Received: 17 June 2024 | Revised: 17 September 2024 | Accepted: 21 October 2024

DOI: 10.1002/suco.202400802

ARTICLE

fib CEB-FIP WILEY

Traditional and modern methods of construction: Comparative study of the sustainability of single-family homes

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Abstract

Modern construction methods, such as additive manufacturing, are aimed to enhance the efficiency and quality of construction processes while potentially reducing waste generation and material use, thus contributing to sustainability performance (SP). However, comprehensively understanding the sustainability trade-offs associated with these methods is crucial for guiding both research and practical applications toward sustainable development. This study aims at quantifying the SP of various construction methods for housing, including traditional, prefabricated, and additive manufacturing approaches. A sustainability index, integrating economic, environmental, social, and technological criteria, is utilized to assess different alternatives. Findings reveal promising aspects of 3D printing technologies, such as potential cost reductions through scale increase and process optimization, minimized material waste generation, creation of skilled employment opportunities, and enhanced construction flexibility and ease. Nevertheless, challenges persist, notably significant greenhouse gas emissions and limited supplier availability. Addressing these challenges is imperative for advancing the sustainable implementation of additive manufacturing in construction.

KEYWORDS

economic impact, environmental impact, housing, LCA, social impact, sustainability, sustainable development

1 | INTRODUCTION

The construction industry is undergoing a transformative phase with the advent of modern technologies, such as the emergence of concrete 3D printing in construction.[1,2] The ability to fabricate complex structures layer by layer is challenging traditional methods and is attracting interest due to its potential to revolutionize the construction landscape.

The use of concrete 3D printing in the construction sector has been popular in different applications, including construction elements, formworks and on-site structures.[3] One particularly promising application is 3D concrete printing for houses. Pioneering projects have already demonstrated the feasibility of this technology, with structures like the world's tallest 3D-printed building in Riyadh,[4] with a height of 9.9 m.

However, 3D concrete printing for houses is still in its early stages. Technical limitations remain, such as the need for reinforcement which can complicate the printing process and reduce overall efficiency.[3] Additionally, a lack of standardized regulations and the initial high costs associated with this emerging technology pose challenges for widespread adoption in the construction market.[5]

As societies confront the urgent need for sustainable development, the construction sector is compelled to reassess its methods and materials. Sustainability in construction extends beyond merely environmental considerations. To ensure positive impacts and avoid unintended consequences, a holistic approach is imperative. This necessitates a comprehensive evaluation encompassing economic efficiency, environmental impact, social implications, and technological aspects. A nuanced understanding of these dimensions can help make informed decisions that balance the need for progress with the imperative of sustainability.

At the same time, traditional methods such as steel structures and in-situ concrete continue to be frequently used as they demonstrate proven reliability and economic feasibility.[6,7]

In this context, and recognizing the complexity of sustainability in construction, multi-criteria evaluation methodologies are useful to integrate several parameters (e.g., economic, environmental, and social) into a single assessment. Until the present, several such methodologies have been developed, including the Integrated Value Method for the Assessment of Sustainability (MIVES). MIVES has been applied as a multiple-criteria decision-making tool in various fields like buildings and structures,[8–10] tunnels,[11,12] electricity generation systems,[13] and post-disaster housing management.[14] Notably, MIVES has also been employed to evaluate the sustainability of 3D-printed structures.[5]

In light of the above, the objective of this study is to assess the sustainability of 3D-printed concrete housing alternatives in comparison to traditional and prefabricated construction methods. Through a multi-criteria analysis based on economic, environmental, social, and technological considerations, the article discusses the advantages and disadvantages of 3D-printed concrete housing, traditional methods, and prefabricated construction. The study's findings hold the potential to inform industry practices, guide policy decisions, and contribute to the ongoing discourse on sustainable construction practices.

2 | MATERIALS AND METHODS

2.1 | MIVES

The methodology employed in this study is MIVES.[15,16] MIVES is a multicriteria decision-making methodology that allows for the estimation of the sustainability index (SI) for each of the alternatives of a defined generic problem. Within this methodology, to obtain the SI for each alternative, a decision tree is developed which is usually structured in three levels—requirements, criteria, and indicators. These levels range from most generic to most specific, being the last level (i.e., indicators) the items that are quantified. Indicators are selected in such a way that they are representative of the systems assessed and independent of each other.

In MIVES, indicators are then normalized using value functions, which convert indicator values into a 0-to-1 scale. These functions have five adjustable parameters that control how sensitive they are to different parts of the indicator's data distribution. The indicators commonly used for this type of sustainability analysis and decision-making processes are modeled by means of concave, convex, linear, and S-shaped curves.

The function is defined by five key parameters ($X_{\min}$, $X_{\max}$, C_i, K_i, P_i) detailed in Equation (1).

$$V_{\text{ind}} = B\left[1-\exp\left(-K_i\left(\frac{|X_i - X_{\min}|}{C_i}\right)^{P_i}\right)\right], \qquad (1)$$

In this equation, $X_{\min}$ represents the minimum value possible for the indicators being evaluated; X_i refers to the specific value of the indicator being assessed; C_i is a parameter that approximates the x-coordinate (abscissa) of the function's inflection point; K_i is a value that influences the function's behavior near the inflection point, tending toward a specific value; and P_i is a "shape factor" that determines the curve's shape. It is less than 1 for concave curves, greater than 1 for convex, equal to 1 for linear, and has a more complex behavior for S-shapes (see Reference [16]). Lastly, the parameter B helps normalize the indicator value within the 0-to-1 range for the final output, as shown in Equation (2).

$$B = \left[1-\exp\left(-K_i\left(\frac{|X_{\max} - X_{\min}|}{C_i}\right)^{P_i}\right)\right]^{-1}. \qquad (2)$$

Once indicators have been normalized, each branch of the tree is aggregated using weights.

2.2 | Decision-making model

The three essential requirements commonly associated with sustainability are economic, environmental, and social impacts. In the case of the present study, in addition to these three aspects, the technological component is also considered to integrate and consider aspects related to innovation, flexibility, and other relevant

TABLE 1 Decision-making tree.

Requirements			Criteria			Indicators		
R_1	Economic	25%	C_1	Costs	100%	I_1	Production and assembly cost	50%
						I_2	Maintenance cost	50%
R_2	Environmental	25%	C_2	Emissions	50%	I_3	Greenhouse gas emissions	100%
			C_3	Resource consumption	50%	I_4	Energy consumption	50%
						I_5	Material consumption	50%
R_3	Social	25%	C_4	Innovation	33%	I_6	Generation of skilled jobs	50%
						I_7	Brand benefits	50%
			C_5	Working conditions	33%	I_8	Occupational Risk Index (ORI)	50%
						I_9	Employment generation	50%
			C_6	Third-party effects	33%	I_{10}	Local nuisance	100%
R_4	Technological	25%	C_7	Adaptability	25%	I_{11}	Design flexibility	50%
						I_{12}	Ease of construction	50%
			C_8	Availability	25%	I_{13}	Availability of providers	50%
						I_{14}	Availability of regulations	50%

Note: In the sensitivity analysis scenarios defined in this study, the range of weights for each requirement are the following. R_1: 20%–60%, R_2: 20%–60%, R_3: 10%–25%, R_4: 10%–25%.

TABLE 2 Value functions of the indicators.

Indicator		Units	Shape	X_{min}	X_{max}	C	K	P
I_1	Production and assembly cost	€	DS	75,000	0	32,500	0.15	4
I_2	Maintenance cost	€	DS	20,000	0	10,000	0.15	4
I_3	Greenhouse gas emissions	$kgCO_2$-eq	DCx	20,000	0	10,000	0.9	0.75
I_4	Energy consumption	MJ	DCx	200,000	0	100,000	0.9	0.75
I_5	Material consumption	Scale (3–9)	IL	3	9	4	0	1
I_6	Generation of skilled jobs	Number	IL	1	3	2	0	1
I_7	Brand benefits	Scale (1–5)	IL	1	3	2	0	1
I_8	Occupational Risk Index (ORI)	Hours × person	DL	100	0	50	0	1
I_9	Employment generation	Number	IL	0	1500	2	0	1
I_{10}	Local nuisance	Scale (1–5)	DL	0.3	0	0.25	0	1
I_{11}	Design flexibility	Scale (1–5)	IL	0	0.5	0.25	0	1
I_{12}	Ease of construction	Scale (1–5)	IL	0	0.3	0.25	0	1
I_{13}	Availability of providers	Scale (1–5)	IL	0	0.5	0.25	0	1
I_{14}	Availability of regulations	Scale (1–5)	IL	1	3	2	0	1

Abbreviations: DL, decreasing linear; DS, decreasing S-shape, DCx, decreasing convex; IL, increasing linear.

factors associated with each technology that impact decision-making. Note that this approach has been recommended in cases where technologies assessed are newly developed or emerging and differ considerably from the traditional construction (see, for instance, Reference [5]), but is not necessarily required in all sustainability assessments. Thus, the tree is formed by four main requirements (R). These requirements are divided into eight criteria (C) and 14 indicators (I).

For this study, the decision-making tree developed together with its components is presented in Tables 1 and 2, presents the value functions assigned to each indicator. Complementarily to Table 2, Figure A1 in the appendix shows the shapes of each value function.

The definition of the indicators and the shapes of the assigned value functions was based on literature in studies of similar nature (i.e., comparison of a 3D-printed or innovative alternative with more traditional construction alternatives).[5,17] The weights were determined after discussion with industry experts (see the appendix for more information regarding the experts consulted). While these discussions resulted in all indicators within the decision-making tree being assigned the same weight—representing a strict perspective of sustainability—the sensitivity analysis presented in Section 2.4.1 allows us to evaluate the results when these weights are not evenly distributed.

Further indicators were also identified (e.g., finishing's quality, technology socials' acceptability). Nonetheless, these indicators were found not to be sufficiently relevant in comparison with the others that compose the decision-making tree. In this regard, should other decision-makers consider other sets of indicators as more representative, these could be incorporated accordingly following the approach presented in Section 2.1 in order to maintain both consistency and coherence. Equivalently, the weights' set could also be adapted to other contexts and stakeholders' preferences.

Note that a summary of data sources for each indicator can be found in Table A2.

2.2.1 | Economic requirement

The economic requirement is composed of a single criterion, C_1, which in turn contains two different indicators: production costs and maintenance costs.

- *Production costs* (I_1). These include material costs, labor, machinery, equipment, and auxiliary elements necessary for the production and assembly of housing. These costs were calculated with data from CYPE Ingenieros.[18] This database allows obtaining construction costs adjusted to the market. It includes both manufacturer products and generic products.
- *Maintenance costs* (I_2). These include the material costs, labor, machinery, equipment, and auxiliary elements necessary to guarantee the service capacity and functionality of the housing throughout its useful life. Database in CYPE Ingenieros[18] was used to calculate this indicator's values.

2.2.2 | Environmental requirement

The environmental requirement is composed of two distinct criteria. The first (C_2) refers to emissions, while the second (C_3) is related to resources consumption, including energy and materials.

The emissions criterion (C_2) is composed of the following indicators:

- *Greenhouse gas emissions* (I_3). This indicator accounts for all greenhouse gas emissions, which are essential to consider as they have a direct relationship with temperature increases on Earth and, consequently, in terms of climate change. Data for this indicator consisted of emissions factors, which were obtained from Catalonia Institute of Construction Technology—ITeC.[19]

The resources criterion (C_3) is composed of the following two indicators:

- Energy consumption (I_4). This indicator includes data on energy consumed in the considered life cycle processes, considering renewable and non-renewable energy sources. Energy consumption factors to calculate this indicator were obtained from Catalonia Institute of Construction Technology—ITeC.[19]
- *Material consumption* (I_5). For this indicator, both renewable materials (such as wood) and non-renewable materials (e.g., cement and aggregates) used in housing construction are considered. This indicator was measured using the scale presented in Table 3. For each of the elements (material scarcity, use potential of recycled materials, end of life recycling potential), a score was assigned (see Tables A3–A6, for details). Afterward, the scores were added in a way that the indicator may range between 3 and 9.

2.2.3 | Social requirement

The social requirement is composed of three criteria: innovation (C_4), working conditions (C_5), and third-party effects (C_6). First, in innovation (C_4), two indicators are

TABLE 3 Items considered in indicator I_5.

Materials scarcity		Use potential of recycled materials		EoL recycling potential	
1	Scarce	1	Low	1	Low
2	Moderate	2	Moderate	2	Moderate
3	Abundant	3	High	3	High

TABLE 4 Scale used for indicators I_6 and I_7.

Generation of skilled jobs		Brand benefits	
1	Low (less than 2)	1	No significant impact on reputation
2	Moderate (between 2 and 4)	2	Moderate impact on reputation
3	High (more than 5)	3	Significant impact on reputation

TABLE 5 Scale used for indicator I_9.

Job generation	
1	Low (less than 2)
2	Moderate (between 2 and 4)
3	High (more than 5)

TABLE 6 Scale used for the AHP of indicators I_{13} and I_{14}.

Availability of suppliers/regulations	
1	Same availability
3	Slightly higher availability
5	Moderately higher availability
7	Significantly higher availability
9	Extremely higher availability

considered: the generation of skilled jobs (I_6) and brand benefits (I_7). Table 4 shows the details of the scale used in each of the indicators. Values were assigned upon discussion with experts.

- *Generation of skilled jobs* (I_6). This indicator is intended to assess the number of skilled jobs generated during the design, production, and construction processes. Skilled jobs are those that require higher education and require a minimum level of experience.
- *Brand benefits* (I_7). It evaluates the technology's contribution to increasing the reputation of the construction company and/or those with knowledge/industrial/exploitation property rights.

For working conditions (C_5), the two indicators evaluated are the following:

- *Occupational Risk Index* (I_8). This index measures the risks associated with activities related to housing construction, as well as the probability of accidents occurring in any phase of execution. Data needed to calculate this indicator (i.e., time spent in each construction activity, number of workers) was obtained from CYPE Ingenieros.[18]
- *Job generation* (I_9). This indicator evaluates the total number of jobs generated during the design and construction processes. It was measured using the scale shown in Table 5.

Lastly, for third-party effects (C_6), the indicator is defined as follows.

- *Local nuisance* (I_{10}). Considers disturbances to the neighborhood due to land occupation and the generation of noise, dust, and traffic, among others. This indicator was evaluated using analytic hierarchy process (AHP),[22] which allowed performing pairwise comparisons between the alternatives regarding local nuisance.

2.2.4 | Technological requirement

In addition to the three pillars of sustainability (economy, environment, and society), this study also considers the technological component of the alternatives under analysis. In this requirement, two aspects are considered: adaptability (C_7) and availability (C_8).

Firstly, the adaptability criterion (C_7) is related to design flexibility and ease of construction:

- *Design flexibility* (I_{11}). Considers adaptability and freedom of design, including complex geometries. This indicator was evaluated using AHP.[22]
- *Ease of construction* (I_{12}). Evaluates the simplicity of the production and construction processes of each alternative. This indicator was evaluated using AHP.[22]

Criterion availability (C_8) is composed of two indicators as detailed below. Both indicators were evaluated using AHP[22] with the scale shown in Table 6.

- *Supplier availability* (I_{13}). Allows considering the availability of technology suppliers (equipment and/or materials).
- *Availability of regulations* (I_{14}). Takes into account the availability of regulations and policies, which is especially relevant in this case because new technologies are sometimes not initially regulated.

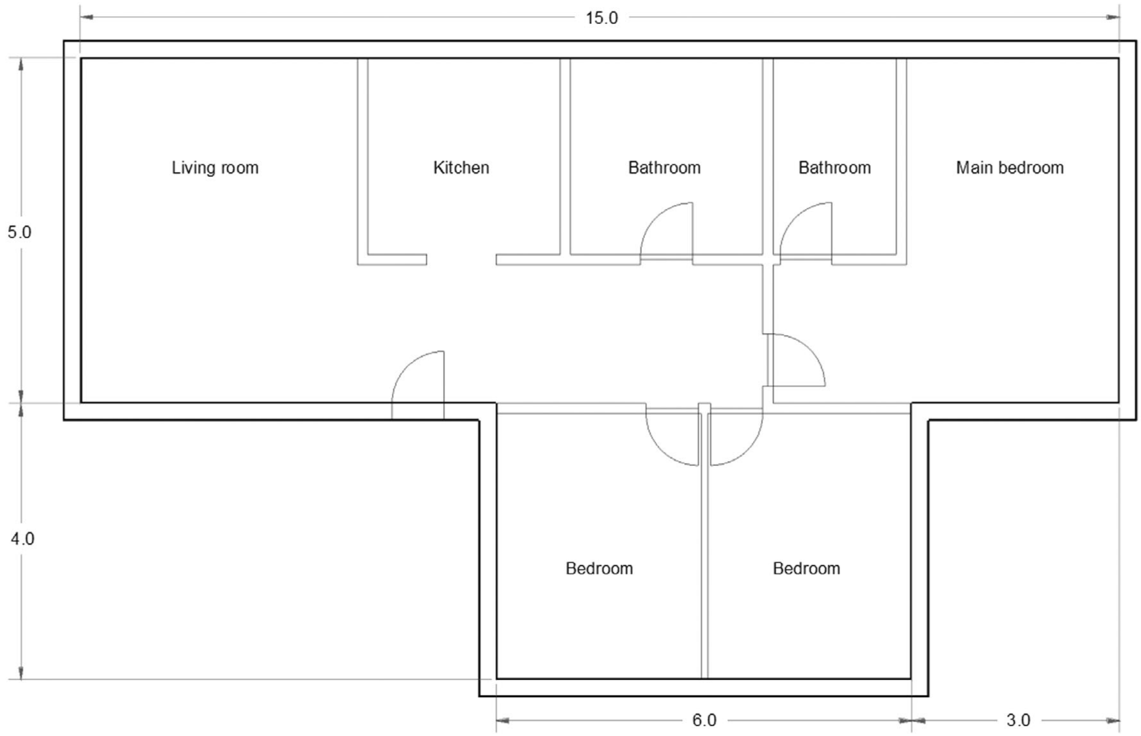

FIGURE 1 Floorplan of the house assessed.

TABLE 7 Technologies considered in this study for housing construction.

Process	Material	Structural typology	Code
Prefabrication (PREF)	Concrete (C)	Frame (F)	PREF-C-F
		Bearing walls (BW)	PREF-C-BW
	Steel (S)	Frame (F)	PREF-S-F
	Timber (T)	Frame (F)	PREF-T-F
In situ (SITU)	Concrete (C)	Frame (F)	SITU-C-F
		Bearing walls (BW)	SITU-C-BW
		3D Printing (3D)	SITU-C-3D
	Masonry (M)	Bearing walls (BW)	SITU-M-BW

2.3 | Case study

The floorplan of the house assessed is shown in Figure 1. It is a one-floor house and, as it can be observed, it consists of a living room, kitchen, two bathrooms and three bedrooms. Given the study's focus on the superstructure's materials and structural typologies, the analysis was restricted to vertical elements, namely walls and frames.

2.3.1 | Scenarios analyzed

After analyzing the literature,[10] the most common and representative structural typologies to consider in this study were defined. They are presented in Table 7 and represented in Figure 2.

For the design of the alternatives, Robot Structural® was used. Details of the sections and materials considered can be found in Table A1 in the appendix.

2.3.2 | Assumptions

The functional unit considered in this study is the complete structure of the housing, considering only the superstructure (i.e., the structure without considering foundation services and operation). The assumed service life for the functional unit is 50 years.

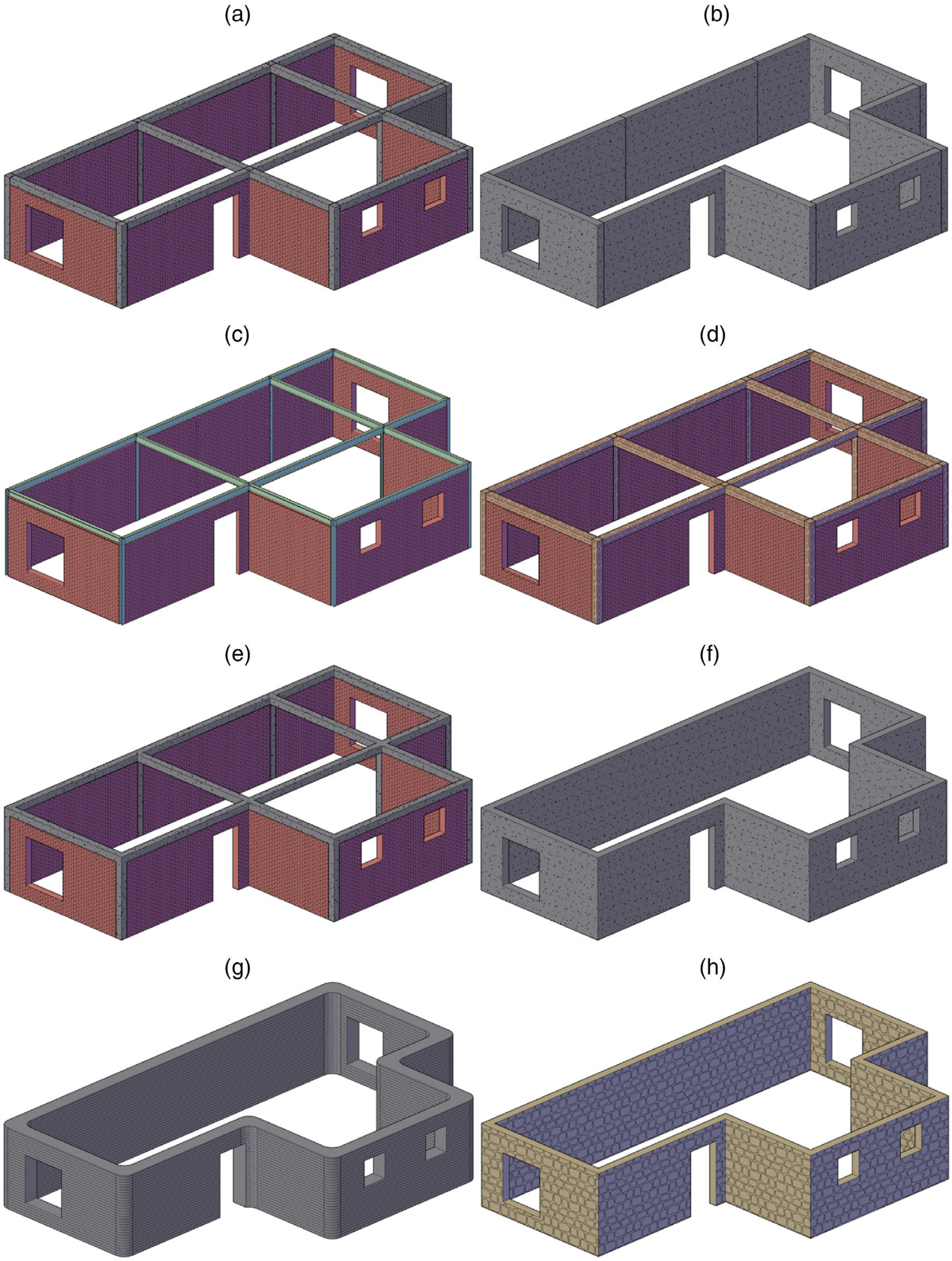

FIGURE 2 Alternative building typologies analyzed in the study, namely (a) PREF-C-F, (b) PREF-C-BW, (c) PREF-S-F, (d) PREF-T-F, (e) SITU-C-F, (f) SITU-C-BW, (g) SITU-C-3D, (h) SITU-M-BW Design details are not shown.

There are several stages during the life cycle of a housing unit that are relevant to consider and have an impact on the life cycle assessment results and, consequently, on the SI. In this study, the following life cycle stages are considered as representative: production stage (raw material supply, transportation, manufacturing), construction process stage (transportation, construction/installation process), and use stage (maintenance). These stages correspond to those defined by EN 15978:2011.[23] Although it is generally accepted that the use phase of a

TABLE 8 Transport distances of materials considered for each alternative.

Alternative	Distance (km)
PREF-C-F	200
PREF-C-BW	200
PREF-S-F	25
PREF-T-F	25
SITU-C-F	30
SITU-C-BW	30
SITU-C-3D	190
SITU-M-BW	25

housing unit has the most significant environmental impacts, it is not included in this case, as the focus of this study is on the impacts in the product and construction stages and, particularly, to quantify the SI of the 3D-printed concrete construction approach and to compare its sustainability performance with the peers. It was assumed that appropriate measures are taken to ensure the same level of insulation (acoustic and thermal) for each alternative, and, consequently, the consumption and emissions associated with achieving the same level of internal comfort during the use phase are independent of the alternative. The impact on the sustainability performance of different insulation techniques could be taken into account by quantifying the economic, environmental, and social effects and incorporating these into the relevant sustainability indicators.

Regarding transportation, the transport distances for the considered materials and components were defined based on the average distances typically involved in transporting the materials and equipment required between main factories and production points in Spain, and the building site of the case study for each typology.

Table 8 presents the distances considered in the results. However, sensitivity analyses regarding transport distances are presented at the end of this document, where sensitivity indices are calculated based on alternative assumptions regarding distances.

Apart from considerations related to transport distances, other relevant aspects must be taken into account regarding the processes included within the system boundaries.

First, in this analysis, the specific characteristics of the housing roofs were not considered. While roofs can play a significant role in terms of insulation, energy efficiency, and sustainability, their exclusion in this study does not affect the ranking of results among the analyzed alternatives, as all housing designs analyzed do not include a roof (and if included, it would be the same). However, it is important to note that roofs can influence the overall sustainability of a house when absolute values are sought, not just relative ones.

Additionally, it was assumed that the maintenance cost of houses does not increase over time. Although maintenance costs can vary over the lifespan of a house due to wear and tear, repairs, and other factors, these changes are minimal and would not significantly impact the final results of this analysis.

Finally, ceramic brick was used as the reference material for the enclosures of those alternatives that do not have the enclosure incorporated into the structural design. However, it is important to highlight that the material of enclosures can vary and adapt to the main structural material used in each alternative.

2.4 | Sensitivity analysis

Performing sensitivity analyses is convenient in multi-criteria decision-making as it helps assess the impact of changes in input values or criteria weights, allowing decision-makers to understand the robustness of their decisions and identify key factors influencing the outcomes. In this study, three types of sensitivity analyses were performed: sensitivity to the weighting system, sensitivity to the transportation distance, and sensitivity to the number of housing units.

2.4.1 | Sensitivity to weights

The decision-making tree presented earlier was based on a set of assigned weights considering equal importance for each part of the tree. However, this set of weights may not be representative of all decision-making contexts, as they can change over time, geographical location, culture, and so forth. Therefore, this section presents a sensitivity analysis in which various weights are modified, examining the impact of these changes on sustainability indices.

The two defined scenarios are presented in Table 9 and are: (1) higher environmental weight than the other two requirements, and (2) higher economic weight than the other two requirements.

2.4.2 | Sensitivity to transportation distance

In order to quantify the impact of transportation (materials and components) on the emissions associated with the execution of each alternative, a sensitivity analysis has been conducted. For this analysis, minimum and maximum transport distances have been defined for the different alternatives (see Table 10).

TABLE 9 Scenarios defined in the sensitivity analysis of the weights.

Requirements		Weight scenario		
		Reference	Environmental	Economic
R_1	Economic	25%	20%	60%
R_2	Environmental	25%	60%	20%
R_3	Social	25%	10%	10%
R_4	Technological	25%	10%	10%

TABLE 10 Scenarios defined in the sensitivity analysis of the transportation distances.

Alternatives	Transportation distance	
	Min	Max
PREF	25 km	500 km
SITU-C	10 km	50 km
SITU-C-3D	0	500 km
Others	0	50 km

2.4.3 | Sensitivity to the number of housing units

In order to quantify the impact on the economic requirement of the number of housing units for the 3D printed alternative, a study has been conducted where the variable construction cost has been varied to account for the construction of 1, 3, 7, 10, 25, 50, and 100 housing units.

3 | RESULTS

In this section, the results obtained for each individual requirement are presented, and subsequently, the aggregated results (corresponding to the overall SI) are provided.

Raw values for each indicator can be found in Table A6 in the appendix, presented in relative terms with reference to the SITU-C-F alternative.

3.1 | Sustainability index

Results for the four requirements are presented in Figure 3.

3.1.1 | Economic requirement

It can be observed that SITU-M-BW, PREF-C-BW, SITU-C-3D, and PREF-C-F yield the lowest values for the economic SI (between 0.01 and 0.59).

The masonry alternative (SITU-M-BW) yields relatively high costs (and therefore a low SI) due to the use of rubble masonry in the design, which is a costly material to produce and obtain.[18] Also, it exhibits notably high maintenance costs, which is due to the intensive and costly maintenance required for masonry due to its composition and construction techniques.

Both PREF-C-BW and PREF-C-F show significant maintenance costs, which is due to the fact that prefabricated concrete structures potentially require regular maintenance to preserve their functionality and esthetic appearance for the case study here.

SITU-C-3D has the highest production costs, which are expected in technology in its early developmental stages.[3,5] It needs to be noted that, in this study, the cost does not include the printer's depreciation percentage. However, if considered, the total cost considered here would decrease with the number of houses (see Section 3.2.3). However, it has lower maintenance costs compared to prefabricated concrete structures, as it does not have joints.

The other alternatives have comparatively lower costs and therefore higher sustainability indices (between 0.75 and 0.89), which is common for more traditional and consequently more optimized construction processes. Notably, the steel structure (PREF-S-F) demonstrates relatively low production costs and medium maintenance costs according to the data collected. Also, the timber structure (PREF-T-F) has a moderate maintenance cost, as it requires proper maintenance to protect it from moisture, insects, and other environmental factors. Lastly, the onsite concrete structures (SITU-C-F and SITU-C-BW) are traditional construction materials and methods that tend to provide benefits in the form of low production costs.

3.1.2 | Environmental requirement

For emissions, the lowest satisfaction is obtained by PREF-C-BW (index of 0.02), followed by PREF-C-F and SITU-C-BW (index of 0.32). These results are expected because the concrete production process is carbon-intensive due to

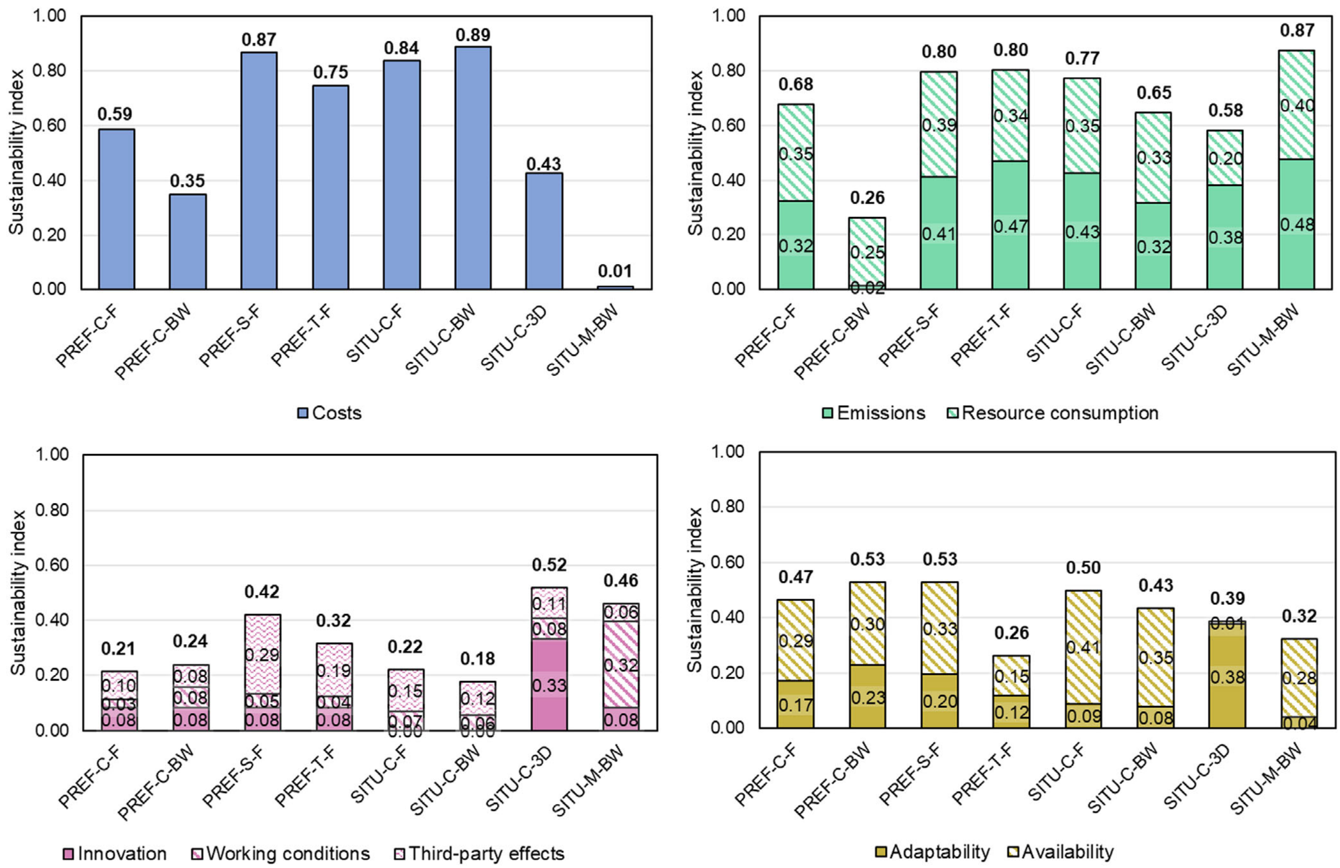

FIGURE 3 Results of the analysis for the (a) economic, (b) environmental, (c) social, and (d) technological requirements of each alternative.

carbon dioxide emissions during cement manufacturing. It is crucial to note that these values may vary based on the energy efficiency and specific composition of the concrete used. Additionally, due to the transportation needs of prefabricated structures, the PREF alternatives present higher emissions generated by their transportation.

At the other end of the spectrum, the best indices for the emissions criterion are obtained by PREF-T-F and SITU-M-BW (indices of 0.47 and 0.48, respectively). The prefabricated wood structure (PREF-T-F) has greenhouse gas emissions between 50% and 83% lower compared to concrete and steel structures. Wood is a renewable material with a relatively low carbon footprint. However, it is crucial to ensure that the wood used comes from sustainable and properly managed sources to ensure emission reduction and forest preservation. Also, the masonry option (SITU-M-BW) shows greenhouse gas emissions similar to wood structures. Masonry may require a significant amount of bricks and mortar, but the emissions associated with these materials are comparatively low given the required manufacturing process and ease of transport.

In the middle range, with emissions criterion indices between 0.38 and 0.43, there are alternatives SITU-C-3D, PREF-S-F, and SITU-C-F. On the one hand, the prefabricated steel structure (PREF-S-F) leads to lower greenhouse gas emissions than prefabricated concrete structures (between 38% and 59% lower). While steel has a lower carbon footprint compared to concrete, its production and manufacturing also generate significant emissions. On the other hand, concrete structures with portal-type frames (SITU-C-F), and concrete 3D printing technology (SITU-C-3D) exhibit greenhouse gas emissions comparable to steel and prefabricated portals. However, they show lower values compared to prefabricated load-bearing walls, which can be attributed to the effect of transporting the pieces and material.

Regarding resource consumption, which is composed of energy and material consumption, all alternatives fall between values of 0.20 and 0.40. The lowest value (0.29) corresponds to the 3D printed alternative and the highest value (0.40) to the masonry alternative.

As for energy consumption, the masonry option (SITU-M-BW) leads to the lowest energy consumption among all alternatives. Masonry is known for its simple construction, resulting in lower energy use during the construction phase. After, the prefabricated timber structure (PREF-T-F) has energy consumption between 19% and 55% lower compared to concrete and steel structures. Wood is a renewable material that requires less energy in its production and processing. The prefabricated concrete structure with portal-type frame (PREF-C-F) shows higher energy consumption than the previously mentioned alternatives. The prefabrication process involves manufacturing elements off-site with more advanced technologies, which may require additional energy for assembly. The prefabricated steel structure has high energy consumption. Steel is a material with a significant energy footprint due to the intensity of the production and manufacturing process.

The options of 3D printing in concrete (SITU-C-3D) and prefabrication of load-bearing walls (PREF-C-BW) have the highest energy consumption among the alternatives. On the one hand, although 3D printing can offer advantages in terms of design freedom and waste reduction, the process itself requires additional energy for machinery operation and material production. On the other hand, the high impact of load-bearing wall structures can be attributed to the energy required during the construction of the structure, as mentioned earlier.

Concerning material consumption, the results highlight that prefabricated steel structures (PREF-S-F) yield the highest values. This indicates greater satisfaction regarding material consumption, given that steel is highly recyclable, and recycled material can be used in its production.[24] This feature contributes to reducing the demand for new resources and promoting the circular economy. Prefabricated concrete structures (PREF-C-F and PREF-C-BW) also receive a high score. This means that, although concrete is not as favorable as steel in terms of recyclability, there is still some satisfaction regarding material consumption, considering the possibility of using recycled materials (e.g., recycled concrete aggregates) in its production or even the structural elements (columns and beams) if the structure is designed with disassembly criteria.

The load-bearing masonry option (SITU-M-BW) receives the same score in material consumption as the previous alternatives. Masonry typically uses materials like bricks or blocks, which, although recyclable in some cases, their manufacturing and transportation processes can impact resource consumption.

Wood structures (PREF-T-F) receive an intermediate score. Wood is a renewable material and generally has good recyclability characteristics, contributing to its positive assessment in this indicator. Finally, the 3D printing in concrete option (SITU-C-3D) receives the lowest score among all alternatives, indicating moderate satisfaction in terms of material consumption. While 3D printing allows optimizing material usage by printing only what is necessary, the availability of recycled materials for this process may still not be as high, limiting its assessment in this indicator.

3.1.3 | Social requirement

Regarding innovation, the 3D printing option in concrete (SITU-C-3D) scores the highest in this criterion (criterion index value of 0.33), as also reflected in other studies.[5] It performs well both in generation of skilled jobs and brand benefits. Implementing this technology can generate a greater number of skilled jobs compared to other alternatives. 3D printing requires specialized personnel to operate and maintain the equipment, potentially creating new employment opportunities in this emerging field. Additionally, this alternative has a greater impact on improving the reputation of the construction company through the adoption of innovative technology like 3D printing. Prefabricated and masonry alternatives all have a moderate score in this criterion, suggesting a similar impact on enhancing the reputation of the construction company through the use of less conventional technologies than in situ concrete.

Regarding working conditions, SITU-M-BW is the alternative showing the best results with a value of 0.32 compared to values between 0.03 and 0.08 for the other alternatives. The ORI evaluates the risks associated with construction activities and the likelihood of accidents. While this solution requires much more time (over 2 times) for construction than others, leading to a significantly higher exposure time to potential risks, the consequences of any potential accidents identified for this solution are significantly less than other alternatives. Additionally, the results for the employment generation indicator indicate that the option of masonry with load-bearing wall structure generates the highest number of work hours (around 1460 h), with the 3D-printed concrete option being the next in evaluation in this indicator (around 673 h). Both alternatives require a higher volume of labor and/or more time for construction, affecting the result of this indicator. Prefabricated concrete options, in situ load-bearing wall concrete, prefabricated steel, and prefabricated wood generate a relatively lower amount of employment (between 214 and 290 h), while the in situ concrete portal option has a slightly higher number of generated work hours (319 h).

Lastly, regarding third-party effects, the highest satisfaction is obtained by the steel frame (PREF-S-F) with a value of 0.29 compared to values between 0.06 and 0.19

for all the other alternatives. This is because production takes place outside of the construction site, and the assembly of the entire structure involves limited activities (mostly welding). Similarly, the timber frame produces fewer local disturbances given that the main components are prepared offsite, and onsite activities only involve bolting the elements together.

As mentioned earlier, it is essential to consider that local disturbances may vary depending on factors such as the construction location, site planning, adopted construction practices, and implemented mitigation measures.

3.1.4 | Technological requirement

Regarding adaptability, it is observed that the 3D printing option (SITU-C-3D) achieves the highest value for this criterion (0.38, compared to values between 0.04 and 0.23 for the other alternatives). 3D printing technologies allow for the creation of complex shapes and geometries more efficiently, providing greater opportunities for innovative and personalized design proposals, as well as topological optimization. Additionally, this alternative shows high ease of construction. 3D printing technology can streamline the construction process by allowing the automated and precise creation of structural elements (an aspect whose improvement is exponentially growing through research in this field).

Following alternative SITU-C-3D, alternatives PREF-C-F, PREF-C-BW, and PREF-S-F yield moderate results for adaptability (between 0.17 and 0.23). Steel is known for its ability to adapt to different shapes and geometries, enabling more flexible and creative designs, albeit with limitations associated with the procedures required to produce the target shapes. For the prefabricated concrete structures, these options have limited capacity in terms of adaptability and design freedom, including complex geometries. In fact, while such geometries can be produced, they come at a cost of special formworks and higher environmental impacts.

Prefabricated concrete structures are often easier to assemble and install compared to other options, thus expediting the construction process (utilizing, as a trade-off, heavy machinery for transport and lifting). Similarly, both wood and steel are materials that can be worked with relative ease on the construction site, contributing to greater efficiency and speed in construction. While prefabricated concrete structures may streamline certain aspects of construction, their assembly and installation require care and precision. On the other hand, on-site constructed concrete structures may be more laborious and time-consuming compared to prefabricated options.

The onsite concrete and masonry structures yield the lowest values for this criterion (between 0.04 and 0.09). This suggests that on-site construction of concrete structures may present challenges and require more effort and time compared to prefabricated options. Finally, the masonry option (SITU-M-BW) obtains the lowest value (0.04). Masonry presents significant limitations in terms of adaptability and design freedom, especially compared to prefabricated structures and 3D printing.

Timber results in moderate results regarding adaptability. Although it can offer some flexibility, its ability to adapt to complex geometries may be more limited compared to steel or 3D printing.

Regarding availability, most alternatives obtain similar values, (between 0.28 and 0.41) except PREF-T-F and SITU-C-3D. In situ, concrete options have a higher availability of suppliers compared to prefabricated options. Prefabricated concrete options with a portal frame structure and prefabricated steel also show relatively high supplier availability. However, the 3D-printed concrete option has lower supplier availability due to its more specialized characteristics (as of 2023, there are fewer than 5 companies in Spain capable of implementing a 3D-printed housing solution). It is worth noting that supplier availability may vary depending on geographical location and the specific market. Similarly, regarding availability and existence of regulations and standards, prefabricated concrete, prefabricated steel, and on-site options have a high availability of regulations and policies. However, the 3D-printed concrete option shows a more limited availability of regulations and policies compared to other alternatives.

3.1.5 | Global sustainability

Figure 4 shows the SI of the different alternatives. The mean value of the SI is 0.51 and its coefficient of

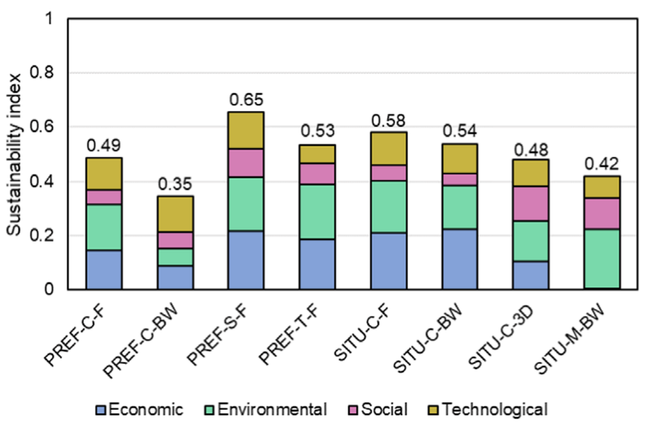

FIGURE 4 Results of the analysis for the sustainability index (SI) of each alternative.

variation, 18.7%. The results of the analysis show that all alternatives are bounded within a range of between 0.35 for the precast concrete load-bearing wall alternative (PREF-C-BW) and 0.65 for the prefabricated steel frame solution (PREF-S-F). Except for these two alternatives, there is not a significant difference of the global SI, as all of them yield values between 0.42 and 0.58.

Considering an ordering of alternatives based on the estimated value of SI in this study, the prefabricated steel frame alternative (PREF-S-F) has the highest SI (0.65), while the precast and cast-in-place concrete solutions and 3D printing obtain an SI between 12% (SITU-C-F) and 47% (PREF-C-BW) lower compared to the SI of the metallic alternative.

3.2 | Sensitivity analysis

This section presents the results of the four sensitivity analyses performed.

3.2.1 | Sensitivity to weights

The results of the weights sensitivity analysis are shown in Figure 5, where (a) corresponds to the economic scenario (i.e., the economic requirement has a weight of 60% weight) and (b) to the environmental scenario (i.e., the environmental requirement has a weight of 60% weight). It can be observed that, despite variations in weights, the ranking of alternatives by the SI value remains consistent. However, there is an increase in both the SI ranges and the mean SI and CoV.

As for the economic scenario, where greater relative importance is assigned to the economic requirement, the SI range expands to between 0.26 and 0.78. The SI of the PREF-S-F solution (0.78) is around three times higher than the SITU-M-BW solution (0.26). The mean SI is 0.56, increasing by 9.8% compared to the SI obtained for the reference scenario (0.51). However, the CoV for this scenario is 34.2% (compared to 18.7% for the reference scenario), as the value of the economic requirement varies between 0.01 (SITU-M-BW) and 0.53 (SITU-C-BW). In this context, for the considered structure and conditions, the SITU-C-3D solution (SI of 0.46) has ample room for improvement from an economic perspective to achieve an SI equivalent to the PREF-S-F (0.78) and SITU-C-BW (0.72) solutions, which show better performance in sustainability in a scenario with a high weight on the economic requirement.

Regarding the environmental scenario, the range of the SI is between 0.30 and 0.74, and the average value of the SI (0.60) increases by 18% compared to the SI obtained for the reference scenario. The PREF-S-F solution leads to the highest SI (0.75). This indicates that the considered alternatives, on average, exhibit a better response to environmental aspects than to other requirements. In this context, the SITU-C-3D solution (SI of 0.52) has room for improvement in terms of environmental impact (e.g., by reducing the use of cement in the material and incorporating recycled aggregates). It presents an environmental impact index of 0.35, compared to 0.48 for the PREF-S-F and PREF-T-F solutions, and 0.52 for the SITU-M-BW solution.

3.2.2 | Sensitivity to transportation distance

Percentages of emissions related to transport with respect to the total emissions were calculated for each alternative

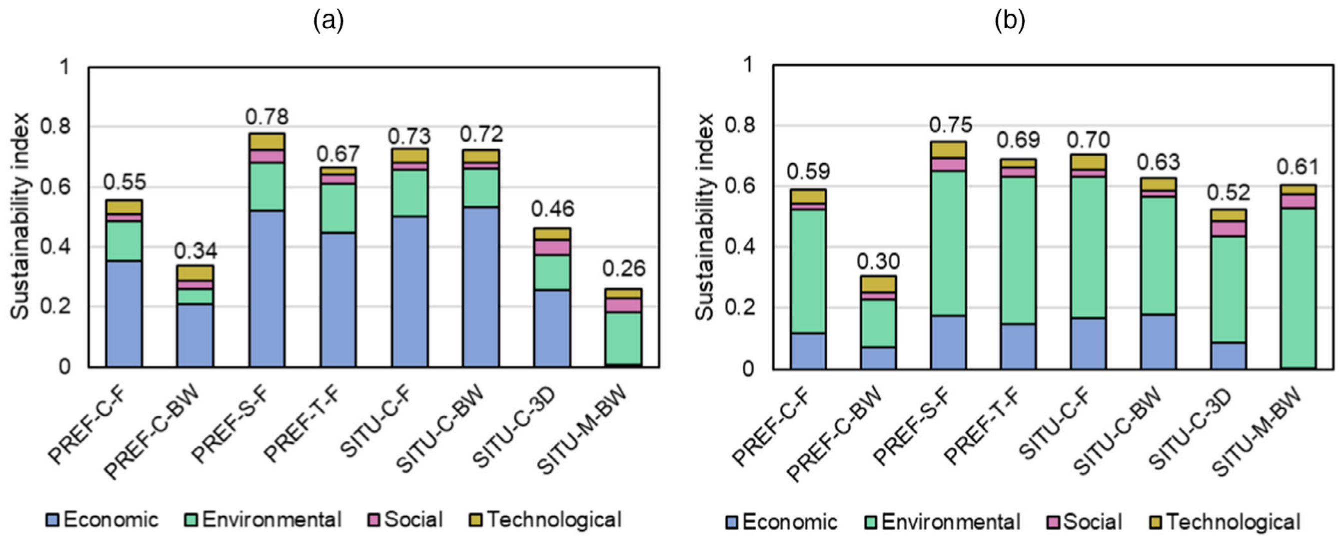

FIGURE 5 Results of the sensitivity analysis on the weights, for (a) economic scenario, and (b) environmental scenario.

TABLE 11 Results of the sensitivity analysis of the transportation distances.

Alternatives	% transport emissions	% transport emissions MIN	% transport emissions MAX
PREF-C-F	1.29	0.16	3.23
PREF-C-BW	2.54	0.32	6.36
PREF-S-F	0.18	0.18	3.63
PREF-T-F	0.41	0.00	0.83
SITU-C-P	0.37	0.12	0.62
SITU-C-MP	0.25	0.08	0.41
SITU-C-3D	1.40	0.00	3.68
SITU-M-BW	5.29	0.00	10.58

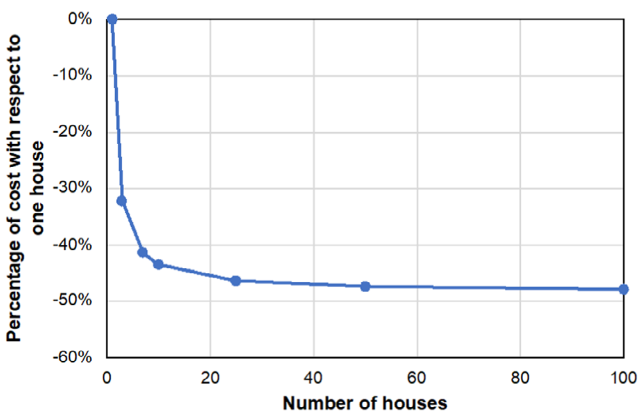

FIGURE 6 Results of the sensitivity analysis with respect to the number of houses.

based on the defined minimum and maximum distances. These percentages represent the contribution of transportation to the total emissions of each alternative. The results of the sensitivity analysis are shown in Table 11, where the percentage of transport emissions is presented for the baseline scenario, as well as the minimum and maximum values obtained.

The results presented in Table 11 lead to the conclusion that the percentages are low, except for the masonry alternative; however, this percentage is still below 10%. This indicates that the SI results are not significantly sensitive to the considered transport distance ranges in terms of emissions and, therefore, the distance variable does not have a high influence in terms of environmental impact.

3.2.3 | Sensitivity to the number of housing units

The variation in the variable construction cost has a significant impact on the total cost and cost per housing unit for the 3D-printed alternative (see Figure 6). As the number of housing units constructed increases, there is a decrease in the variable cost per housing unit. For example, the construction of 25 units allows decreasing the unit cost by around 45%.

This analysis highlights that the construction cost of the 3D-printed housing alternative is more efficient on a larger scale, which can result in greater economic viability for larger projects.

4 | CONCLUSIONS

This article focused on the assessment of the sustainability of one-floor houses, including additive manufacturing as one of the construction methods. In particular, a comparative analysis was conducted among seven traditional housing solutions. These designs were benchmarked against a 3D-printed alternative. Below are the main conclusions of this study:

- *Economic requirement*: traditional options such as steel structures and in-situ concrete constructions have proven to be economically more efficient (with an economic SI 33% higher than the 3D printed alternative). However, emerging technologies like 3D printing promise to revolutionize the industry but currently have high initial costs due to the required upfront investment. It is important to note that costs could decrease by over 30% with an increase in the number of constructed houses (>20 houses per development) and process optimization.
- *Environmental requirement*: 3D printing in concrete presents both challenges and opportunities in terms of environmental sustainability, positioning it 20%–25% lower in environmental sustainability than most alternatives, except for one prefabricated alternative, which is 12% above. While it may generate significant greenhouse gas emissions and require considerable energy consumption, its potential to reduce material waste

and optimize usage could be a step toward improving its environmental performance in the future. Future studies could evaluate the sensitivity of the system to the cement dosage percentage in the mix of the 3D-printed alternative as well as the volume of concrete used.

- *Social requirement*: the concrete 3D printing alternative stands out in terms of generating skilled employment and improving the reputation of the construction company due to its technological innovation. Although it does not show clear advantages in terms of occupational risks and job creation compared to other alternatives, its potential to boost specialized employment and brand image puts it in a competitive position from the social perspective. Overall, the 3D printing alternative is positioned positively above all alternatives with >80% value in relation to social indicators (except for the masonry solution, which has an equivalent value).
- *Technological requirement*: in terms of technological requirements, 3D printing proved to be the best alternative in terms of flexibility and ease of construction. Due to its flexibility and ability to produce complex geometries, it allows for innovative and customized designs. Additionally, ease of construction makes it one of the most favorable alternatives, thanks to its automation and precision in the construction process. However, the availability of suppliers and regulations is still sub-optimal for this alternative, leading the 3D-printed alternative to be, on average, 4.5% below the rest of the alternatives. It is worth noting that the lack of suppliers and regulations is common with emerging technologies, and it is expected that the situation will improve in the coming years.

Lastly, it is important to note that due to the high variability of costs and other determining factors over time and space, it is not advisable to generalize the specific results, including the weights and ordering of the alternatives based on their sustainability index. Nevertheless, the methodology and systematic approach presented for assessing sustainability are both adaptable and applicable in various contexts.

ACKNOWLEDGMENTS

The authors acknowledge ACCIONA, S.A., for the funds provided.

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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How to cite this article: Josa I, de la Fuente A. Traditional and modern methods of construction: Comparative study of the sustainability of single-family homes. Structural Concrete. 2024. https://doi.org/10.1002/suco.202400802

APPENDIX A

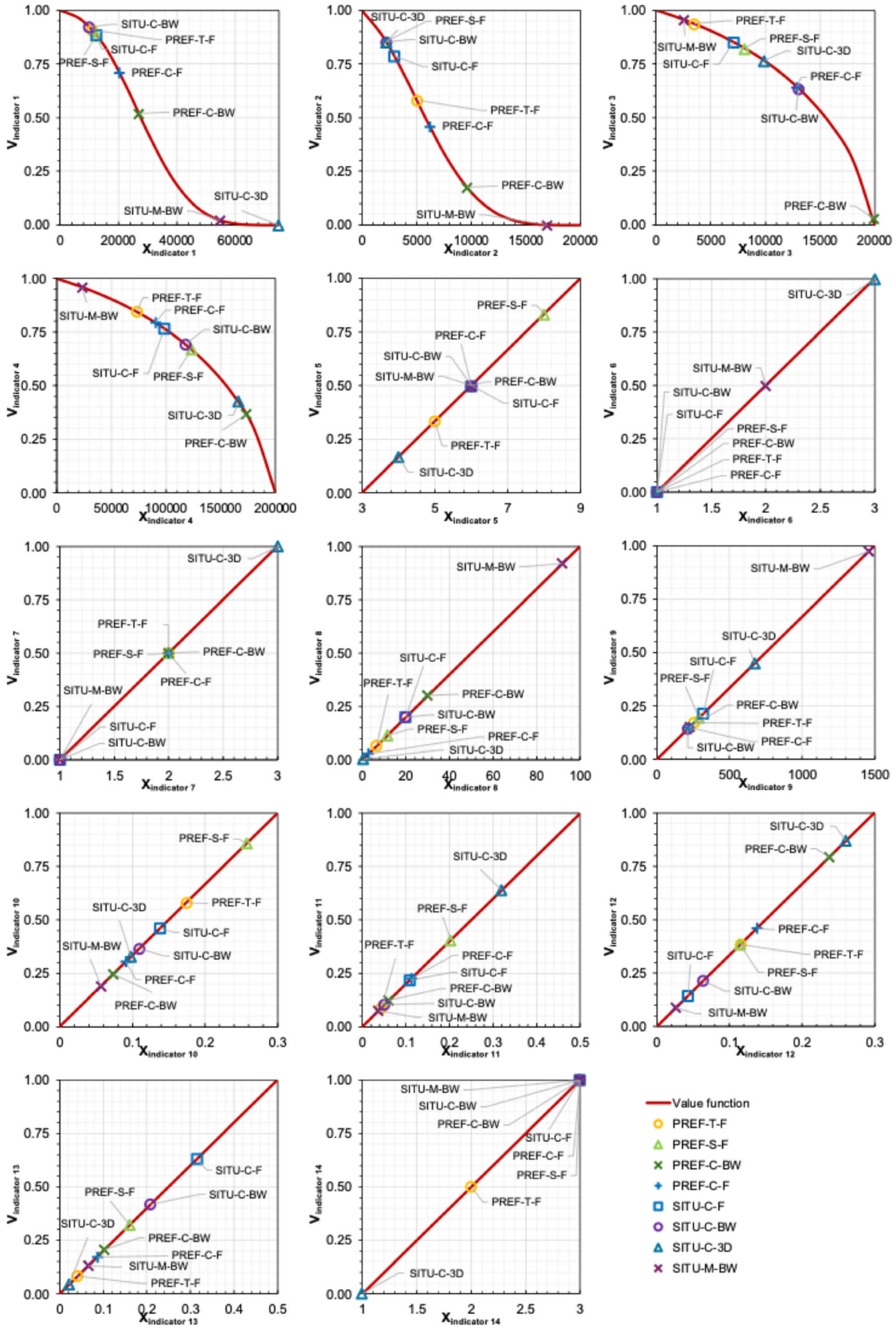

FIGURE A1 Shapes of the value functions for each indicator.

TABLE A1 Design details for each alternative.

Alternative	Design details
PREF-C-F	Concrete HA-25, Pillars: 25 × 25 cm, Beams: 25 × 50 cm
PREF-C-BW	Concrete HA-25, Wall's depth: 30 cm, Beams: 25 × 50 cm
PREF-S-F	Steel S275JR, Pillars: HEA140, Beams: IPE240
PREF-T-F	Timber C40, Pillars: 25 × 25 cm, Beams: 25 × 25 cm
SITU-C-F	Concrete HA-25, Pillars: 25 × 25 cm, Beams: 25 × 50 cm
SITU-C-BW	Concrete HA-25, Wall's depth: 30 cm, Beams: 25 × 50 cm
SITU-C-3D	Total concrete volume: 5.4 m^3
SITU-M-BW	Wall's depth: 50 cm

TABLE A3 Material scarcity scoring for indicator I_5.

Material	Score
Concrete	2
Concrete (3D)	1
Steel	2
Timber	2
Stone	2

TABLE A4 Use potential of recycled materials scoring for indicator I_5.

Material	Score
Concrete	2
Concrete (3D)	1
Steel	3
Timber	1
Stone	2

TABLE A2 Summary of inventory data sources.

Indicator	Data source	Details
I_1 Production and assembly cost, I_2 Maintenance cost	CYPE Ingenieros[18]	Database codes consulted: EPS010, EPV010, FFX010, EPM010, EAS010, EAV010, EMS020, EHS010, EHV010, and EHM010, ECM010
I_3 Greenhouse gas emissions, I_4 Energy consumption	Catalonia Institute of Construction Technology—ITeC[19]; Hegger et al.[20]	Database codes consulted: E4P14795, G4415115, K4F1E15N, and K4G211V9
I_5 Material consumption, I_6 Generation of skilled jobs, I_7 Brand benefits, I_9 Employment generation, I_{14} Availability of regulations	Literature and expert consultation	Literature: Asensio et al.[17]; Josa et al.[16]; Pons-Valladares et al.[5] Experts consulted: junior robotics and automation engineer (>5 years experience), senior robotics and automation engineer (>10 years experience), digital business manager and smart society engineer (>10 years experience), engineering innovation manager (>10 years experience)
I_{10} Local nuisance, I_{11} Design flexibility, I_{12} Ease of construction, I_{13} Availability of providers	AHP based on discussion with experts	Experts consulted: see above
I_8 Occupational Risk Index (ORI)	Casanovas et al.[21]; CYPE Ingenieros[18]	Risks considered: falls of persons to a different level due to winch with movable arm, conventional formwork at height, shoring, work on roofs; direct or indirect electrical contact due to electric concrete mixer; shock or entrapment due to movement or detachment of loads when handling loads by mechanical means (i.e., cranes and forklifts); blows to the upper or lower extremities due to manual handling of loads; cuts, wounds and blows due to welding, oxyacetylene cutting and adhesion of asphalt sheeting to the substrate by torch; traffic accident due to transport of elements and materials to the construction site

TABLE A5 EoL recycling potential scoring for indicator I_5.

Material	Score
Concrete	2
Concrete (3D)	2
Steel	3
Timber	2
Stone	2

TABLE A6 Quantification of indicators (given in relative terms with respect to the alternative SITU-C-F).

Indicator		PREF-C-F	PREF-C-BW	PREF-S-F	PREF-T-F	SITU-C-F	SITU-C-BW	SITU-C-3D	SITU-M-BW
I_1	**Production and assembly cost**	**1.629**	**2.164**	**1.006**	**0.876**	**1.000**	**0.802**	**6.013**	**4.412**
I_2	Maintenance cost	2.089	3.232	0.744	1.692	1.000	0.752	0.752	5.704
I_3	Greenhouse gas emissions	1.817	2.813	1.142	0.490	1.000	1.841	1.396	0.355
I_4	Energy consumption	0.917	1.757	1.249	0.745	1.000	1.194	1.683	0.239
I_5	Material consumption	1.000	1.000	1.333	0.833	1.000	1.000	0.667	1.000
I_6	Generation of skilled jobs	1.000	1.000	1.000	1.000	1.000	1.000	3.000	2.000
I_7	Brand benefits	2.000	2.000	2.000	2.000	1.000	1.000	3.000	1.000
I_8	Occupational Risk Index (ORI)	0.149	1.503	0.573	0.328	1.000	0.995	0.020	4.598
I_9	Employment generation	0.704	0.714	0.909	0.804	1.000	0.670	2.112	4.579
I_{10}	Local nuisance	0.663	0.531	1.863	1.264	1.000	0.794	0.711	0.414
I_{11}	Design flexibility	1.039	0.563	1.859	0.405	1.000	0.473	2.932	0.346
I_{12}	Ease of construction	3.253	5.586	2.705	2.710	1.000	1.504	6.118	0.622
I_{13}	Availability of providers	0.273	0.325	0.510	0.129	1.000	0.659	0.067	0.206
I_{14}	Availability of regulations	1.000	1.000	1.000	0.667	1.000	1.000	0.333	1.000