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ARTICLE

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Sustainability model for precast concrete buildings. Case study: Commercial building in Reggio Calabria (Italy)

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Abstract

The construction industry, a major economic driver, is also a significant environmental polluter. Prefabrication emerges as a sustainable alternative due to its reduced resource consumption, waste generation, and energy use. This study proposes a MIVES-based model to assess the sustainability of precast concrete buildings compared to traditional concrete, considering environmental, economic, and social factors. A five-story commercial building in Reggio Calabria, Italy, was used as a case study. Two construction methods were compared: traditional cast-in-place reinforced concrete and a low-damage precast concrete alternative. Criteria and indicators were defined for each sustainability pillar, weighting them based on importance. Value functions converted indicator values into comparable scores. By combining these scores, a final sustainability index was calculated for each building. Precast concrete showed potential benefits in construction time, reduced emissions, and less construction disturbance. A sensitivity analysis confirmed the results. While this study highlights the potential advantages of precast construction over traditional methods, it is crucial to acknowledge the context-specific nature of the findings. The model's applicability is limited by factors such as building materials, structural conditions, and regional regulations. However, its adaptable framework can be tailored to evaluate diverse construction methods in different settings. By carefully adjusting parameters and functions, the model can offer valuable insights into the relative sustainability of various construction approaches.

KEYWORDS
earthquake, MIVES, multi-criteria decision-making, precast concrete structures, seismic design, sustainability

1 | INTRODUCTION

The construction industry is one of the most important sectors in the world's economy, accounting for approximately 10% of the world's GDP and employing 7% of the world's employed people. Nevertheless, this industry is one of the human activities with the greatest impact on the environment.[1,2] According to studies, construction is responsible for 40% of energy consumption, 16% of water consumption, and around 37% of greenhouse gas emissions worldwide.[3–5] As a consequence, the sector is facing a necessary transformation in terms of sustainability. Minimizing the environmental impact of human activities to safeguard the well-being of current and future generations has become a widely accepted objective by all stakeholders.

To address this challenge, numerous strategies have emerged to promote more sustainable practices and mitigate the environmental impact caused by construction. In general terms, resource conservation stands out as one of the most promising actions.[6,7] This approach involves both new design practices, including the selection of technologies and/or materials,[8] and waste reduction through techniques like reuse and recycling.[9] As a particular example of this perspective, prefabrication has been identified as a valuable solution due to the good sustainability performance of precast concrete structures, which have prompted the use of these structures in numerous construction projects, such as buildings, civil works, or bridges.[10–15]

In environmental terms, prefabrication is a solution that reduces consumption and waste in both the design and fabrication phases. The controlled factory environment allows for a high degree of precision and accuracy, which enables the optimization of the design and the fabrication processes, reducing both consumption and waste. Regarding energy consumption, the thermal inertia of precast concrete structures can be used to reduce the energy consumed for cooling and heating buildings. The consumption related to the loss of raw materials in the production plant is significantly lower than in on-site constructions because of the lower waste. For example, a study conducted in Sweden[16] examined the construction of 400 apartments in 10 separate buildings, divided by half into prefabricated and cast-in-place solutions, and found that the overall volume of construction waste was 35% less for the prefabricated solution compared to the traditional one. On the other hand, collecting and classifying the different types of residual materials (hardened and fresh concrete, steel, plywood, wastewater, insulation or lubricants) is easier in prefabrication plants.

Considering the economic aspects, the use of controlled environments for the fabrication of concrete elements, along with other advantages of prefabrication, allows for the industrialization of the fabrication process. This feature, together with higher requirements in quality control, results in structures with longer service life than those cast in place.[17,18] This translates to reduced maintenance costs over the building's lifespan, a significant economic benefit.

Regarding social considerations, the industrialization of the fabrication process can also lead to a faster construction schedule on-site. While there might be a shift in labor needs toward the factory setting, this can translate to fewer working hours and less exposure to risk factors for the on-site workforce compared to the traditional construction method. Additionally, a faster construction schedule can minimize public disturbance in terms of noise and dust exposure for the surrounding community.

Standardization entities play an active role in promoting sustainable construction by developing guidelines and assessment frameworks. For example, in the field of building construction, the CEN's Technical Committee 350 (CEN/TC 350) have developed a series of European standards[19–21] that utilize life-cycle assessment (LCA) and quantitative indicators to evaluate a building's environmental, economic, and social sustainability. Standard 189.1[22] is the first standard in the United States for providing minimum requirements for the siting, design, construction, and plan for operation of high-performance green buildings. Additionally, other generic rating tools can also be found, such as BREEAM (Building Research Establishment's Environmental Assessment Method),[23] the international standard developed in the UK on sustainability in the design, construction, and use of buildings; the German DGNB (German Sustainable Building Council System)[24] or LEED (Leadership in Energy and Environmental Design),[25] the most widely used green building rating system in the world.

In addition to these broader frameworks, specific assessment methods cater to particular construction approaches. For precast concrete structures, the Task Group 6.3 (TG 6.3)[26] of the International Federation for Structural concrete (*fib*) utilizes, among others, the MIVES (Integrated Value Model for Sustainability Assessment) method.[27] This is a multi-criteria decision-making method that aggregates environmental, economic and social aspects. In fact, this method has already been proposed to assess sustainability in the field of precast concrete products in the *fib* Bulletin 83 "Precast Tunnel Segments in Fibre-Reinforced Concrete."[28] Based on MIVES, a sustainability index is obtained to indicate the level of achievement in terms of overall sustainability of a specific alternative. As a consequence of its flexibility and adaptability to several areas, MIVES method has been proven to be an appropriate approach to assist stakeholders in decision-making processes where sustainability is a determining factor, such as hydraulic and underground infrastructures, buildings, industrial buildings, urban development, electricity generation infrastructure and also the management and reconstruction of post-disaster housing. Table 1 summarizes some

TABLE 1 Sustainability assessments based on MIVES method in the construction sector.

Field	Sustainability assessment	Ref.
Energy	Wind-turbine support systems	29
	Electricity generation systems	30
Urban	Site location of post-disaster temporary housing in urban areas	31
	Sewerage pipe systems	32
	3D-printed concrete footbridges	33
Buildings	Technologies to build schools	34
	Environmental analysis of industrial buildings	35
Building systems and elements	Concrete structures	36
	Structural concrete columns	37
	Reinforced concrete slabs	38

examples of applications related to the use of MIVES in the construction sector.

In this context, the main objective of this paper is to propose a MIVES-based model designed to assist in evaluations of sustainability performance of reinforced concrete buildings for commercial, office, and industrial purposes. To this end, a traditional reinforced concrete (RC) and a seismic low-damage precast concrete construction technology for a 5-story commercial building located in the region of Reggio Calabria (Italy) were considered as a study case. The MIVES method was used to assess sustainability, considering environmental, economic, and social factors. Additionally, a sensitivity analysis to evaluate the robustness of the results obtained was carried out.

2 | CASE STUDY

The case study was an RC building with commercial use located in the city of Reggio Calabria (Italy) and presented by Bianchi et al.[39] To compare the sustainability performance under seismic loads, two construction technologies were evaluated: (1) a traditional cast-in-place RC alternative (REF) and (2) a low-damage precast concrete alternative based on the PREcast Seismic Structural System (PRESSS) technology. Further information related to PRESSS technology can be found below.

The building has a regular layout and adheres to the general design criteria described by the Italian Building Code (point 7.2.1. of NTC2018[40]). Its footprint is equal to 576 m^2 (32 m × 18 m) and has five stories above ground, reaching a total height of 19 m, with an interstory height of 3.8 m. Two perimeter seismic resistant four-bay frames in the longitudinal direction and two shear walls in the transverse direction act to resist seismic action. The dimensions of the seismic elements are shown in Figure 1. Note that this study focuses on comparing alternatives for the primary structural skeleton; horizontal elements (e.g., slabs) and vertical circulation elements (e.g., staircases, elevators) are assumed to be consistent across all options and are therefore excluded from the analysis.

The design of the REF vs. PRESSS solutions was performed considering the same structural layout, geometry, gravitational loads, and service life (i.e., 50 years). The direct displacement-based design (DDBD) procedure, developed by Nigel Priestley[41,42] and later published as a model code,[43] was first implemented to design the structural system targeting the desired level of seismic performance. This is a simple analytical, yet accurate, method whose philosophy is that structures should be designed to achieve a specified performance level – defined by strain or drift limits – under a certain level of seismic intensity. More details on DDBD can be found in.[44,45] In this case study, the low-damage alternative of precast concrete was designed with the same geometry as the reference alternative of cast-in-place RC.

Once the design phase was completed, the structural analysis was carried out through OpenSees (Open System for Earthquake Engineering Simulation),[46] a widely used script-based freeware for seismic analysis of structures. In particular, the frame models related to the two alternatives were built and non-linear static analysis (pushover) was performed. The pushover curves of the two alternatives were compared within the so-called ADRS (Acceleration Displacement Response Spectrum) domain, commonly used in seismic engineering studies to establish the seismic performance of structures under alternative intensity level earthquakes.

As anticipated before, the low-damage precast concrete alternative was based on the PRESSS technology. The PRESSS technology was developed in the 1990's at the University of California San Diego (UCSD),[47–49] and then further investigated at the University of Canterbury, New Zealand.[50,51] PRESSS is a hybrid system that combines unbonded post-tensioned tendons with dissipative elements. These elements can be internal mild steel bars or, more recently and preferably, external and replaceable "Plug&Play" dissipators.[52] The post-tensioned tendons act like springs, pulling the structure back to its original position after an earthquake (self-centering capabilities) and minimizing residual displacement and associated damage. Dissipative elements, on the other hand, contribute to the energy dissipation capability of the structure. This combination of reinforcement systems creates a characteristic "flag shape" hysteretic behavior

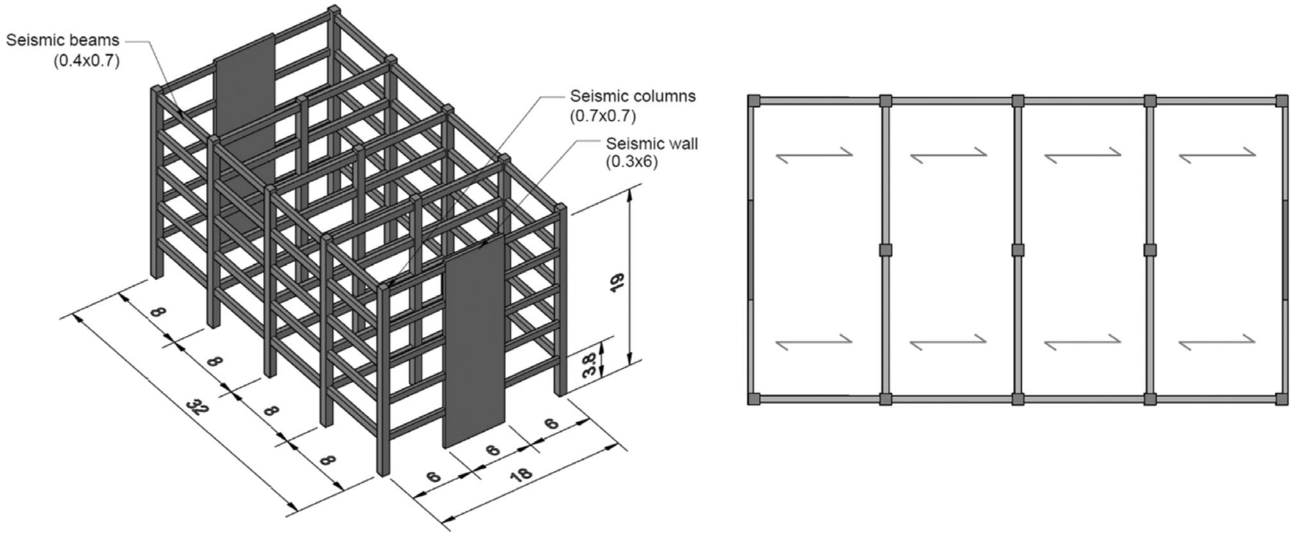

FIGURE 1 Geometry (detail of the seismic elements) of the case study building.[39]

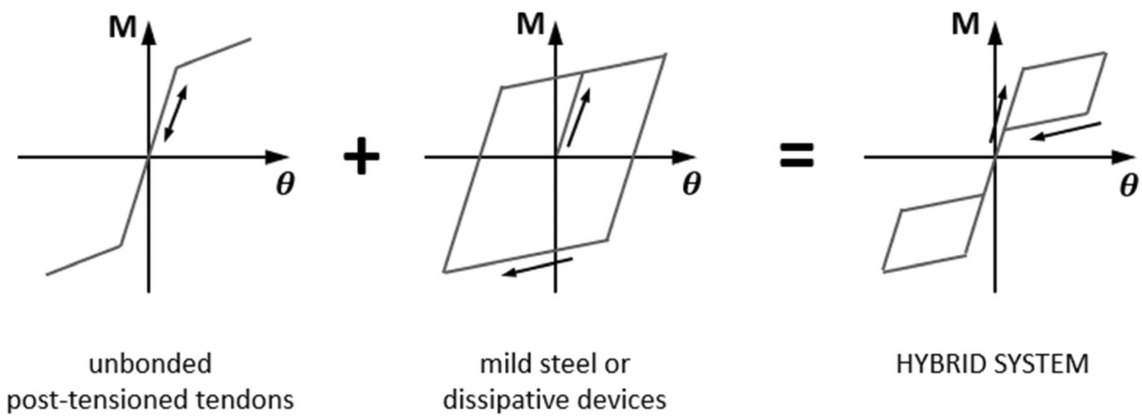

FIGURE 2 The “flag shape” hysteretic behavior for the moment-rotation of hybrid connections.

for the moment-rotation of these connections (refer to Figure 2).[53] This shape depends on the recentering ratio (λ) between the (re-centering) moment contribution and the (dissipative) one provided by the dissipative devise. In the case study, a value of $\lambda = 1.5$ was chosen for the alternative designed by PRESSS, corresponding to a momentum division of 60% associated with post-tensioned tendons and 40% with dissipative devices.

3 | SUSTAINABILITY PERFORMANCE ASSESSMENT

3.1 | MIVES method

MIVES (Integrated Value Model for Sustainability Assessment,[27]) is a multi-criteria decision-making method used to assess the sustainability performance of alternatives valid to provide solutions (with different sustainability performance level) to a specific problem. The method allows obtaining a sustainability index for each alternative that indicates the level of achievement in terms of sustainability. This index aggregates economic, environmental, and social aspects into a single value between 0 and 1.

In this case study, this involved four key phases: (1) definition of the decision-making diagram (also referred to as tree) that includes all those requirements, criteria, and indicators representative of the three pillars of sustainability and representative of the case study; (2) definition of the value functions for normalizing the value of indicators into dimensionless variables between 0 and 1; (3) quantification of the indicators and application of the model to the two alternatives for the case study to assess the sustainability through a transparent and objective approach; (4) implementation of a sensitivity analysis to test the robustness of the method.

TABLE 2 Decision-making tree for the case study.

Requirement	Criterion	Indicator
R_1 Economic (36%)	C_1 Costs (61%)	I_1 Direct costs (61%)
		I_2 Indirect costs (6%)
		I_3 Rehabilitation costs (11%)
		I_4 Dismantling costs (21%)
	C_2 Time (39%)	I_5 Production and assembly time (100%)
R_2 Environmental (39%)	C_3 Emissions (55%)	I_6 Emissions of CO_2-equation (100%)
	C_4 Energy (19%)	I_7 Energy consumption (100%)
	C_5 Materials (26%)	I_8 Index of efficiency (100%)
R_3 Social (25%)	C_6 Safety (60%)	I_9 Index of risk (100%)
	C_7 Third parties' affectations (40%)	I_{10} Social benefits (55%)
		I_{11} Disturbances in construction (45%)

3.2 | Decision-making tree and value functions

Table 2 presents the decision-making tree defined to assess the sustainability for this case study. It includes all the requirements (R), criteria (C) and indicators (I), along with their weight, to be considered in the sustainability assessment. In this case, the decision-making tree (criteria, indicators and weights) was established based on seminars with experts. These experts included international technicians from both academia and industry experienced with prefabrication and involved in the *fib*.

Additionally, the constitutive parameters of the value functions defined for each indicator are shown in Table 3. The value of the indicator i being assessed (V_i) was obtained from the corresponding value function according to:

$$V_i(X) = B \cdot \left[1 - e^{-K_i\left(\frac{|X_i - X_{min}|}{C_i}\right)^{P_i}}\right], \quad (1)$$

where X_{min} is the minimum abscissa value of the indicator interval assessed, X_i is the abscissa value of the indicator being assessed, P_i is the shape factor, C_i approximates the abscissa at the inflection point, K_i tends toward V_i at the inflection point, and B is a factor that prevents the function from exceeding the range (0, 1). Typical shapes obtained through modification of these parameters are linear, concave up, concave down, and *S* shapes. This is represented in Figure 3.

Note that the assessment of the indicators may be made in absolute or relative terms: in absolute terms, the value of the indicator is directly normalized with the value function; in relative terms, the value of the indicator is first compared to a reference value and then the compared value is normalized with the value function. Table 3 specifies what indicators were evaluated in relative terms.

Weights and functions could be adapted to other stakeholders' priorities and sensitivities when those proposed in Table 2 are found to be insufficiently representative. These adaptations must be coherent with the MIVES method in order to maintain its robustness and validity.

3.2.1 | Economic requirement

The economic requirement (R_1, see Table 2) comprised two criteria, including costs (C_1)—assessed by four indicators: direct costs (I_1), indirect costs (I_2), rehabilitation costs (I_3) and dismantling costs (I_4)—and time (C_2)—assessed by one single indicator, namely production and assembly time (I_5).

First of all, direct costs (I_1) refer to the total cost of the structure. This includes the costs associated with the purchase of materials (concrete and steel for the reinforcement)—detailed information of the amount of concrete, steel, and steel for post-tension and dissipators used for both alternatives of the case study can be found in Tables A1–A4 in the Appendix, equipment (e.g., cranes) and labor (related to concreting or placing the precast elements in situ). In this study, direct costs were calculated using the database BEDEC,[54] which contains economic information of several construction materials, products, and processes. The value function chosen was a decreasing S-function (see Figure A1 in the Appendix) since lower costs are associated with higher satisfaction, and the steeper slope of the function emphasizes the importance of cost-efficiency.

As for indirect costs (I_2), these concern all costs that are not directly proportional to the material used and work done, and that are difficult to quantify in the design phase. Some examples of indirect costs are operational costs (e.g., construction site equipment) and legal costs (e.g., insurance costs). Indirect costs are not directly proportional to the quantity of work to be carried out, but also to the duration of the construction site. This is because indirect costs are incurred regardless of the amount of work that is being done, as long as the construction site is active. Here, indirect costs were estimated to be a percentage value of the direct cost: 10% of the

TABLE 3 Value functions of each indicator of the decision-making tree for the case study.

Indicator	Units	X_{min}	X_{max}	C	K	P
I_1. Direct costs	€/m^3 (relative)	0.7	2	1.1	4	2
I_2. Indirect costs	%	0.25	0.05	4	12	0.8
I_3. Rehabilitation costs	% EAL (relative)	0.5	1.5	1.2	3	2
I_4. Dismantling costs	% (relative)	0.7	1.5	1.2	4	2
I_5. Production and assembly time	Days (relative)	0	1.5	1.7	3	1.8
I_6. Emissions of CO_2-eq	t CO_2-eq (relative)	0	1.5	1.2	0.5	0.7
I_7. Energy consumption	GJ-eq (relative)	0	1.5	1.2	0.5	0.7
I_8. Index of efficiency	Points	1	0	0.35	0.3	1.8
I_9. Index of risks	ORI (relative)	0	2	1	0.1	1
I_{10}. Social benefits	Days (relative)	0	1.5	1	0.6	2
I_{11}. Disturbances in construction	Points (relative)	2	0	0.4	0.55	1.5

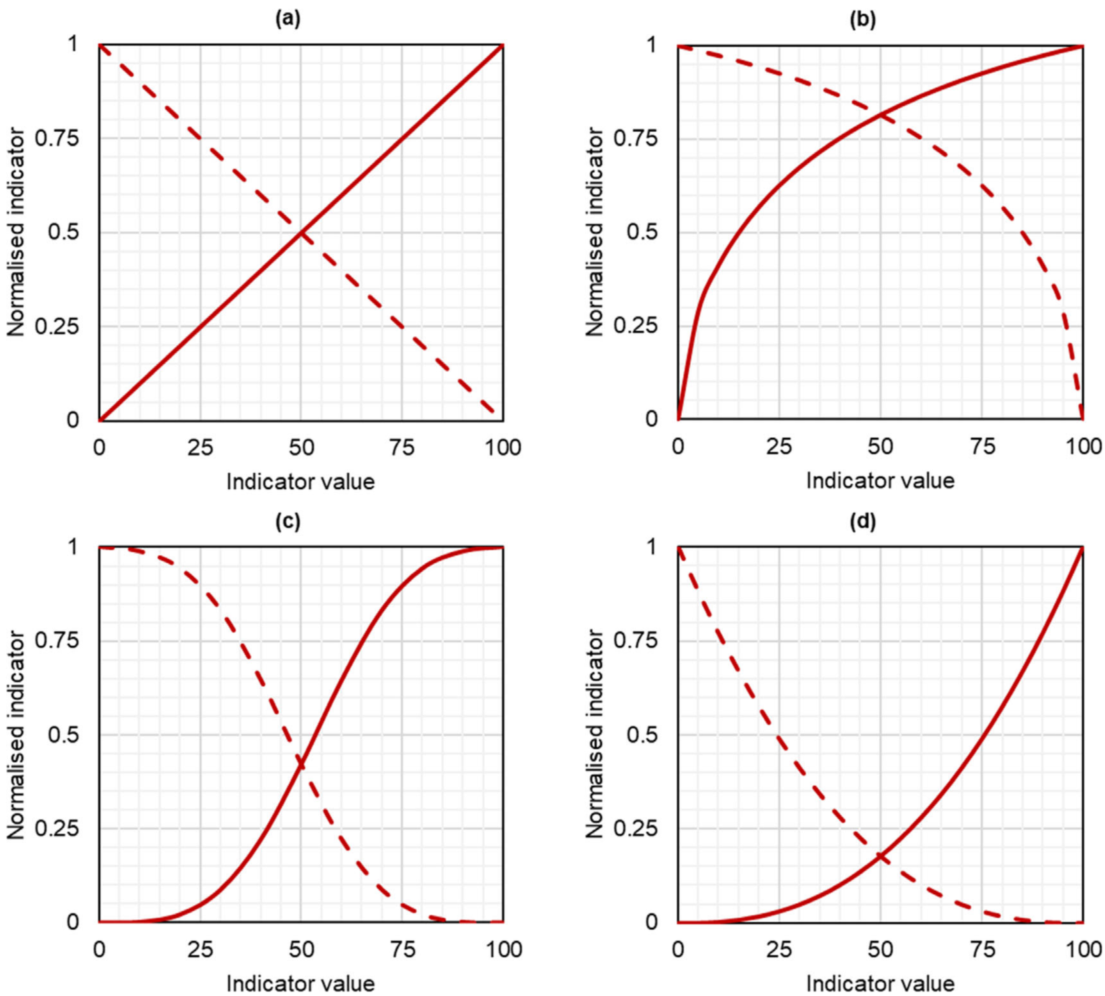

FIGURE 3 Shapes of the value functions: (a) linear, (b) concave down, (c) S shape, (d) concave up.

direct costs for the REF alternative and 6% for the PRESSS alternative, since this is characterized by shorter construction times and, therefore, also less indirect costs. The value function chosen was a decreasing convex function (see Figure A1 in the Appendix) with a particularly pronounced slope to strongly reward solutions with lower indirect costs. This means that solutions with lower indirect costs will receive a relatively greater increase in value than solutions with slightly higher indirect costs. This value function is justified by the fact that indirect costs can have a significant impact on the profitability of a construction project. By reducing indirect costs, contractors can improve their profit margins and make their projects more economically competitive.

For rehabilitation costs (I_3), the repair costs associated with the damage that occurs during the life of the building are considered. The indicator was measured using the percentage of expected annual losses (EAL). In this regard, the fragility curves, the EAL, and the downtime of the structure represent the probability of reaching a certain limit state, the average annual cost incurred, and the average time during which activities are interrupted to repair damage and cover losses induced by seismic events, respectively, and were obtained from the structural analysis. The value function for these costs was a decreasing S-shape (see Figure A1 in the Appendix) because lower rehabilitation costs are more desirable. The S-shape of the function reflects the fact that there is a diminishing return to investing in rehabilitation measures.

Dismantling costs (I_4) are the costs associated with the removal of a structure or component at the end of its useful life. This includes the costs of labor, equipment, and materials, as well as the costs of transporting and disposing of the waste generated. These costs were calculated using the method described by Pun et al.,[55] which includes two different dismantling possibilities: demolition (e.g., mechanical demolition, demolition using explosives) and deconstruction. It is important to note that this indicator does not consider the expected economic benefits that could be generated from the recycling of materials. In fact, this indicator evaluates only the economic part closely related to the end-of-use work, while the environmental aspects related to these factors are considered the environmental requirement of the decision-making tree. As in the previous indicator, the value function defined was a decreasing S-function (see Figure A1 in the Appendix).

The last economic indicator, production and assembly time (I_5), is an important indicator of the sustainability of any construction project. Shorter production and assembly times can lead to a number of benefits, including reduced costs (i.e., shorter construction times can lead to reduced labor costs and overhead costs), increased efficiency (i.e., shorter construction times can help to improve the efficiency of the construction process, leading to lower risks of delays and disruptions) or increased public satisfaction (i.e., shorter construction times can help to improve public satisfaction by reducing the amount of time that construction activities disrupt traffic and other public services). To evaluate this indicator, the time taken in the different construction phases for each solution was studied based on data obtained from CYPE Engineers.[56] In this regard, those activities that were the same for both alternatives (i.e., site preparation, excavation operations and foundation construction) were not considered to make the data collection process more efficient. Detailed information can be found in Tables A5 and A6 in the Appendix for the REF and PRESSS alternatives, respectively. As can be seen from these results, the precast solutions meant a considerable time saving of 78%. Regarding the value function, a decreasing S-function (see Figure A1 in the Appendix) was chosen.

3.2.2 | Environmental requirement

The environmental requirement (R_2, see Table 2) comprised three criteria, namely emissions (C_3)—assessed by the indicator emissions of CO_2-eq (I_6), energy (C_4)—assessed by the indicator energy consumption (I_7)—and materials (C_5)—assessed by the indicator index of efficiency (I_8).

In order to assess indicators I_6 and I_7, the Life Cycle Assessment (LCA) was performed. According to *fib* Bulletin 71,[57] integrated life cycle assessment is the sustainability assessment of a structure within the whole lifecycle; this considers an evaluation of the three pillars of sustainability, comprising economic, environmental, and social considerations. In this sense, the sustainability assessment of a structure requires covering economic, environmental, and social impacts during its entire life cycle, from planning to disposal.[58] In accordance with this statement, the following phases were investigated in this study to perform the LCA: (1) supply phase, (2) construction phase, (3) use phase, (4) rehabilitation phase—after earthquake—and (5) end-of-life phase (EoL). Usually, the construction and EoL phases can be omitted, as these have negligible effects on results[59]; however, in this study, the construction phase and transportation were considered. Database BEDEC[54] was also used to obtain both emissions of CO_2-eq (I_6) and energy consumption (I_7) indicators. Particularly, it must be pointed out that the transportation of materials from production plants to the construction site was included. Different distances were considered for the two alternatives of the case study, in line with guidelines from the Mineral Products Association (MPA),[60] which provides average values observed in the United Kingdom, specifically 11 km for the cast-in-place solution and 95 km for the precast solution. These distances were considered representative for the case study here. In addition, assumptions were made regarding the types of heavy vehicles used for material transportation. Structural elements were presumed to be transported by 28-ton trucks, while non-structural elements were considered to be transported by 16-ton trucks. The number of required loads was calculated based on the quantity of material and the load-bearing capacity of the vehicles. Detailed information can be found in Tables A7 and A8 in the Appendix for the REF and PRESSS alternatives, respectively. For both indicators, the value function used was a

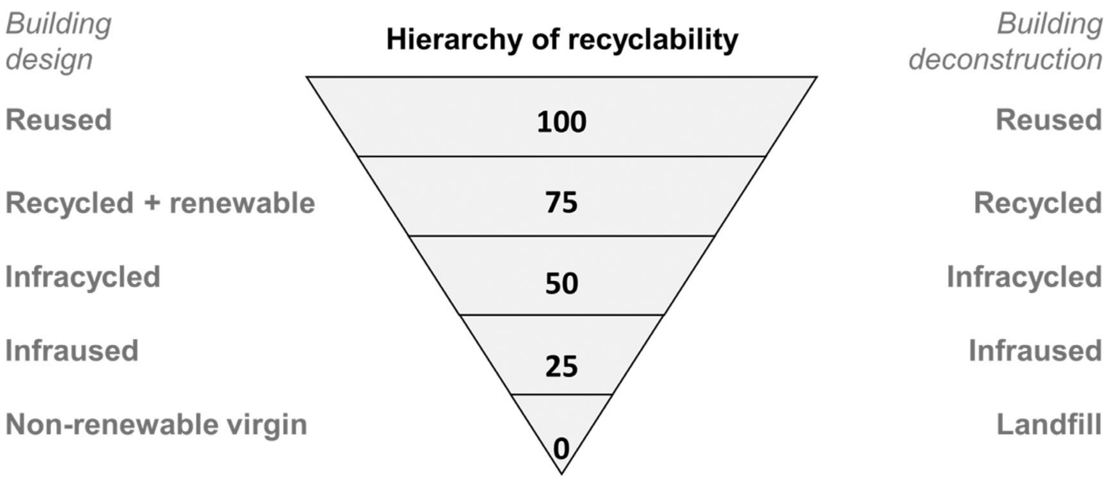

FIGURE 4 Inverted pyramid of the hierarchy of recyclability levels.[61]

decreasing convex function (see Figure A1 in the Appendix), even though it decreases almost linearly. Thus, increases or decreases in emissions or energy consumption are evaluated negatively or positively, respectively, in an approximately similar manner.

Regarding the index of efficiency indicator (I_8), it aims to assess the impact of using non-renewable natural resources to produce building materials (e.g., cement, aggregates, steel, water, additives and other building materials involved). The indicator also takes into account the reuse of materials and their recyclability. In this study, in the design stage (i.e., the use of secondary materials for the building) and the EoL stage (i.e., the reuse of the materials of the building after deconstruction), the index of efficiency was calculated using the method proposed by Vefago and Avellaneda,[61] which is based on an inverted hierarchical pyramid with different levels of recyclability of materials and elements (see Figure 4) that privileges the reuse and recycling of materials.

In this pyramid, the following levels are encompassed: Reused (i.e., Materials or components are reused in their original form and for the same or a similar function, maximizing value retention and minimizing processing), Recycled (i.e., Materials are reprocessed into new products, potentially with some loss of quality or change in application. This level may include renewable materials that are recycled.), Infracycled (i.e., Materials undergo chemical transformation or a change in physical state, resulting in diminished properties and a change in function, but are still repurposed), Infraused (i.e., Materials maintain their chemical structure and physical state but are used in a different application with reduced properties, such as crushed concrete used as aggregate), and Non-renewable virgin (i.e., This represents the use of newly extracted natural resources, with no recycled or reused content, representing the lowest level of recyclability).

Based on the total amount of material used in each alternative (see Tables A1–A4 in the Appendix), the percentage of material associated with each category defined in the inverted hierarchical pyramid (refer to Figure 4) was determined for the design and EoL stage. The results obtained for each alternative were aggregated by making a weighted sum based on the weight corresponding to each category (0 for landfill, 25 for infraused, 50 for infracycled, 75 for recycled and 100 for reused material, according to Figure 4). Finally, the efficiency level of the alternative was defined based on a score scale: low (0 to 30 points), medium (30 to 60 points) and high (60 to 100 points) efficiency level.

The value function chosen was an increasing S-shaped function (see Figure A1 in the Appendix), since these functions are well-suited to represent threshold effects. In the context of materials efficiency, there may be a point at which the efficiency improvements have a significant impact; efficiency gains may be minimal before this threshold, but the gains can be substantial beyond it. The S-shaped value function also reflects the fact that there are some practical limitations to improving the materials efficiency of a building. For example, it may not be possible to reuse all the materials from a demolition project or to use recycled materials for all of the components of a building. Additionally, economic and technological factors could also play a role in materials efficiency. Although efficiency improvements can be implemented easily and at low cost initially, more substantial investments and innovations are required later.

3.2.3 | Social requirement

The social requirement (R_3, see Table 2) comprised two criteria, including safety (C_6)—assessed by one indicator, namely index of risk (I_9)—and third parties' affectations (C_7)—assessed by two indicators, namely social benefits (I_{10}) and disturbances during construction (I_{11}).

The index of risk (I_9) aims to quantify the level of danger faced by workers during construction and, in this study, it was assessed by using the Occupational Risk Index (ORI).[62] The ORI was calculated as the product of the total exposure (this is determined by multiplying the hours of exposure to risk by the number of workers engaged in the specific activity) weighted by the risk associated with the activity to be performed. Meanwhile, the weight varies according to the risk associated with the activity itself and is computed as the product of the probability of occurrence of each risk and the derived consequences of its realization. To evaluate the ORI of each activity, the activities and times considered for the calculation of the economic indicator production and assembly time (I_5) (see Tables A5 and A6 in the Appendix) were used as a first approximation and the data obtained from CYPE Engineers[56] was considered to determine the sub-activities involved, the construction machinery required, and the number of workers assigned to each operation. Detailed data of the evaluation of the risks for each alternative can be found in Tables A9 and A10 in the Appendix. In addition, a linearly decreasing function (see Figure A1 in the Appendix) was proposed as the value function, aiming to reward lower values of the index rather than modest increases relative to a range of values.

Regarding the third parties' affectations criterion, downtime was chosen as the characterizing parameter to evaluate the social benefits (I_{10}) as it denotes the social resilience of the structure by representing the days required for the structure to become accessible again after the earthquake. Nevertheless, a more in-depth evaluation, which takes into account other qualitative aspects related to social benefits (e.g., the generation of new patents, new qualified jobs or new knowledge and skills), should be performed through the estimation of scores associated with different issues beyond downtime, usually united in the literature with an index called "innovation."[63] In this study, the downtime was quantified using the electronic calculation tool FEMA P57 PACT.[64] The value function considered for this indicator was a decreasing S-shaped function (see Figure A1 in the Appendix), tending to reward smaller increments around the standard solution.

Finally, also related to the third parties' affectations criterion, disturbances in construction (I_{11}) are related to the nuisance caused by construction activities of a building on the surrounding area and its inhabitants. In this study, the aspects considered were: noise pollution (including the exposure to noise experienced by workers and the surrounding community due to on-site construction work), impact on pedestrian transit (considering the affection to pedestrian movement in the site area) and influence on urban traffic (influence on traffic flow in urban areas). Each of these aspects was quantified individually—three (or four) levels were defined with a score between 0 for high disturbance and 10 for low (or no) disturbance—and then aggregated—with weights of 60%, 15%, and 25% for noise, transit, and traffic, respectively—to form an overall quantified indicator. Detailed information about the different levels for each aspect can be found in Tables A11 and A12 in the Appendix. Regarding the value function, an increasing S-shape (see Figure A1 in the Appendix) was considered appropriate for this indicator because it reflects the fact that the benefits of reducing construction disturbances increase at a decreasing rate. It also reflects the fact that there are practical limitations to reducing construction disturbances. For example, it may not be possible to completely eliminate noise pollution from a construction site.

4 | RESULTS AND DISCUSSION

4.1 | Quantification of indicators

The quantification of the indicators for the two alternatives of the case study is shown in Table 4.

4.1.1 | Economic requirement

Figure 5a presents the results of the economic requirement. As it can be seen, the traditional cast-in-place RC alternative yielded higher satisfaction in terms of cost (C_1 equal to 0.43 and 0.10 for REF and PRESSS alternatives, respectively), indicating that it is less cost-intensive compared to the precast concrete alternative. On the contrary, in terms of time, the precast alternative showed better results (C_2 equal to 0.13 and 0.36 for REF and PRESSS alternatives, respectively); that is, it is more time-efficient compared to the cast-in-place alternative.

4.1.2 | Environmental requirement

The results of the environmental requirement are shown in Figure 5b. The precast concrete alternative had better performance for all the criteria considered in the environmental pillar (C_3, C_4 and C_5 equal to 0.11, 0.04 and 0.02 for REF alternative and 0.40, 0.15 and 0.05 for PRESSS alternative, respectively). Particularly, the precast alternative had a lower carbon

TABLE 4 Quantification of the indicators for the two alternatives (REF and PRESSS) of the case study.

Indicator	Units	REF	PRESSS
I_1 Direct costs	€ (relative)	531 (1.00)	945 (1.78)
I_2 Indirect costs	%	10	6
I_3 Rehabilitation costs	% EAL (relative)	0.29 (1.00)	0.17 (0.59)
I_4 Dismantling costs	$/m^2 (relative)	30 (1.00)	39 (1.30)
I_5 Production and assembly time	Days (relative)	223 (1.00)	50 (0.22)
I_6 Emissions of CO_2-eq	t CO_2-eq (relative)	170.4 (1.00)	29.8 (0.17)
I_7 Energy consumption	GJ-eq (relative)	1125.4 (1.00)	151.2 (0.13)
I_8 Index of efficiency	Points	0.14	0.26
I_9 Index of risk	ORI (relative)	785 (1.00)	207 (0.26)
I_{10} Social Benefits	Days (relative)	255 (1.00)	76 (0.30)
I_{11} Disturbances in construction	Points (relative)	3.56 (1.00)	6.60 (1.86)

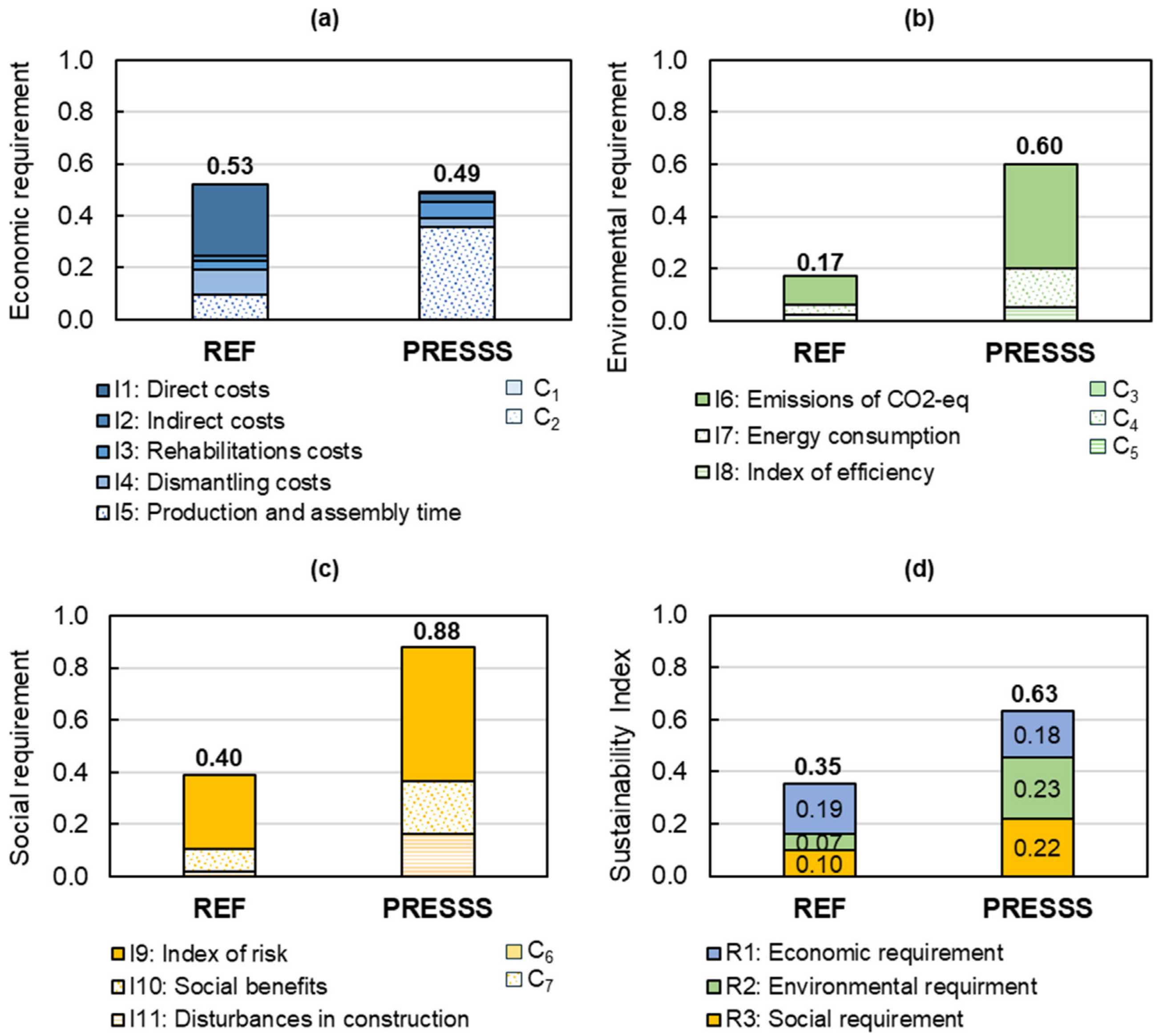

FIGURE 5 Sustainability assessment: (a) social requirement; (b) environmental requirement; (c) social requirement; (d) sustainability index.

footprint than the cast-in-place alternative since precast concrete is typically produced in a factory, where there is more control over the production processes and less generation of waste. This alternative also consumed less energy due to the fact that the production processes are more efficient in the factory, and, in addition, precast construction projects typically require less on-site energy for curing and finishing.

Lastly, in terms of index of efficiency, the environmental impact of cast-in-place concrete is more significant than that of prefabricated concrete due to the greater challenge in recovering and reusing materials.

4.1.3 | Social requirement

Figure 5c shows the results for the social requirement. As it can be observed, the precast concrete alternative outperformed the cast-in-place alternative in both social criteria (C_6 and C_7 equal to 0.29 and 0.11 for REF alternative and 0.52 and 0.36 for PRESSS alternative, respectively). This is because precast construction typically involves less on-site work, which reduces the risk of accidents and injuries. Additionally, precast construction can be less disruptive to the surrounding community, as it can be done more quickly and efficiently than cast-in-place construction. As it can be seen from the results, the solution with the lower ORI index is the one with a smaller impact on the health and safety of workers. Notably, the most influential risk on the overall assessment, appearing first in the tables, pertains to activities at heights exceeding 2 meters. This risk considers falls during the placement and fixing of elements and when using lifting platforms. The primary distinction between the two solutions with the most significant impact on the results is the time workers spend at greater heights, which is considerably longer for the cast-in-place alternative than for the precast one. This disparity is due to this last alternative taking 70% less time than the cast-in-place one, resulting in a substantial gap between their ORI scores.

4.2 | Sustainability index

Finally, the results corresponding to the sustainability index are presented in Figure 5d. The cast-in-place RC alternative reached an index of sustainability of 0.35, whereas it was 0.63 for the precast concrete alternative. Specifically, the precast alternative scored 0.18, 0.23, and 0.22, while the cast-in-place concrete alternative scored 0.19, 0.07, and 0.10 for R_1, R_2, and R_3, respectively. This means that the precast construction method resulted to be more sustainable overall, considering all three pillars of sustainability, upon the conditions considered for this analysis. This is because this method performed better than the cast-in-place construction method's environmental and social requirements: it has a lower carbon footprint, consumes less energy, and uses less material than the cast-in-place method. Additionally, the precast construction method is safer for workers and has less of an impact on the surrounding community. On the other hand, this method underperformed compared to the cast-in-place construction method in the economic requirement but with a relatively small difference. This is because the precast construction method is typically more expensive upfront, with higher expected economic long-run benefits due to its lower maintenance and replacement requirements.

5 | SENSITIVITY ANALYSIS

The sensitivity analysis was carried out to analyze the impact of changing the weights of the requirements assigned in the decision-making tree (see Table 2) on the sustainability performance of each alternative of the case study. The weights considered in this study were defined by a set of experts, but these weights may not be representative of all decision-makers as there can be different approaches depending on time, geographical locations, culture, and so forth.

In this study, three alternative scenarios of weights for the requirements were defined as shown in Table 5. In addition to the standard scenario (for which the results were presented in the previous section), three additional scenarios were defined (referred to as economic, environmental and social scenarios as significant weight (70%) is assigned to each of these requirements).

The weights were applied according to the decision-making tree defined in Table 2 and the results are shown in Figure 6. The results collected show that, regardless of the combination of weights used, the sustainability index of the precast concrete alternative is always greater than the cast-in-place RC alternative for all the scenarios.

6 | CONCLUSIONS

This study aimed at proposing a MIVES-based model oriented to assess sustainability performance of reinforced concrete buildings. Once the components of the model were defined, a case study comparing the sustainability performance of a seismic-resistant office buildings designed to be constructed according to two different construction methods (traditional cast-in-place RC and

Scenario	Requirement weight		
	R_1 economic	R_2 environmental	R_3 social
Standard	36%	39%	25%
Economic	70%	15%	15%
Environmental	15%	70%	15%
Social	15%	15%	70%

TABLE 5 Scenarios of the sensitivity analysis for the weight of the indicators of the case study.

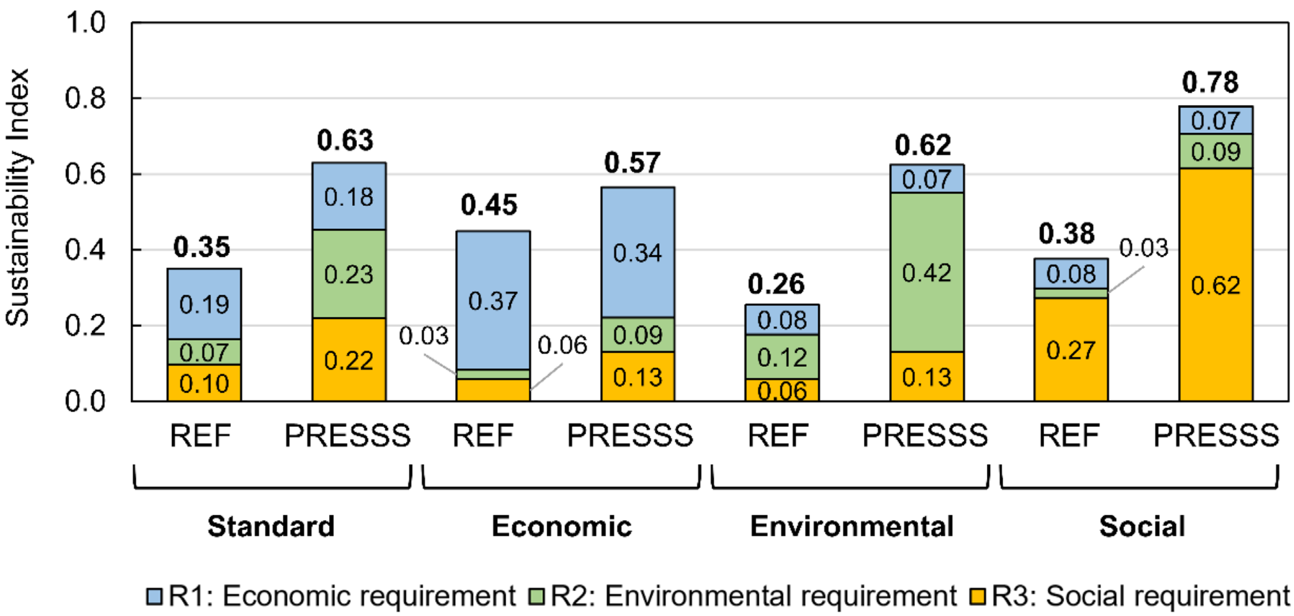

FIGURE 6 Results of the sensitivity analysis of the case study.

low-damage precast concrete) was presented. The three pillars of sustainability (economic, environmental and social) were considered in the model, and the representative indicators belonging to each of the pillars were quantified.

The results showed that the precast alternative was more sustainable than the cast-in-situ alternative in several aspects. Specifically:

- Economic sustainability: the cast-in-place alternative presented better satisfaction in terms of costs and worse in terms of time than the precast alternative (0.43 and 0.10 for cost criterion, and 0.13 and 0.36 for time criterion for cast-in-place and precast alternative, respectively). That is, the precast building had faster construction and repair times, and although this alternative was more expensive upfront, it was estimated to save money in the long run due to its lower maintenance and replacement requirements. The global assessment of the economic sustainability was 8% better for the cast-in-place alternative.
- Environmental sustainability: precast concrete outperformed cast-in-place concrete in terms of environmental impact, with a lower carbon footprint, energy consumption, and waste generation due to controlled factory production and efficient processes; also, precast concrete was evaluated as easier to recycle and reuse (values of satisfaction of 0.11 and 0.40 for emissions criterion, 0.04 and 0.15 for energy criterion, and 0.02 and 0.05 for materials criterion for cast-in-place and precast concrete, respectively). The global assessment of environmental sustainability was 3.5 times better for the precast alternative compared to the cast-in-place.
- Social sustainability: precast concrete was found to perform better than cast-in-place concrete in social terms, primarily due to reduced on-site work leading to fewer accidents and less community disruption (values of satisfaction of 0.29 and 0.52 for safety criterion, and 0.11 and 0.36 for third parties' affectations criterion, for cast-in-place and precast concrete, respectively). In the case of the safety criterion, the key factor in this advantage was the significantly shorter construction time for precast concrete, minimizing worker exposure to hazards at height. The global assessment of social sustainability was more than 2 times better for the precast alternative compared to the cast-in-place.

In addition to the above, the sensitivity analysis performed showed that the precast solution would be more sustainable than the cast-in-place one despite changing the weight of the requirements and considering scenarios with economic, environmental, or social requirements being the predominant.

Overall, the results of this study indicate that precast construction can offer significant sustainability advantages over traditional cast-in-place methods, particularly for high-use buildings in seismic regions. However, it is essential to recognize that these findings are context-specific and tied to the assumptions and boundary conditions of this particular study. The model's results and conclusions may not be directly extrapolated to other cases with varying parameters such as building materials (e.g., steel, timber, hybrid systems), structural conditions, or regional regulations.

To ensure valid comparisons, any application of the model to different scenarios must adhere to the specific requirements outlined in relevant building codes and standards. While the model's findings are not universally applicable, its underlying framework can be adapted to assess the sustainability of various construction methods in different contexts. By carefully adjusting the model's parameters and functions to account for varying factors such as material properties, climate conditions, and regional regulations, it can provide valuable insights into the relative sustainability of different construction approaches.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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APPENDIX

TABLE A1 Total amount of concrete for the two alternatives of the case study.[54]

Element Unit	B m	H m	L m	Quantity –	Total volume m^3	Total mass kg
Seismic frame	0.4	0.7	7.3	40	81.8	204,400
Sec. Frame int	0.4	0.7	8.3	30	69.7	174,300
Sec. Frame ext	0.4	0.7	5.7	20	31.6	79,100
Seismic ext. columns	0.7	0.7	19	4	37.2	93,100
Seismic int. columns	0.7	0.7	19	6	55.9	139,650
Columns (gravity)	0.7	0.7	19	3	28.0	69,825
Walls	0.3	6	19	2	68.4	171,000
Total					**373**	**931,375**

TABLE A2 Total amount of steel for the cast-in-place RC of the case study.[54]

Elements Unit	Number of elements –	Longitudinal bars weight kg	Stirrups weight kg	Total weight kg	Total volume m^3	Reinforcement ratio kg
Seismic frame	40	271.9	77.7	13,984.2	81.8	171.0
Sec. Frame int	30	258.8	77.7	10,094.1	69.7	144. 8
Sec. Frame ext	20	–	–	5159.6	31.6	163.1
Seismic ext. columns	4	108.3	18.1	505.6	37.2	23.6
Seismic int. columns	6	162.5	18.1	1083.3	55.9	19.4
Columns (gravity)	3	957.1	18.1	2925.3	27.9	104.7
Walls	2	19,361.0	–	19,361.0	68.4	283.1
Total				**53,113**	**373**	

TABLE A3 Total amount of steel for the precast concrete alternative of the case study.[54]

Elements Unit	Number of elements –	Longitudinal bars weight kg	Stirrups weight kg	Total weight kg	Total volume m^3	Reinforcement ratio kg
Seismic frame	40	–	77.7	3107.6	81.8	38.0
Sec. Frame int	30	258.8	77.7	10,094.1	69.7	144. 8
Sec. Frame ext	20	–	–	5159.6	31.6	164.2
Seismic ext. columns	4	539.8	18.1	2231.4	37.2	59.9
Seismic int. columns	6	809.7	18.1	4966.5	55.9	88.9
Columns (gravity)	3	957.1	18.1	2925.3	27.9	104.7
Walls	2	2048.1	–	2048.1	68.4	29.9
Total				**30,568**	**373**	

TABLE A4 Total amount of steel for post-tension and dissipators for the precast concrete alternative of the case study.[54]

Elements Unit	Total weight kg
Post-tension	
Beams	4582.0
Walls	5355.7
Dissipator	
Beams	2095.5
Columns	2024.2
Walls	8909.8
Total	**22,967**

TABLE A5 Time construction (days) for the cast-in-place RC of the case study.[56]

		Days
1	Construction site preparation	
1.1	Temporary roads construction and access roads to the site	
1.2	Area for construction machinery parking	
1.3	Construction site fence	
1.4	Installation of temporary services (water supply, heat, power)	
1.5	Temporary buildings (offices, cabins, bathrooms, storage)	
1.6	Clearing the site (debris, cutting green spaces)	
2	Excavation works	7
2.1	Layout for foundation	1
2.2	Foundation pit digging (excavators and bulldozers are needed)	5
2.3	Sealing the pit base for the foundations	1
3	Foundation works	18
3.1	Required machines and materials are delivered to the construction site	–
3.2	Preparation of the base for the R.C. slab	1
3.3	Formwork and reinforcement works are completed	5
3.4	Slab concreting with pump	1
3.5	Concrete casting and formwork dismantling	7
3.6	Excavation backfill (excavators are needed)	4
4	Construction (elevation elements)	198
4.1	Construction of vertical elements 1° floor	17
4.1.1	Formwork and reinforcement works are completed	2
4.1.2	Concreting with pump (vibration is needed)	5
4.1.3	Concrete casting and formwork dismantling	5
4.1.4	Scaffolding installation (up to the 1st floor)	5
4.2	Construction of slab 1st floor	16
4.2.1	Formwork and reinforcement works are completed	10
4.2.2	Concreting with pump (vibration is needed)	1
4.2.3	Concrete casting and formwork dismantling	5
4.3	Construction of vertical elements from 2nd floor to the last floor	68
4.4	Construction of slab from 2nd floor to the last floor	64
Total		**223**

TABLE A6 Time construction (days) for the precast concrete alternative of the case study.[56]

		Days
1	Construction site preparation	
1.1	Temporary roads construction and access roads to the site	
1.2	Area for construction machinery parking	
1.3	Construction site fence	
1.4	Installation of temporary services (water supply, heat, power)	
1.5	Temporary buildings (offices, cabins, bathrooms, storage)	
1.6	Clearing the site (debris, cutting green spaces)	
2	Excavation works	7
2.1	Layout for foundation	1
2.2	Foundation pit digging (excavators and bulldozers are needed)	5
2.3	Sealing the pit base for the foundations	1
3	Foundation works	18
3.1	Required machines and materials are delivered to the construction site	–
3.2	Preparation of the base for the RC slab	1
3.3	Formwork and reinforcement works are completed	5
3.4	Slab concreting with pump	1
3.5	Concrete casting and formwork dismantling	7
3.6	Excavation backfill (excavators are needed)	4
4	Construction (elevation elements)	25
4.1	Construction of vertical elements 1° floor	5
4.2	Formwork and reinforcement works are completed	5
4.3	Concreting with pump (vibration is needed)	5
4.4	Concrete casting and formwork dismantling	5
4.5	Scaffolding installation (up to the 1st floor)	5
Total		**50**

TABLE A7 LCA for the cast-in-place RC alternative of the case study.

Element Unit		Emissions of CO_2-eq ton CO_2-eq	Energy consumption GJ-eq
Components	Columns [kg/m^3] / [MJ/m^3]	445.5	3912.6
	Beams [kg/m^3] / [MJ/m^3]	431.9	1671.2
	Walls [kg/m^3] / [MJ/m^3]	526.5	5055.1
	Sub-Total	**169.0**	**1125.4**
Transportation	Transport	1.4	–
	Sub-Total	**1.4**	–
Total		**170.4**	**1125.4**

TABLE A8 LCA for the precast concrete alternative of the case study.

Element Unit		Emissions of CO_2-eq ton CO_2-eq	Energy consumption GJ-eq
Components	Columns	2,3	35.5
	Beams	13.7	95.6
	Walls	1,3	20.1
	Sub-Total	**17.3**	**151.2**
Transportation	Transport	12.5	–
	Sub-Total	**12.5**	–
Total		**29.8**	**151.2**

TABLE A9 Data used for the assessment of the ORI for the cast-in-place RC alternative of the case study.[62]

Risk—activity—sub-activity	Weight	Exposure	Num. Workers	Total exposure	ORI
Risk: Fall to lower levels—working at height or depths of more					
Steel-tube scaffold					
Installation	0.0208	200	4	800	16.64
Use	0.0208	480	4	1920	39.94
Outside openings in facades					
Construction					
Vertical elements	0.0600	200	6	1200	72.00
Slabs	0.0600	280	8	2240	134.4
Risk: Collision with or entrapment by moving loads					
Cranes and self-propelled industrial trucks					
Lifting					
Scaffoldings	0.0651	48	4	192	12.50
Formworks and reinforcing (vertical elements)	0.0651	8	4	32	2.08
Formworks and reinforcing (horizontal elements)	0.0651	40	4	160	10.42
Risk: Blows to upper and lower limbs					
Installation of reinforcing bars					
Vertical elements	0.021	3	4	13	0.27
Slabs	0.021	16	6	96	2.02
Risk: Collision with or running over by heavy equipment					
Heavy equipment					
Trucks for the transportation of steel					
1st floor	0.0675	3	4	12	0.81
2nd to 5th floor	0.0675	3	2	6	0.41
Concrete mixer truck					
1st floor	0.0675	48	4	192	12.96
2nd to last floor	0.0675	48	2	96	6.48
Concrete pump truck					
1st floor	0.0675	48	4	192	12.96
2nd to last floor	0.0675	48	2	96	6.48
Risk: Cuts, blunt trauma and other injuries					
Rebar bender					
Vertical elements	0.0450	1	1	1	0.04
Horizontal elements	0.0450	4	1	4	0.18
Risk: Traffic accident—transport to construction site					
Concrete					
Transport of concrete to site	0.0400	68	1	68	2.7
Steel (structural and reinforcing bars)					
Transport of structural steel to site	0.0300	0	0	0	0
Risk: Structural risk or macrorisk					
	0.0380	1320	9	11,880	451.44
ORI					**785**

TABLE A10 Data used for the assessment of the ORI for the precast concrete alternative of the case study.[62]

Risk—activity—sub-activity	Weight	Exposure (h)	Num. Workers	Total exposure	ORI
Risk: Fall to lower levels—working at height or depths of more 2 m					
Outside openings in facades					
Placing					
Columns	0.06	8	2	17	1.02
Seism. Beam	0.06	7	4	26	1.57
Sec. Beams	0.06	8	4	32	1.94
Wall	0.06	1	4	6	0.35
Slabs	0.06	48	2	96	5.78
Fixing and finishing					
Columns	0.06	21	2	42	2.50
Seism. Beam	0.06	12	4	48	2.88
Sec. Beams	0.06	10	2	20	1.20
Wall	0.06	4	4	16	0.96
Slabs	0.06	32	5	160	9.60
Self-propelled lifting platform					
Placing					
Seism. Beam	0.02	1	1	1	0.02
Slabs	0.02	2	1	2	0.05
Fixing and finishing				0	0.00
Seism. Beam	0.02	2	1	2	0.05
Wall	0.02	2	1	2	0.03
Slabs	0.02	3	1	3	0.06
Risk: Collision with or entrapment by moving loads					
Cranes and self-propelled industrial trucks					
Cranes in precast factory					
General operations	0.0651	4	8	30	2.00
Cranes in situ (installation of)					0.00
Columns	0.0651	11	6	63	4.10
Seism. Beam	0.0651	7	6	39	2.60
Sec. Beams	0.0651	8	6	49	3.20
Wall	0.0651	2	6	11	0.70
Slabs	0.0651	48	6	289	18.82
Risk: Blows to upper and lower limbs					
Installation of reinforcing bars					
In-situ concrete topping for slabs	0.021	16	8	128	2.69
Risk: Collision with or running over by heavy equipment					
Heavy equipment					
Concrete mixer truck					
1st floor	0.068	8	4	32	2.18
2nd to last floor	0.068	32	2	64	4.35
Concrete pump truck					
1st floor	0.068	8	4	32	2.18
2nd to last floor	0.068	32	2	64	4.35

(Continues)

TABLE A10 (Continued)

Risk—activity—sub-activity	Weight	Exposure (h)	Num. Workers	Total exposure	ORI
Trucks for the transportation of precast elements					
1st floor	0.068	32	4	128	8.70
2nd to last floor	0.068	128	2	256	17.41
Risk: Cuts, blunt trauma and other injuries					
Post-tensioning equipment					
Seismic beams	0.045	6	4	24	1.08
Walls	0.045	2	4	8	0.36
Equipment for the anchoring of bolts					
Columns	0.045	6	2	12	0.56
Seismic beams	0.045	4	4	14	0.65
Walls	0.045	1	4	5	0.22
Risk: Traffic accident—transport to construction site					
Precast pieces					
Transport of precast pieces to site	0.09	135	1	135	12.15
Concrete					
Transport of concrete to site	0.04	11	1	11.25	0.45
Steel (structural and reinforcing bars)					
Transport of structural steel to site	0.03	0.001	1	0.01	0.00
Risk: Structural risk or macrorisk					
	0.05	200	9	1800	90.00
ORI					**207**

TABLE A11 Levels considered for the noise pollution in the case study.

Noise level	Score	Description
Low	10	Completely prefabricated construction site
Medium	5	Partially prefabricated construction site (e.g., elements like slabs and façades are cast on site with some prefabricated components)
High	0	Full cast in situ construction site

TABLE A12 Levels considered for impact on pedestrian transit in the case study.

Disturbance level	Score	Description
None	10	There is no disturbance to the surrounding environment
Low	7	There are minimal disturbances and pedestrian access can be maintained
Medium	4	There is road narrowing and partial deviation of pedestrian paths
High	0	There is complete closure of pedestrian paths

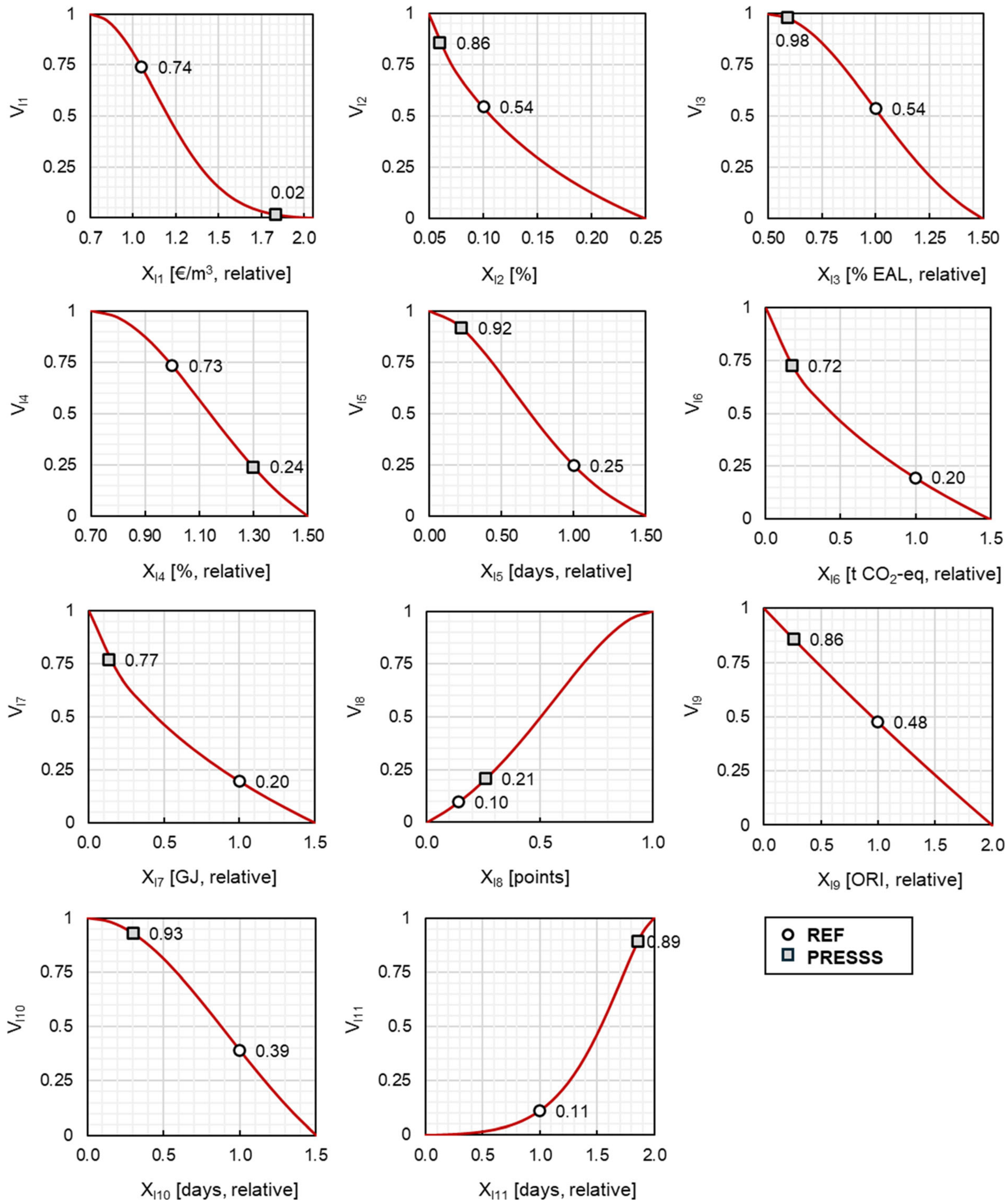

FIGURE A1 Value functions and results for each alternative of the case study.