact of RCF-M, indicating a higher demand for resources or emissions throughout their useful life. In the EoL phase, RCW generates the highest amount of pollutants, doubling the values of LSF. As for the main contributors in endpoint, in RCF-M, clay brick maintains a significant impact of 28 %, reaffirming its high environmental contribution. On the other hand, in RCW, RCF-CP and LBSPS, concrete stands out with an impact above 30 % on average in all endpoint categories, consolidating its position as the material with the highest impact in these options.

The results shown in Fig. 7 indicate that LBSPS generates the highest total impact, while LSF has the lowest. It is important to note that RCF-M, the most widely used alternative in the country, ranks second in environmental impact. In addition, when analyzing the total impacts in endpoint evaluation unit points, it is observed that the Resources category represents 70 % of the impact, followed by Human Health with 25 % and Ecosystem with 5 %. This highlights the strong influence of material and resource consumption on the overall environmental impact.

3.2. Results of the life cycle economic evaluation

Fig. 8 presents the LCC results of the five alternatives, taking RCF-M as a reference. All costs are expressed per square meter. According to the graph, the construction phase represents the highest percentage of costs. In this phase, LBSPS is the most expensive alternative, with an increase of 20 % over RCF-M, while LSF is 15 % cheaper. In the use phase, RCW and RCF-CP present the highest costs, with an average increase of 77 % over the reference, due to the greater need for preventive treatments.

In contrast, LSF is the most economical option in this phase, with 42 % less cost. In the EoL phase, RCW and RCF-CP generate a higher volume of waste due to their composition of monolithically poured concrete and precast concrete panels, respectively. This explains their higher cost than LBSPS, although lower than RCF-M, the most expensive alternative in this phase. This difference is because the clay brick masonry makes recycling difficult, reducing the amount of usable waste. Finally, LSF presents the lowest EoL cost, 77 % less than RCF-M.

3.3. Multicriteria decision making MCDM

The weights of the criteria were determined using the AHP method. Table 5 presents the profiles of the five experts and the credibility index, which reflects the relevance of each expert in the group decision according to the procedures described in Sections 2.4.1 and 2.4.2.

Five experts with between 12 and 35 years of experience in civil engineering, architecture, or construction participated in the assignment of weights. The methodology proposed by Sodenkamp et al. [70] was applied using the simplified version developed by Sánchez-Garrido et al. [67].

First, the individual weights of each criterion were determined using AHP. Then, these values were adjusted by voting power, giving greater influence to decision-makers with greater knowledge and track record. Table 6 presents the final weighting of the criteria after the application of both methods.

According to this table, the order of priority is as follows: C1 Construction Cost (25 %), C8 Technical Necessity (16 %), C7 Duration of works (14 %), C5 Human Health (13 %), C4 Ecosystem (11 %), C6 Resources (11 %), C2 Maintenance Cost (8 %) and C3 EoL Cost (5 %). There is a consensus among all decision-makers that C1 is the most relevant criterion in the evaluation. Regarding the environmental criteria, C5 is considered the most important, although its weight does not differ significantly from the other environmental criteria.

Table 7 shows the relationship matrix obtained using DEMATEL, reflecting the intensity of the interactions between the criteria

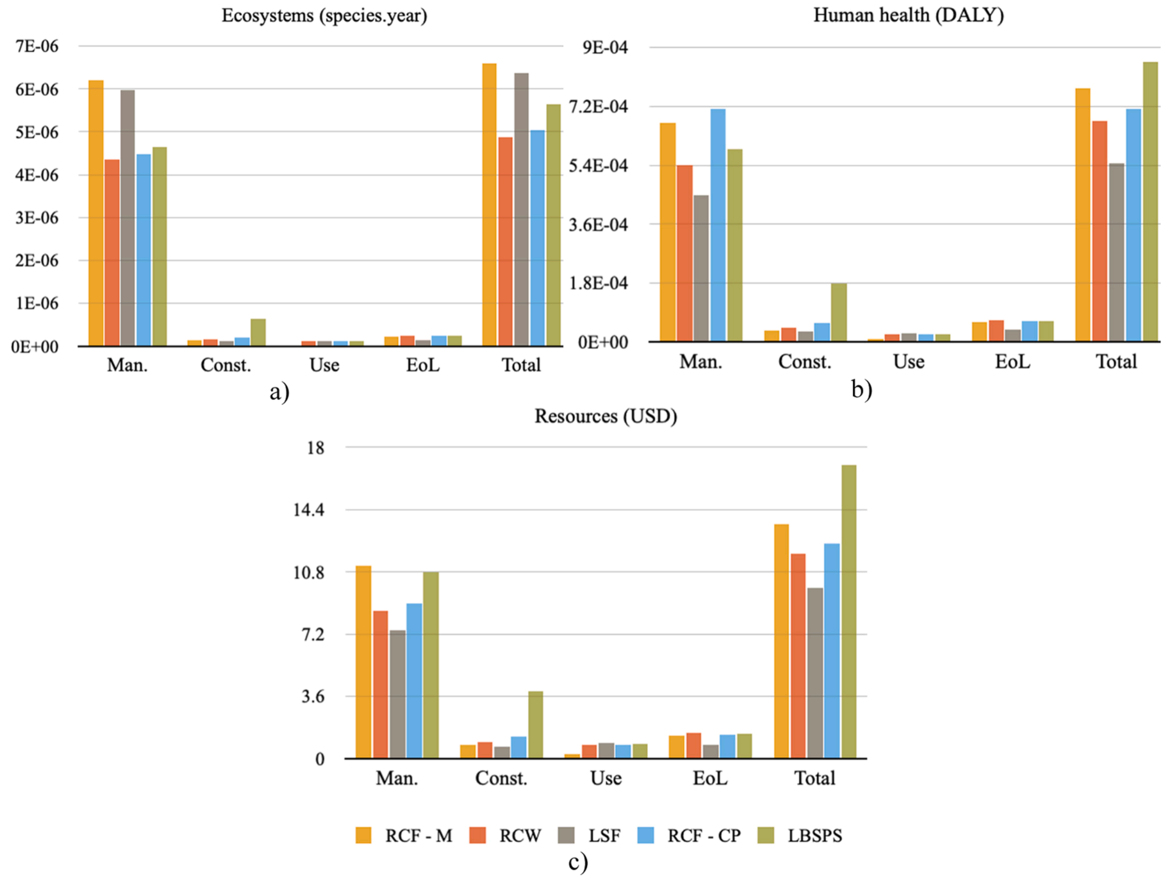

Fig. 6. Endpoint impacts: a) Ecosystems, b)Human health, c) Resources.

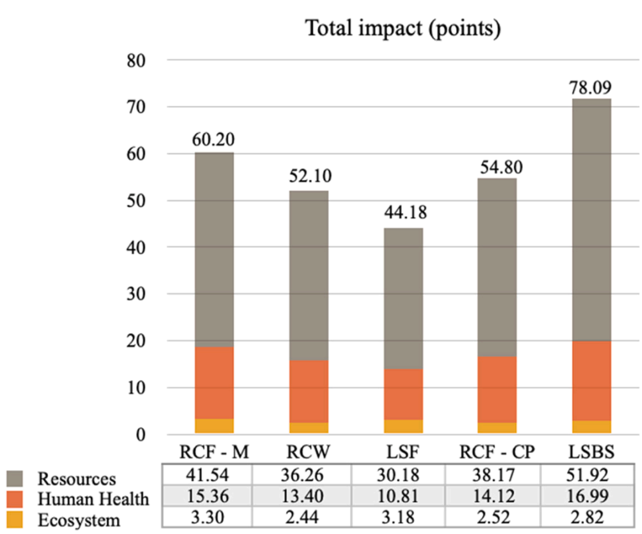

Fig. 7. Total impacts: a) Ecosystems, b)Human health, c) Resources.

evaluated. After establishing a threshold value, the values that exceed it were highlighted, allowing the most significant relationships to be identified and insignificant effects to be filtered out [83]. On the other hand, the criteria classified as effects present values below the threshold, evidencing their receptor role in the model.

To obtain the final weighting of each influential factor, the weights adjusted by AHP and group aggregation technique were combined with the centrality of each factor obtained with DEMATEL, as shown in Table 8. In this way, the values in Table 9 are used in the evaluation of alternatives in later stages, considering both the individual relevance of each criterion and their mutual influence on the decision process.

Table 10 presents the decision matrix, which contains the numerical values obtained through the LCC, the LCA and the technical scales for each housing alternative.

Table 11 presents the final rankings obtained by TOPSIS, WASPAS, EDAS, MABAC and MARCOS, which show a high consistency among the different multicriteria decision making approaches. All methods agree on the same order of preference for the alternatives evaluated, identifying LSF as the best option. This result reinforces the robustness of LSF's performance in the criteria analyzed, validating its suitability as the optimal alternative.

4. Discussion of results

This study analyzes five construction systems for social housing, considering three dimensions: economic, environmental, and technical throughout the life cycle. All alternatives were designed by Peru's National Building Regulations, ensuring compliance with current structural and comfort standards. RCF-M, representing Peru's conventional system, was used as a reference to assess the relative performance of other technologies, including traditional and industrialized systems like bolted sandwich panels. An MCDM analysis integrating costs, environmental impacts, and technical performance identified LSF as the most optimal option, followed by RCW, RCF-CP, RCF-M, and LBSPS.

These findings are particularly relevant for programs such as Techo Propio and Fondo Mi Vivienda, which promote large-scale housing delivery under strict budget and time constraints. Identifying LSF as a system that outperforms traditional methods in environmental and economic terms provides actionable insights for policymakers and developers in Peru's rapidly urbanizing areas.

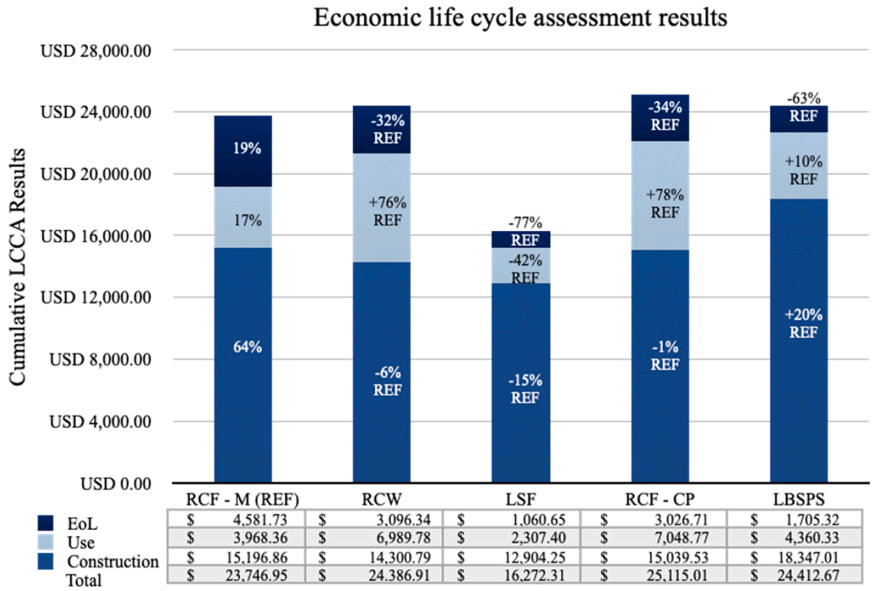

Fig. 8. Economic life cycle assessment results.

Table 5
Relevance of AHP group experts.

Definition of the experts' profile	Attribute	D1	D2	D3	D4	D5
Expertise						
Years of professional activity	PEk	35	20	20	13	12
Years of sustainability experience	ESk	13	3	3	1	1
Research						
Academic level	ADk	3	2	2	1	1
Scientific generation	AAk	3	1	1	0	0
Specific knowledge						
Construction Engineering	Kc1	4	4	4	4	4
Structural design	Kc2	4	4	4	2	2
Budgeting	Kc3	4	3	3	4	3
Enviromental assessment	Kc4	4	3	3	1	1
Social assessment	Kc5	3	2	2	2	1
Expert's inconsistency	ε_k	0.393	0.315	0.569	0.257	0.517
Coefficient	ψ_k	0.780	0.500	0.500	0.338	0.295
Credibility of the expert	θ_k	0.477	0.349	0.267	0.310	0.232

Table 6
Weights resulting from the AHP pairwise comparison matrices weighted with the credibility of each expert.

Criteria	DM1	DM2	DM3	DM4	DM5	AHP - G
C1	0.101	0.082	0.083	0.072	0.072	0.250
C2	0.032	0.041	0.012	0.036	0.010	0.080
C3	0.024	0.022	0.011	0.017	0.010	0.052
C4	0.040	0.038	0.036	0.038	0.031	0.112
C5	0.055	0.041	0.036	0.042	0.031	0.126
C6	0.040	0.038	0.036	0.038	0.029	0.111
C7	0.087	0.043	0.032	0.033	0.027	0.136
C8	0.099	0.043	0.021	0.033	0.021	0.134

Notably, this study uses a cradle-to-grave approach—still uncommon in Latin America, where cradle-to-gate studies predominate [5] or studies focused on specific stages of the life cycle [12]. By incorporating all phases, including use and EoL, a more realistic representation of the total environmental impact of each alternative is obtained [11]. This is especially relevant in countries such as Peru, where construction practices and waste management systems show great regional variability. The need for comprehensive scope is consistent with Kamali & Hewage [38], who highlight that partial LCAs can obscure important sustainability trade-offs across different life cycle stages. The study also contributes to bridging the gap in Latin American literature regarding complete cradle-to-grave assessments, offering a replicable framework for urban districts experiencing similar urbanization challenges. This aligns with recent reviews such as that of Dsilva et al. [17], which emphasize the importance of LCA for material optimization in the construction sector to support circular economy transitions in developing regions.

In environmental terms, the LCA shows that the traditional RCF-M system generates the highest carbon footprint in the manufacturing stage, primarily due to the energy-intensive fired brick production process. This aligns with previous studies on ceramic material impacts in residential buildings [37,53]. In contrast, LSF exhibits lower emissions thanks to its lightweight structure and more efficient logistics, consistent with findings from Bianchi et al. [8], Aghazadeh et al. [1], and Kamali et al. [39], who all underscore the environmental benefits of lightweight and modular systems. However, in the TETP category, LSF shows a greater impact due to the steel galvanizing process, which introduces toxic substances throughout the material's life cycle, demonstrating that not all of LSF's benefits are generalizable. This observation highlights the importance of using both midpoint and endpoint indicators, as the aggregation of individual categories can hide relevant negative effects, as discussed by Finnveden et al. [23], who warns about the loss of environmental traceability in highly aggregated indicators, and Hauschild et al. [31], who emphasize that the combination of both levels improves transparency and interpretation of results.

System-specific construction methods also influenced impacts observed during the construction phase, mainly due to variations in mechanization and energy requirements. The high emissions in the LBSPS system can be attributed to its reliance on specialized equipment throughout the entire process—from factory prefabrication to transportation and on-site installation. In contrast, other systems showed lower impacts due to more conventional, labor-intensive construction techniques with reduced mechanization. These differences are consistent with the construction-phase energy intensities obtained from the BEDEC database, which accounts for technical execution parameters such as construction method, degree of mechanization, and material specifications.

Table 7
Total relationship matrix for criteria.

	C1	C2	C3	C4	C5	C6	C7	C8
Construction Cost – C1	**0.1363**	**0.3331**	**0.1865**	**0.2261**	**0.2147**	**0.3681**	**0.1445**	0.0682
Maintenance Cost – C2	0.0173	0.0113	0.0880	0.0731	0.0445	0.0833	0.0022	0.0010
EoL Cost – C3	0.0078	0.0056	0.0040	0.0067	0.0145	0.0439	0.0010	0.0005
Ecosystem – C4	0.0842	0.0412	0.0275	0.0426	**0.3610**	**0.2340**	0.0107	0.0051
Human Health – C5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Resources – C6	**0.1938**	**0.1395**	**0.1004**	**0.1675**	**0.3621**	0.0963	0.0246	0.0116
Duration of works – C7	**0.4108**	**0.1207**	0.0677	**0.1023**	**0.1045**	**0.1372**	0.0522	0.0246
Technical necessity – C8	**0.3242**	**0.2159**	0.0835	0.0755	0.0697	**0.1157**	**0.1612**	0.0195

Table 8
Direct effect, indirect effect, weights and ranking of criteria.

	Influencing degree *D* value	Influenced degree *R* value	Centrality *D* + *R* value	Cause degree *D* - *R* value	Attribute	AHP - G	Final weight	Ranking
C1	1.678	1.174	2.852	0.503	Cause	0.25	0.408	1
C2	0.321	0.867	1.188	−0.546	Effect	0.08	0.055	7
C3	0.084	0.558	0.641	−0.474	Effect	0.05	0.019	8
C4	0.806	0.694	1.500	0.112	Cause	0.11	0.096	4
C5	0.000	1.171	1.171	−1.171	Effect	0.13	0.084	6
C6	1.096	1.078	2.174	0.017	Cause	0.11	0.137	2
C7	1.020	0.397	1.417	0.623	Causa	0.14	0.110	3
C8	1.065	0.130	1.196	0.935	Cause	0.13	0.091	5

Table 9
Criteria and indicators considered in MCDM.

Perspective	Criteria		Indicator		Description
Economic	Construction Cost	C1 41 %	Construction cost (USD)	I1 100 %	Investment required for materials, equipment, and labor.
	Maintenance Cost	C2 5 %	Preventive maintenance (USD)	I2 100 %	Preventive maintenance costs for coatings to protect against corrosion and carbonation.
			Decenal maintenance (USD /m2.10years)	I3 100 %	Cost of maintenance for the first 10 years.
	EoL Cost		Structure overthrow (USD)	I4 25 %	Cost of demolishing the structure using machinery.
		C3 2 %	Waste crushing (USD)	I5 25 %	Cost of shredding construction waste for recycling or disposal.
			Waste treatment and transport (USD)	I6 25 %	Waste sorting: crushed concrete and masonry are transported to the landfill, while steel and CFS profiles are sent to the steel mill for recycling.
			Treatment and transport waste (USD)	I7 25 %	Crushed concrete and masonry are taken to the landfill, while steel and CFS profiles are recycled at the steel mill.
Environmental	Ecosystem	C4 10 %	Ecosystem quality (Points)	I8 100 %	Annual loss of species in a specific region (species.year).
	Human health	C5 8 %	Human health (Points)	I9 100 %	Measures the impact in terms of disabilities and deaths (DALY)
	Resources	C6 13 %	Resources (Points)	I10 100 %	Energy required for future extraction of minerals and fossil fuels (USD)
Technical	Duration of works	C7 11 %	Execution schedule (scale)	I11 100 %	Duration of works. (Literature reference / experience)
	Technical necessity	C8 9 %	Need for skilled labor (scale)	I12 100 %	Assessment of specialized labor requirements for different construction methods (AHP).

Table 10
Decision matrix.

Criteria	Unit	RCF - M	RCW	LSF	RCF - CP	LBSPS
C1	USD/m^2	15,196.859	14,300.794	12,904.255	15,039.526	18,347.011
C2	USD/m^2	3968.358	6989.780	2307.402	7048.772	4360.334
C3	USD/m^2	4581.730	3096.337	1060.655	3026.711	1705.324
C4	Points	3.297	2.441	3.183	2.518	2.822
C5	Points	15.362	13.401	10.813	14.118	16.993
C6	Points	41.536	36.258	30.182	38.166	51.923
C7	Scale	0.323	0.216	0.194	0.161	0.106
C8	Scale	0.066	0.118	0.253	0.190	0.374

Moreover, prefabricated systems like RCF-CP and LBSPS exhibit EoL benefits, as they allow for controlled demolition and easier separation of materials for recycling. This aligns with circular economy strategies and supports the conclusions of Pomponi & Moncaster [62] and Zhao et al. [88]. Similarly, Fang et al. [20] emphasize the role of early-stage design strategies' role in reducing embodied carbon across the life cycle, particularly structural system selection and modularization.

For the full LCC analysis revealed that LSF and RCF-M offer economic advantages in initial investment and maintenance due to the reduced need for surface treatments. In contrast, concrete-based systems like

Table 11
Scores and ranking for each MCDM technique.

	TOPSIS	R	WASPAS	R	EDAS	R	MABAC	R	MARCOS	R
RCF - M	0.526	4	0.723	4	0.483	4	−0.061	4	0.614	4
RCW	0.655	2	0.760	2	0.711	2	0.174	2	0.644	2
LSF	0.681	1	0.834	1	0.922	1	0.305	1	0.715	1
RCF - CP	0.603	3	0.727	3	0.588	3	0.094	3	0.618	3
LBSPS	0.360	5	0.647	5	0.209	5	−0.302	5	0.556	5

RCW involve higher use-phase expenses due to protective and anti-corrosion requirements. These findings align with Vitorio Junior et al. [81], who emphasize the importance of including operation and maintenance in economic assessments.

Selecting the most suitable construction alternative requires a comprehensive evaluation of economic, environmental, and technical criteria, as each influences project sustainability and feasibility differently. This study weighted the criteria using AHP and analyzed their interrelations via DEMATEL. In addition, uncertainty was addressed with sensitivity analysis and the group aggregation technique, allowing for the evaluation of how changes in criteria weights impact the prioritization of alternatives. These approaches (hierarchy, criteria interaction, and uncertainty) have been identified as key elements in multicriteria decision making, according to Baykasoǧlu & Gölcük [6] and Zhu et al. [90].

The contrast between alternatives across the evaluation criteria (Fig. 9) underscores the selected framework's internal consistency and practical relevance. The observed dispersion reflects meaningful trade-offs, reinforcing the ability of the criteria to differentiate performance and support more robust decision-making. For instance, LSF excels in economic aspects such as EoL cost (C3), while LBSPS shows stronger results in execution time (C7), and RCF-M performs well in terms of labor requirements (C8).

The results indicate that the criterion with the most significant weight in decision-making was C1, followed by C6 and C7. This finding is consistent with previous studies that highlight the determining role of initial cost in the viability of construction systems in social housing projects. In addition, its relationship with criterion C8 and C7 underlines its relevance in the planning and implementation phases. In technical terms, criterion C8 strongly influenced C1, C2 and C7, influencing criterion C6. Regarding the environmental dimension, the results suggest that prioritizing sustainability can significantly modify decision-making, as criteria C4 and C5 were highly influential. This explains why the LSF option, which showed less environmental impact on the LCA, was the most favorable alternative. In contrast, the criteria with lower weight - C2, C3, and C5 - were effect factors, i.e., they do not drive the selection of the construction method but depend on the decisions made on the influential factors.

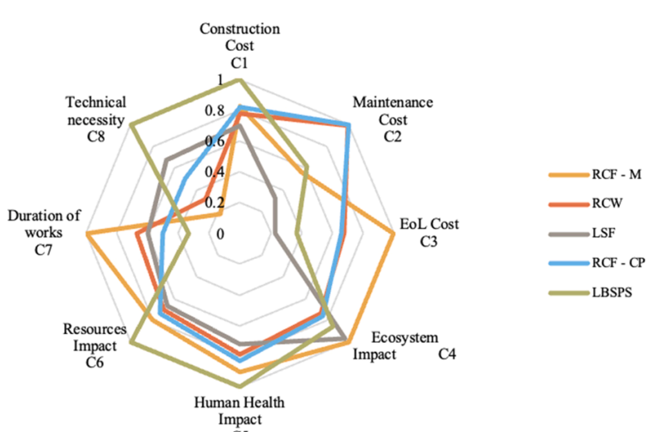

Fig. 9. Comparison of criteria between alternatives.

Although LSF emerged as the top-performing alternative in the final ranking, it is important to note that not all systems performed equally across all evaluation dimensions. While LSF excelled in cost-related criteria such as C1 and C3, other alternatives showed relative advantages in specific aspects. For example, RCW demonstrated favorable environmental performance (C4), RCF-M benefited from lower technical requirements (C8), and LBSPS stood out in execution speed (C7). However, the overall ranking results from the weighted aggregation of all criteria reflect their relative importance as defined through the AHP method. This outcome underscores the relevance of combining multiple decision-making tools to reveal the trade-offs among alternatives and justify their final positioning within the multicriteria framework.

The integrated multicriteria evaluation showed high consistency among the methods used (TOPSIS, WASPAS, EDAS, MABAC, and MARCOS), with LSF consistently ranked as the best-performing option, followed by RCW and RCF-CP (Fig. 10). To assess the robustness of these results, a comprehensive sensitivity analysis was conducted, involving 17 scenarios that included $a \pm 15$ % variation in the weight of each criterion and a scenario with equal weights across all criteria. This approach enabled an evaluation of how expert judgment or prioritization changes could affect the final rankings. The results confirmed that the rankings remained stable in most cases, particularly for the top-ranked alternative (LSF), which retained its position in over 90 % of the scenarios. Minor shifts were observed in mid- and lower-ranked alternatives depending on the criteria modified, especially those related to technical performance (C7 and C8). This indicates that while the overall decision is robust, the methodology remains sensitive enough to capture nuanced trade-offs under different planning priorities.

This robustness reinforces the value of integrating AHP (for criteria weighting), DEMATEL (for evaluating interdependencies), and multiple MCDM techniques to strengthen result reliability and support evidence-based decision-making. The integration of multiple MCDM methods, as recommended in Sánchez-Garrido et al. [68], allows contrasting different decision models and increasing the transparency of the process. The stability of the ranking suggests that decisions do not depend on small changes in the weighting of criteria, which strengthens the usefulness of the model for applications in public policies or technical tenders.

To evaluate the performance of each MCDM method, the differentiation capacity is analyzed. This is quantified through the index C_i, which measures how effectively a given technique is based on their scores, as proposed by Navarro et al. [55] for comparative method assessment:

$$C_i = \frac{Q_{best,i} - Q_{2nd,\ i}}{Q_{best,\ i} - Q_{worst,\ i}} \quad (2)$$

where $Q_{best,i}$ is the score of the best solution according to each $MCDM_i$, $Q_{2nd,\ i}$ the score of the second-best solution, and $Q_{worst,\ i}$ is the score of the worst alternative. The distinguishing indices of each solution are shown in Table 12:

WASPAS and MARCOS appear to be more effective in distinguishing between alternatives in this context. This is consistent with Navarro et al. [55] observation that hybrid or average-based models can provide stronger separation due to their mathematical structure, unlike distance-based methods such as TOPSIS.

In addition to the sensitivity analysis on criteria weights to assess

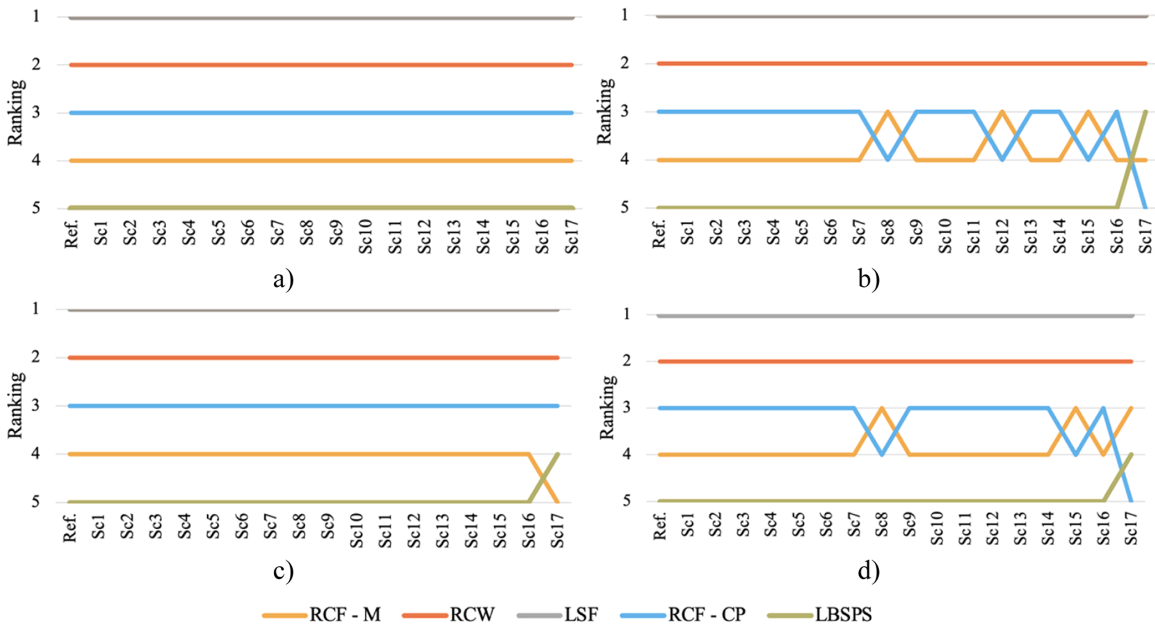

Fig. 10. Sensitivity analysis of MCDM model: a) TOPSIS, b)WASPAS, c) EDAS and MABAC, d) MARCOS.

Table 12
Differentiation indices for each MCDM method.

	TOPSIS	WASPAS	EDAS	MABAC	MARCOS
$Q_{best,i} - Q_{2nd,\ i}$	0.026	0.075	0.211	0.131	0.070
$Q_{best,\ i} - Q_{worst,\ i}$	0.321	0.187	0.713	0.607	0.158
C_i	0.082	0.3978	0.2956	0.2162	0.4443

ranking robustness, a one-way sensitivity analysis was also conducted on the normalized input values of the MCDM matrix. Specifically, the three most influential criteria (C1, C6, and C7), identified using AHP with group aggregation, were individually varied by ±15 %, while all other values remained unchanged. This perturbation range follows literature recommendations for LCA-based sensitivity tests [30]. The results in Table 13 show high-ranking stability across all methods, with only minor shifts in intermediate positions, particularly in the TOPSIS and MARCOS models. The LSF system consistently ranked first in all scenarios, reaffirming the robustness of the integrated decision-making framework.

5. Conclusions

This study evaluated different construction systems for low-income housing using a multi-criteria approach integrating LCA, LCC, and MCDM. Five alternatives were analyzed: (RCF-M) reinforced concrete columns and beams with brick masonry, (RCW) cast-in-place concrete slabs with metal formwork, (LSF) Light Steel Frame with gypsum panels, (RCF-CP) reinforced concrete columns and beams with sandwich panels, and (LBSPS) lightweight structure of bolted concrete sandwich panels.

The LCA covered the manufacturing, construction, use (maintenance), and EoL phases, enabling a complete life cycle analysis ('cradle to grave') through midpoint and endpoint approaches. The LCC estimated costs for construction, maintenance, and EoL. Eight criteria and 12 indicators were defined within an MCDM framework to rank the alternatives. A sensitivity analysis was also conducted to evaluate ranking stability and ensure the robustness of the results.

The results revealed that no single alternative excels in all criteria, showing notable differences in cost, environmental impact, and technical aspects:

- RCF-M, commonly used in Peru, has long execution times, high environmental impacts, and EoL costs but low skilled labor requirements.
- RCW shows average performance in most criteria, which is notable for high maintenance costs and low labor demand.
- LSF is the most economical in all cost phases (construction, use, EoL). While its manufacturing phase is impact-intensive, it shows the lowest total environmental impact.
- RCF-CP is among the most expensive in construction and use but has minimal environmental impact and skilled labor needs.
- LBSPS is the most expensive to build, with moderate maintenance and EoL costs. It enables fast execution but has high environmental impacts and skilled labor requirements.

These findings highlight the value of combining LCA and LCC in sustainable construction decisions. Concrete is the primary contributor to environmental impact in all systems except RCF-M, where reinforcing steel and brick play a larger role. This underlines the need to evaluate materials with their construction methods, as system-specific factors

Table 13
Sensitivity analysis of MCDM rankings (±15 % variation in key criteria).

ALTERNATIVES	TOPSIS		WASPAS		EDAS		MABAC		MARCOS	
	+ 0.15	−0.15	+ 0.15	−0.15	+ 0.15	−0.15	+ 0.15	−0.15	+ 0.15	−0.15
RCF - M	4	4	4	4	4	4	4	4	**3**	4
RCW	2	**1**	2	2	2	2	2	2	2	2
LSF	1	**2**	1	1	1	1	1	1	1	1
RCF - CP	3	3	3	3	3	3	3	3	**4**	3
LBSPS	5	5	5	5	5	5	5	5	5	5

may mitigate or exacerbate their impacts. Despite its high environmental burden, concrete remains prevalent due to execution efficiency—which is crucial for large-scale projects like social housing. Shorter construction times can optimize costs and lower impacts by reducing prolonged machinery use. Nevertheless, MMC represent an emerging technology that could potentially transform the industry. Although they still require further research for widespread adoption, their application in repetitive and standardized projects could facilitate the transition to more sustainable systems.

In this sense, the results reinforce the need to further evaluate modern materials and techniques, especially in comparison with traditional systems, to better understand their challenges and opportunities. This study offers valuable information for MSHPs, presenting a detailed analysis of advantages and disadvantages throughout the life cycle of the evaluated alternatives.

By calculating the differentiation capacity C_i, we assessed each method's ability to distinguish between alternatives. WASPAS and MARCOS demonstrated the highest differentiation capacity, aligning with Navarro et al. [55], who note that hybrid or average-based models often provide more precise separation due to their mathematical structure. In contrast, methods like TOPSIS, EDAS, and MABAC showed more limited distinguishing power. Thus, while applying multiple MCDM methods remains good practice, we recommend MARCOS and WASPAS for professionals seeking greater transparency and decisiveness in evaluation processes.

This study has limitations that offer helpful directions for future research. First, it focused on environmental, economic, and technical aspects, excluding the social dimension of sustainability. Including SLCA or stakeholder engagement tools could provide a more holistic view of structural systems for mass housing. Second, although expert weighting helped address uncertainty in MCDM, more robust methods—such as fuzzy or neutrosophic logic—could better represent ambiguity and variability in expert opinions and criteria prioritization. Third, while the study is contextualized in Carabayllo (Lima, Peru), reflecting local practices and socioeconomic conditions, the framework applies to regions with similar constraints and development patterns. Future research may examine its adaptability across diverse regions, potentially incorporating dynamic datasets and local policy scenarios to enhance relevance and accuracy.

CRediT authorship contribution statement

Ximena Luque Castillo: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Victor Yepes:** Writing – review & editing, Writing – original draft, Validation, Supervision, Data curation, Conceptualization.

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.buildenv.2025.113294.

Data availability

Data will be made available on request.

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