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Research paper

A multi-criteria life-cycle decision framework for sustainable modular hospitals in seismic regions

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ABSTRACT

The rapid deployment and life-cycle performance of hospitals are critical in seismic-prone regions, where construction speed affects social resilience and access to healthcare services. This study proposes a decision-support framework that integrates life cycle assessment (LCA), life cycle cost (LCC), social life cycle (S-LCA), and temporal performance within a multi-attribute decision-making (MADM) approach. Criteria weights are determined using the Best–Worst Method (BWM), with expert-judgment consistency ratios verified to reduce subjectivity; alternative rankings are obtained via an ensemble of emerging MADM techniques (EDAS, MABAC, and MARCOS). The framework is applied to a reference hospital block derived from a real healthcare complex and evaluated under seismic conditions representative of Quito, Ecuador, comparing three prefabricated volumetric modular systems—reinforced concrete, hot-rolled steel, and a concrete–steel hybrid—against a conventional cast-in-place reinforced concrete alternative. Temporal performance is quantified via a normalized indicator, ET, which accounts for reduced construction duration and financial benefits from earlier operational start-up. Environmental, social, and economic uncertainties are addressed through Monte Carlo simulation and sensitivity analyses, based on a process-based comparative life-cycle approach using secondary data sources and indicator-based social assessment, rather than a fully exhaustive ISO-compliant life-cycle assessment. Hot-rolled steel modular systems demonstrate the best overall performance, significantly reducing environmental and social impacts and construction time, despite higher initial costs. Sensitivity analyses confirm that the ranking remains stable under parameter variations of ±15%. The proposed framework offers a replicable, transparent tool to support procurement, planning, and emergency decision-making for critical healthcare infrastructure in high-seismic areas.

1. Introduction

The global construction sector is currently facing stagnant productivity characterized by rising costs, labor shortages, and concerns about safety and sustainability [1]. This stagnation is exacerbated by rapid urbanization, as the global built area is expected to double by 2050, exceeding 415 billion square meters [2]. As a major environmental player, the industry consumes 32% of global energy, produces 34% of CO_2 emissions, and generates 40% of global solid waste, making it one of the main drivers of climate change [3]. To meet international climate goals and satisfy demand for resources, the industry must undergo a technological transformation. Off-site construction and modular construction have become essential strategies for improving resource efficiency and environmental performance [3–5]. Modular construction represents the pinnacle of prefabrication, allowing 70% to 95% of building components to be manufactured in controlled industrial environments. This approach significantly enhances productivity and quality control while minimizing waste on-site, providing a scalable solution to the growing pressures on natural resources and the environment [6].

Prefabricated volumetric modular buildings (PVMBs) are ideal for high-rise projects with repetitive layouts; however, increased height complicates both structural and logistical requirements [7]. To address

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these challenges, recent research focuses on enhancing performance against seismic and wind forces [8]. While reinforced concrete modules offer robustness, steel modules are often preferred for their superior strength-to-weight ratio and ease of connection, which lowers transportation and installation costs [5]. Structurally, PVMBs are categorized by their load transfer mechanisms: concrete modules typically use shear wall systems, whereas steel modules utilize corner-supported frame systems. In these configurations, gravity loads are managed by beams and columns, while lateral stability is ensured through specialized bracing systems, shear walls, or cast-in-situ cores, to maintain safety under critical loading conditions [9,10].

While modular construction is recognized for promoting sustainable practices [11,12], research remains heavily biased toward environmental life cycle assessments (LCA). Existing studies confirm that modular methods tend to have a lower environmental impact than traditional construction [7,13]; however, the remaining pillars of sustainability are still insufficiently addressed. Economic life cycle assessments (LCC) have received minimal attention, and social life cycle assessments (S-LCA) remain largely unexplored. Assessing the social dimension is particularly difficult due to the lack of standardized indicators, scarcity of data, and absence of universal methodological frameworks [14]. Furthermore, the complexity of diverse stakeholder interests, cultural contexts, and issues such as social justice and community well-being makes a comprehensive assessment of social impact in the modular sector an ongoing challenge [15].

In the absence of a universally standardized S-LCA framework for modular hospital construction, the indicator selection in this study followed a structured filtering process. Initially, commonly recognized stakeholder categories and impact areas described in established S-LCA methodological literature [14,15] were reviewed. These generic categories were subsequently screened to retain only those directly relevant to hospital infrastructure and to highly seismic urban environments, where occupational safety, service continuity, local employment generation, and community resilience are particularly critical. The preliminary indicator set was then discussed and refined through expert consultation to ensure alignment with Ecuador's regulatory framework and healthcare infrastructure conditions.

Modular construction is increasingly recognized for its ability to meet rigorous project requirements, especially in terms of speed of delivery. This agility is essential in situations that require the provision of large-scale housing within a short timeframe, such as post-disaster reconstruction or the rapid establishment of essential facilities, including medical centers and hospitals. A notable example is Leishenshan Hospital in Wuhan, China, which was built in just 12 days during the COVID-19 pandemic [16]. The success of such projects suggests that modular technologies are poised to become the cornerstone of rapid healthcare infrastructure development [17]. Beyond emergency applications, PVMBs offer distinct advantages over traditional methods, including greater scheduling reliability, superior quality control, reduced labor dependency, and a significantly smaller environmental footprint [18].

Despite its significant potential, the global adoption of modular construction is hampered by a limited understanding of its comparative advantages over conventional methods [8]. These advantages depend primarily on the adaptability of project stakeholders and regional market dynamics, two factors that drive ongoing research. While current studies prioritize the optimization of the execution phase [19] the literature tends to underestimate the actual execution time. As a critical variable linking speed of delivery to economic, environmental, and social performance, its omission prevents informed decision-making for the implementation of PVMBs. Therefore, construction time should be integrated as a quantifiable, transferable, and decision-oriented indicator within a balanced evaluation framework that encompasses temporal, financial, and social dimensions.

Effective decision-making in the construction sector requires a scientific and systematic approach grounded in both qualitative and quantitative analyses, rather than reliance on intuition [20]. This approach is crucial for ensuring optimal resource utilization, cost-effectiveness, and sustainable outcomes [21]. Multi-Criteria Decision-Making (MCDM) methods, particularly Multi-Attribute Decision-Making (MADM) techniques, provide valuable tools for evaluating multiple criteria and identifying optimal solutions [22]. Recent review studies emphasize the prevalence of well-established methods due to their maturity and ease of application [22,23]. However, comprehensive analyses also reveal a lag in the adoption of more advanced MADM approaches within the construction industry. As a result, the use of emerging MADM techniques under comparable conditions has been explicitly recommended to enhance robustness and decision reliability [24,25].

Although research on PVMB has advanced, the current scientific literature remains fragmented from a methodological standpoint, obscuring the full potential of this technology. Previous studies, particularly those by [26,12,27] have employed MADM techniques; however, these approaches tend to focus on isolated sustainability dimensions rather than a holistic life-cycle perspective. Even the cutting-edge work of [28,29], which integrates the three pillars of sustainability, does not explicitly incorporate construction time as a fundamental decision criterion. This omission is critical for essential infrastructure such as hospitals, where speed of construction directly determines community access to vital healthcare. Furthermore, the diversity of materials in the existing literature is limited; only [29] comparatively evaluates steel, concrete, and wood, but without considering the rigorous demands of highly seismic environments. Consequently, there is a clear need for integrated decision frameworks that jointly assess sustainability performance and execution speed under demanding seismic conditions.

To address these gaps, this study aims to develop and apply an integrated multi-criteria life-cycle decision framework capable of simultaneously evaluating environmental, economic, social, and temporal performance in prefabricated volumetric modular building (PVMB) systems under seismic conditions. The framework is applied to a reference hospital block derived from a real healthcare complex in Ecuador and used as a controlled comparative case study, preserving its architectural and functional configuration while enabling the evaluation of alternative structural systems under equivalent conditions.

Specifically, the research is guided by the following questions:

(RQ1) How can construction time be systematically incorporated as a quantified and economically meaningful decision variable within a life-cycle sustainability framework?
(RQ2) Do modular steel, concrete, and hybrid PVMB systems exhibit consistent superiority over conventional construction when evaluated under integrated sustainability and temporal criteria?
(RQ3) How robust are the resulting rankings under variations in weighting schemes and technical uncertainty?

To answer these questions, construction time is incorporated through a normalized economic–temporal indicator that enables a balanced comparison between life-cycle impacts and early operational benefits. Criteria weighting is performed using the Best–Worst Method (BWM), while alternative ranking is conducted using complementary emerging MADM techniques to enhance methodological robustness. The remainder of this paper is structured as follows. Section 2 describes the materials and methods, including the methodological framework, expert weighting procedure, and life-cycle assessment approach. Section 3 presents the case study results, multi-attribute optimization, and robustness analyses. Finally, Section 4 discusses the implications and conclusions of the study.

2. Materials and methods

This research proposes a quantitative methodological framework based on MADM for selecting the optimal PVMB alternative. Using a cradle-to-grave approach, the model integrates sustainability and temporal efficiency through eight criteria and 15 indicators. The solution is obtained by combining emerging MADM methods, including pair comparison for weighting criteria according to expert judgment, and distance-to-reference-point methods for final classification. The stability of the results is validated through a three-stage sensitivity and robustness analysis: First, the uncertainty in the weighting of criteria is evaluated. Second, technical uncertainty is addressed using stochastic matrices linked to the variability of life cycle analyses (LCC, LCA, and S-LCA). Finally, parametric uncertainty is incorporated through stochastic alterations in the performance of the decision criteria. The alternative with the most consistent performance across these scenarios is identified as the optimal solution (Fig. 1).

For clarity, the methodological framework shown in Fig. 1 is organized into three sequential stages. **Stage 1** comprises the definition of the hierarchical evaluation structure and the determination of criteria weights through expert consultation and the Best–Worst Method (Section 2.3). **Stage 2** involves the empirical application of the framework through the defined case study, including life-cycle performance quantification (LCC, LCA, S-LCA) and temporal performance assessment (Section 2.4). **Stage 3** consists of the multi-attribute optimization process (EDAS, MABAC, MARCOS) and the subsequent sensitivity and robustness analyses (Sections 3.6 and 3.7). This structure ensures traceability between the conceptual framework and the operational evaluation steps.

The selection of the specific MADM techniques responds to complementary analytical requirements within the decision framework rather than to claims of methodological novelty. The Best–Worst Method (BWM) was adopted for criteria weighting due to its reduced cognitive burden compared to full pairwise comparison matrices and its built-in consistency verification mechanism, which enhances reliability in expert-based weighting processes.

For the ranking stage, EDAS, MABAC, and MARCOS were selected because they are distance-based but conceptually distinct aggregation methods. EDAS evaluates alternatives based on their positive and negative deviations from the average solution; MABAC determines performance through border approximation areas relative to a reference domain; and MARCOS relies on comparisons with both ideal and anti-ideal reference points. Although mathematically compatible, these methods operate under different decision logics. Their combined application enables cross-validation of ranking stability and reduces

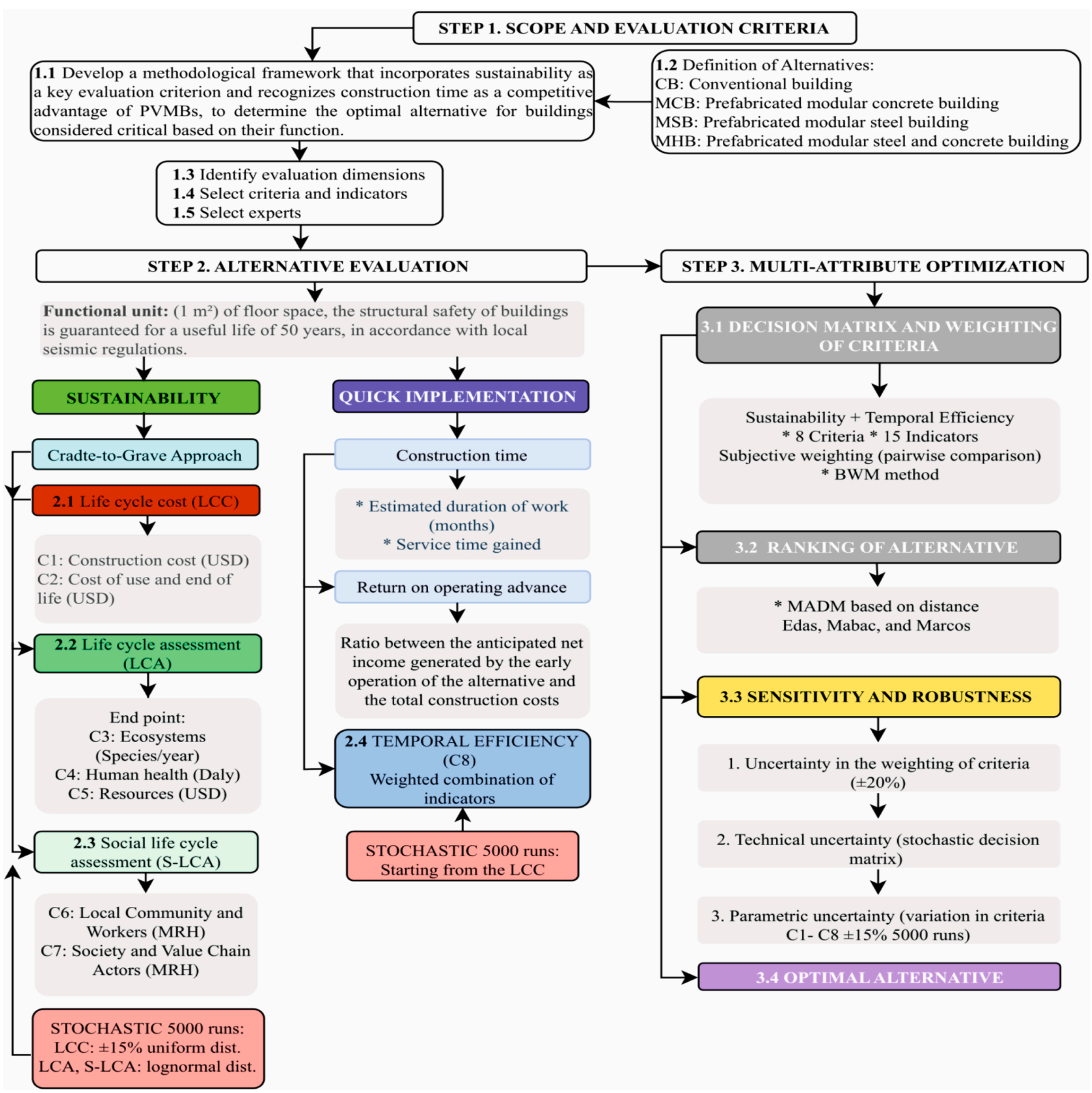

Fig. 1. Methodological framework of the research.

dependence on a single decision paradigm, thereby strengthening the robustness of the final selection.

A panel of six experts was convened to select and analyze the criteria and indicators used to evaluate sustainability and temporal efficiency. The detailed selection criteria, professional profiles, and consistency validation procedure of the experts are described in Section 2.3.3 to ensure transparency and methodological traceability. During this process, the availability, accuracy, and applicability of data were carefully examined, with an emphasis on minimizing the number of criteria to streamline the evaluation and mitigate potential limitations [30]. The experts also determined the relative importance of each criterion. This analysis yielded a hierarchical structure that organizes the assessment parameters into dimensions, criteria, and quantitative indicators, thereby forming the foundation of the evaluation framework. Table 1 presents the resulting evaluation tree, which integrates the three dimensions of sustainability along with temporal efficiency.

2.1. Sustainable performance assessment of earthquake-resistant modular structures

Modular construction represents an effective and well-justified alternative for advancing sustainability objectives within the built environment [31]. A comprehensive evaluation of the sustainability performance of PVMB necessitates an in-depth analysis across the entire life cycle of the structure. Accordingly, this study integrates economic, environmental, and social dimensions to quantify the impacts of manufacturing and construction, extending through to the use phase and end-of-life stages. While analysis was traditionally limited to the operational phase of buildings, contemporary studies have shown that the impacts arising from the manufacture of materials and construction processes can account for the majority of the total life cycle impact [32].

The economic dimension encompasses all costs incurred throughout the structure's service life, as prescribed by ISO 15,686–5 [33]. Simultaneously, environmental impacts are evaluated following the methodological structure of ISO 14,040/44 [34] while the social dimension adheres to the UNEP/SETAC Guidelines for Social Life Cycle Assessment [35]. Adherence to these standards ensures a systematic and transparent four-phase framework: goal and scope definition, inventory analysis, impact assessment, and interpretation of results.

It is important to clarify that, although internationally recognized standards guided the methodological structure, the present study adopts an indicator-based life-cycle evaluation approach focused on selected and decision-relevant impact categories rather than a fully exhaustive ISO-compliant assessment covering all possible impact categories and lifecycle modules. This approach is intended as a comparative, process-based evaluation to ensure consistency across alternatives within the MADM framework. The selection of indicators and phases was constrained by data availability, comparability across alternatives, and relevance to hospital infrastructure under seismic conditions.

In the case of PVMB, evaluation criteria must be tailored to reflect their distinctive characteristics and the specific conditions of each project. These criteria can be further decomposed into sub-criteria or quantifiable indicators that enable the monitoring and evaluation of changes throughout the life cycle, thereby ensuring effective alignment with sustainability objectives [36]. In general, the selected criteria and indicators should be applicable, representative, comprehensible, complementary, measurable, and verifiable [37]. The integration of these criteria through MADM facilitates a holistic assessment of sustainability performance, supporting more informed and optimized decision-making in the design, implementation, and management of modular buildings.

2.1.1. Alternatives and scope definition

This study assessed the impacts associated with the construction of structural elements for three earthquake-resistant PVMB alternatives: reinforced concrete modules (MCB), hot-rolled steel modules (MSB), and a hybrid system combining hot-rolled steel and reinforced concrete modules (MHB). For comparative purposes, a conventional cast-in-place reinforced concrete structure (CB) was included to quantify the relative advantages of modular construction. The evaluation encompassed structural elements, foundations, and masonry infill to ensure methodological consistency and a balanced comparison among systems. All building models were designed to resist seismic and gravitational loads in accordance with relevant seismic design standards and to demonstrate comparable structural performance.

Table 2 summarizes the structural systems of the proposed alternatives. The load transfer mechanisms differ across systems: shear walls and perimeter beams for the MCB, columns, beams, and bracing

Table 1
Dimensions, criteria, and evaluation indicators.

Dimensions		Criteria		Indicators	Unit
Economy	C1	Cost of construction	I1	Cost of construction	USD
	C2	Cost of use and end of life	I2	Preventive maintenance	USD
			I3	Decennial maintenance (first 10 years)	USD
			I4	Structure demolition	USD
			I5	Waste shredding	USD
			I6	Waste treatment	USD
Environmental	C3	Ecosystem quality	I7	Ecosystem quality	Species per year
	C4	Human health	I8	Human health	DALY
	C5	Resources	I9	Recycling	USD
Social	C6	Workers and Local Community	I10	Workers	MRH
			I11	Local Community	MRH
	C7	Society and Value Chain Actors	I12	Society	MRH
			I13	Value Chain Actors	MRH
Temporal performance	C8	Time efficiency	I14	Construction time	Score
			I15	Cost-time efficiency	Score

MRH: med risk hours
DALY: disability-adjusted life years

Table 2
Description of the structural systems of the alternatives.

Alternative	Description	% Pref. [a]	Reference
(MCB)[b]	Volumetric modules use corner shear walls with high beams and roof slabs. Horizontal connections are bolted, while vertical connections use bolts, nuts, and coupling beams steel for structural synergy.	75	[4]
(MSB)[b]	Volumetric modules feature columns, beams, and a concrete floor slab. Horizontal connections use bolted or welded plates, while vertical connections link columns. Bracing is required for seismic load demands.	90	[38,39]
(MHB)[b]	The MSB is modified by replacing the steel stiffeners with cast-in-place reinforced concrete shear walls to meet the seismic loading requirements of the building.	82	[38,39]
(CB)[b]	The conventional structural system consists of two-way reinforced concrete moment-resisting portal frames built on site, with a concrete mezzanine slab lightened in two directions.	–	–

[a] % of prefabrication determined based on cost.
[b] Each alternative incorporates a cast-in-place reinforced concrete foundation slab. The design includes soil improvement measures to achieve an allowable stress of 20 T/m^2 in all cases.

elements for the MSB, and cast-in-place columns, beams, and shear walls for the MHB. Furthermore, all modules are designed to ensure compatibility with transportation using commercially available vehicles and equipment, which may necessitate partial pre-assembly prior to final on-site installation.

The subsequent phase defines the functional unit in accordance with ISO 14,040, establishing system boundaries to ensure a consistent comparison across all alternatives. The selected unit is one square meter (1 m^2) of floor area, with structural integrity guaranteed for a 50-year service life as per seismic design standards. This life cycle spans from the completion of construction to final demolition or rehabilitation necessitated by seismic damage. By adopting a 'cradle-to-grave' approach, this definition standardizes results and ensures comparability across economic, environmental, and social dimensions.

However, not all lifecycle modules or impact subcategories defined in ISO standards were included. The assessment focuses on structural elements and associated processes that differ across alternatives and significantly influence sustainability performance, ensuring methodological consistency while avoiding overextension beyond reliable data boundaries.

The LCC encompasses expenses related to materials, supplies, equipment, machinery, tools, labor, transportation, and assembly. During the use phase, preventive maintenance costs are included to ensure a service life of 50 years. Preventive measures include the application of anti-carbonation coatings on concrete elements, anti-corrosion primers on steel components, and fire protection treatments that provide a minimum fire resistance of 60 min. At the end-of-life stage, the analysis accounts for costs associated with demolition, concrete crushing, material sorting, waste treatment, transportation to recycling facilities, landfill fees, and final disposal operations.

For the LCA, the manufacturing stage encompasses the extraction of raw materials, their transportation to production facilities, and the manufacture of key construction materials, including aggregates, cement, concrete, concrete blocks, mortars (made from cement and concrete), drywall, reinforcing steel, structural steel, and prefabricated steel components. Materials and components are transported to three main destinations: the precast plant, the ready-mix concrete plant, and the construction site. On-site activities include the mobilization and operation of heavy equipment and machinery. The construction phase encompasses all processes and machinery utilized in both the precast factory and on-site assembly operations. During the use phase, preventive maintenance materials are included to ensure a service life of 50 years. These treatments consist of anti-carbonation coatings for concrete elements and anti-corrosion fire-retardant mortar for steel components. The end-of-life phase involves dismantling, crushing, sorting, and recycling of concrete and steel elements. Transport routes for final disposal mirror those used in the manufacturing stage, with recyclable materials sent to steel mills and concrete recycling plants, while non-recyclable materials are directed to landfills. The S-LCA follows the framework established by ISO 14,040 and ISO 14,044, applying the same four phases—goal and scope definition, inventory analysis, impact assessment, and interpretation [40]—and incorporating the same processes considered in the LCA.

2.1.2. Inventory analysis

For the environmental assessment, input data were collected for each life cycle stage in accordance with the defined functional unit. Material quantities were derived from the structural systems and construction specifications of each alternative. As previously noted, transportation included three delivery points—the ready-mix concrete plant, the precast plant, and the construction site—with distances determined based on actual transport routes. The machinery employed during both the construction and end-of-life phases was modeled by estimating non-renewable primary energy consumption using data from the BEDEC database [41]. Energy consumption at the precast plant was determined based on its level of automation; for this study, an automation level of four was adopted, representing an intermediate degree of mechanization as defined by [42]. The use phase incorporated all materials and supplies required for preventive maintenance, while the end-of-life phase included transportation to recycling facilities and landfills, following real routes. All inventory components were modeled as interconnected processes using the Ecoinvent 3.7.1 database [43] within the OpenLCA 2.3 software environment [44].

When local Ecuadorian datasets were unavailable, internationally recognized databases (e.g., Ecoinvent and BEDEC) were used as proxy datasets. In such cases, transportation distances, energy mixes, and contextual parameters were adjusted where feasible to better approximate Ecuadorian conditions. Remaining geographical variability was addressed through the uncertainty characterization and stochastic sensitivity analyses described in Section 3.7.

In S-LCA, impact categories are evaluated through specific impact indicators that quantitatively measure the social performance of a product or process and are directly linked to the life cycle inventory data. The selection of appropriate indicators remains a complex task, as S-LCA is still an emerging field of study. Unlike environmental impacts, social impacts are not governed by natural laws but are primarily influenced by human perception and contextual factors; consequently, no universally accepted standard or reference framework for standardized application currently exists [45]. This study utilized the SOCA v2 database, which was derived from the PSILCA (Product Social Impact Life Cycle Analysis) database [46]. This integration enabled the alignment of processes from the Ecoinvent database with social modeling, allowing social assessments to be performed using the same life cycle processes as environmental assessments. Given the absence of Ecuador-specific social inventory databases compatible with process-based LCA modeling, SOCA v2 was employed using global average data as a proxy. This limitation is acknowledged as a constraint of regional specificity; however, its influence on ranking stability was examined through the robustness and stochastic analyses performed in Stage 3 of the methodological framework. Such consistency ensures methodological coherence and comparability across sustainability dimensions [47].

2.1.3. Impact assessment

Eight criteria, measured through 15 indicators, were employed to evaluate the three dimensions of sustainability. The LCC considered two criteria: C1, representing direct construction costs, and C2, encompassing costs incurred during the asset's use and end-of-life stages. Six indicators were used to quantify these impacts. Indicator I1 captures costs associated with the construction phase, including materials, supplies, equipment, machinery, tools, labor, transportation, and assembly. Indicators I2 and I3 address the economic impacts during the use phase. I2 accounts for preventive maintenance costs, including anti-carbonation coatings for concrete, anti-corrosion primers for steel, and fire protection treatments, while I3 represents decennial maintenance expenses. These indicators highlight the importance of systematic maintenance in ensuring the structure's functionality, quality, comfort, and safety throughout its service life [48]. Indicators I4, I5, and I6 relate to the end-of-life stage. I4 measures demolition costs, I5 assesses expenses related to concrete crushing, and I6 encompasses costs associated with sorting, waste treatment, transportation to recycling facilities, landfill fees, and final disposal.

Future decennial and end-of-life costs were discounted to present values via Eq. (1) using a social discount rate, following ISO 15,686–5. A social discount rate of 2% was selected following [49] who argue for lower rates in long-term infrastructure appraisal to avoid undervaluing future environmental and social impacts. While structural engineering standards typically suggest rates between 2% and 3% to account for long-term risks [50] adopting a rate lower than the financial market equivalent promotes greater investment in social and natural capital [51]. Although Ecuador does not prescribe an official social discount rate for healthcare infrastructure, this 2% value is consistent with guidance for long-term investments in developing countries, providing a balanced and conservative approach suitable for critical hospital projects in seismic-prone urban areas such as Quito.

$$LCC = \sum_{t=t_0}^{t_{SL}} C_i \Big/ (1+d)^{t-t_0} \tag{1}$$

Where LCC is the life cycle cost of the structure, C_i are the costs associated with time *t*, to is the time from the start of the period (*to=0*), t_{SL} is the expected number of years, and d is the discount rate.

The second set of criteria evaluates the environmental impacts of the alternatives. The OpenLCA software was employed to perform the LCA. The analysis utilized the Ecoinvent database, applying a semi-quantitative pedigree matrix approach to characterize data uncertainty through probability distributions [52]. This matrix evaluates five quality indicators—reliability, completeness, temporal correlation, geographical correlation, and technological correlation—introducing an uncertainty factor that, when combined with the pedigree data, yields the standard deviation of a lognormal distribution.

Environmental impacts were quantified using the ReCiPe method, which integrates both endpoint and midpoint approaches. The endpoint ReCiPe method assesses three damage categories: ecosystem quality (species lost per year), human health (disability-adjusted life years, DALYs), and resource availability (expressed in USD). The hierarchical (H) version of ReCiPe was adopted, as it accounts for long-term impacts. Results were normalized using the overall H/H [person·year] set. No discount rate was applied to environmental impacts since future emissions from the end-of-life phase were considered within a 50-year time horizon [53]. The midpoint approach provided a detailed breakdown of impacts across 18 environmental categories, offering higher granularity in the interpretation of results. Given the critical importance of CO_2 emissions in the construction sector, particular attention was devoted to assessing the global warming potential (GWP) category. The results of the environmental dimension were analyzed through three criteria corresponding to ReCiPe's endpoint indicators: Criterion C3 (Indicator I7) for ecosystem quality, Criterion C4 (Indicator I8) for human health, and Criterion C5 (Indicator I9) for resource availability. Each indicator captures the total cumulative impact over the entire life cycle.

The third group of criteria pertains to the social dimension of sustainability. The analysis was conducted using OpenLCA software in conjunction with the SOCA database, applying global average data to address gaps arising from incomplete regional or national datasets [54]. A semi-quantitative pedigree matrix was used to address data uncertainty. The SOCA database is derived from the PSILCA database; therefore, the Social Impact Weighting method was employed to quantify social impacts [55]. This method classifies impacts according to four principal stakeholder groups: workers, value chain actors, society, and the local community, which are further subdivided into 20 social and socio-economic subcategories encompassing 55 indicators. As in the environmental dimension, no discount rate is considered.

For the workers category, the indicators include child labor, forced labor, fair wages, working hours, discrimination, health and safety, social benefits, legal compliance, and freedom of association and collective bargaining. The value chain actors category considers fair competition, corruption prevention, and the promotion of social responsibility. The society category encompasses contributions to economic development, health, and safety. In contrast, the local community category addresses access to material resources, respect for indigenous rights, safe and healthy living conditions, local employment opportunities, migration, greenhouse gas emissions, and environmental footprint. These categories are consistent with the UNEP/SETAC guidelines for Social Life Cycle Assessment. Social impacts were quantified using the Mean Risk Hours (MRH) indicator. Results were evaluated using two criteria: Criterion C6, assessed through Indicators I10 (workers) and I11 (local communities), and Criterion C7, assessed through Indicators I12 (society) and I13 (value chain actors). All indicators are expressed in MRH per functional unit and represent impacts of S-LCA. The selected indicators represent the most decision-relevant social impact dimensions for hospital infrastructure projects under data availability constraints, rather than an exhaustive representation of all potential social impact categories.

2.2. Time efficiency of modular construction

In recent years, PVMBs have gained significant prominence compared to conventional methods, which offer safer processes, predictable schedules, enhanced quality control, reduced on-site labor requirements, minimized waste generation, and decreased dependence on environmental conditions [8]. The shorter construction time of PVMBs is due to a parallel workflow: fully equipped modules are manufactured in controlled environments, unaffected by weather conditions. At the same time, the foundations are built simultaneously on site. Once the foundations are ready, the modules are assembled, significantly shortening the time frame.

In contrast, traditional construction follows a sequential and linear approach, which increases exposure to external delays and labor constraints. This reduction in PVMB execution time enables earlier operational start-up, resulting in a direct economic benefit through accelerated revenue generation [56]. PVMBs are particularly effective for buildings with repetitive configurations, such as offices, hospitals, or schools, where standardization maximizes efficiency. In such projects, construction time is significantly reduced. Given the well-established correlation between time and cost in construction, this reduction translates directly into financial savings. Consequently, schedule optimization not only reduces total project costs but also improves financial viability by optimizing return on investment and increasing return on investment [57].

Relevant studies indicate savings in PVMB construction times of between 40% [58] and 50% [59]. While reduced construction time is a key indicator of the advantages of PVMBs, the additional economic value generated by the early start of building operation is an important indicator of efficiency. Criterion C8 was established to evaluate the cost and temporal performance of different PVMB alternatives. Indicator I14 measures the total construction time for each system, and Indicator I15 assesses the Economic–Temporal (ET) time efficiency by comparing the expected net income derived from the early start of the project with its total construction cost. Thus, this indicator captures not only the advantage of reduced construction time inherent in PVMBs but also the profitability resulting from early project delivery. The ET indicator is calculated using Eq. (2).

$$ET = \frac{(T_{conv} - T_i) \times IM}{C_i} \tag{2}$$

Where T_{conv} is the estimated duration in months of the CB system, T_i is the duration of the PVMB alternative *i, IM* represents the estimated monthly economic value associated with the operational use of the building once construction is completed, and C_i is the total construction cost of alternative *i*. Since all alternatives correspond to the same building program and operational capacity, a consistent *IM* value is applied across all alternatives to ensure a valid comparative assessment. This parameter enables the economic relevance of construction time reduction to be expressed proportionally relative to total construction cost, facilitating its integration into the multi-criteria decision-making framework.

The ET was developed to capture the relative reduction in construction duration achieved by prefabricated volumetric modular building (PVMB) systems compared with conventional construction. In hospital infrastructure projects, particularly in seismic-prone urban areas, reducing construction time is essential to ensure timely availability of critical healthcare facilities and to minimize exposure to operational and environmental risks during the construction phase.

The indicator uses conventional construction duration as a reference baseline and evaluates each alternative based on its relative execution time. This formulation ensures consistency with the environmental, economic, and social life-cycle criteria, enabling a balanced and coherent comparison of construction alternatives.

2.3. Multi-attribute optimization

2.3.1. Method selection rationale

In the search for the optimal alternative, scientific literature identifies a wide range of MADM methods, generally classified into six fundamental categories: multi-attribute utility functions, pairwise comparison methods, distance-to-benchmark approaches, top-ranking-based methods, fuzzy logic and its variants, and other MADM methodologies [24]. Within civil engineering, research has reported a prevalence of pairwise comparison methods, with the Analytic Hierarchy Process (AHP) being the most widely used technique. Likewise, distance-based approaches are also widely used, with the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) as the predominant method [60,25]. However, it has been documented that these conventional techniques have intrinsic structural limitations, which have driven the development and adoption of emerging methodologies designed to mitigate these shortcomings.

In this context, the present study adopts a comprehensive approach by integrating four cutting-edge techniques. The Best Worst Method (BWM) was implemented as an alternative to AHP for determining the weights of the criteria. For the evaluation of alternatives, the techniques Evaluation Based on Distance to Average Solution (EDAS), Multi-Attribute Boundary Area Comparison (MABAC), and Measurement of Alternatives and Classification According to the Compromise Solution (MARCOS) were used, all of which are based on distance. The convergence of their results provides a high-fidelity compromise solution, which allows traditional evaluations to be overcome and mitigates the statistical bias inherent in the application of a single technique. Table 3 summarizes the comparative advantages of these selected methodologies and describes how they address the theoretical shortcomings of the first-generation MADM methods.

Table 3
Comparative analysis of emerging MADM methods: Technical advantages and methodological contributions.

Method	Characteristics	Technical Advantage	Methodological Contribution	Reference
BWM	Structured pair-wise comparison of best and worst criteria	Requires fewer comparisons than AHP, allowing for greater consistency.	Reduces bias in expert judgments.	[61]
EDAS	Evaluation based on deviation from the average, not on fictitious extremes.	Stability in the face of extreme values	Stable hierarchy in the face of data with high variance	[62]
MABAC	Definition of gain/loss zones using a clear mathematical boundary.	Allows visualization of how far each alternative is from a neutral zone.	Establishes a clear approximation of the limits, reducing subjective bias.	[63]
MARCOS	Integration of ideal and anti-ideal solutions into a utility function from the outset	Resistance to the Rank Reversal phenomenon	Robust solution for large-scale problems	[64]

2.3.2. Weighting of criteria

The weighting of criteria in MADM plays a fundamental role, as it reflects the relative importance of each criterion and directly influences the ranking of alternatives. These weightings can be derived from the criteria of decision makers or from the decision matrix itself. Weighting approaches are generally classified into three groups: subjective, objective, and integrated methods [65]. As previously indicated, this study used BWM, a subjective weighting method based on expert criteria, to evaluate the relative importance of the criteria.

BWM provides a systematic and consistent approach to determining the weights of criteria. This method structures pairwise comparisons in a manner that requires less input data while enhancing consistency in judgments. The procedure involves identifying the best (most important) and worst (least important) criteria and then performing pairwise comparisons between these and the remaining criteria. In some applications, the BWM may yield multiple optimal solutions, resulting in different sets of criteria weights. However, in cases where a unique solution is desired, the problem can be expressed and solved using a linear optimization model, ensuring the derivation of a single, consistent set of weights. However, due to its nature, the method requires essential human interpretation; this can prolong the decision-making process, as it is susceptible to debates and disagreements among decision-makers [66].

2.3.3. Relevance among the group of experts

The study engaged six experts with professional experience ranging from 5 to 35 years in the fields of civil engineering, architecture, and construction. According to the literature, the inclusion of at least six experts is necessary to ensure reliable and representative results in sustainability assessments [67].

In addition to their general professional experience, the expert panel was intentionally composed to ensure specific competence in (i) structural design under high seismic hazard conditions, (ii) hospital and special-occupancy infrastructure, and (iii) sustainability assessment in construction. Two experts have >18 years of experience in structural design of buildings in high seismic regions, including direct involvement in hospital projects. One expert has over 30 years of experience in civil engineering with >15 years dedicated to sustainability research and a strong JCR-indexed scientific record. Two additional experts combine >15 years of professional practice with academic production in construction engineering and sustainability. The remaining expert contributes specialized experience in structural design and emerging sustainability applications. This composition ensures balanced technical, academic, and sector-specific expertise aligned with the objectives of the study.

The experts applied the BWM to determine the weighting of the evaluation criteria. In this process, they first identified the best and worst criteria and subsequently performed pairwise comparisons among them. To complement this analysis, a simplified neutrosophic approach was employed to evaluate the relative relevance of each expert within the group decision-making process. This method assessed both the competence and consistency of each expert in completing the evaluation matrices [68]. The competence of expert i is expressed as a coefficient between 0 and 1, determined based on their professional experience, research background, and domain knowledge, and is defined according to Eq. (3).

$$\psi_i = \left(\frac{PE_i}{\max(PE_k)} + \frac{ES_i}{\max(ES_k)} + \frac{AD_i}{\max(AD_k)} + \frac{AA_i}{\max(AA_k)} + \sum_{m=1}^{n} KC_{m,i} \Big/ n \right) \Big/ 10 \tag{3}$$

Where PE_i quantifies the years of professional experience of expert i, $\max(PE_k)$ is the maximum number of years of experience among the experts, ES_i is the number of years of specialization of the expert in sustainable design, max(ES_k) is the maximum value of the group of experts, AD_i indicates the academic degree of the expert (1=engineering, 2=master's degree, and 3=doctorate), AA_i indicates scientific output as lead author according to the number of JCR articles (0=none, 1 = 1–3, 2 = 4–10, and 3=>10), $KC_{m,i}$ represents the expert's knowledge in different fields; five areas of specialization were chosen (construction, structural design, budgeting, environmental and social assessment) and a scale n = 5.

The expert's inconsistency ε_i is defined according to Eq. (4).

$$\varepsilon_i = CR/CR_{lim} \tag{4}$$

CR is the consistency ratio of your decision matrix, and CR_{lim} is the maximum acceptable consistency ratio according to the BWM method. High inconsistency values can render the expert's assessment invalid. In this study, a CRl_{im} value of 0.1 was used, following Rezaei (2015), which is recognized as the standard threshold for acceptable consistency in BWM evaluations. This value ensures that minor deviations in subjective judgments are tolerated while preserving the reliability of the calculated criterion weights. Values above this threshold may compromise weight validity, whereas stricter limits are unnecessary given the expertise of the six professionals involved.

It is important to emphasize that the credibility factor (θ_i) directly incorporates both competence and consistency, thereby reducing potential bias associated with subjective weighting. Consequently, experts with higher domain alignment and matrix consistency exert proportionally greater influence on the aggregated weights, reinforcing the methodological rigor of the decision framework.

The credibility of expert$i$ is defined by the Euclidean distance between each point and the ideal point of maximum credibility (1.0), expressed by Eq. (5).

$$\theta_i = 1 - \sqrt{\left\{\left(1 - \psi_i^2\right) + \varepsilon_i^2\right\}/2} \tag{5}$$

Finally, with the weights (Wik) defined for each criterion *i,* decided by each expert k, and the credibility θi of each expert is also defined, the final weights for each of the eight criteria are obtained from Eq. (6).

$$W_i = \frac{\sum_k W_{ik}\theta_k}{\sum_k \theta_{ik}} \tag{6}$$

The experts focused their evaluation on eight criteria. Previous studies indicate that variations in the weighting of indicators exert only a minor influence on the overall ranking of preferences. Therefore, when the relative importance of individual indicators is not explicitly defined, applying equal weighting is recommended to ensure neutrality and impartiality in the results [68].

2.3.4. Optimal alternative

Based on a selection of modern MADM frameworks, this study uses three methods developed over the last decade (EDAS, MABAC, and MARCOS). The EDAS method identifies the best alternative by means of distance to the average, using the PDA (positive distance) and NDA (negative distance) metrics; an alternative is superior if it has a high PDA and a low NDA. MABAC, on the other hand, evaluates the distance of each criterion's function from the limit approximation area. Finally, MARCOS classifies alternatives using utility functions calculated from the distances to ideal and anti-ideal solutions. The optimal solution is the one with the highest utility, as it approaches the ideal point and moves away from the anti-ideal.

The EDAS, MABAC, and MARCOS methods were applied independently using the same decision matrix and criteria weights. As each method employs a distinct aggregation logic and reference framework, their numerical scores are method-specific and not directly comparable in absolute terms. Therefore, the comparative interpretation focuses on ordinal rankings and the recurrence of the best-performing alternatives across methods. This approach allows identification of solutions that demonstrate stable performance under different evaluation logics, which is further whose performance is assessed through sensitivity and robustness analyses within the case study.

2.4. Case study: selection of the optimal earthquake-resistant PVMB system for hospital applications

The case study is presented within the methodological section because it provides the empirical context necessary for the life-cycle quantification stage (Stage 2 of Fig. 1), ensuring direct alignment between methodological formulation and practical application. An eight-story hospital building with a total floor area of 8909.48 m^2 was considered for analysis. This study adopts a scenario-based comparative approach using a reference building derived from a real private hospital complex recently constructed in the city of Manta, Ecuador. From this complex, a single building block was selected due to its architectural configuration, which is suitable for modular adaptation.

The architectural layout adopted in this study is based on a real hospital block recently constructed in the city of Manta, Ecuador. This reference block is not analyzed as an operational facility; instead, it is used to define a consistent architectural and functional baseline for the controlled comparison of alternative structural systems. The functional distribution and spatial organization of this block were preserved in order to ensure representativeness of typical private healthcare infrastructure within the Ecuadorian context. The selected block corresponds to a mid-scale hospital typology (208 beds distributed over eight levels), which is consistent with common spatial configurations of healthcare facilities in Ecuador. The selection of this specific hospital block was strategic, as its architectural configuration allowed direct adaptation to volumetric modular systems without altering the original hospital functionality or spatial requirements. This guarantees that the dimensional, functional, and operational requirements analyzed in this research are consistent with actual healthcare practice in Ecuador.

The project site is located in the southern region of Quito, Ecuador, an area characterized by a high seismic hazard resulting from two principal seismic sources: the subduction zone along the Pacific coast and a system of active geological faults. Although the reference building is located in Manta, the structural analysis is conducted assuming a hypothetical location in Quito in order to evaluate the alternatives under one of the most demanding and representative seismic scenarios in Ecuador. The structures were designed to resist seismic and gravitational loads in accordance with the Ecuadorian Construction Standard NEC-15 [69].

Although the original reference building was constructed using conventional reinforced concrete, all structural systems evaluated in this study — including the conventional baseline (CB) and the three modular alternatives (MCB, MSB, and MHB) — were fully redesigned for the seismic conditions of Quito. Therefore, the analyzed alternatives should be understood as comparative design scenarios rather than representations of existing buildings. They do not correspond to currently implemented hospital construction systems in Ecuador, but to structurally validated scenarios based on established principles of prefabricated volumetric modular construction. This ensures that all systems are evaluated under equivalent architectural, functional, and seismic conditions. The structural design of each alternative strictly complies with NEC-15 provisions for special occupancy buildings such as hospitals, which require higher importance factors and enhanced seismic performance levels. Currently, Ecuador does not have additional structural regulations specifically differentiated for hospital structural systems beyond these special occupancy requirements; therefore, the most demanding national seismic standards were applied consistently to all alternatives to ensure regulatory compliance and comparability.

The input parameters assumed rigid soil conditions, with a shear wave velocity (V_{s30}) ranging between 180 m/s and 360 m/s, and a design earthquake corresponding to a return period of 2500 years. A peak ground acceleration (PGA) of 0.4 g and a design service life of 50 years were adopted as specified in the standard. All structural systems were designed to meet the exact seismic performance requirements, ensuring comparable structural behavior and identical service lives. The service life of each building begins upon completion of construction and extends until either demolition at the end of its life cycle or rehabilitation following earthquake-induced damage. The PVMB consists of 208 modules, each measuring 4.25 m in width, 3.20 m in height, and 8.85 m in depth.

In summary, the case study does not represent a direct empirical evaluation of an existing hospital, but rather a controlled comparative framework based on a real reference building, enabling the systematic assessment of alternative structural systems under consistent and contextually relevant conditions.

Fig. 2a shows the building plan for all alternatives. Note the location of the X-shaped steel bracing for the MSB alternative and the reinforced concrete shear walls cast in situ for the MHB alternative. Figs. 2b) and 2c) show the geometry of the MCB, MSB, and MHB modules, respectively.

2.4.1. Assumptions and parameters

The technical and financial parameters presented below were carefully selected to reflect typical construction industry practices in Ecuador and to provide a clear basis for the economic and performance assessment of the PVMB alternatives. A useful life of 50 years was established in compliance with current earthquake-resistant design regulations. As indicated above, a discount rate of 2% was applied to economic flows, while the environmental and social dimensions were not discounted. The prefabrication coefficients for the MSB, MCB, and MHB systems were adjusted according to the previously detailed levels of industrialization, allowing for logistical differentiation from the CB.

Transport distances for materials were estimated based on the average location of suppliers and production facilities in urban areas of Ecuador. For ready-mix concrete, an average delivery distance of 2.5 km was assumed, reflecting the typical proximity of plants to construction sites. Reinforcing steel and hot-rolled steel factories were considered to be located approximately 21 km away, in line with the presence of steel suppliers in industrial areas on the outskirts of cities. The precast plant was assumed to be located 43 km from the project site. For the LCA and LCA-S assessments, transportation was considered for the MCB, MSB, and MHB alternatives, covering the delivery of prefabricated modules from the manufacturing plant to the construction site for final assembly and integration. On-site activities also involved the mobilization of heavy equipment and machinery. Transport during the end-of-life phase followed the same logistics routes as the manufacturing phase: steel elements were sent to the steel mill, and concrete components were sent to the concrete plant for recycling and reuse. At the same time, non-

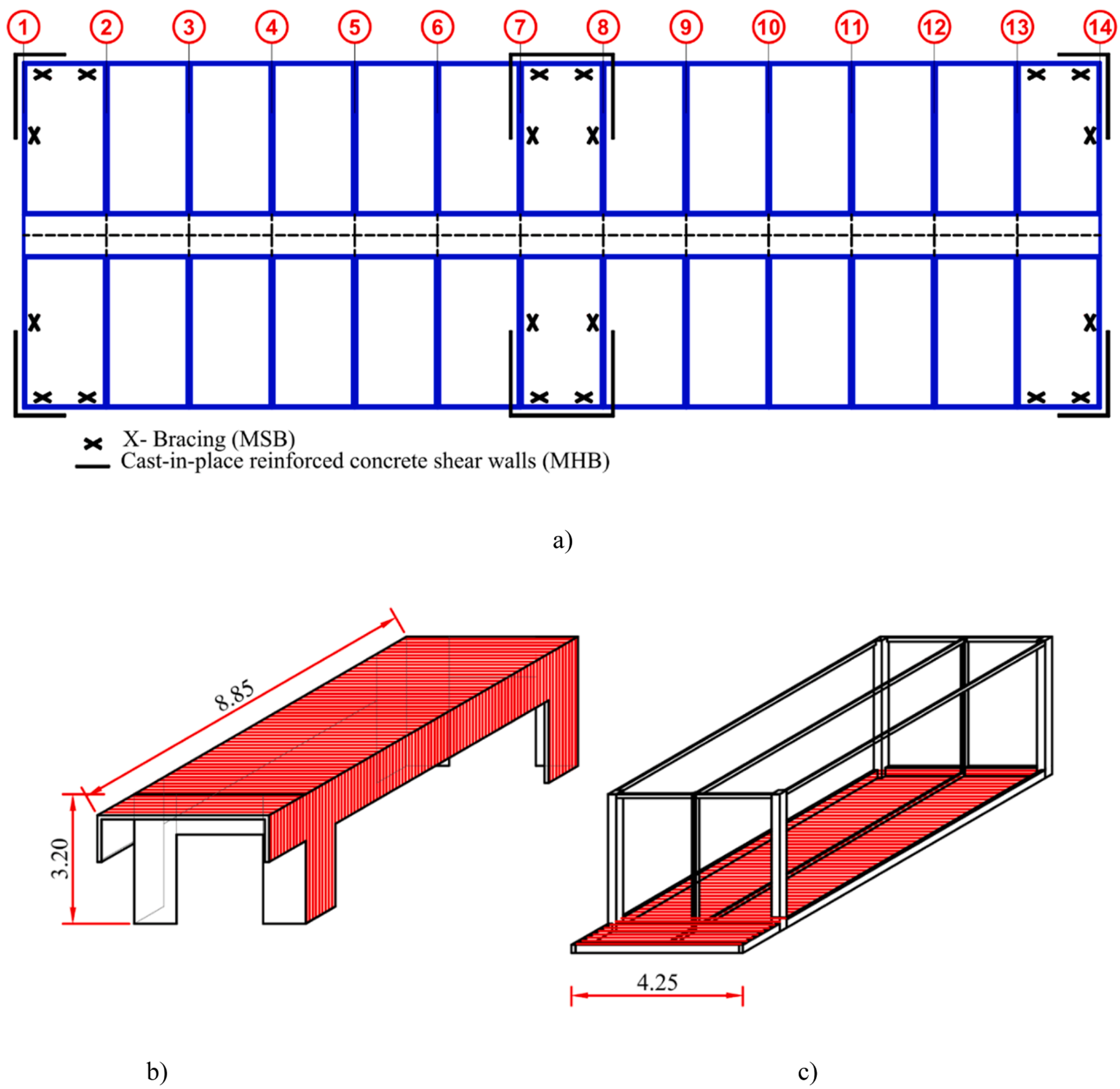

Fig. 2. a) Plan of the case study building, b) Alternative geometry MCB, c) Alternative geometry MSB and MHB. Dimensions in meters.

recyclable materials were transported to a landfill located approximately 7 km from the project site.

2.4.2. Assessment of sustainability dimensions

Specific data on LCC for Ecuador were obtained from the CYPE Ingenieros database (December 2025), which provides regionally calibrated construction cost information. For the MCB, MSB, and MHB systems, the analysis considered costs associated with both the construction site and the prefabrication plant, including materials, supplies, equipment, machinery, labor, transportation, and assembly. In contrast, the CB system accounted for costs related to materials, equipment, machinery, tools, and labor only.

Table 4 presents the life cycle inventory for the LCA and S-LCA of each alternative, together with its corresponding equivalents in the Ecoinvent and SOCA databases. Given the limitations of the database in terms of specific construction materials used for preventive maintenance, the impacts of anti-corrosive and anti-carbonation paints were represented by the production of epoxy resin. Fireproof mortar was modeled as a cement-based compound. The table includes the non-renewable primary energy consumption values associated with the machinery used in construction, adjusted with data from the BEDEC database. All transport activities relevant to each stage of the life cycle were included in the analysis. The pedigree matrix of all processes was included to characterize data uncertainty. A base uncertainty value of 2.0 was used for transport processes and 1.05 for all other processes.

2.4.3. Temporary performance assessment

The case study considered the total construction time for the CB alternative to be 17 months. In contrast, PVMB alternatives show an average reduction of approximately 45% in the execution time of the CB. The calculation of the total construction time for the PVMB alternatives takes into account the varying levels of prefabrication inherent in each system, acknowledging that certain activities must still be performed on-site. Specifically, the MCB alternative incorporates approximately 75% prefabrication, the MSB alternative achieves the highest degree at 90%, and the MHB alternative achieves 82%. These prefabrication percentages were determined based on a detailed analysis of the respective on-site and off-site activities for each system, reflecting the degree of industrialization inherent in MCB, MSB, and MHB alternatives. While local industry benchmarks are limited, these values align with published data for PVMB construction in similar contexts [8,58,59] ensuring that the construction time reductions used in ET calculations are realistic and representative.

The ET calculation was specifically adjusted to the hospital's 208-bed capacity and its southern Quito location. Relevant economic parameters from the National Institute of Statistics and Census of Ecuador (INEC) Health Satellite Accounts [73] including average revenue per discharge, average length of stay, and bed occupancy rate, were scaled proportionally to the hospital's bed count to estimate the total monthly operational income (IM). This adjustment ensures that IM reflects the expected economic benefits from earlier operational start-up for this specific facility. IM is applied consistently across all PVMB alternatives, so differences in ET values arise solely from variations in construction duration (T_i) and total construction cost (C_i). By combining these adjusted income estimates with the reduced construction duration of PVMB alternatives, ET provides a normalized and contextually valid measure of ET and economic performance.

To further contextualize the economic implications of temporal performance, an illustrative estimation of the investment payback period for the MSB alternative relative to the CB baseline was conducted using life-cycle cost differentials and early operational income. This complementary calculation, provided as Supplementary Material, is intended to illustrate investment recovery trends and does not replace a full discounted cash-flow analysis.

3. Results and discussion

3.1. Environmental life cycle assessments

The end-point approach provides a comprehensive evaluation of the environmental impacts associated with each construction alternative. Fig. 3 illustrates the results for the three damage categories—Ecosystems (3a), Human Health (3b), and Resources (3c)—disaggregated by life cycle phase. Overall, the manufacturing phase exhibits the highest environmental impacts, followed by the construction stage. For the construction and use phases, the modular alternatives demonstrate

Table 4
Life Cycle Inventory.

Description	Unit	CB	MCB	MSB	MHB	Ecoinvent and SOCA process
Manufacturing						
Concrete, 28MPa	m^3	0.32	0.25	0.10	0.13	concrete, 25–30MPa
Ballast	Kg	228.98	231.37	251.23	267.84	gravel, round
Reinforcing steel ASTM A706 Gr.60	Kg	38.16	47.81	8.52	15.53	reinforcing steel
Structural steel ASTM A572 Gr.50	Kg	-	10.60	51.61	36.74	hot rolling, steel
Steel components	Kg	-	-	1.02	1.02	average for steel product manufacturing
Steel sheet	Kg	-	-	5.43	5.22	sheet rolling, steel
Cement mortar	Kg	25.61	14.12	-	-	cement mortar
Concrete block	Kg	172.07	71.16	-	-	concrete block
Gypsum fibreboard	Kg	-	-	25.61	25.61	gypsum fibreboard
Construction						
Preliminary	MJ	53.05	53.60	58.20	62.05	diesel, burned in building machine [c]
Foundation slab	MJ	6.00	4.69	4.50	5.15	
Columns	MJ	10.01	-	-	-	
Floor slab	MJ	28.76	-	-	-	
In-situ concrete cores	MJ				2.76	
Module building [a, c]	MJ	-	75.35	323.45	232.46	
Assembly, Crane (40T, 24T, 12T) [b]	MJ	-	40.26	23.46	22.56	
Masonry	MJ	0.39	0.25	-	-	
Use						
Anti-carbonation paint	Kg	0.56	1.67	0.00	0.11	epoxy resin, liquid
Anti-corrosion paint	Kg	-	-	0.69	0.57	epoxy resin, liquid
Fireproof mortar	Kg	-	-	10.68	8.82	cement mortar
End of life						
Structure overthrow	MJ	133.11	103.16	50.65	59.69	diesel, burned in building machine [c]
On-site crushing	Kg	684.48	550.84	228.50	277.84	rock crushing

[a] energy consumption taken from reference [70]. [b] performance according to reference [71,72]. [c] BEDEC database

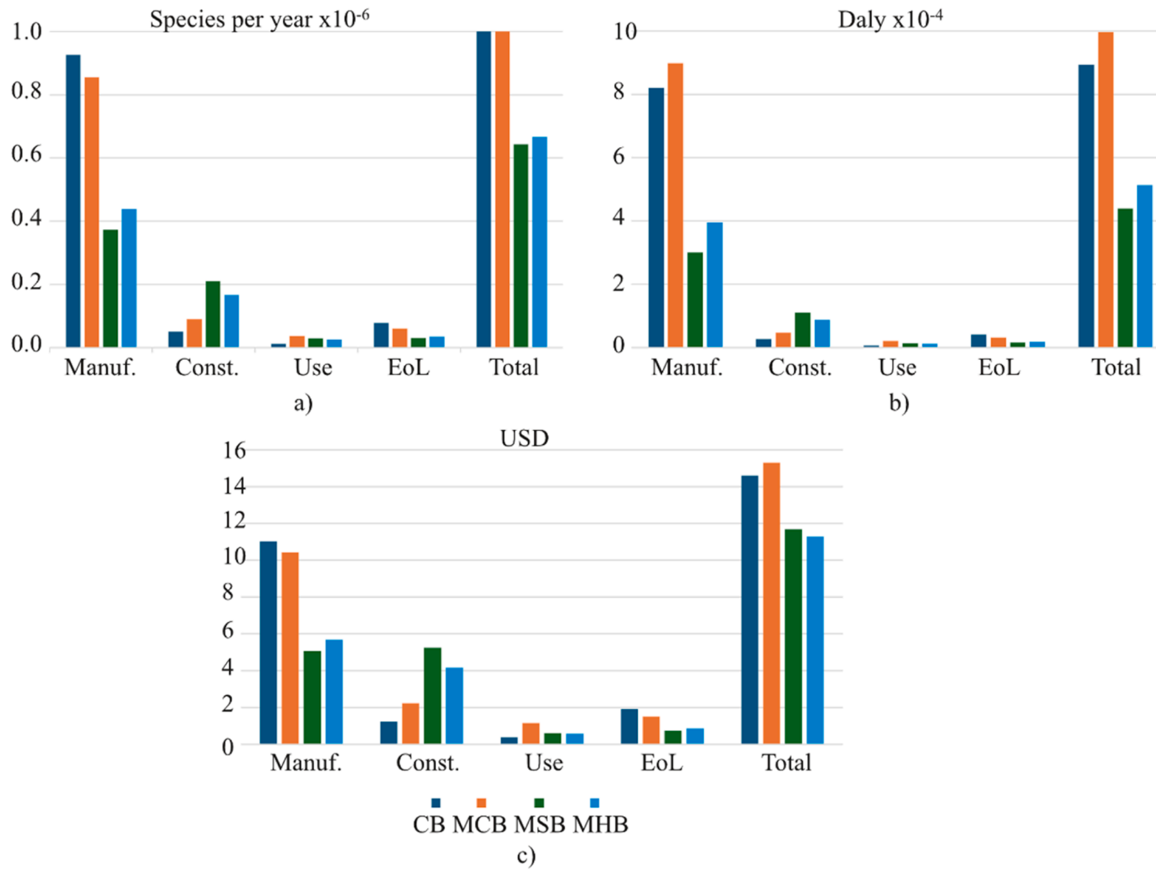

Fig. 3. Endpoint impacts: a) Ecosystems, b) Human health, c) Resources.

relatively higher impacts compared to the conventional system, primarily due to the assembly processes during construction and the preventive maintenance activities required for the materials employed in each structural system.

Compared with the CB system, the MCB alternative achieves a 2% reduction in the ecosystem damage category. However, it exhibits increases of 12% in human health impacts and 5% in resource use, thereby limiting its overall environmental advantages. In contrast, MHB demonstrates notable improvements, with average reductions of 51% during the manufacturing phase and life–cycle–wide decreases of 37% in ecosystem impacts, 43% in human health, and 23% in resource consumption. The MSB alternative achieves the best environmental performance, resulting in a 63% reduction in human health impacts during manufacturing and total reductions of 40%, 51%, and 20% in ecosystem, human health, and resource categories, respectively. These results confirm the superior environmental efficiency of steel-based modular systems relative to the other alternatives.

Given that CO_2 emissions serve as a key indicator of environmental performance, a specific analysis of this impact was conducted. For the defined functional unit, CB generates 240.01 kg CO_2 over its entire life cycle. The MCB alternative achieves a modest 3% reduction, whereas the MHB and MSB exhibit substantially greater decreases of 41% and 45%, respectively. These reductions are directly linked to the material composition, construction processes, and energy requirements characteristic of each structural system. These findings are consistent with those reported in relevant studies comparing modular systems with conventional systems [28] and [74] report a decrease of 6% and 12%, respectively, for concrete modular systems. On the other hand, [11] document a 36% reduction for hybrid modular systems.

Fig. 4 illustrates the contribution of the primary materials and processes to total CO_2 emissions. In the CB and MCB alternatives, reinforcing steel and concrete are the predominant contributors, jointly accounting for approximately 70% of total emissions. In the MHB alternative, the primary contributors are reinforcing steel, concrete, and diesel, the latter associated with non-renewable primary energy consumption during both the construction phase and the end-of-life stage, with an average contribution of 24%. Finally, in the MSB system, emissions are dominated by non-renewable energy use from machinery operations (32%), followed by concrete (23%) and structural steel, which contributes only 11%.

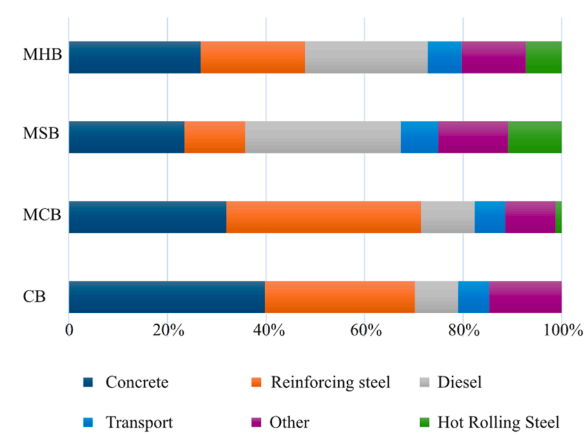

Fig. 4. Contribution of principal materials in each alternative to the global warming potential.

It is important to note that the 32% contribution of machinery energy use refers to the internal distribution of emissions within the MSB alternative and does not imply a higher absolute CO_2 burden compared to the conventional system. Although machinery-related energy represents the largest single contributor within MSB, the total life-cycle CO_2 emissions of this alternative remain substantially lower than those of the CB system. This is primarily due to the significant reduction in high-impact materials, as the MSB requires only 33% of the concrete and 22% of the reinforcing steel used in CB. Consequently, the overall material optimization achieved through the steel modular configuration more than compensates for the relative increase in machinery energy contribution, resulting in the observed reduction in total CO_2 emissions.

In terms of material composition, the MCB and CB alternatives exhibit the highest environmental impacts, primarily due to the extensive use of concrete and reinforcing steel, with the latter identified as the most environmentally burdensome material. In contrast, the MSB and MHB demonstrate superior environmental performance, as hot-rolled steel production results in lower emissions compared to reinforced concrete. The MSB requires only 33% of the concrete and 22% of the reinforcing steel used in the CB, contributing approximately 25% to the total environmental impact, compared to 12% associated with hot-rolled steel. These findings align with previous research, which suggests that steel structures typically exhibit lower environmental impacts compared to reinforced concrete structures. For instance, studies have reported that concrete structures can generate up to 38% higher impacts than their steel counterparts [75]. Similar trends have been observed in comparative analyses of single-family dwellings [76] mid-rise buildings [77] and modular systems [78] all of which emphasize the significant contribution of reinforcing steel to overall environmental burdens [79].

3.2. Social life cycle assessment

The S-LCA results are presented in Fig. 5. The most significant impacts are observed in the workers (30%) and society (29%) categories across all construction alternatives. The impacts on workers primarily arise from issues related to fair wages, workload, occupational health and safety, and discrimination. For society, the main contributing factors include education levels, illiteracy rates, and economic development conditions. The local community accounts for approximately 24% of the total impact, primarily attributed to unemployment, migration, and environmental pollution. The lowest contribution corresponds to value chain actors (17%), primarily linked to anti-competitive practices, corruption, and concerns related to corporate social responsibility. Compared to the CB, the MCB alternative exhibits a 4% increase in the overall social life cycle impact, with the most significant increases observed in the society and value chain actor categories (both rising by approximately 5%). In contrast, the MHB achieves a 47% reduction in total social impacts. At the same time, the MSB alternative demonstrates the most significant overall improvement, with a 55% decrease and the most favorable performance in the society category.

From a social life cycle perspective, steel-based systems outperform concrete-based systems [29]. The social and environmental performance of construction alternatives is closely related: both CB and MCB have disadvantages compared to MSB and MHB. This is mainly due to the superior performance of hot-rolled steel compared to reinforced concrete. These results are consistent with previous research. For example, studies on concrete bridge structures have demonstrated the advantages of hot-rolled steel and the limitations of reinforcing steel [55]. Similarly, other investigations have concluded that hot-rolled steel is socially more favorable than both concrete and reinforcing steel [80].

Despite advances in S-LCA assessment, its implementation remains an emerging discipline and subject to methodological debate. In this study, the results derived from the SOCA database are based on the assumption of a correlation between economic flows and social risks, using global averages. To mitigate the uncertainty inherent in mapping Ecoinvent processes to PSILCA sectors, a systematic application of the pedigree matrix was used for each inventory process. This tool enabled the evaluation of data quality in terms of reliability, completeness, and temporal/geographic correlation, ensuring a uniform comparative basis for all structural alternatives evaluated. Thus, although the model identifies potential risks at the macroeconomic level and not site-specific impacts, the use of a single database and a standardized quality protocol ensures the technical consistency of the comparison. The social results are therefore presented as relative risk indicators, enabling robust decision-making within the proposed multi-criteria framework.

3.3. Economic life cycle assessment

Fig. 6 presents the LCC results for the four design alternatives. The construction phase constitutes the largest share of the total life cycle cost, accounting for an average of 73%. Among the evaluated options, the MSB system exhibits the highest construction cost, exceeding the CB alternative by 56%. The MHB follows with a 42% increase. In contrast, MCB achieves a 7% reduction in construction costs compared to CB. These cost variations are primarily attributed to differences in structural system configurations, which directly influence the quantities of materials used. The MCB, composed of six-sided volumetric modules, reduces concrete consumption by 23% but requires 25% more steel. Meanwhile, MSB and MHB alternatives, also based on six-sided volumetric modules reinforced with frames, include multiple columns along each vertical axis of the building. The MSB employs braced steel frames, whereas the MHB incorporates reinforced concrete cores cast in situ to resist lateral loads.

The use phase represents, on average, 21% of the total cost for modular alternatives, compared to 9% for the CB. The higher proportion observed in PVMBs is primarily attributed to preventive maintenance requirements, including anti-carbonation treatments for concrete, as well as anti-corrosion and fire protection measures for steel components. The end-of-life phase accounts for the smallest share of total costs, ranging from 5% for the MSB to 13% for CB. Based on the assumptions adopted in this study, the MCB emerges as the most cost-effective modular alternative, exhibiting an 8% increase in total costs compared

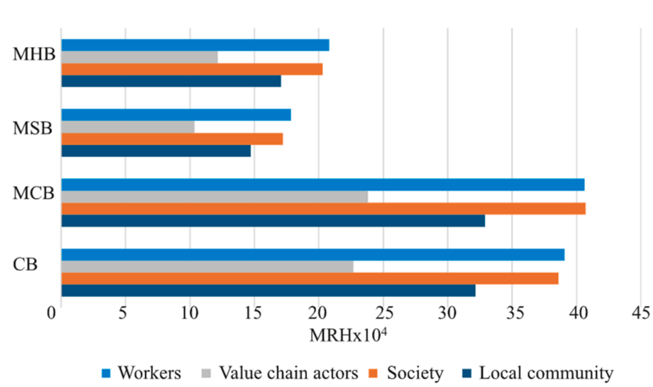

Fig. 5. Social impacts of the life cycle.

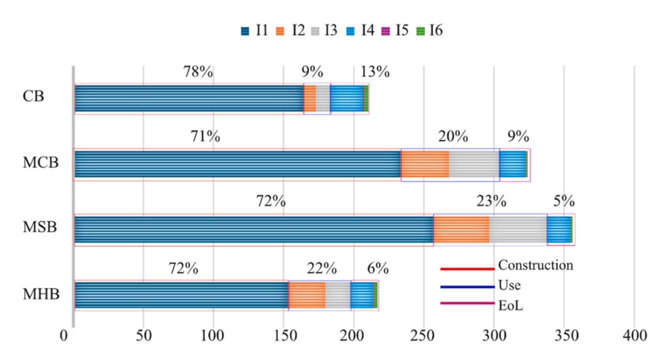

Fig. 6. Economic life cycle of the alternatives.

with traditional construction. In contrast, the MHB and MSB show cost increases of 53% and 69%, respectively. Understanding the cost–benefit dynamics of the prefabrication industry is crucial for accurately assessing its economic potential [81]. Nevertheless, the impact of prefabricated construction on overall project costs remains unestablished [58]. Several studies emphasize the need for transparent and standardized cost analyses to strengthen the feasibility and comprehensive understanding of the prefabrication sector [81].

Although the MSB alternative exhibits a 69% increase in total life-cycle cost relative to the CB system, this result must be interpreted within the integrated decision-making framework adopted in this study. The MSB alternative achieves the shortest construction duration and

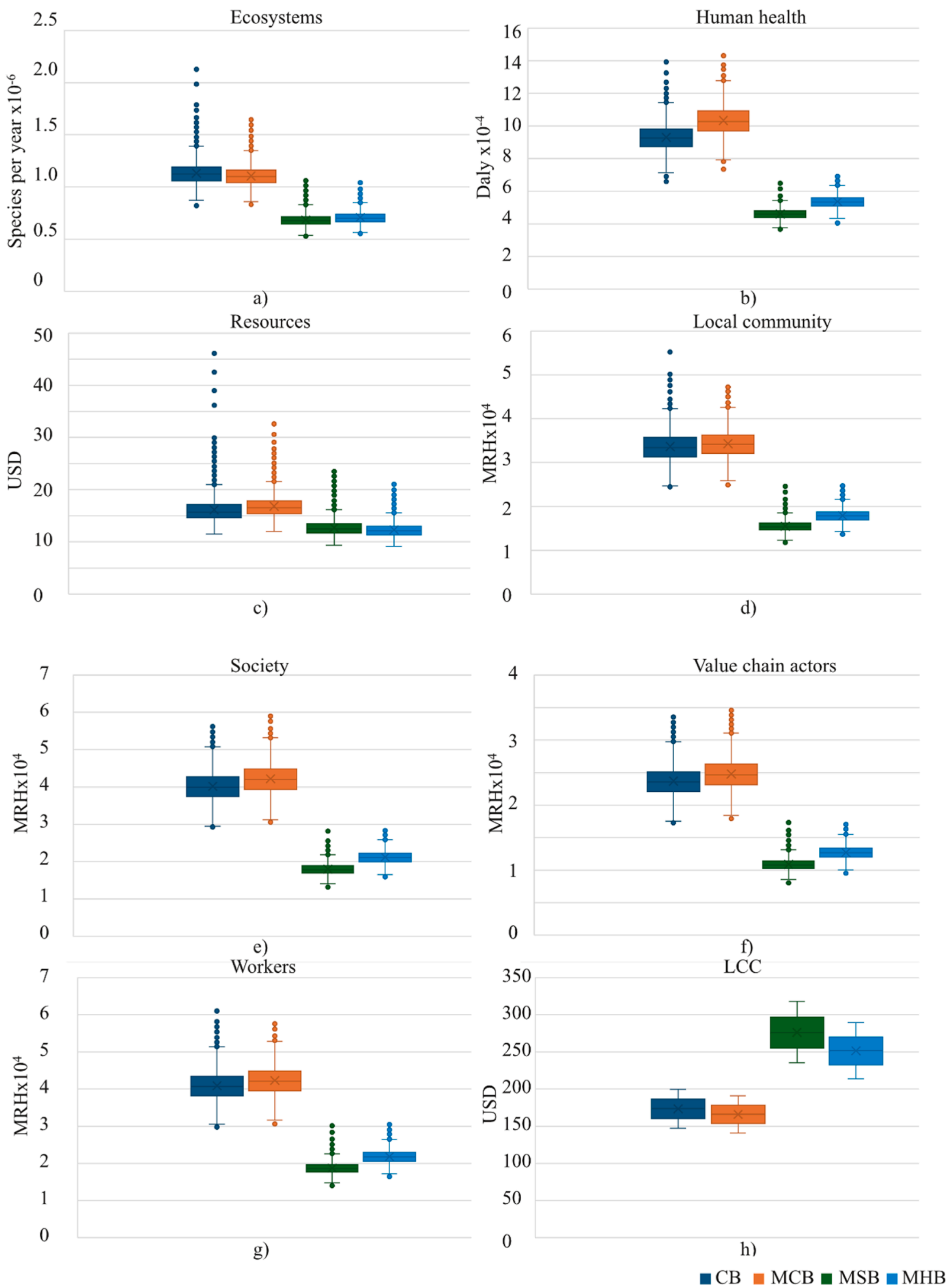

Fig. 7. Uncertainty associated with LCA, S-LCA, LCC; a) Ecosystems, b) Human health, c) Resources, d) Local community, e) Society, f) Value chain actors, g) Workers, and f) LCC.

substantial environmental impact reductions, including a 45% decrease in total CO_2 emissions. These improvements are explicitly captured through the ET and environmental indicators incorporated into the multi-criteria analysis.The ranking results obtained from EDAS, MARCOS, and MABAC consistently identify MSB among the top-performing alternatives, demonstrating stable performance across different evaluation methods. Sensitivity and uncertainty analyses further confirm the robustness of this result under variations in key parameters. This integrated assessment demonstrates that the higher initial investment associated with the MSB alternative is balanced by its superior environmental and temporal performance, resulting in the most favorable overall sustainability outcome among the evaluated alternatives.

3.4. Uncertainty in life cycle assessments

Life cycle assessment is intrinsically dependent on the quality and variability of inventory data. In this research, the technical uncertainty of the Ecoinvent and SOCA databases was addressed by applying the pedigree matrix. At the same time, financial variability in LCC was managed through parametric modeling of market costs, ensuring the robustness of comparisons. A robust stochastic analysis, based on Monte Carlo simulations with 5000 iterations, was implemented in openLCA for both the environmental and social dimensions. Log-normal probability distributions were assigned to the main inventory flows. The results reveal a clear segregation between the alternatives containing CB and MCB concrete and the MSB and MHB alternatives, which have a lower socio-environmental impact. As illustrated in Figs. 7a, 7b, and 7c, the environmental indicators exhibit remarkable stability; despite stochastic fluctuations, the confidence intervals for MSB and MHB do not overlap with the lower bounds of CB and MCB, confirming the environmental superiority of steel and hybrid systems. A similar trend is observed in the social dimension (Figs. 7d, 7e, 7f, and 7g), where the lack of convergence between confidence intervals indicates that the superior social performance of these alternatives is statistically significant and resilient to variations in inventory data.

In contrast, the economic dimension was evaluated using a stochastic analysis assuming a uniform distribution with a variance of ±15% on the base values. The findings reveal a trade-off: while MSB and MHB demonstrate statistical dominance in mitigating environmental and social impacts, the CB and MCB alternatives offer a competitive advantage in terms of costs, as illustrated in Fig. 7h

Finally, the stochastic analysis demonstrates high reliability in the results. Table 5 shows the coefficients of variation (CV) for LCC, LCA, and S-LCA. The calculated values are below 0.10, indicating very low dispersion. Only the LCA Resources indicator showed dispersion that is considered acceptable. Overall, the proposed evaluation framework demonstrates low sensitivity to input data variability, validating the robustness of the study's comprehensive conclusions.

Table 5
Coefficients of variation of alternatives for life cycle assessment indicators.

Dimension	Indicator	CB	MCB	MSB	MHB	Level of uncertainty
LCC	Total Costs	0.087	0.087	0.087	0.087	Very low
LCA	Ecosystems	0.098	0.088	0.088	0.086	
	Human Health	0.089	0.089	0.071	0.073	
	Resources	0.149	0.122	0.122	0.122	Moderate
S-LCA	Local Community	0.099	0.093	0.080	0.080	Very low
	Society	0.099	0.098	0.083	0.084	
	Value Chain Actors	0.097	0.096	0.083	0.083	
	Workers	0.096	0.095	0.082	0.083	

Table 6
Quick implementation and time efficiency.

	Construction time months	Construction Cost USD	Anticipated income USD	Relative time savings	ET
CB	16.82	164.25	-	-	-
MCB	9.91	153.24	1414.22	41%	9.23
MSB	8.5	256.86	1702.64	49%	6.63
MHB	9.23	233.46	1553.78	45%	6.66

3.5. Quick implementation and time efficiency

Table 6 presents the construction time and cost per square meter for both alternatives, along with the anticipated net income per square meter for the PVMB. This income represents the economic benefits derived from the earlier commissioning of modular buildings. It was estimated based on a value of USD 204.69 per square meter per month, calculated using data from Ecuador's National Institute of Statistics and Census (INEC), reflecting the financial gains associated with shorter construction durations. The results indicate that the MSB alternative achieves the most significant time savings, reducing the construction period by 49% compared to the CB, thereby generating the highest anticipated income, albeit with higher construction costs. Conversely, the MCB exhibits the lowest time savings (41%), yet achieves the highest ET index, demonstrating a more favorable balance between cost, time, and economic return. The MSB and MHB alternatives, in turn, achieve an average efficiency of approximately 72% relative to the MCB.

Among emerging construction technologies, PVMBs have emerged as an effective solution for reducing construction times and accelerating post-disaster recovery. In contrast to traditional methods, which can require years to complete new facilities, modular technology offers a rapid, adaptable, and scalable approach that can meet both construction and functional demands in a fraction of the time. As such, PVMBs represent a key strategy for enhancing the resilience and sustainability of healthcare infrastructure. ET is a critical factor in the planning and management of hospital facilities, as hospitals are essential buildings whose early commissioning has a direct impact on the responsiveness of the healthcare system, particularly during emergencies or periods of high service demand. Shortening construction schedules not only yields economic advantages through earlier revenue generation but also significantly improves the availability and accessibility of medical services for the population.

3.6. Multi-attribute optimization

Table 7 presents the weights assigned by each expert to the eight criteria considered in the evaluation process, along with their respective relevance within the group (θi). The calculated consistency indices for all experts were within acceptable limits, confirming the internal coherence and reliability of their assessments. Among the participants, Expert DM3 exhibited the highest credibility factor, followed by DM1 and DM2, indicating a higher degree of reliability in their judgments within the overall decision-making group. The application of the BWM proved particularly advantageous for this study, as it enabled the efficient and consistent evaluation of all eight criteria. Compared with the conventional AHP, BWM is more intuitive for experts, requiring fewer pairwise comparisons (13 versus 28 in AHP) while achieving greater judgmental consistency [24,61]. These methodological strengths reduced the cognitive effort required of evaluators and enhanced the robustness of the resulting criterion weights.

Table 8 summarizes the weights assigned to each sustainability dimension, as well as the relative and overall weights of the criteria analyzed. According to the results, the Environmental dimension was identified by the panel of experts as the most significant, with a weighting of 30.7%, followed by the Economic and Temporal

Table 7
The weighting of criteria and credibility of BWM group experts.

Criterion	DM1	θ1	DM2	θ2	DM3	θ3	DM4	θ4	DM5	θ5	DM6	θ6
C1	0.25	0.37	0.28	0.36	0.17	0,48	0.10	0.28	0.15	0.29	0.17	0.33
C2	0.14		0.10		0.04		0.03		0.04		0.08	
C3	0.07		0.03		0.09		0.15		0.08		0.11	
C4	0.10		0.10		0.12		0.27		0.12		0.14	
C5	0.11		0.07		0.07		0.10		0.10		0.08	
C6	0.06		0.08		0.11		0.10		0.10		0.07	
C7	0.03		0.06		0.09		0.15		0.15		0.05	
C8	0.24		0.28		0.31		0.10		0.26		0.29	

Table 8
Weighting of dimensions and criteria.

Dimension	Weight	Criteria	Relative Weight	Overall Weigth
Economy	0.265	C1	0.720	0.191
		C2	0.280	0.074
Environment	0.307	C3	0.280	0.086
		C4	0.438	0.135
		C5	0.282	0.086
Society	0.172	C6	0.506	0.087
		C7	0.494	0.085
Temporal	0.255	C8	1.000	0.255

performance dimensions. Within the Economic dimension, the Construction Costs criterion emerged as the most influential, accounting for 72% of its dimension's weight. This result underscores the strategic importance of optimizing initial investment in hospital infrastructure projects. In the Environmental dimension, the Human Health criterion received the highest weighting, 43.8%, reflecting the experts' emphasis on the impact of the built environment on user well-being. Within the Social dimension, the criteria exhibited similar weightings, suggesting a balanced perception among experts regarding their collective contribution to social value generation across the building's life cycle. The Temporal performance dimension, represented by Criterion 8, achieved a total weighting of 25.5%, underscoring the importance of economic efficiency in relation to construction duration.

Table 9 presents the decision matrix for 1 m^2 of construction, which describes the performance of the four alternatives based on the eight evaluation criteria representing the three dimensions of sustainability and temporal efficiency. For C8, construction time and temporal efficiency were processed using min-max normalization. This procedure unified both indicators on a homogeneous benefit scale, allowing for their consistent aggregation in the decision matrix. To integrate criteria with different signs and scales into MADM, specific normalization procedures were applied for each algorithm. In EDAS, heterogeneity was managed by calculating PDA and NDA from the average solution, adjusting the logic according to the cost or benefit criterion. In MABAC, linear normalization was used to place the values in a weighted matrix, comparing them against a borderline approximation area. Finally, in MARCOS, ideal (AI) and anti-ideal (AAI) solutions were established to measure the robustness of the alternatives against the extremes of the domain. These mechanisms ensure that differences in units of measurement do not skew the final ranking, allowing for a coherent and statistically valid multidimensional combination.

Table 10 summarizes the ranking results obtained using the applied MADM methods. The CB alternative consistently achieved the lowest performance across all methods, followed by MCB. The EDAS and MARCOS methods identified MSB as the optimal alternative, whereas the MABAC method ranked MHB first, followed by MSB. These discrepancies are attributable to the different aggregation logics and reference frameworks used by each method. EDAS evaluates alternatives based on their distances from the average solution, MARCOS assesses utility relative to ideal and anti-ideal reference points, and MABAC determines performance based on distance from a defined borderline approximation area.

It is important to emphasize that the numerical scores generated by each MADM method are internally normalized and method-specific, and therefore are not directly comparable in absolute terms across algorithms. Consequently, the interpretation focuses on ordinal rankings and the recurrence of best-performing alternatives across methods, rather than on cross-method numerical comparisons. This approach ensures that the final assessment reflects stable performance patterns and provides a robust basis for decision-making.

3.7. Stability and robustness analysis

Sensitivity analysis is fundamental in MADM for evaluating how variations in input parameters affect results, which are often conditioned by subjective judgments and measurement errors [65]. This process reinforces the reliability and robustness of the final decision. Initially, a global sensitivity analysis was performed to quantify the variability of the rankings in relation to changes in the weighting system. Next, an assessment of the model's robustness against the inherent variability of life cycle impacts was performed using stochastic decision matrices. Finally, parametric uncertainty was addressed by introducing stochastic perturbations into the performance criteria, ensuring that the decision-making process remains robust across a range of probabilistic scenarios.

The uncertainty of the weighting system included an analysis of variations of ±20% in the weights of the criteria and dimensions, as well as scenarios of equal weighting. Fig. 8a shows the classification results obtained by varying the weights of the criteria in 48 scenarios for the three MADM methods. The results position the MSB alternative as the optimal option in 67% of the scenarios. The second position showed high competitiveness between the MHB (35%), MSB (33%), and MCB

Table 9
Decision matrix for 1 m^2 of construction.

Criteria	Unit	Optimal	CB	MCB	MSB	MHB
C1	USD	Min.	164.25	153.24	256.88	233.46
C2	USD	Min.	9.26	12.73	19.83	18.11
C3	Species per year	Min.	1.07E-06	1.04E-06	6.43E-07	6.67E-07
C4	DALY	Min.	8.94E-04	9.98E-04	4.39E-04	5.14E-04
C5	USD	Min.	1.46E+01	1.53E+01	1.17E+01	1.13E+01
C6	MRH	Min.	35,603.83	36,754.07	16,271.00	18,942.56
C7	MRH	Min.	30,632.49	32,260.72	13,786.88	16,228.91
C8	Score	Min.	1.00	0.08	0.14	0.18

Table 10
Ranking of alternatives according to the MADMs applied.

Alternatives	EDAS	Ranking	MABAC	Ranking	MARCOS	Ranking
CB	0.105	4	−0.194	4	0.478	4
MCB	0.783	3	0.009	3	0.668	2
MSB	0.936	1	0.218	2	0.693	1
MHB	0.860	2	0.225	1	0.634	3

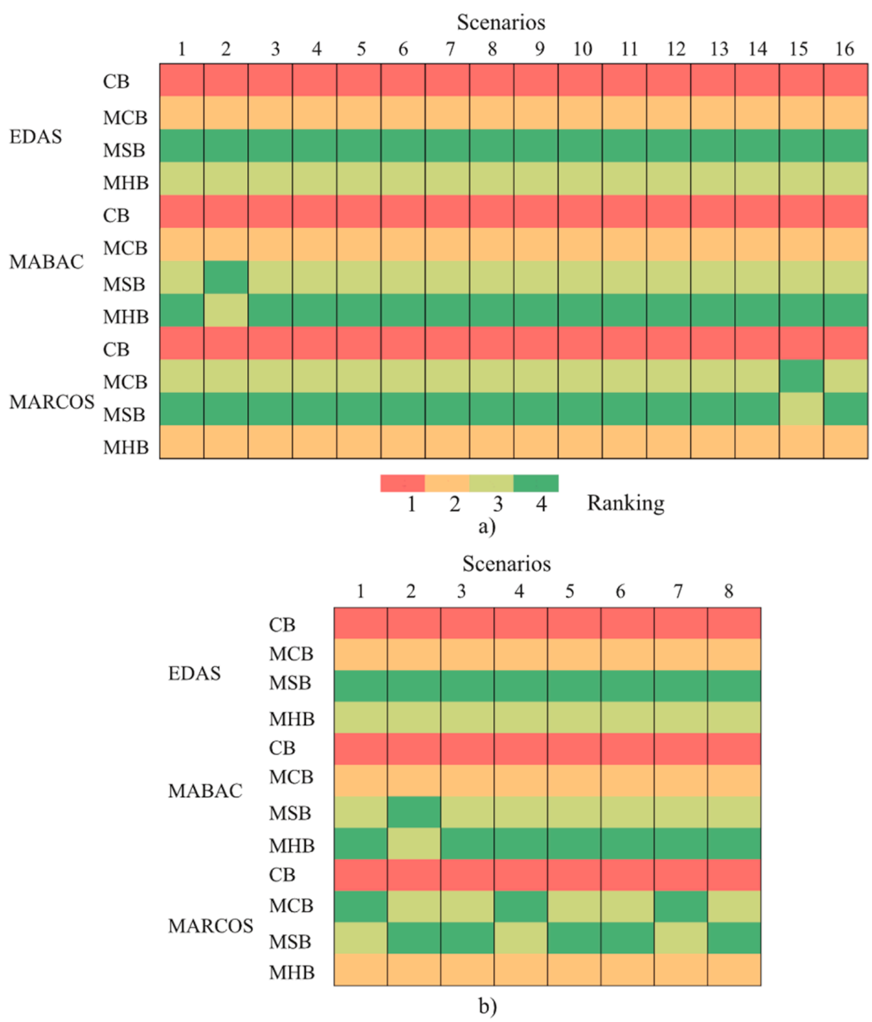

Fig. 8. Ranking of alternatives. a) Variation in criterion weights. b) Variation in dimension weights.

(31%) alternatives. On the other hand, Fig. 8b reflects the variations in the weightings of the dimensions. MSB is the preferred modular alternative in 58% of the 24 scenarios analyzed, while MHB is the winner in 29% of the cases. In the second analysis, to generate a neutral scenario and eliminate the possible bias of any criterion that dominates the model, equal weightings were assigned to all criteria and equal

Table 11
Results of the Monte Carlo simulation: Ranking stability under uncertainty in life cycle assessments.

MADM	Alternative	Means	Standard deviation	P5%	P95%	First-rank frequency (%)
EDAS	CB	0.1045	0.0191	0.0737	0.1361	0%
	MCB	0.7806	0.0658	0.6701	0.8868	3%
	MSB	0.9290	0.0339	0.8595	0.9688	76%
	MHB	0.8573	0.0749	0.7330	0.9837	21%
MABAC	CB	−0.1849	0.0505	−0.2623	−0.0963	0%
	MCB	0.0243	0.0473	−0.0460	0.1084	0%
	MSB	0.20322	0.0443	0.1317	0.2822	48%
	MHB	0.20321	0.0584	0.1065	0.2974	52%
MARCOS	CB	0.4759	0.0204	0.4425	0.5107	0%
	MCB	0.6607	0.0354	0.5846	0.6981	31%
	MSB	0.7021	0.0554	0.6276	0.8053	57%
	MHB	0.6383	0.0516	0.5648	0.7340	12%

weightings to the dimensions; the three MADM methods systematically ranked MSB as the optimal alternative.

The robustness of the decision model was validated through sensitivity analysis using Monte Carlo simulations with 5000 iterations, which constructed a stochastic decision matrix that consolidated the probabilistic behavior. This procedure enables a robust assessment of decision stability under conditions of real-world uncertainty [82]. Similar robustness requirements have been highlighted in recent life cycle sustainability assessments of healthcare buildings, where uncertainty propagation and sensitivity analyses are considered essential to support evidence-based decision-making in hospital infrastructure planning [83,84]. These studies emphasize that hospital projects, due to their long service life and critical societal function, require particularly resilient evaluation frameworks capable of maintaining decision stability under data variability. In the first phase of analysis, Table 11 presents the results derived from technical uncertainty, capturing the inherent variability of the pedigree matrix for LCA and S-LCA, as well as cost fluctuations in LCC. Subsequently, in a second stage detailed in Table 12, the stability of the ranking was evaluated in the presence of a stochastic disturbance of ±15% in the performance values of the alternatives for the eight evaluated criteria. This comprehensive approach allows us to capture the parametric uncertainty inherent in the volatility of market costs, the variability of environmental and social impacts, and fluctuations in the temporal efficiency of execution.

The results confirm the competitive superiority of modular systems over CB, which showed no probability of positioning itself as the optimal solution. This finding is consistent with recent hospital-focused LCA studies, which report that structural system selection and material efficiency are dominant drivers of life-cycle emissions in inpatient facilities, often outweighing operational or transport-related contributions [83]. In this context, the strong performance of the MSB alternative aligns with international evidence indicating that steel-based modular systems can significantly reduce embodied carbon in hospital buildings. The findings in Table 11 confirm that, even given the uncertainty of the primary data, MSB maintains a clear dominance in the EDAS (76%) and MARCOS (57%) methods. The percentile analysis reinforces the robustness of this alternative: the lower confidence limit of MSB is higher than that of the other alternatives in all cases, and even exceeds the 95th percentile of MHB in the MARCOS method, demonstrating a significant statistical advantage. The parametric sensitivity detailed in Table 12 confirms the superiority of MSB as the optimal modular alternative, achieving a success rate of 95% in EDAS and 73% in MARCOS. Except in the specific case of the 95th percentile in MABAC, the analysis of confidence intervals shows that MSB ranks first in the classification.

The MABAC method identified close competition between MSB (48%) and MHB (52%), suggesting similar levels of technical efficiency. This parity reflects MABAC's sensitivity to geometric proximity, in contrast to EDAS and MARCOS, which evaluate relative distances. On the other hand, MCB led 29% on average in the simulations in the MARCOS method. However, when integrating the results, MSB is the optimal solution based on the average values of all simulations, achieving a success rate of 66% in all scenarios. This recurrence validates the robustness of the decision in the face of external fluctuations. To complement the validation, the critical cost threshold for the MSB alternative was determined. Its cost per m^2 would have to increase by 14% in the EDAS method and 20% in MARCOS to lose its leading position. These margins demonstrate that MSB's competitive advantage is resistant to market volatility, confirming that its temporary efficiency and sustainability more than offset the initial investment.

Beyond statistical robustness under standard conditions, it is imperative to evaluate the system's response to disruptive scenarios. Emergency healthcare infrastructure requires industrialized processes, simplified assembly, and high productivity to ensure rapid and scalable deployment [85]. Recent policy-oriented sustainability assessments of healthcare buildings stress that decision models for hospital infrastructure must explicitly account for emergency deployment scenarios, where time efficiency and construction industrialization become decisive criteria [16,84]. The emergency scenario analyzed in this study directly responds to this gap by reweighting priorities under extreme healthcare demand conditions.

For this analysis, an extreme health emergency scenario was modeled by redefining strategic priorities. Criteria weights were recalculated using the Best–Worst Method (BWM), based on a new expert consultation reflecting emergency deployment requirements. The resulting weights are presented in Table 13. In this scenario, the temporal performance (C8) received the highest overall weight of 0.354. This adjustment reflects the critical importance of minimizing construction duration under emergency conditions, where rapid infrastructure availability directly affects healthcare response capacity. Under these conditions, the MADM methods identified the MCB alternative as the optimal solution. This change in ranking is due to the MCB system's ability to minimize delivery times while maintaining competitive costs in emergencies. While the standard scenario favors the versatility of MSB, the extreme scenario demonstrates that MCB offers the optimal synthesis between cost and time. This finding is key for public policy: MSB is the preferred option for standard hospital development, but MCB emerges as the most effective solution when speed of deployment is the critical requirement.

Table 13
Weightings for dimensions and criteria for health emergency scenarios.

Dimension	Weight	Criteria	Relative Weight	Overall, Weight
Economy	0.247	C1	0.674	0.167
		C2	0.326	0.081
Environment	0.243	C3	0.272	0.066
		C4	0.392	0.095
		C5	0.336	0.081
Society	0.156	C6	0.586	0.091
		C7	0.414	0.065
Temporal	0.354	C8	1.000	0.354

Table 12
Results of the Monte Carlo simulation: Ranking stability under parametric uncertainty.

MADM	Alternative	Means	Standard deviation	P5%	P95%	First-rank frequency (%)
EDAS	CB	0.10528	0.02246	0.06891	0.14269	0%
	MCB	0.78368	0.03860	0.72025	0.84795	0%
	MSB	0.93598	0.01566	0.90946	0.96105	95%
	MHB	0.86047	0.03962	0.79805	0.92814	5%
MABAC	CB	−0.18928	0.03687	−0.24979	−0.12693	0%
	MCB	0.02016	0.03012	−0.02931	0.07021	0%
	MSB	0.20699	0.02898	0.16109	0.25798	48%
	MHB	0.20692	0.03730	0.14691	0.26925	52%
MARCOS	CB	0.47503	0.01743	0.44530	0.50245	0%
	MCB	0.66637	0.01337	0.64360	0.68757	26%
	MSB	0.69023	0.02067	0.65715	0.72531	73%
	MHB	0.63301	0.02374	0.59440	0.67210	1%

Although the results presented are based on a specific case study in Ecuador, their technical validity can be extended to other contexts. To validate this transferability, scenarios with variations of ±20% in transport distances and labor costs were initially evaluated, with no changes observed in the final classification. Subsequently, a Monte Carlo simulation (5000 iterations) analyzed the overall uncertainty by adjusting costs and transport by ±20%, with a discount rate ranging from 0% to 4%. The level of prefabrication was varied by ±10%, considering that the base value of the MSB (90%) is close to the operating limit. The results in Table 14 show stable confidence intervals for the ET, LCC, and CO_2 emissions indicators, confirming the model's generalizability in the face of logistical and macroeconomic variability. The CV values remained below 0.10, except for the ET of the MCB and MHB alternatives and the LCC of the CB alternative, which reached maximum values of 0.12. The minimal variation in CO_2 emissions is due to transport, which represents only between 6% and 8% of the total in the LCA. To test the robustness of MSB in regions with higher transportation impacts, additional simulations were conducted considering transport contributions exceeding 8% of total LCA impacts. The results show that MSB retains its superiority across all key indicators, including CO_2 emissions, LCC, and ET, as its environmental and temporal advantages primarily arise from material efficiency and modular assembly. Even with increased transport-related impacts, MSB's overall performance remains higher than that of CB, MCB, and MHB, confirming the robustness of the conclusion.

Consequently, the results confirm that the superiority of modular construction is transferable to other geographical contexts with similar seismic challenges. The robustness of the model demonstrates that the selection of the optimal alternative does not depend on fluctuating local factors, but rather on the intrinsic efficiency of the construction system, allowing for its scalability as a strategic solution in various regions. These findings provide a scientific basis to support decision-making in public procurement of public infrastructure, promoting criteria that prioritize sustainability and temporal efficiency over initial cost alone.

4. Conclusions

This research presents a quantitative multi-attribute decision-making (MADM) framework to identify the optimal prefabricated volumetric modular building (PVMB) alternative based on sustainability and temporal performance, applied and evaluated through a case study and supported by sensitivity and robustness analyses. The main contribution of this study lies in the case-based integrated evaluation of environmental, economic, social, and time-efficiency dimensions within a unified life-cycle decision-making approach. Using a hierarchical structure of eight criteria and 15 indicators, the model captures key sustainability and temporal performance dimensions within a unified decision-making framework. A three-stage sensitivity analysis ensures the robustness of the results, evaluating uncertainty in the weighting of criteria, technical variability associated with life cycle cost (LCC), life cycle assessment (LCA), and social life cycle assessment (S-LCA), as well as parametric uncertainty in all evaluation criteria. Finally, the alternative exhibiting the most stable and consistent performance across all simulation scenarios is identified as the optimal solution, reinforcing the reliability of the proposed framework.

The results of the analyzed case study indicate that PVMBs tend to reduce environmental and social impacts while improving temporal performance, confirming the suitability of modular construction for rapid deployment in critical facilities. Overall, the results of this case study consistently indicate that modular solutions outperform conventional approaches when both sustainability and time efficiency are jointly considered. These results reinforce the role of modular construction as a viable strategy for critical facilities requiring both rapid deployment and long-term performance. Regarding dimensional performance, the MSB and MHB systems achieve the lowest environmental and social impacts, maintaining their superiority even under stochastic variations derived from database uncertainty. However, these alternatives are characterized by higher initial investment costs. Conversely, MCB emerges as the most time-efficient solution, offering competitive costs and execution timelines compared to other PVMB systems.

Beyond the specific hospital analyzed, the framework may be adapted to other building typologies and regional contexts, subject to the availability of reliable life-cycle data and appropriate contextual calibration. This adaptability supports its application as a decision-support tool beyond the specific case study, while preserving methodological consistency. Its structure enables application across different building typologies and construction technologies under comparable evaluation conditions. Moreover, the explicit incorporation of time efficiency (ET) enables the evaluation of trade-offs that are often overlooked in conventional sustainability assessments but are critical for infrastructure subject to functional urgency.

The MSB alternative stands out as the optimal solution, a selection validated by rigorous sensitivity and robustness analysis. Specifically, MSB achieved the highest ranking in the EDAS and MARCOS methods and maintained a consistently high position across all evaluated scenarios. This alternative achieved a superiority rate of 63% in scenarios involving variations in the weighting of criteria. Furthermore, within the framework of stochastic variations in life-cycle analyses and the performance of evaluation criteria, MSB secured first place with a frequency of 66%. The absence of overlaps in confidence intervals across competing alternatives confirms the statistical significance of this result and highlights the robustness of MSB under uncertainty. These results support the need to explicitly integrate sustainability and temporal performance as core decision-making dimensions in critical infrastructure projects.

In addition, complementary analyses have been developed to further substantiate the robustness of the results. These include an illustrative estimation of the investment payback period for the MSB alternative based on life-cycle cost differentials and early operational benefits, a cross-verification of selected S-LCA indicators against official Ecuadorian statistical sources, and a comparative assessment of alternative weighting approaches (BWM, Entropy, and Equal Weights). The

Table 14
Monte Carlo simulation results: Transferability and uncertainty analysis of key performance indicators.

Indicators	Unit	Alternative	Original value	Means	Standard deviation	P5%	P95%
ET	Scale	CB	0.00	0.00	0.00	0.00	0.00
		MCB	9,.3	9.36	1.14	7.55	11.39
		MSB	6.63	6.68	0.70	5.60	7.90
		MHB	6.66	6.70	0.82	5.44	8.15
LCC	USD	CB	210.53	214.95	24.05	177.72	258.20
		MCB	216.90	220.50	21.21	186.56	257.06
		MSB	356.02	359.64	30.56	310.38	411.05
		MHB	323.98	327.47	29.36	279.44	377.84
CO_2 emissions	kg CO_2	CB	240.07	240.05	1.73	237.32	242.77
		MCB	231.79	230.56	1.55	228.16	232.96
		MSB	132.49	132.48	1.17	130.67	134.31
		MHB	140.53	140.55	1.10	138.80	142.26

outcomes, provided as Supplementary Material, confirm the consistency of the MSB ranking and reinforces the consistency of the proposed framework within the evaluated case study.

Despite the robustness of these findings, this research acknowledges limitations related to the management of uncertainty in subjective weighting processes and the need for further exploration of interdependencies among evaluation criteria. To mitigate uncertainty in subjective weighting, the study employed BWM with consistency checks, assigned credibility factors to experts, and conducted sensitivity and scenario analyses. Additionally, stochastic perturbations in performance criteria via Monte Carlo simulations were applied to further ensure robustness.

Regarding transferability to other building typologies with limited life-cycle data, the framework can be adapted using proxy or benchmark data from similar structures, component-level aggregation, and scenario-based sensitivity analyses. The rankings can be refined incrementally as more local or typology-specific data become available, preserving the robustness of the MADM-based decision-making process. From a practical perspective, the framework provides decision-makers with a transparent and evidence-based tool to support public procurement, project planning, and resilient design strategies, advocating for selection criteria that prioritize long-term sustainability and rapid functionality over initial capital expenditure alone. Ultimately, this model contributes to more resilient, sustainable, and socially responsive healthcare infrastructure systems, aligned with the urgent demands of high-risk and resource-constrained contexts.

This study acknowledges that some of the environmental and social inventory data were sourced from international databases: BEDEC, developed in Spain by ITeC for construction and environmental data, and SOCA, a social add-on developed by the German company GreenDelta, based on ecoinvent and PSILCA inventories to assess social impacts, while the case study is located in Ecuador. Although adjustments were applied to approximate local conditions, residual uncertainties may remain. The stochastic and sensitivity analyses conducted throughout Stage 3 of the methodology help mitigate these uncertainties, but the geographic transferability of some indicators should be considered when interpreting results or extending the framework to other regions.

It is important to note that the findings and rankings presented in this study are specific to the analyzed case study and scenario conditions, and further applications in different contexts would require additional validation.

CRediT authorship contribution statement

Byron Guaygua: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Antonio J. Sánchez-Garrido:** Writing – review & editing, Writing – original draft, Validation, Supervision, Data curation, Conceptualization. **Lorena Yepes-Bellver:** Writing – review & editing, Supervision, Conceptualization. **Víctor Yepes:** Validation, Supervision, Funding acquisition, 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.rineng.2026.110371.

Appendix A: List of abbreviations and acronyms used in the study

- BWM – Best–Worst Method
- CB – Conventional Building
- EDAS – Evaluation based on Distance from Average Solution
- ET – Economic–Temporal indicator
- INEC – National Institute of Statistics and Census of Ecuador
- LCA – Life Cycle Assessment
- LCC – Life Cycle Cost
- MADM – Multi-Attribute Decision-Making
- MABAC – Multi-Attributive Border Approximation Area Comparison
- MARCOS – Measurement Alternatives and Ranking according to Compromise Solution
- MCB – Modular Concrete Building
- MHB – Modular Hybrid Building
- MSB – Modular Steel Building
- PVMB – Prefabricated Volumetric Modular Building
- S-LCA – Social Life Cycle Assessment

Data availability

Data will be made available on request.

References

[1] W. Pan, Z. Wang, Y. Zhang, Module equivalent frame method for structural design of concrete high-rise modular buildings, J. Build. Eng. 44 (Dec. 2021), https://doi.org/10.1016/j.jobe.2021.103214.

[2] V. Gaigbe-Togbe, L. Bassarsky, D. Gu, T. Spoorenberg, L. Zeifman, World Population Prospects 2022, Department of Economic and Social Affairs, Population Division, New York, NY, USA, 2022.

[3] & A. G, United Nations Environment Programme, *Not just Another Brick in the wall: The solutions Exist - Scaling them Will Build On Progress and Cut Emissions fast. Global Status Report for Buildings and Construction 2024/2025*, United Nations Environment Programme, 2025, p. 2025, https://doi.org/10.59117/20.500.11822/47214.

[4] B. Zhao, D. Wu, H. Zhu, New modular precast composite shear wall structural system and experimental study on its seismic performance, Eng. Struct. 264 (Aug. 2022), https://doi.org/10.1016/j.engstruct.2022.114381.

[5] H.-T. Thai, T. Ngo, B. Uy, A review on modular construction for high-rise buildings, Structures 28 (2020) 1265–1290, https://doi.org/10.1016/j.istruc.2020.09.070.

[6] Z. Li, et al., On the investigation of modular high-rise concrete buildings in the Asia Pacific region: engineering application analysis and future directions, Results. Eng. 26 (2025) 104830, https://doi.org/10.1016/j.rineng.2025.104830.

[7] Y.-W. Lim, P.C.H. Ling, C.S. Tan, H.-Y. Chong, A. Thurairajah, Planning and coordination of modular construction, Autom. Constr. 141 (2022) 104455, https://doi.org/10.1016/j.autcon.2022.104455.

[8] W. Ferdous, Y. Bai, T.D. Ngo, A. Manalo, P. Mendis, New advancements, challenges and opportunities of multi-storey modular buildings – A state-of-the-art review, Eng. Struct. 183 (2019) 883–893, https://doi.org/10.1016/j.engstruct.2019.01.061.

[9] P. Sharafi, M. Mortazavi, B. Samali, H. Ronagh, Interlocking system for enhancing the integrity of multi-storey modular buildings, Autom. Constr. 85 (2018) 263–272, https://doi.org/10.1016/j.autcon.2017.10.023.

[10] K. Elsayed, A.A. Mutalib, M. Elsayed, M.R. Azmi, Numerical study of PPVC modular steel constructions (MSCs) with selected connection strategies under varied earthquake scenarios, Results. Eng. 22 (2024) 102076, https://doi.org/10.1016/j.rineng.2024.102076.

[11] H. Jang, Y. Ahn, S. Roh, Comparison of the embodied carbon emissions and direct construction costs for modular and conventional residential buildings in South Korea, Buildings 12 (1) (2022), https://doi.org/10.3390/buildings12010051.

[12] M. Kamali, K. Hewage, R. Sadiq, Economic sustainability benchmarking of modular homes: a life cycle thinking approach, J. Clean. Prod. 348 (2022) 131290, https://doi.org/10.1016/j.jclepro.2022.131290.

[13] M. Kamali, K. Hewage, Development of performance criteria for sustainability evaluation of modular versus conventional construction methods, J. Clean. Prod. 142 (2017) 3592–3606, https://doi.org/10.1016/j.jclepro.2016.10.108.

[14] Y. Dong, S.T. Ng, P. Liu, Towards the principles of life cycle sustainability assessment: an integrative review for the construction and building industry, Sustain. Cities. Soc. 95 (2023) 104604, https://doi.org/10.1016/j.scs.2023.104604.

[15] G. da M. Passos Neto, L.H. Alencar, R. Valdes-Vasquez, Multiple-criteria methods for assessing social sustainability in the built environment: a systematic review, Sustainability 15 (23) (2023), https://doi.org/10.3390/su152316231.
[16] L.-K. Chen, et al., Modular composite building in urgent emergency engineering projects: a case study of accelerated design and construction of Wuhan Thunder God Mountain/Leishenshan hospital to COVID-19 pandemic, Autom. Constr. 124 (2021) 103555, https://doi.org/10.1016/j.autcon.2021.103555.
[17] R. Li, W.J.C. Verhagen, R. Curran, A systematic methodology for Prognostic and Health Management system architecture definition, Reliab. Eng. Syst. Saf. 193 (2020) 106598, https://doi.org/10.1016/j.ress.2019.106598.
[18] A.W. Lacey, W. Chen, H. Hao, K. Bi, Structural response of modular buildings - an overview, J. Build. Eng. 16 (Mar. 2018) 45–56, https://doi.org/10.1016/j.jobe.2017.12.008.
[19] S. Abdelmageed, T. Zayed, A study of literature in modular integrated construction - critical review and future directions, J. Clean. Prod. 277 (2020), https://doi.org/10.1016/j.jclepro.2020.124044.
[20] J.A. Edmundas, Kazimieras Zavadskas, O. Kapliński, Multi-criteria decision making in civil engineering. Part II – applications, Eng. Struct. Technol. 7 (4) (2015) 151–167, https://doi.org/10.3846/2029882X.2016.1139664.
[21] F. Sitorus, J.J. Cilliers, P.R. Brito-Parada, Multi-criteria decision making for the choice problem in mining and mineral processing: applications and trends, Expert. Syst. Appl. 121 (2019) 393–417, https://doi.org/10.1016/j.eswa.2018.12.001.
[22] E.K. Zavadskas, Z. Turskis, S. Kildienė, State of art surveys of overviews on MCDM/MADM methods, Technol. Econ. Develop. Econ. 20 (1) (Jan. 2014) 165–179, https://doi.org/10.3846/20294913.2014.892037.
[23] I.J. Navarro, V. Yepes, J.V. Martí, A review of multicriteria assessment techniques applied to sustainable infrastructure design, Adv. Civil Eng. 2019 (1) (2019) 6134803, https://doi.org/10.1155/2019/6134803.
[24] X. Zhu, X. Meng, M. Zhang, Application of multiple criteria decision making methods In construction: a systematic literature review, J. Civil Eng. Manage. 27 (6) (2021) 372–403, https://doi.org/10.3846/jcem.2021.15260. SI.
[25] P. Villalba, A.J. Sánchez-Garrido, V. Yepes, A review of multi-criteria decision-making methods for building assessment, selection, and retrofit, J. Civil Eng. Manage. 30 (5) (2024) 465–480, https://doi.org/10.3846/jcem.2024.21621.
[26] M.Q. Vargas, A. Briga-Sá, D. Boer, M.K. Najjar, A.N. Haddad, Integrating off-site modular construction and BIM for sustainable multifamily buildings: a case study in Rio de Janeiro, Sustainability 17 (17) (2025), https://doi.org/10.3390/su17177791.
[27] M. Kamali, K. Hewage, A. Rana, M.S. Alam, R. Sadiq, Environmental sustainability assessment of single-family modular homes using performance benchmarks of conventional homes: case studies in British Columbia, Canada, Clean. Technol. Environ. Policy. 25 (8) (2023) 2603–2628, https://doi.org/10.1007/s10098-023-02495-2.
[28] A.T. Balasbaneh, W. Sher, Life cycle sustainability assessment analysis of different concrete construction techniques for residential building in Malaysia, Int. J. Life Cycle Assess. 26 (7) (2021) 1301–1318, https://doi.org/10.1007/s11367-021-01938-6.
[29] A.Tighnavard Balasbaneh, B.S. Ramadan, Integrating three pillars of sustainability for evaluating the modular construction building. Construction Innovation, Jul. 2024, https://doi.org/10.1108/CI-01-2024-0002.
[30] M. Kamali, K. Hewage, A.S. Milani, Life cycle sustainability performance assessment framework for residential modular buildings: aggregated sustainability indices, Build. Environ. 138 (2018) 21–41, https://doi.org/10.1016/j.buildenv.2018.04.019.
[31] Y.H. Ahn, K.-T. Kim, Sustainability in modular design and construction: a case study of 'the Stack, Int. J. Sustainable Build. Technol. Urban Develop. 5 (4) (2014) 250–259, https://doi.org/10.1080/2093761X.2014.985758.
[32] M.S.M. Almulhim, M.J. Logaby, U.M. Bongwirnso, Environmental impact assessment of floor system spans: a life cycle approach for sustainable structures, Results. Eng. 27 (2025) 106851, https://doi.org/10.1016/j.rineng.2025.106851.
[33] International Organization for Standardization (2017), "ISO, 2017 Buildings and Constructed Assets — Service Life Planning — Part 5: Life-cycle Costing (ISO 15686–5:2017)".
[34] I. ISO, "ISO 14040. Environmental management–Life cycle assessment–Principles and framework (ISO 14040: 2006)," 2006.
[35] Catherine. Benoît and Bernard. Mazijn, Guidelines for social life cycle assessment of products, United Nations Environment Programme (2009).
[36] K.W. Robert, T.M. Parris, A.A. Leiserowitz, What is sustainable development? Goals, indicators, values, and practice, Environment 47 (3) (2005) 8–21.
[37] P. Pujadas, F. Pardo-Bosch, A. Aguado-Renter, A. Aguado, MIVES multi-criteria approach for the evaluation, prioritization, and selection of public investment projects. A case study in the city of Barcelona, Land. use policy. 64 (2017) 29–37, https://doi.org/10.1016/j.landusepol.2017.02.014.
[38] A. Fathieh, O. Mercan, Seismic evaluation of modular steel buildings, Eng. Struct. 122 (2016) 83–92, https://doi.org/10.1016/j.engstruct.2016.04.054. Sep.
[39] R. Sanches, J. Tao, A. Fathieh, O. Mercan, Investigation of the seismic performance of braced low-, mid- and high-rise modular steel building prototypes, Eng. Struct. 234 (2021), https://doi.org/10.1016/j.engstruct.2021.111986. May.
[40] A. Bhatnagar, A. Härri, J. Levänen, K. Niinimäki, Exploring the role of social life cycle assessment in transition to circular economy: a systematic review, Resour. Conserv. Recycl. 207 (2024) 107702, https://doi.org/10.1016/j.resconrec.2024.107702.
[41] BEDEC, Catalonia Institute of Construction Technology, BEDEC ITEC Mater. Database (2022).
[42] D. Liu, J. Gambatese, Construction worker and equipment energy consumption for offsite precast concrete, Practice Periodical Struct. Design Constr. 25 (2) (May 2020), https://doi.org/10.1061/(ASCE)SC.1943-5576.0000474.
[43] J. Pascual-Gonzalez, G. Guillen-Gosalbez, J.M. Mateo-Sanz, L. Jimenez-Esteller, Statistical analysis of the ecoinvent database to uncover relationships between life cycle impact assessment metrics, J. Clean. Prod. 112 (1) (2016) 359–368, https://doi.org/10.1016/j.jclepro.2015.05.129.
[44] A. Ciroth, ICT for environment in life cycle applications openLCA — A new open source software for life cycle assessment, Int. J. Life Cycle Assess. 12 (4) (2007) 209–210, https://doi.org/10.1065/lca2007.06.337.
[45] J.G. Backes, M. Traverso, Social life cycle assessment in the construction industry: systematic literature review and identification of relevant Social indicators for carbon reinforced concrete, Environ. Dev. Sustain. 26 (3) (2024) 7199–7233, https://doi.org/10.1007/s10668-023-03005-6.
[46] K. Maister, C. Di Noi, A. Ciroth, M. Srocka, PSILCA database v. 3 documentation, PSILCA (2020).
[47] I.J. Navarro, I. Villalba, L. Yepes-Bellver, J. Alcalá, Social life cycle assessment of railway track substructure alternatives, J. Clean. Prod. 450 (2024) 142008, https://doi.org/10.1016/j.jclepro.2024.142008. Art.
[48] V. Yepes, C. Torres-Machi, A. Chamorro, E. Pellicer, Optimal pavement maintenance programs based on A hybrid greedy randomized adaptive search procedure algorithm, J. Civil Eng. Manage. 22 (4) (2016) 540–550, https://doi.org/10.3846/13923730.2015.1120770.
[49] A.J. Sánchez-Garrido, I.J. Navarro, V. Yepes, Optimizing reactive maintenance intervals for the sustainable rehabilitation of chloride-exposed coastal buildings with MMC-based concrete structure, Environ. Impact. Assess. Rev. 116 (2026) 108110, https://doi.org/10.1016/j.eiar.2025.108110.
[50] K. Jin, W. Jin, B. Liu, K. Wu, Z. Wang, Cost calculation model for engineering structures based on a life cycle perspective, Buildings 15 (16) (2025), https://doi.org/10.3390/buildings15162923.
[51] D. Schoenmaker, W. Schramade, Which discount rate for sustainability? J. Sustainable Finance Account. 3 (2024) 100010 https://doi.org/10.1016/j.josfa.2024.100010.
[52] E. Marsh, S. Allen, L. Hattam, Tackling uncertainty in life cycle assessments for the built environment: a review, Build. Environ. 231 (2023) 109941, https://doi.org/10.1016/j.buildenv.2022.109941.
[53] S. Lueddeckens, P. Saling, E. Guenther, Temporal issues in life cycle assessment-a systematic review, Int. J. Life Cycle Assess. 25 (8) (2020) 1385–1401, https://doi.org/10.1007/s11367-020-01757-1.
[54] T. Jiang, P. Yin, Q. Jin, Performances of typical photovoltaic module production from the perspective of life cycle sustainability assessment, in: Sustainable Energy Technologies and Assessments, 64, Apr. 2024, https://doi.org/10.1016/j.seta.2024.103703.
[55] D. Martínez-Muñoz, J.V. Martí, V. Yepes, Social impact assessment comparison of composite and concrete bridge alternatives, Sustainability 14 (9) (2022), https://doi.org/10.3390/su14095186.
[56] F. Ahmed, M. Gkantou, G. Nikitas, M. Ferentinou, A. Bras, M. Riley, A review of recent developments in structural elements of modular steel building systems, J. Build. Eng. 111 (2025) 113087, https://doi.org/10.1016/j.jobe.2025.113087.
[57] Z. Zhou, D. Syamsunur, L. Wang, F. Nugraheni, Identification of impeding factors in utilising prefabrication during lifecycle of construction projects: an extensive literature review, Buildings 14 (6) (2024), https://doi.org/10.3390/buildings14061764.
[58] M. Kamali, K. Hewage, Life cycle performance of modular buildings: a critical review, Renew. Sustain. Energy Rev. 62 (Sep. 2016) 1171–1183, https://doi.org/10.1016/j.rser.2016.05.031.
[59] M. Zohourian, A. Pamidimukkala, S. Kermanshachi, D. Almaskati, Modular Construction: a comprehensive review, Buildings 15 (12) (2025), https://doi.org/10.3390/buildings15122020.
[60] X. Luque Castillo and V. Yepes, "Multi-criteria decision methods in the evaluation of social housing projects," *J. Civil Eng. Manage.*, vol. 31, no. 6, pp. 608–630, doi:10.3846/jcem.2025.24425.
[61] J. Rezaei, Best-worst multi-criteria decision-making method, Omega 53 (2015) 49–57, https://doi.org/10.1016/j.omega.2014.11.009.
[62] M. Keshavarz Ghorabaee, E.K. Zavadskas, L. Olfat, Z. Turskis, Multi-criteria inventory classification using a new method of evaluation based on distance from average solution (EDAS), Informatica 26 (3) (Jan. 2015) 435–451, https://doi.org/10.15388/Informatica.2015.57.
[63] D. Pamučar, G. Ćirović, The selection of transport and handling resources in logistics centers using multi-attributive border approximation area comparison (MABAC), Expert. Syst. Appl. 42 (6) (2015) 3016–3028, https://doi.org/10.1016/j.eswa.2014.11.057.
[64] Ž. Stević, D. Pamučar, A. Puška, P. Chatterjee, Sustainable supplier selection in healthcare industries using a new MCDM method: measurement of alternatives and ranking according to COmpromise solution (MARCOS), Comput. Ind. Eng. 140 (2020) 106231, https://doi.org/10.1016/j.cie.2019.106231.
[65] G. Demir, P. Chatterjee, D. Pamucar, Sensitivity analysis in multi-criteria decision making: a state-of-the-art research perspective using bibliometric analysis, Expert. Syst. Appl. 237 (2024) 121660, https://doi.org/10.1016/j.eswa.2023.121660.
[66] S. Hamdouni, M. Benaicha, A.H. Alaoui, Y. Burtschell, Optimizing self-compacting concrete: a comprehensive analysis of weighting methods and multi-response optimization, Results. Eng. 26 (2025) 105138, https://doi.org/10.1016/j.rineng.2025.105138.
[67] T.U. Daim, A. Udbye, A. Balasubramanian, Use of analytic hierarchy process (AHP) for selection of 3PL providers, J. Manuf. Technol. Manage. 24 (1) (2012) 28–51, https://doi.org/10.1108/17410381311287472.

[68] A.J. Sánchez-Garrido, I.J. Navarro, V. Yepes, Multi-criteria decision-making applied to the sustainability of building structures based on Modern methods of construction, J. Clean. Prod. 330 (2022) 129724, https://doi.org/10.1016/j.jclepro.2021.129724.
[69] N.E. de la, C. MIDUVI, NEC, Ministerio de Desarrollo Urbano y Vivienda. Quito, Ecuador, 2015.
[70] L. Ding, G. John, Construction worker and equipment energy consumption for offsite precast concrete, Practice Periodical Struct. Design Constr. 25 (2) (May 2020) 4020007, https://doi.org/10.1061/(ASCE)SC.1943-5576.0000474.
[71] N. Bertram, S. Fuchs, J. Mischke, R. Palter, G. Strube, and J. Woetzel, "Modular construction: from projects to products| McKinsey," 2019, McKinsey.
[72] R.E. Smith and T. Rice, "Permanent modular construction: process, practice, performance," MBI Modular Building Institute and University of Utah, Integrated Technology in Architecture Center, College of Architecture and Planning, 2015.
[73] INEC, "Cuentas-satelite-de-salud." Accessed: Nov. 09, 2025. [Online]. Available: Gobierno del Ecuador Instituto Nacional de Estadística y Censos.
[74] M. Kamali, K. Hewage, R. Sadiq, Conventional versus modular construction methods: a comparative cradle-to-gate LCA for residential buildings, Energy Build. 204 (2019), https://doi.org/10.1016/j.enbuild.2019.109479.
[75] A. Oladazimi, S. Mansour, S.A. Hosseinijou, Comparative life cycle assessment of steel and concrete construction frames: a case study of two residential buildings in Iran, Buildings 10 (3) (2020), https://doi.org/10.3390/buildings10030054.
[76] H. Gervasio, Comparative housing case study (Steel vs. Concrete) through a quantitative life cycle approach, World Steel Constr. Council (2007).
[77] H.R. Lu, A. El Hanandeh, B.P. Gilbert, A comparative life cycle study of alternative materials for Australian multi-storey apartment building frame constructions: environmental and economic perspective, J. Clean. Prod. 166 (2017) 458–473, https://doi.org/10.1016/j.jclepro.2017.08.065.
[78] A.T. Balasbaneh, M.Z. Ramli, A comparative life cycle assessment (LCA) of concrete and steel-prefabricated prefinished volumetric construction structures in Malaysia, Environ. Sci. Pollut. Res. 27 (34) (2020) 43186–43201, https://doi.org/10.1007/s11356-020-10141-3. SI.
[79] B. Liu, Y. Jiang, W. Zhang, J. Yan, L. Xie, P. Gurung, Enhancing performance and sustainability: CRB600H high-strength reinforcement in recycled concrete, Sustainable Mater. Technol. 39 (2024) e00788, https://doi.org/10.1016/j.susmat.2023.e00788 p.
[80] S.A. Hosseinijou, S. Mansour, M.A. Shirazi, Social life cycle assessment for material selection: a case study of building materials, Int. J. Life Cycle Assess. 19 (3) (2014) 620–645, https://doi.org/10.1007/s11367-013-0658-1.
[81] W. Zhang, M.W. Lee, L. Jaillon, C.S. Poon, The hindrance to using prefabrication in Hong Kong's building industry, J. Clean. Prod. 204 (2018) 70–81, https://doi.org/10.1016/J.JCLEPRO.2018.08.190. Dec.
[82] B. Moradi, M. Jahangiri, A. Khechekhouche, M.S. Hashemi Mehr, M. Nahavandi, Towards resilient energy decisions: integrating scenario-based weighting and Monte Carlo sensitivity in hybrid renewable system selection in Algeria, Results. Eng. 27 (2025) 107020, https://doi.org/10.1016/j.rineng.2025.107020.
[83] Z. Ullah, A.R. Nasir, F.K. Alqahtani, F. Ullah, M.J. Thaheem, A. Maqsoom, Life cycle sustainability Assessment of healthcare buildings: a policy framework, Buildings 13 (9) (2023) 2143, https://doi.org/10.3390/buildings13092143.
[84] L. Zhao, C. Guo, L. Chen, L. Qiu, W. Wu, Q. Wang, Using BIM and LCA to calculate the life cycle carbon emissions of inpatient building: a case study in China, Sustainability 16 (13) (2024) 5341, https://doi.org/10.3390/su16135341.
[85] L. Chen, C. Zhai, L. Wang, X. Hu, X. Huang, Modular structure construction progress scenario: a case study of an emergency hospital to address the COVID-19 pandemic, Sustainability 14 (18) (2022), https://doi.org/10.3390/su141811243.