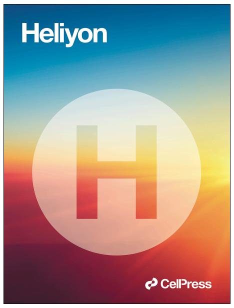

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Life cycle assessment of seismic resistant prefabricated modular buildings.

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Abstract

Prefabricated Volumetric Modular Buildings (PVMB) have the potential to transform the construction industry and make a significant contribution to reaching sustainable development goals. Nevertheless, it is crucial to carefully evaluate the tangible benefits of implementing these systems, especially in buildings that require seismic calculations. This article compares three innovative PVMB structural systems, two reinforced concrete and one steel, with a conventional system, focusing on the economic and environmental aspects of a high seismic hazard zone. An end-to-end life cycle analysis was performed, and the results were used as quantitative criteria for a two-dimensional sustainability assessment. Five multi-criteria decision-making methods were used to identify the optimal alternative, resulting in a ranked list of solutions. The modular steel alternative is the most favorable option due to its balanced performance across all evaluation criteria despite being the most expensive. The conventional reinforced concrete alternative comes in second place, followed closely by the reinforced concrete modular alternative with dry connections. The modular reinforced concrete alternative with wet connections is the least favorable regarding environmental impact due to the extensive use of concrete and reinforcing steel. This study contributes significantly to sustainable construction research by establishing the tangible benefits of innovative systems compared to traditional methods. It offers specific insights into overcoming barriers to their more widespread adoption.

KEYWORDS: Volumetric Modular Building, Life Cycle Analysis, Multi-criteria decision-making, Off-site construction.

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1. Introduction

Building construction impacts global sustainability, accounting for 35% of primary energy use, 25% of water consumption, and 12% of land use while generating about 25% of waste and 38% of greenhouse gases [1], [2]. With the global built-up area expected to exceed 415 billion m² by 2050 due to population growth [3], balancing resource management, environmental preservation, and building demand poses a significant challenge [4]. Increasing attention is being paid to innovative technologies prioritizing sustainability within tight budgets and schedules [5]. Prefabricated volumetric modular building (PVMB) represents a cutting-edge approach. PVMB uses prefinished three-dimensional modules manufactured in a factory and assembled on-site, resulting in over 70% prefabrication. Construction times are substantially reduced, as demonstrated in the COVID-19 outbreak, with the rapid construction of emergency hospitals in Wuhan, China, completed in only 12 days [6]. It has been demonstrated that using PVMB can lead to reductions of up to 50% in construction time and 30% in costs, positioning this technique as a transformative and sustainable option for the future of construction [7].

However, some argue that the applications of PVMBs are limited due to difficulties in demonstrating tangible benefits. Often, customers need help to understand the benefits [8] entirely. The wide range of advantages associated with modular construction can justify its use. Comprehensive analyses considering the entire life cycle and sustainability compared to traditional on-site construction are essential to validate modular technologies. Life cycle analysis (LCA) assesses the economic, environmental, and social impact of a system or product over its lifetime and is increasingly applied in construction and civil engineering [9]. While LCA methodology has been standardized [10], life cycle costing (LCC) is also well developed despite the lack of an ISO standard [11]. Building construction involves multiple phases: design, material selection, construction, operation, and maintenance. Life cycle studies effectively assess impacts in all these phases [8]. In the case of PVMBs, the life cycle includes phases similar to those of conventional buildings, where the construction phase encompasses both module fabrication and on-site assembly.

Recent studies have used LCA to evaluate the environmental impact of modular steel buildings. One research revealed a 47% reduction in greenhouse gas emissions from modular steel buildings compared to conventional concrete buildings [12]. In California, modular housing construction showed up to 20% reduction in embodied greenhouse gas emissions [13]. Previous research considered the manufacturing and construction stages. In contrast, another study comparing volumetric concrete and steel construction concluded that steel offered the most favorable environmental results, albeit at a high cost, considering all life cycle stages [14]. Research on the environmental impacts of PVMBs is still scarce, showing results with significant variability of PVMBs due to factors such as assumptions, choice of materials, prefabrication rate, stages, and geographical boundaries [15]. Life cycle assessments have paid less attention to other environmental impacts and have focused primarily on the manufacturing and construction stages, overlooking operation and end-of-life stages [16]. A shift towards quantitative assessments is recommended to evaluate modular construction effectively, and incorporating economic and social criteria can facilitate the identification of the optimal construction system [8].

Building attributes are often interrelated, resulting in different advantages and disadvantages based on the criterion assessed. Multi-criteria decision-making methods (MCDM) can be used to prioritize building alternatives over traditional methods to optimize results and aid in the selection process [17]. MCDMs have gained importance in sustainable design by addressing challenging issues involving contradictory criteria [18]. The literature reports few studies in modular buildings based on MCDM methods. One study applied the Analytical Hierarchical Process (AHP) to compare conventional and modular building alternatives, considering the cradle-to-gate life cycle. The results indicate that there is no absolute green option due to the variability of the results [19]. In Australia, the AHP identified sustainable construction methods; off-site construction was very efficient for high-rise buildings [20]. Another AHP and TOPSIS study concluded that volumetric construction was the most sustainable for single-family dwellings, although not all life-cycle phases were considered [21].

Modular technologies are increasingly used in low-rise buildings and are now applied to mid-rise and high-rise projects [22]. Significant advances in modular systems, especially in their response to seismic loads, have sought to encourage their adoption. Researchers have developed innovative structural solutions that facilitate modular construction in various geographic regions around the world [23], [24], [25]. However, there is a need to evaluate the benefits of different PVMB seismic-resistant structural systems so that decision-makers can select the optimal alternative from different perspectives. The lack of quantitative research is the obstacle to overcome to generate a much broader application [8].

Research on the benefits of PVMB is continuously evolving. However, a quantitative comparison of the benefits of innovative seismic-resistant structural systems has yet to be performed. This article comprehensively evaluates seismic-resistant PVMB alternatives from economic and environmental perspectives, using life cycle assessments and MCDM to identify the optimal solution. Specifically, the study will compare the environmental and economic impact of three earthquake-resistant PVMB structural solutions - two reinforced concrete and one steel - versus a conventional reinforced concrete system for an outpatient hospital block in Quito-Ecuador, an area of high seismic hazard, using a cradle-to-grave life cycle analysis. A two-dimensional MCDM approach then ranks the alternatives based on weighted criteria and quantitative performance indicators, evaluating whether modular buildings offer advantages over conventional systems and identifying the optimal solution.

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

2. Materials and methods

2.1. Definition of the problem

This work aims to provide an economic and environmental analysis focusing on constructing an outpatient hospital as a case study. The study compares different design options for the structural system from a life cycle perspective. Specifically, four anti-seismic structural solutions are proposed for constructing this four-story building. The options evaluated include three based on volumetric modular systems: a wet-assembled precast reinforced concrete volumetric modular system (CM1), a dry-assembled precast reinforced concrete volumetric modular system (CM2), and a steel volumetric modular system (MSC) versus a conventional cast-in-place (CB) reinforced concrete system. The study deals exclusively with the structural systems' materialization, including the structural elements and their foundations. Since modular buildings consist of six-sided modules, the architectural requirements for the primary partition and exterior walls are inherently met. However, to ensure a fair comparison across the options, it was necessary to quantify the quantification of masonry infill where appropriate. Assumes a hypothetical location for the building in the southern part of the capital of Ecuador, Quito, 2800 m above sea level, with more than 2.5 million inhabitants; the city has two seismic sources: the subduction zone on the coast of the Pacific Ocean and a system of active geological faults, both of which are capable of generating large earthquakes. [26], [27].

The buildings were designed to withstand gravity and seismic loads by the Ecuadorian construction standard (NEC-15) [28]. Consequently, the design assumes a rigid soil classified as type D, with a shear wave velocity between 180 m/s and 360 m/s within the upper 30 meters. The design earthquake is determined for a return period of 2500 years and a service life of 50 years; a maximum ground acceleration (PGA) of 0.4 g is established according to the standard. The service life of each alternative is calculated from completion of construction to demolition (end of service life) or rehabilitation required due to earthquake damage. The evaluation assumed that all alternatives would be designed by code requirements, with adequate structural performance and the same lifespan.

2.1.1. Definition of alternatives

The subject of this study is a four-story block with a total building area of 4950 m^2, characterized by a repetitive architecture well suited to the modularization approach [29]. The structural characteristics of the alternatives are detailed below:

Conventional building (CB): The structural system consists of bi-directional reinforced concrete moment resisting frames (MRF) built in situ. This structural typology is most commonly used in Ecuador for low-rise buildings.

Prefabricated reinforced concrete modular building (CM1): By the structural system proposed by reference [30], which comprises six-sided volumetric modules formed by walls that serve as shear walls, the building is assembled using horizontal connections between modules and from module to corridor through the use of steel bars and cast-in-place concrete, which serve to integrate the roof slabs of a floor into a unified entity in the plane. All horizontal connections on the same floor are designed to function collectively in a manner that substantiates the traditional assumption of the rigid diaphragm. The shear walls are formed with the module walls connected vertically utilizing grouted sleeves. The rigid diaphragm prevents lateral buckling of the shear walls and ensures they function as a unified structure. No torsion effect is considered due to the regularity of the plant.

Prefabricated reinforced concrete modular building (CM2): The structural system proposed by reference [31] consists of a volumetric modular structure of shear walls with a roof slab, beams, and cantilever beams. Bolts and nuts secure the union of adjacent modules on the same floor, while the union between upper and lower modules is made using bolts, nuts, and steel beams. The connection above systems are of paramount importance in seismic performance. The horizontal joints facilitate the coordinated deformation of adjoining modules, while the vertical joints play a pivotal role in the structure's overall synergistic performance.

Prefabricated modular steel building (MSC): By the structural system proposed by reference [32], [33], which comprises prefabricated steel volumetric modules comprising beams, columns, and suspenders as frame elements, a concrete floor slab is incorporated as a discrete rigid diaphragm, resulting in a system comprising corner-supported and corner-tied units that act in concert for lateral load transfer. The modules are connected vertically by column connections, and the horizontal connections of the finished units are made by bolting steel plates or welded steel angles. It is important to note that separate diaphragms are considered per module.

The primary criterion for the blocks is their transport capacity, which is determined by the availability of vehicles and machinery on the market; this, in turn, determines the dimensions of the blocks, thus necessitating on-site coupling between blocks to create a unit (module). This study, 104 modules are considered, each consisting of two blocks. The modules have a width of 4.25 meters and a height of 3.2 meters. While the depth of the blocks may vary, a maximum value of 7.80 m is considered. Figures 1 a) and b) show the case study floor plan and the architectural scheme of the modules; the structural configuration of the modules and their geometry is shown in Figures 1 c), d), and e) for alternatives CM1, CM2, and MSC, respectively.

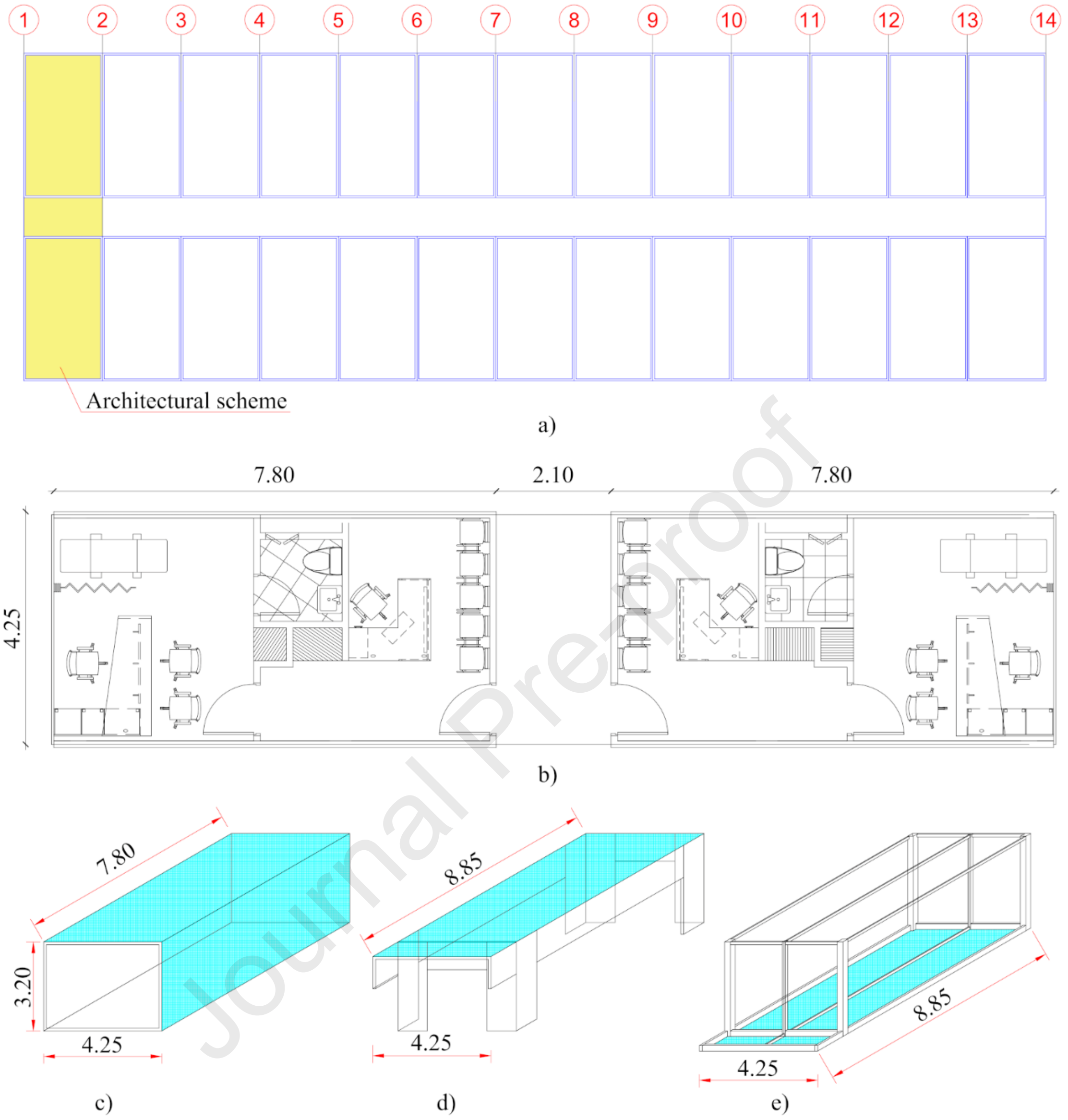


Figure 1. a) Case study floor plan, b) Architectural scheme of the modules, c) Modules CM1, d) Modules CM2, and e) Modules MSC (some modules require bracing). Dimensions in meters.

2.2. Environmental life cycle assessment LCA

LCA is a technique used to assess and compare the environmental impacts of a product throughout its life cycle. This assessment can include all production phases, including raw material extraction, manufacturing, use, disposal, and post-consumer processes such as recycling and reuse [10]. As stated in ISO 14040:2006, the LCA framework consists of four procedures: (1) Establishing the objective and scope, (2) Life Cycle Inventory Analysis (LCI), (3) Life Cycle Impact Assessment (LCIA), and (4) Interpretation.

2.2.1. Establishing the objective and scope

This procedure starts with defining the functional unit and establishing the scope. A process-based LCA is carried out, adapted to the study's objective, and uses available data. The effectiveness of a process-based LCA is demonstrated in case studies, where relevant data can be accessed [34]. The functional unit is a square meter of building (m²) to ensure comparability between different building systems. Consequently, the results quantify environmental and economic impacts based on this standardized unit. Figure 2 outlines the approach used in this research, which reflects a cradle-to-grave analysis encompassing four distinct stages: manufacture, construction, use, and end-of-life.

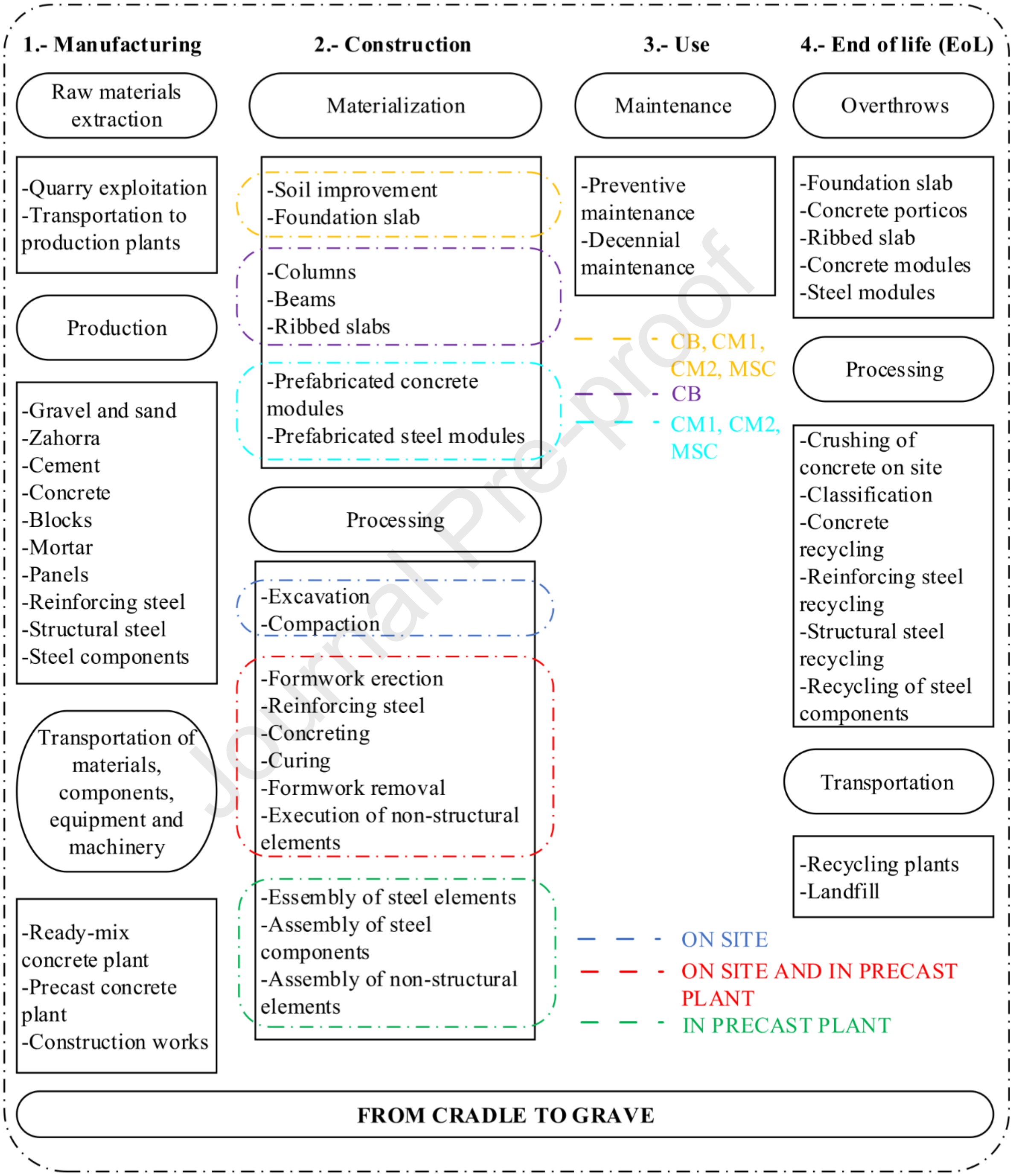


Figure 2. Life cycle stages

2.2.1.1. Manufacturing.

The environmental impact evaluation begins to identify the primary materials used to manufacture the various components of each alternative; this includes raw material extraction, resource consumption, transportation to production facilities, and manufacturing processes for aggregates, cement, concrete, concrete block, cement mortar, gypsum board, reinforcing steel, structural steel, and steel components. The primary materials involved are concrete, reinforcing steel, and structural steel. Transportation logistics are also evaluated, focusing on three key delivery points: the ready-mixed concrete plant, the precast production site, and the emplacement. The mobilization of the heavy equipment and machinery necessary for the on-site execution of the structural systems is also considered.

The project site, located on the southern outskirts of Quito-Ecuador, experiences moderate vehicular traffic. It is bordered by roads that, while congested at peak hours, generally maintain a steady flow at other times [35]. The site is 2.5 km from the ready-mix concrete plant, 21 km from the steel mill, and 43 km from the volumetric modular precast production plant.

2.2.1.2. Construction.

The construction of the PVMB differs significantly from that of conventional buildings due to the different methodologies employed. The foundation work is on-site in all four alternatives, including ground improvement activities. In the CB building, the in-situ activities involve formwork erection, reinforcing steel installation, concrete pumping, curing, stripping, and masonry work. In the CM1 and CM2 buildings, formwork erection, reinforcing steel installation, concreting, curing, and stripping are carried out in a precasting plant. The modules are then shipped to the site for erecting and final assembly. CM1 building also requires on-site concreting of the connections between the horizontal and vertical modules. Finally, the MSC building requires welding and erecting structural steel elements, assembly of steel components, installation of reinforcing steel, concreting of floor slabs, and cladding walls at the precast plant. The modules are then shipped to the site for erecting and final assembly.

2.2.1.3. Use and end-of-life.

The environmental impacts during the use phase of these structures are primarily associated with maintenance activities. These activities include manufacturing materials utilized in preventive maintenance work to ensure the structure's longevity. Insufficient investment in or poor maintenance practices can lead to significant long-term economic costs and may compromise the system's durability [36]. Maintenance of reinforced concrete structures (CB, CM1, and CM2) involves applying anti-carbonation paint based on acrylic resin in aqueous dispersion. The MSC structure requires two treatments: first, anti-carbonation paint for the concrete elements (foundation slab), and second, a two-component anti-corrosion paint based on epoxy resin coupled with fireproof mortar. This mortar, applied by spraying, provides passive fire protection, ensuring a 60-minute fire resistance for the steel structural elements.

Within the system boundaries, operations include dismantling foundations, concrete structural elements, precast concrete modules, and steel modules. This phase also encompasses on-site crushing, sorting, and recycling processes for concrete, rebar, and structural steel waste. The transport distances of the recycled materials coincide with those of the manufacturing phase, specifically from the emplacement to the ready-mixed concrete factory and the steel mill. Non-recyclable materials are transported to a dump located 7 km from the emplacement.

2.2.2. Environmental life cycle inventory analysis LCI

In this phase, input data are collected for each life cycle phase, according to the functional unit. All systems include a cast-in-place reinforced concrete foundation slab with soil improvement to achieve a 20T/m² allowable stress. Prefabrication levels of 79%, 75%, and 86% were achieved for buildings CM1, CM2, and MSC, respectively. The percentages for CM1 and CM2 were calculated based on the total volume of concrete, while the percentage for MSC was determined by its total cost.

Table 1. presents the inventory of all alternatives in the case study. The primary materials used include concrete with a specified compressive strength of 28 MPa for all structural elements, ASTM A706 Gr.60 reinforcing steel, and ASTM A572 Gr.50 hot-rolled structural steel. Transportation considerations cover three delivery points: the ready-mixed concrete plant, the precast manufacturing plant, and delivery to the construction site, including routes to recycling plants or landfills. Distances were quantified based on actual routes between these points. The construction phase includes using materials and non-renewable primary energy, accounting for energy consumption by construction equipment and machinery on-site and at the prefabrication plant. The use phase incorporates all materials and supplies required for preventive maintenance. Additionally, the demolition phase includes crushing and classifying waste at the construction site.

Several software tools and databases are available for LCA studies. Given the variety of materials and construction methods in the industry, selecting the right software depends on the limit of the investigation. This study selected the open-source OpenLCA software, which offers several advantages in performing LCA applications. [37] with the Ecoinvent database. The Ecoinvent database, widely recognized for its reliability and regular updates, is used in most processes [38]. The machinery required for construction and end-of-life activities was modeled using the BEDEC database [39], estimating the non-renewable primary energy use. The energy expenditure of the precast plant was quantified in terms of MJ. consumed per m^3 of precast concrete produced; this value depends on the plant's automation level; the value associated with automation level four, as established by reference [40], was used.

Model building in OpenLCA allows for integrating site-specific material and process characterization factors and uncertainty distributions [41]. It is essential to consider uncertainties in model development, as processes may vary depending on geographic location, the currency of the data, and the type of technology available [42]. The pedigree matrix helps to incorporate uncertainty by evaluating five parameters: reliability, completeness, temporal correlation, geographical correlation, and technological correlation; this, together with a base parameter related to the material or process, determines the overall uncertainty in the model [43].

Table 1. Inventory by functional unit

Description	Unit	CB	CM1	CM2	MSC	Data source
Manufacturing						E
Concrete, 28MPa	m^3	0.311	0.35	0.253	0.12	E
Ballast	Kg	298.56	298.56	298.55	298.55	E
Reinforcing steel	Kg	33.85	63.61	45.79	12.5	E
Hot rolling, steel	Kg	-		7.15	37.95	E
Steel components	Kg	-			0.92	E
Steel sheet	Kg	-			4.88	E
Cement mortar	Kg	23.04		11.81		E
Concrete block	Kg	154.86		59.54		E
Gypsum fibreboard	Kg	-			23.05	E
Construction						
Preliminary	MJ	67,46	67,46	67,46	67,46	B
Foundation slab	MJ	9,33	5,68	6,97	6,24	B
Columns	MJ	7,14	-			B
Floor slab	MJ	25,28	-			B
Module building	MJ	-	102,79	68,87	239,26	[40], B
Assembly, Crane (40T, 24T, 12T)	MJ	-	49,38	36,24	31,67	B, [44], [45]
Concrete for connections (corridor)	MJ	-	2,69	-	-	B
Masonry	MJ	0,35	-	0,21	-	B

Use						
Anti-carbonation paint	Kg	0.52	1,85	1,50	0,090	E
Anti-corrosion paint	Kg	-	-	-	0,57	E
Fireproof mortar	Kg	-	-	-	8,794	E
End of life						
Structure overthrow	MJ	140,01	119,62	111,18	60,02	B
On-site crushing	Kg	634,65	772,62	553,48	246,06	E

E: Ecoinvent, B: Bedec

2.2.3. Life Cycle Impact Assessment LCIA

LCIA measures the environmental impact of resource use and emissions released throughout a product's life cycle, generating vital environmental indicators [14]. This study used the ReCipe 2008 method, which includes two focuses called midpoint and endpoint. The midpoint focus encompasses 18 impact categories, which are described below: agricultural land occupation (ALO), global warming potential (GWP), fossil depletion (FD), freshwater ecotoxicity (FEPT), freshwater eutrophication (FEP), human toxicity (HTP), ionizing radiation (IRP), marine ecotoxicity (MEPT) marine eutrophication (MEP), metal depletion (MD), natural soil transformation (NLT), ozone depletion (ODP), particulate matter formation (PMF), photochemical oxidant formation (POFP), terrestrial acidification (TAP), terrestrial ecotoxicity (TEPT), urban land occupation (ULO) and water depletion (WD). Although this approach provides accurate and reliable data, its interpretation can be complex.

The endpoint approach, on the other hand, quantifies impacts in three main categories: Damage to human health (measured in disability-adjusted life years), Damage to ecosystems (measured in species per year), and Damage to resource availability (measured in US dollars). Although more interpretable, this method introduces more significant uncertainty [46]. The hierarchical "H" version was chosen for the assessment considering long-term impacts. Results were standardized by selecting the World ReCipe H/H [person/year] set option, allowing global environmental impact comparison [47].

2.2.4. Interpretation of analysis

The final phase consists of interpreting the results; in this study, a two-level analysis will be carried out: (1) an overall comparison and (2) a phase-by-phase comparison over a 50-year life cycle. The first one allows us to know the environmental performance of the alternatives in the different categories. The second examines the impacts generated in extraction and manufacturing, construction, use, and end of life; the phase that generates the most significant impact can be established. A general and specific environmental impact analysis was conducted using the midpoint and endpoint approaches. Subsequently, the endpoint approach was used to develop quantitative indicators to compare alternatives through multi-criteria decision-making.

2.3. Cost life cycle LCC

This study has performed a complete life cycle cost analysis. The analysis covered construction, in-use, and end-of-life, with cost estimates generated using the CYPE platform adapted to Ecuador. For the construction phase, the costs of the CB system included all the necessary materials, the use of equipment, machinery, and tools, as well as the necessary labor. The costs for the CM1, CM2, and MSC systems included materials, supplies, use of equipment, tools, and machinery, as well as the necessary labor at the prefabrication plant and the site, and transportation costs from the factory to the emplacement were also considered. The assembly process yields were adjusted from data in references [44] and [45]. Maintenance costs covered preventive measures, including anti-carbonation painting for the concrete elements in all alternatives; the MSC alternative used a corrosion protection primer and passive fire protection by spraying fireproof mortar. Decennial maintenance costs were also determined, considering the planned preservation operations. Finally, end-of-life costs were considered, including complete demolition, waste sorting, concrete crushing, transportation to recycling plants, and disposal fees for non-recyclable waste in landfills.

Future costs related to decennial maintenance and end-of-life expenses are discounted and converted to present value, for which discount rates must be defined, using low values to minimize burdens on future generations; values of 2% are adequate and are also called social discount rates [48]. Equation 1 is used to convert the cost of the future into the cost of the present.

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

LCC: Life Cycle Cost, C_i: costs for time t, t_0: start time of the evaluation period ($t_o=0$), t_{SL}: expected time in years, and d: discount ratio.

2.4. Multi-criteria decision making

The final stage of this investigation will be to assess the options based on the scores obtained in the various analyses according to several criteria. MCDM techniques convert the results of the environmental and economic assessments. The structuring, modeling, and weighting of the problem are carried out to determine the most appropriate alternative. Five MCDM methods widely recognized in civil engineering and construction are employed [18]: AHP (pairwise comparison) to derive criteria weights; SAW and COPRAS (scoring methods); TOPSIS and VIKOR (distance-based methods); and AHP to select the best alternative and establish rankings, which 15 indicators and six criteria were used to integrate the economic and environmental dimensions.

2.4.1. AHP (Analytic Hierarchy Process)

The pairwise comparison method, introduced by Saaty T. L. in 1980 [49], helps to select alternatives based on hierarchical and commonly contradictory selection criteria. This method creates pairwise comparisons at each level of the hierarchy and assigns a score on a basic scale that translates qualitative relevance into quantitative scores ranging from 1 to 9. The scale indicates the importance of a parameter, criterion, or alternative i compared to another j, where one indicates "equally important" and nine indicates that "i is significantly more important than j." The results are obtained from the decision matrix A={aij}, a square matrix, reciprocal (if $a_{ij}=x$ then $a_{ij}=1/x$ $\forall_{ij} \in \{1,...,n\}$, n is the number of parameters to be compared) and homogeneous (if i and j have the same importance, $a_{ij}=a_{ji}=1$, and $a_{ii}=1$ $\forall i \in \{1,...,n\}$. Using the Consistency Index (CI), the approach evaluates the consistency of the decision. The judgments expressed in matrix A must not be contradictory.

$$CI = (\lambda_{max} - n)/(n-1) \quad (2)$$

λ_{max}: highest value of equity, and n: dimension of the decision matrix; the matrix consistency index is calculated by applying the following expression:

$$CR = CI/RI \quad (3)$$

RI: the randomness ratio, which is a measure of the consistency of a random matrix that is defined in Table 2. Inconsistency is acceptable if the CR does not have a higher value than the values in Table 3.

Table 2. Random index (RI).

Criterion number (n)	2	3	4	5	6	7	8	9	10
RI	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Table 3. Maximum consistency ratio (CR).

Matrix size (n)	CR(%)
3	5
4	9
≥5	10

The AHP is one of the most widely used methods within the MCDM to solve practical problems [50]. Its ability to translate a decision-maker's perception into numerical scores has attracted the scientific community's attention. This method works best with hierarchically structured models. Additionally, AHP allows for a consistency check, where the logic and coherence of the decision-maker's responses can be verified using a consistency ratio (CR) cross-check [51].

2.4.2. Group aggregation technique

In this research, the AHP method was used to define the weightings of each criterion. The process involved a panel of five expert individuals, each possessing 6 to 30 years of experience in civil engineering and construction. The experts' voting influence was assessed using a simplified neutrosophic approach, which considered two main parameters: their self-assessed experience and consistency in adhering to the evaluation matrix. Characterizing the experts' profiles followed the principles of the Delphi method using the formulation adapted by Sánchez-Garrido et al. [52].

A coefficient between 0 and 1 expresses the resulting competence of expert i, calculated based on experience, research, and knowledge, which is determined by the following expression:

$$\psi_i = \left(\frac{PE_i}{\max(PE_k)} + \frac{ES_i}{\max(ES_k)} + \frac{AD_i}{\max(AD_k)} + \frac{AA_i}{\max(AA_k)} + \sum_{m=1}^{n} KC_{m,i}/n\right)/10 \tag{4}$$

PE_i: number of years of professional experience of expert i, $max(PE_k)$: maximum number of years of professional experience among the experts, ES_i: number of years of specialization of the expert in the field of sustainability, $max(ES_k)$: maximum value in years in the field of sustainability of the group of experts, AD_i: academic level of the expert (1=engineering, 2=masters, and 3=doctorate), AAi: scientific generation as primary author according to the number of JCR articles (0=none, 1=1-3, 2=4-10 and 3=more than 10), $KC_{m,i}$: experience of the expert in various topics, five fields of knowledge were chosen (construction, structural design, budgeting, environmental and social assessment) and a scale n=5.

The following expression defines the inconsistency ε_i of the expert:

$$\varepsilon_i = CR/CR_{lim} \tag{5}$$

CR is the consistency index when completing the decision matrix, and CR_{lim} is the maximum tolerable consistency index; if there are more than five criteria, the inconsistency can be up to 10%.

The credibility of decision maker i is defined by calculating the Euclidean distance from the point to the ideal point of maximum credibility (1,0) using the following expression:

$$\theta_i = 1 - \sqrt{\{(1-\psi_t^2) + \varepsilon_t^2\}/2} \tag{6}$$

Finally, the following expression is used to obtain the final weighting of each criterion related to the expert's credibility.

$$W_i = \frac{\sum_k W_{ik}\theta_k}{\sum_k \theta_{ik}} \tag{7}$$

W_{ik} is the weight for each criterion i determined by decision-maker k, and θ_k is the voting power obtained in the AHP group.

Table 4. presents the six evaluation criteria and the 15 indicators used in this analysis. The order of priority is as follows: C1-Construction and construction management costs (30%), C4-Manufacturing environmental impacts (26%), C6-End-of-life environmental impacts (18%), C3-End-of-life costs (15%), C5-Construction and use phase environmental impacts associated with maintenance (7%) and, finally, C2-Use phase costs associated with maintenance (4%). The group of experts considered a total weighting of 49% for the economic and 51% for the

environmental criteria. Varying the weights at the indicator level causes a minor impact on the ranking of the different options; this impact decreases as one moves up to the criterion level; equal weights can be used in the indicators without any relevant effect [52].

Table 4. Weights of the criteria.

Criteria		Indicators		
Cost (Construction) 30%	C1	Construction cost (USD)	I1	100,00%
Cost (Maintenance) 4%	C2	Preventive maintenance (protection) (USD)	I2	50,00%
		Maintenance (USD first 10 years) (USD)	I3	50,00%
Cost (End of life) 15%	C3	Overthrow of structure (USD)	I4	33,33%
		Waste crushing (USD)	I5	33,33%
		Waste treatment (USD)	I6	33,34%
Impacts (Manufacturing) 26%	C4	Ecosystem quality (Points)	I7	33,33%
		Human health (Points)	I8	33,33%
		Resources (Points)	I9	33,34%
Impacts (Construction y Use) 7%	C5	Ecosystem quality (Points)	I10	33,33%
		Human health (Points)	I11	33,33%
		Resources (Points)	I12	33,34%
Impacts (End of life) 18%	C6	Ecosystem quality (Points)	I13	33,33%
		Human health (Points)	I14	33,33%
		Resources (Points)	I15	33,34%

2.4.3. SAW (Simple Additive Weighting)

Direct scoring method that directly sums the normalized scores of each criterion C'_{ki} and multiplies them by their relative weight W_k. The S_i indices obtained are compared to determine the best solution.

$$S_i = \sum_{k=1}^{m} W_k * C'_{ki} \tag{8}$$

The best solution is the resulting maximum or minimum index. When the solution is maximal, the normalization of each criterion is performed by dividing the values of the criterion C_{ki} by the highest value for that criterion among all the alternatives ($max_k\{C_{ki}\}$). If the solution is minimum, the criteria are normalized by dividing their values by the lowest value for that criterion among all the alternatives ($min_k\{C_{ki}\}$).

2.4.4. COPRAS (Complex Proportional Assessment)

It was proposed by Zavadskas [53]. The method determines the optimal solution according to the relative importance of each option based on the positive and negative attributes (benefits and obstacles) previously determined. The index for each alternative is calculated using equation 9, which allows simultaneous consideration of the benefit and cost criteria:

$$S_i = S_{i+} + S_{i-} \tag{9}$$

S_{i+} only considers the criteria Ck_{i+} to be maximized by applying the SAW method:

$$S_{i+} = \sum_{k=1}^{m} W_{k+} * C'_{ki+} \tag{10}$$

The S_{i-} term is calculated similarly to S_{i+}, although the criteria C_{ki-} to be minimized are considered in this case.

$$S_{i-} = \frac{\sum_{k=1}^{m} W_{k-} * C'_{ki-}}{W_{k-} * C'_{ki} * \sum_{j=1}^{n} \frac{1}{W_{k-} * C'_{ki-}}} \quad (11)$$

In conclusion, the final index is proportional and inversely proportional to the maximization and minimization criteria.

2.4.5. TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution)

Devised by Hwang and Yoon in 1981 [54], it chooses the best option by simultaneously checking how close it is to both the positive ideal solution (SIP) and the negative ideal solution (SIN). In the first step, the method normalizes the r_{ij} scores *of* each option *i* and criterion *j* using equation 12.

$$r'_{ij} = \frac{r_{ij}}{\sqrt{\sum_{j=1}^{n} r_{ij}^2}} \quad (12)$$

n: number of criteria considered. In the next step, the weighted normalized scores v_{ij} are calculated. Then, the distance between the positive ideal solution (d_i^+) and the negative ideal solution (d_i^-) is obtained by calculating the Euclidean distances by applying the following expressions:

$$d_i^+ = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^+)^2} \quad (13)$$

$$d_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2} \quad (14)$$

In the last equations, $v_j^+$and v_j^- are the best and worst scores for criterion *j* for each alternative *i*. In the last step, the index C_i^* is determined, expressing each alternative's final valuation.

$$C_i^* = \frac{d_i^-}{(d_i^+ + d_i^-)} \quad (15)$$

2.4.6. VIKOR (VlseKriterijuska Optimizacija I Komoromisno Resenje)

It was developed in the late 1990s by Opricovic [55]. The first step consists of establishing the decision matrix $R = [r_{ij}]$ and previously calculating the W_i weights; next, the best and worst values of the criterion among the alternatives are identified (r_i^+ and r_i^-), and then the decision matrix *R* is normalized with the following expression:

$$r'_{ij} = \frac{r_i^+ - r_{ij}}{r_i^+ - r_i^-} \quad (16)$$

Then, the weighted and standardized Manhattan S_j and Chebyshev R_j distances of each alternative *j* are determined with equations 17 and 18.

$$S_j = \sum_{i=1}^{n} W_i r'_{ij} \quad (17)$$

$$R_j = max[W_i r'_{ij}] \quad (18)$$

Finally, the next step is to evaluate the measurement index Q_j for each alternative j; the following expression determines that:

$$Q_j = v * \frac{S_j - min[S_j]}{max[S_j] - min[S_j]} + (1 - v) * \frac{R_j - min[R_j]}{max[R_j] - min[R_j]} \tag{19}$$

In the last expression, v is a dynamic coefficient that determines the significance of the two distances; generally, the two distances are balanced by setting $v=0.5$. According to this method, the best option is the one with the lower Q_j score, under the condition that the difference with the Q score of the second-best option is more significant than $1/(j-1)$.

3. Analysis of results and interpretation.

3.1. Environmental life cycle assessment

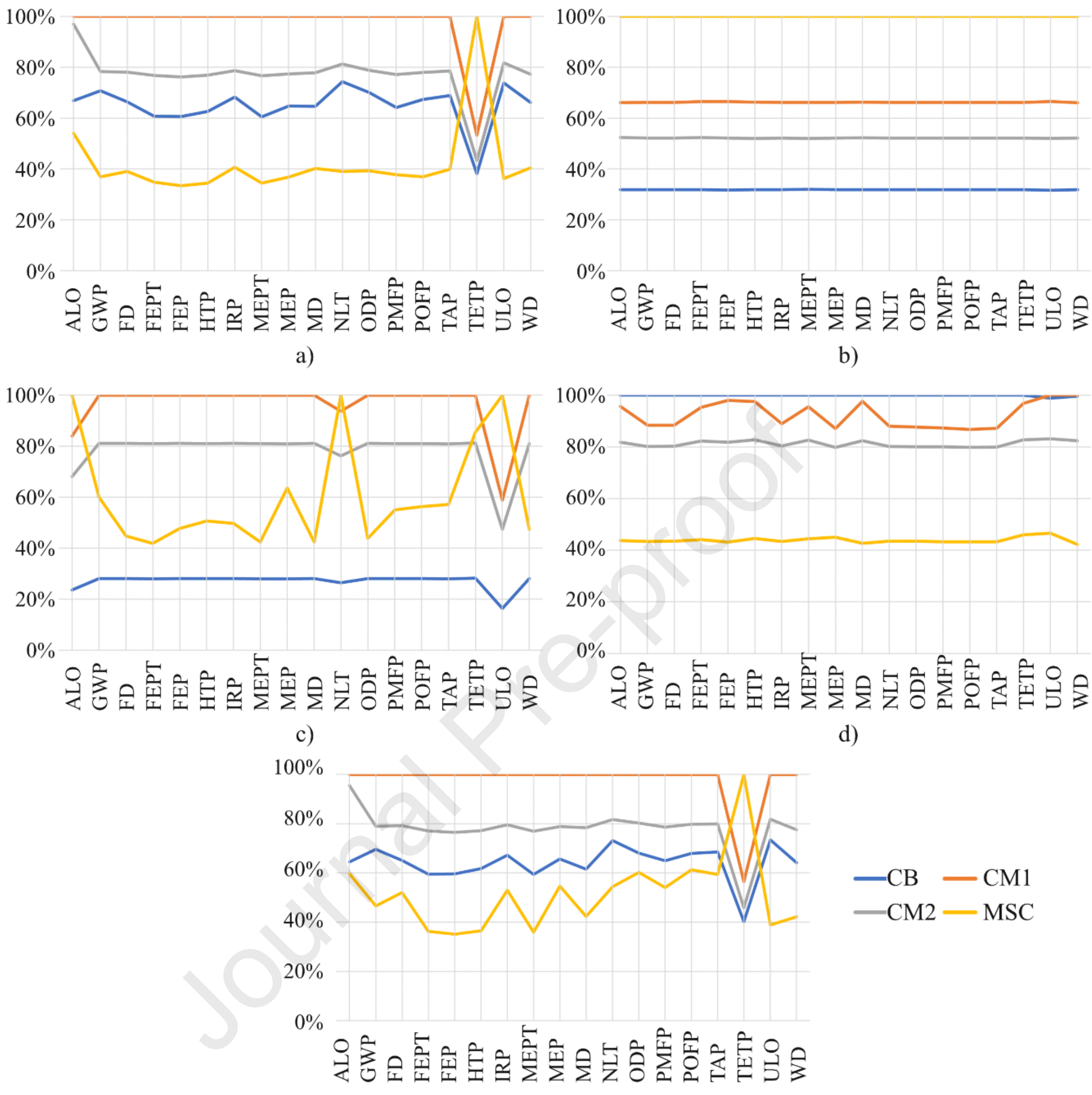
3.1.1. Midpoint

The midpoint impact categories offer comprehensive data, creating a detailed environmental profile yet not yielding an overall impact assessment. However, they help to identify significant types or categories of impact, facilitating focused solutions based on crucial environmental issues. Figures 3 a), b), c), d), and e) show the midpoint impacts for the manufacturing, construction, use, and end-of-life stages, as well as the total impact, respectively. These results are shown relative to the highest impact for each category.

We begin by analyzing the life cycle results by stage. CM1 presents the highest impact in most categories during the manufacturing phase, closely followed by CM2. On average, the BC system produces 67% of the impact generated by CM1. In contrast, MSC is the most favorable alternative, with an average impact of only 38% of that caused by CM1 and 43% less impact than the BC system. These differences are directly related to the quantities of material used in each alternative. However, MSC shows the highest impact during the construction phase, generating 3.1 times more impact than CB and 1.5 times more than CM1, mainly due to the construction and installation of volumetric steel modules, which result in higher fuel consumption for machinery and equipment, both in the prefabrication plants and on-site. In this phase, CB is the best alternative.

During the use stage involving maintenance activities, CM1 and CM2 show significantly higher impacts than CB across most categories, with increases of approximately 3.6 and 2.9 times on average, respectively. MSC also exhibits a substantial average impact, 79% higher than CB in most categories, except for "ALO," "NLT," and "ULO," where MSC has the most significant impact. These results are linked to the larger structural surfaces requiring maintenance and the application of multiple treatments, which increase the overall impact. CB has the highest impact in the end-of-life phase, while CM1, CM2, and MSC show average impact reductions of 7%, 19%, and 56%, respectively. This difference is primarily due to the material volumes, particularly the dimensions of structural elements. For example, the CB foundation slab has larger dimensions due to design factors like punching shear, significantly contributing to the higher impact.

Considering all midpoint impact categories and life cycle stages, CM1 consistently emerges as the least favorable alternative due to its higher material quantities, particularly reinforcing steel and concrete, required by its structural configuration. In contrast, the MSC alternative has the lowest overall impact. Despite its substantial material requirements—including concrete, reinforcing steel, and hot-rolled steel—MSC's average overall impact is 48% of that of CM1. Additionally, when compared to CB, MSC shows a significantly lower impact, approximately 27% less.



a) b) c) d) e)

Figure 3. Midpoint impacts. a) Manufacturing, b) Construction, c) Use, d) End of life and e) Total.

Due to the critical role of CO_2 emissions in global warming, climate change is a critical impact category at the midpoint. Figure 4. illustrates the emissions per stage and total emissions per square meter of construction. When analyzed by stage, the MSC alternative shows the most favorable performance during the manufacturing stage. MSC CO_2 emissions are 48% lower than CB, 63% lower than CM1, and 53% lower than CM2. However, in the construction phase, MSC is the least favorable alternative. CB is the most advantageous during the in-use stage, while CB performs worst in the end-of-life stage. It should be noted that CM1 and CM2 have a 44% and 13% higher climate change impact than CB, respectively, while MSC generates a 33% lower climate change impact than CB.

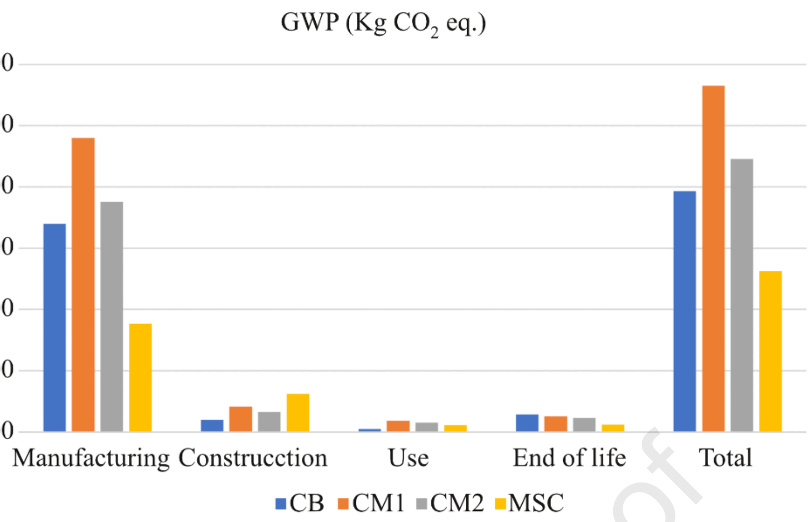


Figure 4. Cradle-to-grave climate change emissions for alternatives.

When analyzing the primary contributors to each impact category, it becomes clear that reinforcing steel and concrete production are the most significant factors. Reinforcing steel production accounts for an average of 49% of the impact for CB, 52% for CM1, 47% for CM2, and 27% for MSC across most categories. In the climate change category, concrete production contributes 47% for CB, 37% for CM1, 34% for CM2, and 27% for MSC. Meanwhile, reinforcing steel production contributes 32%, 41%, 38%, and 17% for CB, CM1, CM2, and MSC, respectively. Notably, in the case of MSC, which is constructed with hot-rolled steel, this material contributes only 8% to the overall impact.

3.1.2. Endpoint

This analysis provides an overview that allows direct comparisons between impact categories and simplifies interpretation. The three categories evaluated - ecosystem damage, human health, and resource availability - are vital in determining which alternative has the most significant environmental impact. An overall impact score is calculated by normalizing the categories into a standard unit. Figures 5 a), b), and c) show the contribution of each life cycle stage to the categories Ecosystems, Human Health, and Resources. The manufacturing phase contributes significantly to impacts in all categories; by contrast, the contributions of the construction, use, and end-of-life phases are minimal. In addition, this work quantified the environmental impacts of pre-recycling preparation work on concrete, reinforcing steel, and hot-rolled steel. The potential benefits of recycling should be considered in future evaluations where these materials are used.

For all impact categories, the following pattern is presented: In the fabrication phase, CM1 is on average 46% more polluting than CB, CM2 is on average 17% more polluting than CB, while MSC is the best with 43% less emissions on average than CB, again, reinforcing steel and concrete use marks the highest emission levels. In the construction phase, the worst is the MSC, which is, on average, 3.1 times more polluting than the CB, which is the best of all the alternatives. In the use phase, the worst is CM1, which is 3.6 times more polluting than CB on average. Lastly, in the end-of-life phase, the worst is CB; the impact of CM1, CM2, and MSC is, on average, 11%, 20%, and 57% lower, respectively; the best alternative is MSC. Figure 5d. also shows the total normalized endpoint values, allowing straightforward interpretation. First, it is determined that the implementation of the alternatives provokes the most excellent affectation on the resources, with an average of 71% of the total impact, followed by damage to human health, which contributes an average of 26% of the total damage, and damage to ecosystems only contributes an average of 3%. Therefore, the best alternative is MSC, and the worst is CM1. If we compare them with CB, MSC causes 23% less damage, and CM1 52% more.

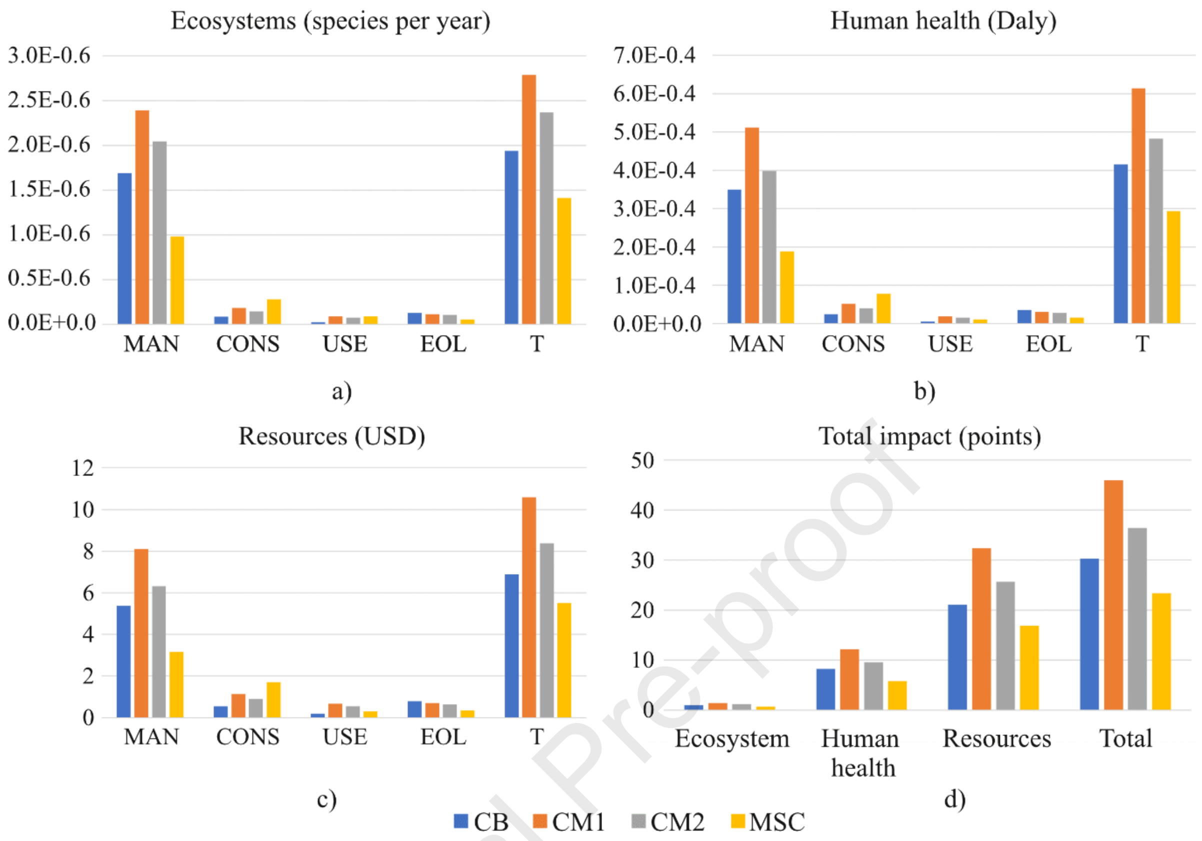


Figure 5. Life-cycle endpoint impacts. a) Ecosystems, b) Human health, c) Resources, d) Total impact.

3.2. Results of the life cycle economic evaluation.

This paragraph analyzes the life cycle economic repercussions of the option, assessed on a per square meter (m²) basis. Figure 6a shows the individual economic metrics (I1-I6) in US dollars per square foot and the percent rating of the lifecycle phases by criteria (C1-C3). These costs are presented in present values for the year 2023. Figure 6b compares the total costs of each alternative in the different life cycle phases, taking the CB as a reference.

Analysis of Figures 6a and 6b reveals that the construction phase constitutes the most significant percentage of total costs, averaging 76% of total expenditure across all alternatives. The MSC alternative incurs the highest economic impact, with a total cost 60% higher than the CB system. CM1 is 6% more expensive during construction, while CM2 is 6% less costly. These differences in construction costs are linked to similar quantities of materials used. However, the MSC's higher cost is primarily due to its greater material volume and the higher cost of raw materials. The use stage proves significantly more expensive for CM1, CM2, and MSC than CB, with cost differences of 182%, 129%, and 294%, respectively; this is due to the more significant areas requiring preventive maintenance in CM1 and CM2 and the more extensive preventive treatments (anti-carbonation paint, anti-corrosion paint, and fireproof mortar) required for MSC. Finally, costs for the end-of-life stage decrease, with reductions of 1%, 2%, and 15% for CM1, CM2, and MSC, respectively, compared to CB. Despite these reductions, end-of-life costs represent only 9% of the total costs, making the differences relatively minor.

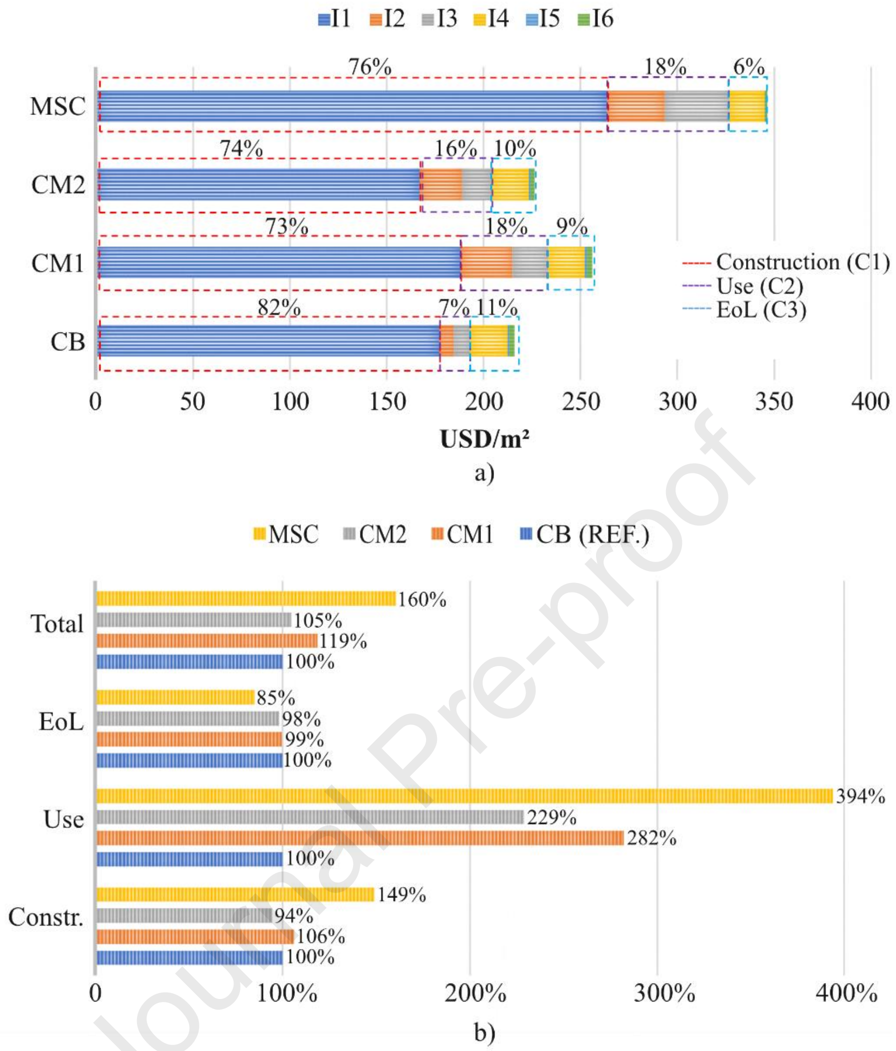


Figure 6. Life cycle economic impacts. a) comparison of the total according to indicators for each alternative, and b) comparison of the total value of the alternatives with respect to the conventional building (CB).

3.3. Multicriteria decision making MCDM.

This section aims to rank and identify the best alternatives throughout their life cycle by considering economic and environmental factors within the defined analysis parameters. Five MCDMs, AHP, SAW, COPRAS, TOPSIS, and VIKOR, were used based on six evaluation criteria to calculate a score for each alternative, reflecting its overall performance. The criteria weights, detailed in Sections 2.3.1 and 2.3.2, were used as inputs for these methods. Table 5 presents the quantitative evaluations of each criterion for all alternatives.

Table 5. Life cycle impact results according to criteria established for each alternative.

CRITERIA	Unit	CB	CM1	CM2	MSC
C1	USD/m²	177,06	188,04	167,15	263,82
C2	USD/m²	8,02	22,62	18,36	31,59
C3	USD/m²	7,61	7,57	7,46	6,46
C4	points/m²	8,07	12,03	9,41	4,63

C5	points/m²	0,96	2,35	1,87	2,70
C6	points/m²	1,06	0,94	0,85	0,46

Table 6 shows the scores, and ranking obtained for each alternative, providing information on its performance in terms of economic and environmental approaches during its life cycle.

Table 6. Scores and ranking of the alternatives for the MCDM techniques used in this study.

Alternative	AHP [a]	R	SAW [a]	R	COPRAS [a]	R	TOPSIS [a]	R	VIKOR [b]	R
CB	0,26	II	0,75	II	0,80	II	0,53	II	0,193	II
CM1	0,21	IV	0,63	IV	0,68	IV	0,32	IV	0,851	IV
CM2	0,24	III	0,71	III	0,78	III	0,51	III	0,105	I
MSC	0,29	I	0,82	I	0,83	I	0,61	I	0,500	III

[a]: Higher score is best, [b] The shorter the distance, the better
R: Ranking

4. Discussion of results.

This study evaluates and compares four earthquake-resistant structural systems' economic and environmental impacts on a four-story building. The systems considered are a conventional reinforced concrete (CB) system, two modular reinforced concrete alternatives (CM1 and CM2), and a modular steel system (MSC). The principal objective of this work is to determine if the modular construction options offer better results than the conventional system.

Specific standards have yet to be established for the design of PVMBs. However, the existing literature on their dynamic performance aims to achieve a performance comparable to that of traditional buildings that conform to the specifications of the relevant standards. The lateral load-resisting structural systems used in the modular alternatives of this study are based on seismic-resistant solutions from accredited research. For CM1, we adopted the system developed by Pan et al. (2020) [30], in which prefabricated shear walls integrated into the volumetric modules provide lateral force resistance. Finite element modeling, cyclic loading tests, and nonlinear static and dynamic analyses validated this system. For CM2, the system proposed by Zhao et al. (2022) [31] was used, which included comparative shaking table tests with a conventional model. The system demonstrated adequate performance, with comparable dynamic responses to the conventional model, less damage to the shear wall, and better energy dissipation. Finally, for the MSC, we followed the design model proposed by Sanches et al. (2021) [32], [33], which considered the specific constraints of modular construction. This model included thrust analysis and bidirectional nonlinear time history analysis, showing acceptable behavior under severe seismic loads. These systems ensure that the alternatives exhibit similar seismic resistance behavior over their lifetime, allowing for a fair comparison.

The following is a discussion of the critical factors that influence the environmental and economic outcomes of the alternatives:

1) *The seismic-resistant structural system:* The configuration is crucial, affecting material quantities and overall performance. In the case of concrete structures, CM1 consists of six-sided volumetric modules with double walls and double slabs. This design results in high concrete and reinforcing steel consumption, leading to increased loads and the need for additional in-situ concrete to complete the system. Compared to CB, CM1 uses 12% more concrete and 88% more reinforcing steel. CM2 improves on CM1 by eliminating double slabs and employing discrete shear walls, thus avoiding the need for in-situ concrete. This optimization results in a 20% reduction in concrete use, although it increases steel use by 35% compared to CB. Although CM2 offers better environmental performance than CM1, it still produces 20% more environmental impact than CB. For CM1 and CM2, reinforcing steel contributes to the environmental impact, accounting for an average

of 43%. Effective management of material quantities in modular systems presents scientific challenges, mainly due to their structural requirements, as these may even require cast-in-place reinforced concrete central cores or cast-in-place concrete horizontal connections between modules to ensure robust floor diaphragms and adequate resistance to lateral loads [56]. In addition, the structural integrity of the modules must be maintained during production, transportation, and installation. They must support their weight, temporary loads in the assembly and erection process, and permanent stresses during their service life [57].

2) *The type of material used:* The strategy of selecting materials with lower environmental impact during the design phase is a widely recognized approach to reducing the environmental footprint of buildings. Although this strategy can be effective, more is needed; in some cases, more comprehensive approaches may be necessary [58]. In this study, the use of hot-rolled steel in the MSC option yields more favorable life cycle assessment results than other alternatives. Specifically, MSC results in an average 23% reduction in environmental impact compared to the CB system. Hot-rolled steel contributes approximately 8% of the total environmental impact as the primary material of the MSC system. On the other hand, approximately 20% and 17% of the total impact is due to concrete and reinforcing steel used in the foundations and floor slabs of the steel modules. These results are consistent with previous research, which suggests that incorporating steel in modular construction can reduce the environmental impact, although it may have a higher cost than concrete alternatives [14]. LCA studies have shown that the cost of MSCs is up to 60% higher than that of CBs, underscoring the importance of carefully considering economic and environmental factors when selecting structural materials in the initial design phases.

The results of the analysis reveal the need to adopt a holistic approach to identify the best solution from an environmental and economic point of view throughout its life cycle. The application of the MCDMs reveals that the MSC alternative is the best-rated in AHP, SAW, COPRAS, and TOPSIS. At the same time, CM2 appears to be the best option for VIKOR. In all methods, CB consistently ranks second. Although the overall distribution of criteria weights is relatively balanced, environmental criteria play a significant role in decision-making: economic criteria account for 49% and environmental criteria for 51%. MSC's good performance on criteria C3, C4, and C6, which account for 59% of the total weight, makes this alternative the leading one. When comparing MSC with CB, MSC is 49% more expensive in criterion C1. However, it outperforms CB in criteria C3, C4, and C6, showing reductions of 15%, 43%, and 56%, respectively, as illustrated in Figure 6.

The evaluations conducted using the SAW and COPRAS methods are straightforward, as they involve summing the standardized values of each weighted criterion. These methods are well-suited for cases with quantitative variables, as in this study. TOPSIS and VIKOR, on the other hand, aim to identify the alternative closest to the optimal solution. TOPSIS confirms MSC as the optimal solution by favoring alternatives that deviate least from the ideal point. The quadratic standardization metric used in TOPSIS highlights the departure from less optimal solutions, thus supporting MSC's superior performance. VIKOR, which employs linear standardization, seeks a compromise solution closest to the positive ideal solution (SIP). If the value of "v" increases, MSC gains prominence while CM2 loses its relative importance; this is because the Manhattan distance (Sj) favors MSC for higher values of "v," while for values of "v" more significant than 0.80, the infinite distance (Rj) suggests that CM2 is preferable. Nonetheless, for "v" values of 0.80 or lower, the measurement index (Qj) indicates that CM2 is the best. According to the quantitative variation of criteria among the alternatives (see Figure 7), CM2 excels in C1 and ranks second in C2, C3, C5, and C6. In the comprehensive application of MCDM methods, CM2 closely trails CB. Conversely, CM1 fares poorly due to its extensive use of concrete and reinforcing steel, which significantly impacts its environmental performance, particularly affecting the fabrication phase—a crucial factor in the overall impact assessment.

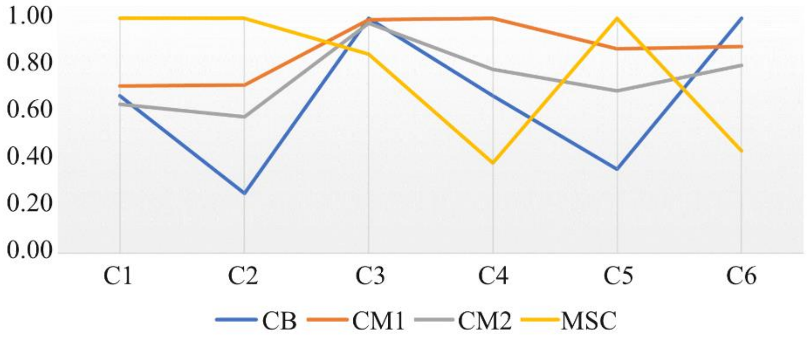


Figure 7. Comparison of criteria between alternatives

Finally, the performance of each applied MCDM method is evaluated through its differentiation capacity by calculating the C_i index.

$$C_i = \frac{|Q_{best,i} - Q_{2nd,i}|}{|Q_{best,i} - Q_{worst,i}|} \quad (20)$$

In the last equation, $Q_{best,i}$ is the score of the best option according to the MCDMi, $Q_{2nd,i}$ is the score of the second-ranked alternative, and $Q_{worst,i}$ is the score of the worst alternative. The formulation adopted by Navarro et al. [59] was used.

Table 7 shows the differentiation indices, showing that VIKOR has the lowest differentiation capacity, and AHP, SAW, and TOPSIS differentiate more significantly among the alternatives.

Table 7. Differentiation indices for each MCDM method.

	AHP	SAW	COPRAS	TOPSIS	VIKOR
$\lvert Q_{best,i} - Q_{2nd,i}\rvert$	0,03	0,07	0,03	0,08	0,088
$Q_{best,i} - Q_{worst,i}$	0,08	0,19	0,15	0,29	0,746
C_i	0,38	0,37	0,21	0,28	0,12

The experts involved in this study ensured a diversity of approaches and perspectives. Five experts were selected, consistent with practices in other relevant research within civil engineering and sustainability [60], [61]. Their experience, ranging from 6 to 30 years, spanned structural engineering, construction, and sustainability, with varied professional, academic, and research backgrounds. Expert opinions were captured using the widely recognized AHP method. The relevance of each expert within the group was determined by their competence and consistency in completing the evaluation matrix. However, it is crucial to recognize that criteria weighting is the primary source of subjectivity in MCDM models and can influence the prioritization of alternatives.

Therefore, the sensitivity of alternative rankings obtained from the MCDM model should be analyzed. Twelve new scenarios were created by adjusting the weights of the evaluation criteria, increasing and decreasing their values by 15%. The unchanged weights in each scenario were adjusted to ensure that the total sum equaled one. Past research has indicated that the final evaluation results show minimal variation when the weighting factors initially considered are adjusted by less than 10% [61]. Applying the five MCDMs under these conditions generated 60 additional rankings of the alternatives.

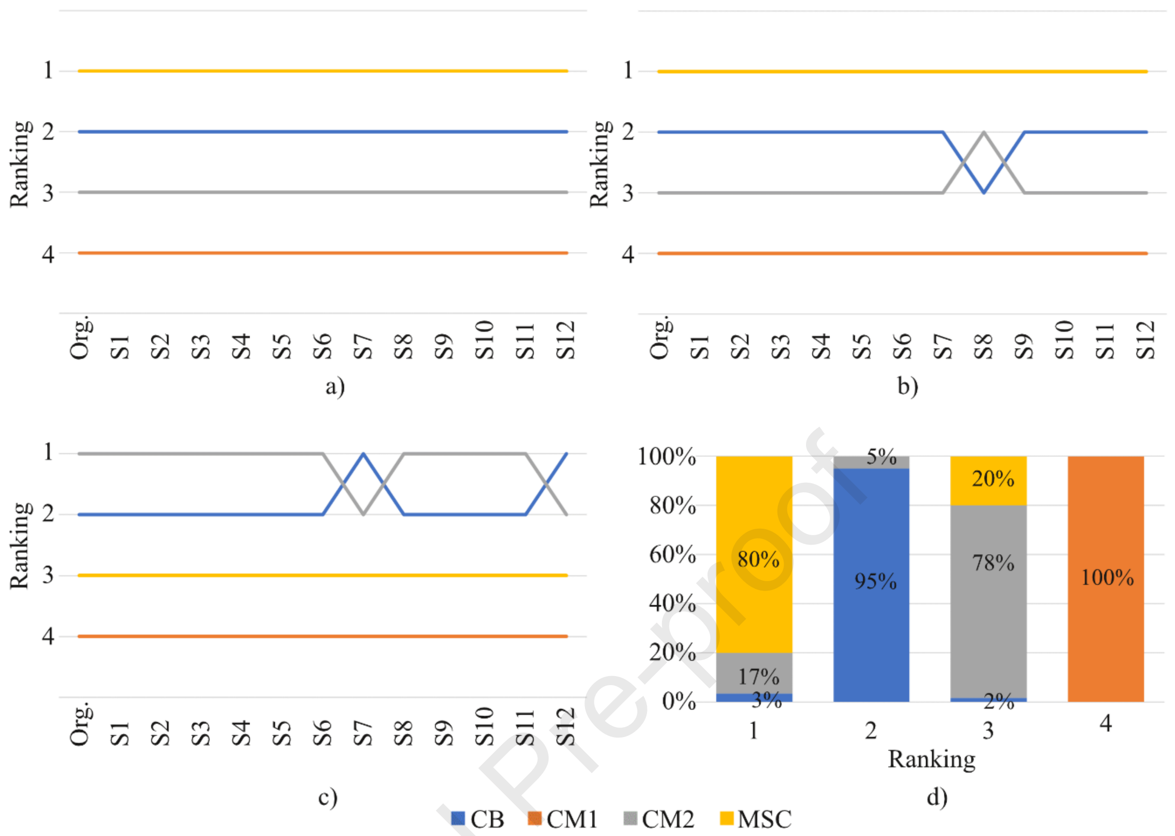


Figure 8. Sensitivity analysis of MCDM model. a) AHP, SAW and COPRAS. b) TOPSIS. c) VIKOR. d) Total.

Figure 8. presents the final rankings obtained. The rankings for the AHP, SAW, and COPRAS methods remain consistent with the original scenario, showing no changes (Figure 8a). In contrast, the TOPSIS method shows an alteration in Scenario 8, where a decrease in the weighting of C4 (manufacturing environmental impacts) affects the ranking (Figure 8b). With the VIKOR method, the original ranking differs from the other methods, with CM2 emerging as the top alternative, which holds in most new scenarios. Exceptions include Scenario 7, where an increase in the weighting of C4, and Scenario 12, where a decrease in the weighting of C6 (end-of-life environmental impacts) results in CB being ranked first (Figure 8c). Overall, MSC is the best alternative in 80% of the scenarios analyzed, while CB ranks second-best in 95% of the cases; this indicates that the initial model results are robust (Figure 8d).

The alternatives have been compared, assuming they all exhibit similar structural behavior throughout the helpful life studied in compliance with seismic regulations. However, it is crucial to consider the possibility of an earthquake occurring during the building's lifespan, the economic losses resulting from structural repairs, and the associated environmental impacts, which could reveal significant differences in the behavior of the alternatives. This new scenario, framed in an analysis based on resilience and sustainability, could be incorporated into a revised decision model. Relevant studies in seismic design [62] and rehabilitation [63], [64] of buildings have included this issue in their investigations.

5. Conclusions

This study presents a comprehensive methodology to evaluate four alternative earthquake-resistant structural systems for an outpatient block of a hospital in Quito, Ecuador. The alternatives include a conventional reinforced concrete system (CB) as a base alternative, two volumetric modular reinforced concrete systems (CM1 and CM2), and a volumetric modular steel system (MSC). An integrated analysis was performed combining an environmental life cycle assessment (LCA), which determined the impact of each alternative in the manufacturing, construction, use (maintenance), and end-of-life phases using midpoint and endpoint approaches, and a life cycle cost analysis (LCA), which evaluated total construction costs, preventive maintenance during the use phase and costs associated with the end-of-life, including recycling of materials. A two-dimensional framework of 6 criteria and 15 quantitative indicators was then defined based on the analysis results using MCDMs. The framework was used to establish a ranking of the alternatives.

The CM1 and CM2 structural systems, designed as seismic-resistant solutions for low-rise buildings, may involve more extensive reinforcing steel usage than the CB structural system; this directly influences environmental and economic performance throughout the life cycle. CM1 uses more reinforcing steel and employs a higher volume of concrete than the CB system, resulting in the highest environmental impacts among the alternatives. In light of this, the primary focus becomes minimizing material usage or enhancing its efficiency to design structures with reduced impact. Notably, CM2 presents a significant reduction in material usage compared to CM1. Its design optimizes the box configuration, allowing for competitive environmental and economic performance compared to the CB system. Despite being only 5% more expensive, CM2 generates 20% more environmental impact than CB. Conversely, compared to CM1, CM2 is up to 12% more cost-effective and can reduce environmental impact by up to 22%.

Utilizing materials with a lower environmental impact emerges as a critical strategy in creating modular buildings with minimal environmental footprints. In this context, the MSC stands out as the most favorable alternative environmentally. Achieved a 23% reduction in total environmental impact compared to CB, 49% reduction compared to CM1, and 36% reduction compared to CM2. Despite its noteworthy environmental performance, the primary material used in this structural system, hot-rolled steel, contributes merely an average of 8% to the total environmental impact. However, regarding overall economic analysis, the MSC faces a disadvantage—it is 60% more expensive than the CB.

Considering economic and environmental factors, the holistic evaluation shows that the MSC is the best-performing alternative despite its higher cost. It maintains a balanced performance in the six criteria analyzed. The CB is close behind. The MSC stands out, especially in criteria C3, C4, and C6, representing end-of-life economic, manufacturing, and environmental impacts. On the other hand, CM2 emerges as a strong competitor to CB, ranking best in C1. However, it falls to second position in C2, C3, C5, and C6, where the use of higher amounts of reinforcing steel, compared to CB, significantly affects its ranking.

As a disruptive technology, seismic-resistant Prefabricated Concrete Volumetric Buildings (PCVB) may need extensive and informed research to gain market share in traditional construction. This study is a significant advance in sustainable construction research, providing valuable insights. Life cycle analyses guide decision-makers to mitigate environmental and economic impacts from the earliest stages of building design. By evaluating new seismic-resistant PCVB structural systems using quantitative indicators, this study compares the actual benefits versus traditional buildings. The hierarchical decision-making methodology allows the optimal alternative to be identified from a holistic perspective.

Future research could focus on three key areas. First, optimizing the structural design using high-quality concrete and incorporating admixtures could reduce component dimensions and material quantities, representing a crucial strategy for minimizing the overall life-cycle impact of PVMB. Secondly, it is crucial to incorporate criteria such as construction time and, above all, the social dimension into the decision-making model, as these factors can significantly affect the decision dynamics, allowing for a more comprehensive sustainability analysis. Finally, while this study included seismic-resistant alternatives, incorporating resilience-based criteria alongside sustainability in the decision model could help identify optimal design solutions.

Author contribution statement

Byron Guaygua: Writing – original draft, Validation, Software, Methodology, Investigation, Conceptualization. Antonio J. Sánchez-Garrido: Writing – review & editing. Víctor Yepes: Writing – review & editing.

Data availability statement

Data will be made available on request.

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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Declaration of interests

☒ 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.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: