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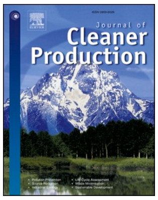

Approach for sustainability assessment for footbridge construction technologies: Application to the first world D-shape 3D-Printed fiber-reinforced mortar footbridge in Madrid

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ABSTRACT

As a means to improve sustainability in the construction sector, the 3D-printed concrete technologies (3DPCTs) are emerging as potential alternatives to traditional construction for reinforced concrete structural components. Traditional technologies are still used in most architecture and civil engineering applications, although D-shape technology for 3DPCTs (DS-3DPCT) has proven technically feasible for producing pilot structural elements such as footbridges. These pilots have been contextualized within research and industrial frameworks, in which relevant technical information is confidential and cost and environmental performance related conclusions are still to be validated and reported. Moreover, scarce research has been conducted on sustainability performance by DS-3DPCT, and that carried out is primarily incipient and focused on identifying governing indicators and some specific non-generalizable quantifications. Former studies ack dealing with sustainability by DS-3DPCT from a holistic and integrated perspective, which requires quantifying and coupling the three main economic, environmental and social pillars. This research project comprehensively develops a sustainability-oriented decision-making approach for assessing construction technologies for footbridges based on MIVES and Delphi method. The Castilla-La Mancha park DS-3DPCT footbridge constructed by ACCIONA S.A. in 2016 in Madrid was the representative case study to validate this approach applicability. The results quantify the case study as sustainable, with excellent values for greenhouse gas emissions reduction, generation of qualified jobs, benefits to brand, occupational risk prevention, and design flexibility. However, this DS-3DPCT requires more maturity in the technology to improve its economic values. This approach range of application might be extended to other structural typologies by introducing -when necessary-other relevant indicators and weights' distributions.

1. Introduction

In the current global context of social, environmental, and economic awareness (United Nations, 2022) it is crucial to quantify the sustainability performance by construction systems and structures to be built and, particularly, to compare this performance with that derived from existing technologies and materials. Therefore, the issue of sustainability must be approached holistically by considering the three main pillars of sustainability in decision-making processes (Brundtland, 1987; ICLEI, 1994): economic, environmental, and social including other factors, such as technical, governance, and cultural (Brković et al., 2015). Available methods, standards and tools could be unsuitable for performing holistic agile assessments on some specific construction elements and processes, especially for those more innovative and still under development ones (Pons-Valladares and Nikolic, 2020).

At present, the building sector is shifting toward construction automation and robotics (CAR) (Pan et al., 2018) as scientific publications evolve. The number of related publications from several databases (Clarivate, 2022; Elsevier B.V., 2022; Google, 2022) confirm a growing tendency in the number of papers, books, and congress contributions as shown in Fig. 1. There are several reasons for this tendency, these include the promotion of construction waste reduction, natural resource savings, speed and ease of construction, and worker safety (Bock and

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Abbreviations

3DPC	3D concrete printing
3DPCT	3D-printed concrete technology
A_i	value of VI_{ind} for $X_{\min}$
ASA	Acrylonitrile Styrene Acrylate, a robust plastic
B_i	factor that prevents the function from exceeding the range [0, 1]
CAR	construction automation and robotics
CGl	carbon and glass fibers
C_i	approximation of the abscissa at the inflexion point
Cyc	cyclist
DCv	decreasing concave
DCx	decreasing convex
DL	decreasing linear
DS	decreasing S-shape
DS-3DPC	D-shape technology for 3DPC
DS-3DPCT	D-shape technology for 3DPCT
$\mathrm{E_i}$	time for which the workers are exposed to the risk W_i
FRP	fiber-reinforced plastic composite
GHG	greenhouse gas
Gl	glass
ICv	increasing concave
ICx	increasing convex
$\mathrm{I_{ind}}$	Indicator
IL	increasing linear
K_i	tends to VI_{ind} at the inflexion point
MAD median	mean of the absolute deviation from the median
MIVES	modelo integrado de valor para una evaluación sostenible (integrated value model for sustainability assessment)
N/A	not applicable
NQJP	new qualified job positions
ORI	occupational risk index
Ped	pedestrian
P_i	shape factor that defines the curve shape of the $\mathrm{VI_{ind}}$
Prot	prototype
R1	economic requirement
R2	environmental requirement
R3	social requirement
R4	technological requirement
RC	reinforced-concrete
RSW	reinforced with steel wire during 3D printing
SI	sustainability index
$\mathrm{VI_{ind}}$	indicator value function
$X_{\max}$	maximum abscissa value of the indicator
$X_{\min}$	minimum abscissa value of the indicator
X_{ind}	abscissa value for the indicator assessed
W_i	weight or importance of the risk
Ws1	weighting of the research project based on Delphi
Ws2	weighting scenario with equal weights for all indicators
Ws3	weighting scenario with economic requirement decision-making driver
Ws4	weighting scenario with environmental requirement decision-making driver

Linner, 2015; Craveiro et al., 2019).

There are different CAR alternatives in development, such as additive manufacturing (Cruz et al., 2020), 3D printing (Duballet et al., 2017), robotic technologies (Gharbia et al., 2020), and industrialization (He et al., 2021), among others. These alternatives are based on the use of various materials and technologies, such as 3D concrete printing (3DPC) (Souza et al., 2020), stone waste (Esposito Corcione et al., 2018), and earth (Perrot et al., 2018). These alternatives are being developed for use in numerous applications, such as construction of new facades (Ali et al., 2021), residential houses (Sakin and Kiroglu, 2017), and restoration of historical buildings (Xu et al., 2017). 3DPC includes numerous technologies such as the extrusion-based approach (Alhumayani et al., 2020) or the D-shape technology for 3DPCT (DS-3DPCT) (Al Jassmi et al., 2018).

One of the most promising applications of 3D-printed concrete technologies are short-span footbridges (Sara et al., 2022). Proof of that is the significant number of pilots of this typology constructed so far (15 cases as presented in Table 1). These are currently subjected to service conditions and the governing structural variables (i.e., deflections, crack widths, and others) are being monitored for research and optimization purposes. There is scarce information published on these experiences due to confidential issues and industrial competitiveness. Nevertheless, despite the existence of these technically successful pilots, constructors and other stakeholders have doubts about the economic and environmental competitiveness of this technology compared to the other consolidated construction technologies for constructing footbridges.

In this regard, the majority of the research on 3D printing technologies has focused on the assessment of environmental issues and have a general scope beyond the construction sector (Jeremy et al., 2015; Kreiger and Pearce, 2013; Saade et al., 2020). Within this general approach to all sectors, few studies have presented an approach to sustainability, either for additive manufacturing (Ford and Despeisse, 2016; Kohtala, 2015) or for 3D printing (Gebler et al., 2014).

Within the construction sector, only a few studies have focused on the environmental impacts of additive manufacturing (Agustí-Juan and Habert, 2017; Esposito Corcione et al., 2018) and energy efficiency (Mahadevan et al., 2020). Since 2016, some researchers have studied the social and economic impacts and sustainability of 3D printing (Donofrio, 2016; Hager et al., 2016; Ma et al., 2018; Mohan et al., 2021; Sakin and Kiroglu, 2017). Some researchers have proposed technical, economic, and environmental indicators and key performance indicators for additive manufacturing (Ghaffar et al., 2018) and 3DPC (De Schutter et al.,

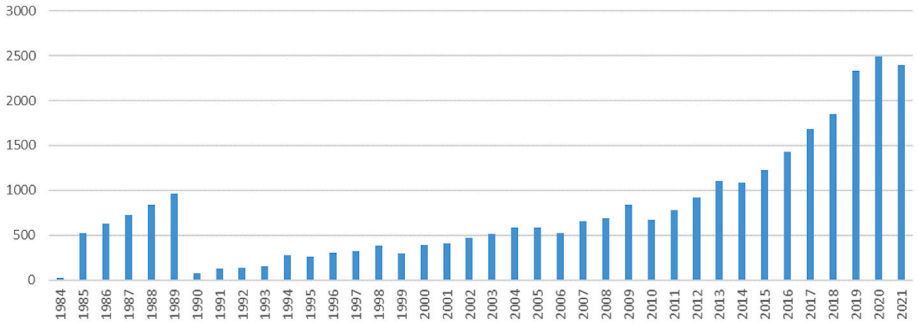

Fig. 1. CAR related publications per year in the Web of Science (Clarivate, 2022).

Note: This search considers the following three groups of keywords: (1) architecture/civil engineering, (2) building/built/construction, and (3) automation/robot/additive manufacturing/3D printing. Consequently, the following search has been defined: (TOPIC (architecture OR civil engineering) AND TOPIC (build* OR built* OR construct*) AND TOPIC (automati* OR robot* OR additive manufactur* OR 3D print*).

Table 1
3D printing experiences for pedestrian and cycling bridges.

	Type	Location	Cons. period	Span (m)	Material	Technology	Reference
1	Ped.	Madrid, Spain	2014–2016	12	micro-RC	Seg. Prin. Ass. Rec. manuf.	de la Fuente et al. (2022); IAAC (2018a); Lowke et al. (2018)
2	Cyc.	Gemert, Netherlands	2017	8	Concrete RSW	6 Seg. Prin. Ass.	Salet et al. (2018)
3	Ped. Cyc.	Shanghai, China (Prot.)	2017	11; 4	Plastic	Seg. Prin. Ass.	Yuan et al. (2018)
4	Ped.	Amsterdam, Netherlands	2018–2021	12,5	Steel	Six-axis welding robot	Buchanan and Gardner (2019); Gardner et al. (2020)
5	Ped.	California, USA (Prot.)	2019	3,4	RC	Slabs and columns	Jagoda et al. (2020)
6	Ped.	Shanghai, China	2019	14,4	RC	176 Seg. Prin. Ass.	Tsinghua University (2019); XU et al. (2020)
7	Ped.	Shanghai, China (Prot.)	2019	11,4	Steel, CGl fibers	Filament winding on 3d printed	Sabina (2019)
8	Ped.	Ghent, Belgium	2019	4	Grout mortar	18 Seg. Prin. Ass. Post-tensioned	Vantyghem et al. (2020)
9	Ped.	Darmstadt, Germany (Prot.)	2019	2	Steel	2 segments welded on site	Feucht et al. (2021)
10	Ped.	Tokyo, Japan	2020	6	Concrete	44 Seg. Prin. Ass. Post-tensioned	Friis (2020) Kinomura et al. (2020)
11	Ped.	Shanghai, China	2020	15,2	ASA, Gl. fibers	Printed in one part and installed	Polymaker (2020)
12	Ped.	Rotterdam, Netherlands	2021	6,5	FRP	Printed in one. Rec. manuf.	Vasilev (2020)
13	Ped. Cyc.	Nijmegen, Netherlands	2021	5 uts x 5,8	Concrete	23 Seg. Prin. Ass. Post-tensioned	Commerce (2022); TU/e (2022); Ahmed et al. (2022)
14	Ped.	Venice, Italy	2021	4,95–15,1	Concrete	53 blocks	Architects and Zurich (2021); ETH Zurich et al. (2022)
15	Ped.	Shanghai, China (Prot.)	2021	9	Carbonate polyester	36 panels	Figovsky and Shteinbok (2022)
16	Ped. Cyc	Ghent, Belgium (Prot.)	2022	4,75	Concrete	Outer shell filled on site and 2 anchorage blocks for post-tensioning	Ooms et al. (2022)

Legend: Cons. period: construction period; Ped.: pedestrian; Cyc.: cyclist; Prot.: prototype; RC: reinforced concrete; CGl: carbon and glass fibers; Seg. Prin. Ass.: segments printed and assembled; Rec. manuf.: recycling raw materials during manufacturing; RSW: reinforced with steel wire during 3D printing; ASA: Acrylonitrile Styrene Acrylate, a robust plastic; Gl.: glass; FRP: fiber-reinforced plastic composite.

2018); however, these are presented in a disaggregated manner, without coupling or deriving a quantifiable and meaningful sustainability performance index. The first consistent framework of indicators for assessing the sustainability performance of the CAR for buildings was reported by Pan et al. (2018). Nonetheless, these indicators were unquantified, and an approach for this purpose is still pending since this research had another driver.

Based on the abovementioned points, the main research question is whether it would be possible to develop an agile unique tool for evaluating pedestrian bridges economic, environmental and social performance. Thus, this research project aimed at developing a comprehensive holistic sustainability-oriented approach to allow construction stakeholders assessing existing reinforced concrete construction technologies for pedestrian and cycling bridges. This research paper also applies this new approach for the first time to quantify the sustainability performance of the 3D-Printed fiber-reinforced mortar pedestrian bridge in the Castilla-La Mancha urban park in Alcobendas, Madrid, constructed by ACCIONA, S.A. (de la Fuente et al., 2022). Therefore, this project has two main parts: first the definition of the novel approach and second the validation of this novelty. Sections 2 and 4 explain in detail these two parts respectively. Specifically, Section 2 presents and justifies the tools and methods used to develop the new approach while Section 3 describes the case study. Section 4 presents and comments on the results as well as their implications. Finally, conclusions are drawn in Section 5. The proposed approach has been designed so it could be applicable to other contexts (i.e., countries with different databases and indicator weights) and for other similar projects after rigorously considering the particularities of each case.

2. Methodology for the definition of the novel approach

The first part of this research project, which is the definition of the novel approach for the sustainability assessment of footbridge construction technologies, is based on the multi-criteria decision-making method entitled integrated value model for sustainability assessment, from the Spanish *Modelo Integrado de Valor para una Evaluación Sostenible* (MIVES). This research project's authors have chosen this model because it enables a sustainability evaluation for any kind of construction process or product. MIVES minimizes the subjectivity related to indicators, especially within the environmental and social branches, and integrates a sustainability index (SI). This decision also relies on the successful development of similar approaches to assess different construction technologies to build façades (Gilani et al., 2022), foundations (Pons et al., 2021; Pujadas-Gispert et al., 2020), pipes (de la Fuente et al., 2016), post disaster housing (Hosseini et al., 2016), roofs (Josa et al., 2020), structures (De La Fuente et al., 2019; Pons and De La Fuente, 2013), and school centers (Habibi et al., 2020; Pons and Aguado, 2012). This model consists of three steps to define the decision tree, value functions and weights; as presented in Fig. 2 and described in detail in the following subsections.

2.1. *Requirements tree*

The definition of the requirements tree presented in Table 2 took into consideration the aforementioned previous research (Pan et al., 2018). The requirements tree was defined based on the information presented in expert seminars (Section 2.3). A fourth requirement, of a technological nature, was included in addition to the three traditional pillars of sustainability since CAR is still incipient and differs considerably from the traditional construction methods regarding technological aspects.

2.2. *Value functions*

Each indicator (I_{ind}) value/satisfaction (VI_{ind}) was simulated using a value function (Alarcon et al., 2011), the shape of which was defined by experts during the seminars. These value functions were calibrated (shape and range of the function argument) for the sustainability assessment of footbridges. These allowed the magnitudes of the

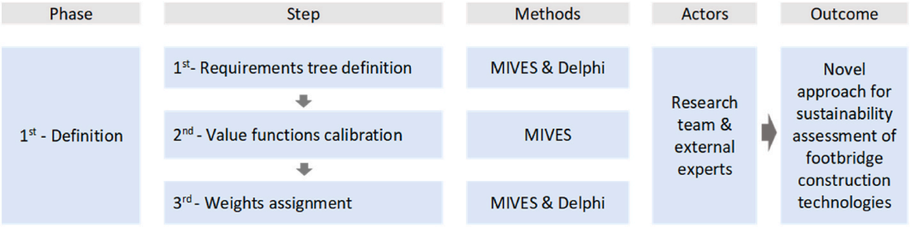

Fig. 2. framework followed for the definition of the novel approach for the sustainability assessment of footbridge construction technologies.

Table 2
Requirements tree and the weights for assessing the sustainability index of footbridges.

Requirements	Criteria	Indicators
R$_1$-Economic (26.8%)	C$_1$-Cost (100%)	I$_1$-Construction and maintenance cost (100%)
R$_2$-**Environmental (29.6%)**	C$_2$-Emissions (46.2%)	I$_2$- Greenhouse gas (GHG) emissions (100%)
	C$_3$-Resource consumption (53.8%)	I$_3$-Energy consumption (43.3%) I$_4$-Material consumption (56.7%)
R$_3$-**Social (22.7%)**	C$_4$-Innovation (33.6%)	I$_5$-Generation of qualified jobs (64.6%) I$_6$-Benefits to brand (35.4%)
	C$_5$-Working conditions (43.5%)	I$_7$-Occupational risk index (ORI) (57.3%) I$_8$-Employment generation (42.7%)
	C$_6$-Third-party effects (22.9%)	I$_9$-Disturbances to site neighbors (occupancy, noise, dust, and traffic) (100%)
R$_4$-**Technological (20.9%)**	C$_7$-Adaptability (55.7%)	I$_{10}$-Design flexibility (49.9%) I$_{11}$-Ease of construction (50.1%)
	C$_8$-Availability (44.3%)	I$_{12}$-Suppliers & regulations/ provisions availability (100%)

indicators (with the respective units) to be converted to the values (understood as satisfaction) of the indicators (VI$_{\text{ind}}$). The indicator values were modeled using Eq. (1), in which the constitutive parameters were calibrated for each indicator (Table 2).

$$VI_{ind} = A_i + B_i\left[1 - e^{-K_i\left(\frac{|X_{ind}-X_{min}|}{C_i}\right)^{P_i}}\right], \tag{1}$$

where A_i is the value of VI_{ind} for $X_{\min}$, $X_{\min}$ is the minimum abscissa value of the indicator range assessed, X_{ind} is the abscissa value for the indicator assessed, P_i is the shape factor that defines the curve shape, C_i is the approximation of the abscissa at the inflexion point, K_i tends to VI_{ind} at the inflexion point, B_i, is the factor that prevents the function from exceeding the range [0, 1] according to Eq. (2), and $X_{\max}$ is the maximum abscissa value of the indicator.

$$B_i = \left[1 - e^{-K_i\left(\frac{|X_{max}-X_{min}|}{C_i}\right)^{P_i}}\right]^{-1} \tag{2}$$

VI$_{\text{ind}}$ ranges from 0 to 1, which represents the minimum and maximum satisfaction, respectively. The result of multiplying VI$_{\text{ind}}$ by the corresponding weight (Table 3) and adding this result to those indicators from the same criterion leads to criterion satisfaction. This process is repeated at both criterion and requirement levels to compute the sustainability index (SI). Following this sequential addition, researchers can guarantee that the resulting SI integrates the values of the representative indicators and requirements of the sustainability performance for the footbridge under analysis.

Within the context of this study case, if different construction techniques (i.e., precast concrete, in-situ concrete, 3DPC, etc.) for constructing the same footbridge, with equivalent mechanical and functionalities for the same span, were to be compared in a decision-making process, the construction technique with the highest SI should be selected, provided sustainability performance is the driver. This type of analysis can also be considered from a stochastic perspective (del Caño et al., 2016; I. Josa et al., 2020), and variable uncertainties (i.e., indicator values, weights, and constitutive parameters of the value functions) can be modeled so that the probability density distribution of the SI (for each alternative) can be derived and scenarios can be analyzed instead of comparing the deterministic values of the SI. However, this approach is beyond the scope of this study, and the mean values of all the variables are assumed to be sufficiently representative, considering the objective of this study.

Table 3
Equations of the Indicator Value functions and the respective constitutive parameters.

Indicator	Unit	Equation	Shape	X_{max}	X_{min}	C	K	P
I$_1$. Construction and maintenance cost	[€/bridge]	(1, 2)	DS	1.25	0.75	1.00	20	1.93
I$_2$. GHG emissions	[kgCO2-eq]			1.25	0.50	1.3	2.6	1
I$_3$. Energy consumption	[MJ]		DCx					
I$_4$. Material consumption	[kN]							
I$_5$- Generation of qualified jobs	Number of qualified job positions generated for the design and construction	Linear (punctuation)	IL	–				
I$_6$- Benefits to brand	Qualitative scale							
I$_7$- ORI	[Hours] Weighted by risk	$VI_7 = -\frac{0.4}{ORI_{RC}}ORI + 1$ (3)	DL					
I$_8$-Employment generation	Total number of job positions generated during the design and construction	Linear (punctuation)	IL					
I$_9$-Disturbances to neighbors	Qualitative scale		DL					
I$_{10}$-Design flexibility			IL					
I$_{11}$-Ease of construction								
I$_{12}$-Suppliers & regulations								

Legend: DS: Decreasing S-shape; DCx: Decreasing convex; DCv: Decreasing concave; ICx: Increasing convex; IL: Increasing linear; ICv: Increasing concave; DL: Decreasing linear; N/A: Not applicable.

Indicators I_1 – I_4 are quantified based on the reference alternative, which is considered to be a full in situ reinforced-concrete (RC) solution with the same cross-sectional geometry (i.e., the openings and architectural details). Therefore, $X_{ind} = X_{alt}/X_{Ref}$, where X_{alt} and X_{Ref} are the values of the argument in Eq. (1) for indicators I_1–I_4 for the alternative under evaluation (DS-3DPC) and alternative of reference (RC). To calibrate the constitutive parameters of Eq. (1) for I_i ($i = 1$–4), the following assumptions were made during the expert seminars.

- *Construction and maintenance costs* (I_1) include the costs from material, labor, machinery, equipment, and auxiliary elements required for the production, assembly, and guarantee of the serviceability and functionality of the footbridge during the entire service life span (Pons and Aguado, 2012). The amortization costs (i.e., 3D printers), maintenance costs, and operational costs should be considered for the quantification of this indicator. The time-dependent and/or inflation-sensitive costs should be treated accordingly. $X_{min} = 0.75$, which represents a reduction of 25% of the total costs with respect to the RC solution ($X = 1.00$), is assigned maximum satisfaction ($VI_1 = 1.0$). A 25% cost reduction implies significant efforts in research and innovation to develop alternatives with this level of cost optimization, which is a challenge within the construction sector. In contrast, $X_{max} = 1.25$ represents a 25% increase in cost with respect to the reference, and the minimum satisfaction ($VI_1 = 0.0$) is assigned accordingly. These extremes are connected through a decreasing S-shaped function, which has been reported to be a representative approach to simulate the stakeholder satisfaction of the construction market, which is very competitive and sensitive to changes with respect to accepted technologies (Pons et al., 2021).
- *GHG emissions* (I_2), *energy consumption* (I_3), and *material consumption* (I_4) are assessed using the same value function. These promote the innovation and application of construction processes that generate lower GHG emissions and reduce the consumption of non-renewable materials (i.e., cement, aggregates, and water) and energy with respect to existing techniques. The quantification of these indicators relies on carbon inventories and energy consumption databases for the materials, processes, and operations conducted (ITEC, 2021). In this context, the reference RC alternative has been assigned $VI_1 = 0.6$, and solutions that reduce 50% of the environmental impact with respect to the reference alternative receive maximum (1.00) satisfaction, whereas solutions that worsen 25% of the reference impact receive null satisfaction. This function has a convex shape to encourage eco-friendly solutions (Pons et al., 2021).
- *Generation of qualified jobs* (I_5) is intended to assess the satisfaction in relation to the number of qualified job positions generated during the design, production, and construction processes. Its quantification is based on the following scale: (a) 0.25/1.00 satisfaction is assigned if there are workers training that involves increasing the existing skills of the plant crew; (b) 0.50/1.00 satisfaction is achieved when the previous condition is achieved plus one new position is generated (i.e., software programmer); (c) 0.75/1.00 satisfaction is assigned when the alternative generates up to two new qualified job positions (NQJP); (d) 1.00/1.00 satisfaction is achieved when more than four NQJPs are generated.
- *Benefit to brand* (I_6) evaluates the contribution of the technology in increasing the reputation of the construction company. Its quantification is assigned a satisfaction of 0.20/1.00 per accomplished benefit with a maximum satisfaction of 1.00. Among others, I_6 considers benefits, such as: (1) publicity, (2) patents, (3) national/international prize, (4) recognized scientific paper, (5) administration recognition, and (6) consumer satisfaction tracked record.
- *ORI* (I_7) is defined in Eq. (3) in Table 3 and Eq. (4), as reported in a study conducted by Casanovas et al. (2014):

$$ORI = \sum_i \frac{P_i \bullet C_i}{1000} \bullet E_i = \sum_i W_i \bullet E_i \tag{4}$$

where i is the risk associated with an activity, P_i is the probability of the occurrence of an accident when there is exposure to the risk, C_i is the severity of the most probable consequence if the accident occurs, $W_i = \frac{P_i \bullet C_i}{1000}$ is the weight or importance of the risk, and E_i is the time for which the workers are exposed to the risk. For I_7, a decreasing linear value function has been considered, so that an ideal situation from the occupational risk perspective with null risk (a complete automatized process without any person exposed to risk) obtains the maximum value of 1.00 and the conventional in situ construction process obtains a value of 0.60, as observed in previous studies (I. Josa et al., 2020; Pons et al., 2021).

- *Employment generation* (I_8) evaluates the total number of job positions generated during the design and construction processes (Hossain et al., 2020). It has a linearly increasing function from the minimum employment generation (completely automated technology with a 0.00 satisfaction) to the maximum (number of job positions required by the most handwork technique with a satisfaction of 1.00).
- *Disturbance to site neighbors* (I_9) takes into consideration nuisances to the neighborhood due to the occupancy of land and generation of noise, dust, and traffic, among others. It considers the following qualitative scale: (a) 0.20/1.00 satisfaction is assigned if the alternative requires numerous in situ machinery and operations; (b) 0.40/1.00 satisfaction is assigned when several in situ machinery and operations are required; (c) 0.60/1.00 satisfaction requires machinery and operations to pour concrete on the joints and move heavy precast elements (>1000 kg/m^3); (d) 0.80/1.00 satisfaction requires machinery and operations to pour concrete on the joints with lightweight precast elements (<1000 kg/m^3); and (e) maximum satisfaction when only dry connections or no connections are required on site.
- *Design flexibility* (I_{10}) considers the design adaptability and freedom, including complex geometries. A qualitative scale assigns points according to the possible geometries, materials, colors, textures, and finishing that the technology can provide or be adapted to (de la Fuente et al., 2017). This quantification is based on the following scale: (a) 0.20/1.00 satisfaction is assigned if only orthogonal 90° geometries can be produced; (b) 0.40/1.00 score is achieved if all angles within the same plane are feasible; (c) 0.60/1.00 satisfaction is assigned if single curvature geometries can be produced; (d) 0.80/1.00 score is achieved if double curvature geometries can also be produced; and (e) maximum satisfaction is assigned if all geometries can be produced, including complex, free, and non-uniform rational basis splines (Moya and Pons, 2014).
- *Ease of construction* (I_{11}) assesses the simplicity of the production and building processes of each alternative. It also uses a qualitative scale as follows: (a) 0.17/1.00 satisfaction if only on-site manual construction is required; (b) 0.33/1.00 satisfaction for on-site industrialized construction (machinery, industrialized formwork, and operation); (c) 0.50/1.00 score for on-site assembly with wet joints (mortar join); (d) 0.67/1.00 satisfaction for on-site assembly with less than two joints per m^2 and lightweight elements (<1000 kg/m^3); (e) 0.83/1.00 satisfaction for direct placement or with less than one dry joint per m^2; (f) maximum satisfaction for direct placement without wet joint off-site.
- *Supplier and regulation availability* (I_{12}) allows for the consideration of the availability of technology suppliers (equipment and/or materials) as well as regulations and policies. The following qualitative scale is used to quantify this indicator: (a) 0.20/1.00 satisfaction if five or fewer suppliers (Ss) of the technology can be found in the

country and no regulations (Rs) are available; (b) 0.40/1.00 satisfaction if there are more than five Ss and no Rs; (c) 0.60/1.00 satisfaction if more than five Ss, without a regulation framework and experiences of application of the technology; (d) 0.80/1.00 satisfaction if there are suppliers in the relevant cities of the country along with Rs for the technology; and (e) maximum satisfaction if both technology and market are mature.

2.3. Weights assignment

The weight assignment (see Table 2) was performed according to the Delphi method, as presented in a previous study (Hallowell and Gambatese, 2010). Twenty-three external contributors experienced in design and management, including R&D chiefs in construction and precast construction companies and engineering consultancies and researchers at universities were initially contacted. These experts were asked to assign weights to the requirements, criteria, and indicators (Table 2) through direct assignment. Eighteen experts finally participated in the first round and seventeen in the second round. Randomized question order, iteration, anonymity, and reporting of the results (means of the weights of the first round) were used to reduce judgment-based biases. As in previous studies (Casanovas-Rubio and Armengou, 2018; Pons et al., 2021), it was assumed that consensus was reached when the mean of the absolute deviation from the median (MAD median) was less than 1/10 of the range of possible values (i.e., <10%), as presented in Eq. (5). This was achieved for all weights in the second round. The weights assigned by each of the experts in the two rounds and the verification of the consensus can be found in Tables A1 and A2 of Annex A.

$$MAD\ median_i = \frac{\sum_{j=1}^{n} \left| w_{ij} - median_i \right|}{n} < 10\% \tag{5}$$

where i is the requirement, criteria, or indicator; j is an expert; n is the total number of experts (18 in the first round and 17 in the second); w_{ij} is the weight assigned to the requirement, criterion, or indicator i by expert j; and the $median_i$ is the median of the weights assigned by the experts to the requirement, criteria, or indicator i.

The resulting weights are listed in Table 2. The environmental requirement (29.6%) was found to be the most important, with 10 points above the technological requirement (20.9%), the least important with respect to sustainability assessment of footbridges. Economic (26.8%) and social (22.7%) requirements are considered the second and third most important. It can be remarked that there is a noticeable balance in terms of weights, with all requirements ranging between 20.9 and 29.6% and thereby confirming the relative importance of each for the stakeholders.

Within these criteria, a reduction in *resource consumption* (53.8%) is preferred over a reduction in *emissions* (46.2%). *Working conditions* (43.5%) are considered the priority within the social requirements, followed by *innovation* (33.6%) and *third-party effects* (22.9%). The design and construction *adaptability* (55.7%) of the method is assumed to be more important than the *availability* of technology (44.3%).

Regarding the indicators, reducing *material consumption* (56.7%) is considered more important than reducing *energy consumption* (43.3%). The reason provided by some experts is that the availability of energy resources is higher than material availability; likewise, higher material consumption leads to higher waste generation and management. However, an expert argues that the different technological alternatives do not significantly differ in the amount of consumed material, while the companies involved in the production, including raw material extraction and the production of the structure itself, may emphasize the reduction of energy consumption and thus globally improve the environmental factor. While the *generation of qualified jobs* (64.4%) is prioritized over *benefits to the brand* (35.4%), some experts disagree and consider that benefits are necessary to generate qualified jobs or that the generation of qualified jobs may not be the objective of the company but the benefits. The reduction in *occupational risks* (57.3%) is considered more important than *employment generation* (42.7%). *Design flexibility* (49.9%) and *ease of construction* (50.1%) are prioritized equally.

3. Case study: Castilla-La Mancha park footbridge in Alcobendas, Madrid

A footbridge with a 12.0 m span made of 3D printed mortar reinforced with steel microfibers was placed in the Castilla-La Mancha park in Alcobendas in Madrid, Spain in December 2016. The footbridge was designed by the Catalan Institute of Advanced Architecture in Barcelona using a topological approach with the aim of minimizing material consumption by reducing the tensile stresses to be resisted (IAAC, 2018b). The material was developed and characterized by the Universitat Politècnica de Catalunya, also located in Barcelona. The footbridge production and installation were led by Acciona S.A. The components were produced at Acciona S.A. facilities using a DS-3CPT, a particle-bed approach based on the D-Shape® system developed by Enrico Dini in 2013 (Cesaretti et al., 2014; Dini, 2017; Lowke et al., 2018).

The footbridge consisted of eight U-shaped cross-sectional segments made of steel microfiber-reinforced mortar. A single segment was cast per production cycle, each of which (a total of eight) required a curing stage in a temperature-controlled chamber (Fig. 3a) to guarantee an appropriate degree of hydration by the cement. After curing, the segments were transported to the yard (Fig. 3b). These were stored at the yard while the delicate railing parts were braced (Fig. 3c) to minimize the likelihood of cracking or the occurrence of permanent deformations owing to environmental loads (i.e., differential solar radiation, wind loads, etc.). Once the 3D-printed mortar achieved a compressive strength greater than 25 N/mm^2, the segments were lifted (Fig. 3d) and placed on an arched steel frame (Fig. 4a). Table 4 summarizes the main features of this footbridge, without presenting its costs owing to confidentiality limitations.

The steel frame was used as a temporary support to facilitate the sealing of the vertical joints and the finishing operations (i.e., smoothing surfaces to prevent users from cuts due to fibers). This steel frame was embedded in the final structure (Fig. 4b) to increase the global carrying capacity of the footbridge. In this regard, it is worth mentioning that this steel frame (as a permanent structure) was structurally redundant because the 3D-printed structure was designed to be sufficient for resisting transient and service loads. Nevertheless, it was reasonable to provide the structure with an additional structural safety margin owing to (1) the lack of experience in the long-term behavior of the 3D-printed composite designed; (2) the innovative character of this structural application and lack of standards; and (3) the collateral social and economic impacts that a partial/total failure by this first footbridge could cause the technology and the business projection for the company.

The footbridge was transported and placed on the abutments using a single crane (Fig. 5a). It must be emphasized that the webs of the segments placed on to the supports were covered with methacrylic plates to prevent the structurally sensitive areas from vandalism, and the upper face of the deck was covered with a resin (Fig. 5b) to increase the grip factor and reduce the risk of slipping.

4. Results and discussion on the novel approach validation

As previously explained this section presents the second part of this research project, which is the first application of the novel approach to

Fig. 3. (a) Accelerated curing chamber, b) transport of a segment to the external yard, a) segments stored at yard environmental conditions, and d) 4-point lifting of the segments with a single crane.

Fig. 4. a) Segments supported onto the arched steel frame and b) painted footbridge with the steel frame already embedded.

the aforementioned case study. Fig. 6 presents the framework for this part and the following subsections explain it in detail.

4.1. *Sustainability performance*

The magnitudes of the indicators (Section 3) considered for the computation of the indicator satisfaction and SI in the DS-3DPC footbridge assessment are presented in Table 5. Values for I_1 (costs) are excluded for confidentiality. The requirements satisfaction and SI

Fig. 5. a) Support and leveling operations of the footbridge and b) walking area of the deck.

Table 4
Main characteristics of the case study.

Dimensions	Span (m)	Volume (m^3)	Weight (kN)	Segments (units)	
	12	6	132	8	
Timing (days)	**Production**		**Transport**		**Assembly**
	45		1		1
Mortar composition (kg/m^3)	**Cem I 52,5 (Portland)**	**Sand 0/1**	**Sand 0/2**	**Water**	**Microfibers**
	500	200	1250	210	100
Steel microfibers	**Material**	**Tensile strength (N/mm^2)**		**Length (mm)**	**Ø (mm)**
	Cold-drawn	3000		13	0.15

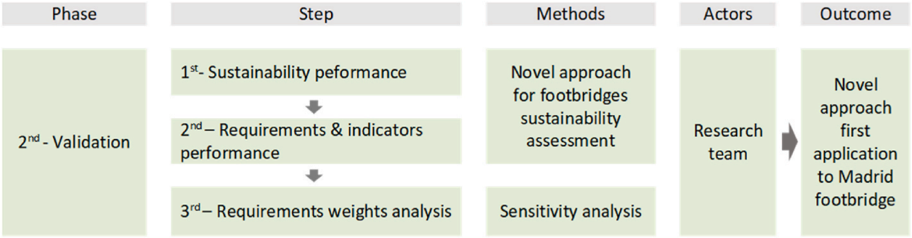

Fig. 6. framework followed for the validation of the novel approach for the sustainability assessment of footbridge construction technologies to the first world D-shape 3D-Printed Fiber-Reinforced Mortar footbridge in Madrid.

Table 5
Indicator quantification for the case study (DS-3DPC footbridge).

Indicator	Quantification
I_2. GHG emissions	3346 $kgCO_{2eq}$
I_3. Energy consumption	22630 MJ
I_4. Material consumption	136 kN
I_5- Generation of qualified jobs	1 point
I_6- Benefits to brand	5 points
I_7- ORI	5.024
I_8-Employment generation	0.17
I_9-Disturbances to neighbors	3 points
I_{10}-Design flexibility	5 points
I_{11}-Ease of construction	3 points
I_{12}-Suppliers & regulations	3 points

obtained by applying the proposed approach (Section 2) are presented in Fig. 7.

To calculate the ORI for the 3D printed bridge, the main activities and risks were identified and evaluated, as presented in Table 6, and the following hypotheses were considered (the numbers correspond to those in Table 6).

1. Risks during construction of the foundations were not considered, as these were believed to be very similar regardless of whether the pedestrian bridge was 3D printed, built in situ, or precast.
2. The bags with a mix of materials were transported from the warehouse to the 3D printer via a self-propelled industrial truck.
3. Each printed piece was transported from the 3D printer to the place where smoothing of the surface was performed.
4. Smoothing of the surface of the printed pieces was performed with an angle grinder.
5. The printed pieces were transported from the place where the smoothing of the surface was performed to the curing chamber with a self-propelled truck.
6. The printed pieces from the curing chamber were transported to an outdoor warehouse with a self-propelled truck.
7. The steel arch was transported and positioned.
8. The steel arch was positioned via manual load handling.
9. The steel arch pieces were welded.
10. The printed pieces were placed onto the steel arch with a crane.
11. The footbridge was placed onto the truck.
12. The transport of the bridge from the ACCIONA S.A. facilities to Castilla-La Mancha park, Alcobendas, and back required approximately 35 min × 2 (round trip), according to Google maps.
13. Finally, the bridge was placed at its final location with a crane.

To calculate the ORI of a similar pedestrian bridge if it is to be built in situ, which is necessary for the value function in Table 3, the same procedure was followed. An $ORI_{RC} = 17.516$ was obtained.

According to the results presented in Fig. 7, the sustainability performance (SI) of the DS-3DPC footbridge was 0.64. As per decision making or other purposes, this SI should be compared with those obtained for different alternatives (i.e., materials and/or construction processes) because this value would be meaningless unless there was a target value to be achieved (i.e., a minimum performance established by the local authorities and/or client). In this regard, until the present, studies differ in their environmental and economic performance for 3DCP and traditional reinforced concrete construction alternatives depending on their locations (Han et al., 2021; Kaszyńska et al., 2020; Kuzmenko et al., 2020). Likewise, it must be stressed that if the weights of the requirements are different (i.e., other sensitivity/importance assigned as stakeholders to the pillars considered), the SI performance is

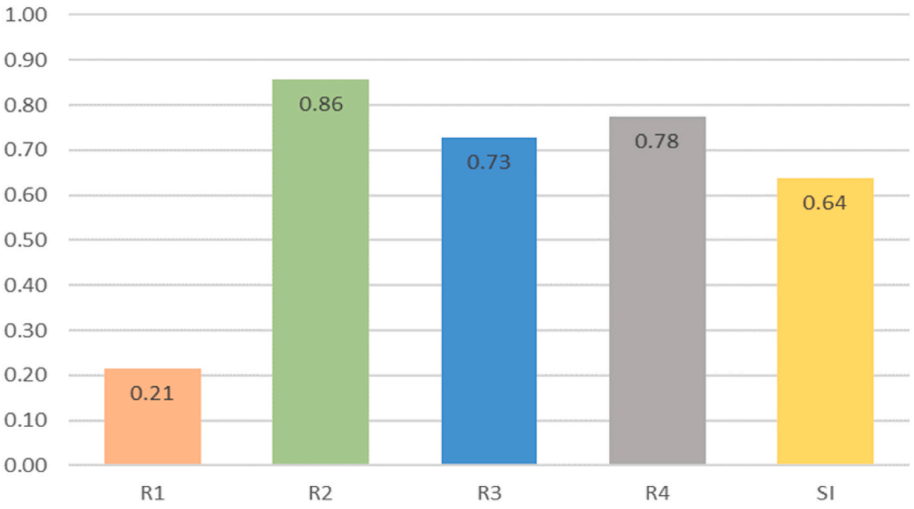

Fig. 7. Satisfaction of the economic (R_1), environmental (R_2), social (R_3), and technological (R_4) requirements as well as the sustainability global index (SI).

Table 6
Risks related to the activities of the 3D printing of the pedestrian bridge and calculation of the ORI.

	Risk - activity	W (P × C/1000) (dimensionless)	Exposure time E (h)	W × E (weighted hours)
1	Collision with or entrapment by a moving load due to its movement or detachment - mechanical load handling: self-propelled industrial trucks	0.065	1.333	0.087
2	Collision with or entrapment by a moving load due to its movement or detachment - mechanical load handling: self-propelled industrial trucks	0.065	1.333	0.087
3	Cuts, blunt trauma, and other injuries due to light equipment - work with light equipment: angle grinder	0.060	20.000	1.200
4	Collision with or entrapment by a moving load due to its movement or detachment - mechanical load handling: self-propelled industrial trucks	0.065	1.333	0.087
5	Collision with or entrapment by a moving load due to its movement or detachment - mechanical load handling: self-propelled industrial trucks	0.065	1.333	0.087
6	Collision with or entrapment by a moving load due to its movement or detachment - mechanical load handling: cranes	0.065	16.000	1.040
7	Blows to upper and lower limbs - manual load handling: materials and auxiliary elements	0.042	16.000	0.672
8	Burns - welding	0.007	5.000	0.035
9	Collision with or entrapment by a moving load due to its movement or detachment - mechanical load handling: crane	0.065	16.000	1.040
10	Collision with or entrapment by a moving load due to its movement or detachment - mechanical load handling: crane	0.065	1.000	0.065
11	Traffic accident - transport of elements to the construction site: precast pieces	0.090	1.167	0.105
12	Collision with or entrapment by a moving load due to its movement or detachment - mechanical load handling: cranes	0.065	8.000	0.520
	ORI		**5.024**	

affected accordingly. To cover different scenarios, a straightforward sensitivity analysis was conducted, the results of which are presented in Section 4.3. By obtaining these results the authors consider that the initial research question has been answered positively because an agile holistic tool for evaluating pedestrian bridges economic, environmental and social performance has been defined and applied.

4.2. *Requirements & indicators performances*

Regarding the requirements performance, it is noticeable that the satisfaction for the requirements R_2 (environmental), R_3 (social), and R_4 (technical) are, in all cases, higher than 0.70, the satisfaction for R_2 being 0.86, which is an added value that should be emphasized. In contrast, economic requirement performance is low ($R_1 = 0.21$). However, this was expected owing to the costs of the (1) 3D printer, (2) curing chamber, (3) other equipment necessary for conducting the production of the segments, and (4) printer adjustments and other costs related to the innovation and low degree of maturity of this technology. In this regard, a substantial portion of these costs, as well as an unusually short period of amortization, were assigned to this footbridge to account for the potential scenario of a reduced number of orders of structures made with the equipment acquired by the company. Therefore, it was expected that, with a higher degree of maturity in the technology and a consolidated market, the costs could be significantly optimized, and the economic indicator performance would improve. As previously explained these findings differ from previous studies probably due to their different locations and 3DPC alternatives (Han et al., 2021).

In Fig. 8, the performance of all indicators is depicted. Regarding the environmental requirement (R_2), low GHG emissions ($VI_2 = 0.94$) and energy consumption ($VI_3 = 1.00$) lead to outstanding satisfaction values for these indicators. Material consumption ($VI_4 = 0.62$) reflects room for improvement. It should be emphasized that the cross section of the footbridge was oversized, and a steel arch was embedded to provide further structural safety. This approach, as mentioned previously, was deemed necessary because this was the first application of this DS-3DPC concrete technology, and both the technology and reputation of the company justified the incremental costs and other extra consumptions assumed.

Concerning the performance of the social indicators, researchers found that *generation of qualified jobs* (I_5), *benefits to brand* (I_6), and *ORI* (I_7) presented an excellent valuation (≥0.90) according to the metrics established in Table 2. As previously explained, to the authors' best knowledge, this assessment is the first time that social indicators have been quantified and aggregated to an integrated SI regarding a 3D-printed concrete technology concrete (De Schutter et al., 2018; Ghaffar et al., 2018). These results strengthen the potential social benefits anticipated from the use of this technology and previous generic studies (Sakin and Kiroglu, 2017) because: (a) new skilled jobs that involve training and hiring are generated; (b) this DS-3DPC technology requires research conducted by the R&D departments of the construction companies along with researchers from academia, publications in scientific and technical sources, marketing campaigns, and forms of publicity of both the technology and the company; and (c) it involves less occupational risks owing to a reduction in the product of exposure, probability, and severity during production on account of the automated process. However, *employment generation* (I_8) is expected to be low; the

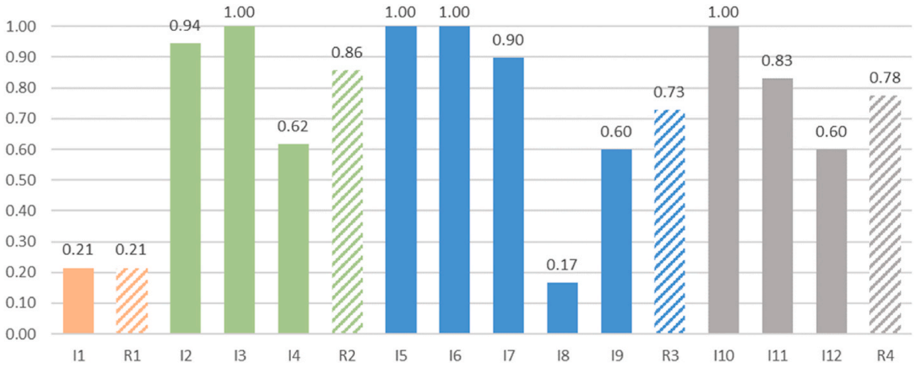

Fig. 8. Satisfaction of the 12 indicators and the economic (R_1), environmental (R_2), social (R_3), and technological (R_4) requirements.

Table 7
Weighting scenarios considered in the sensitivity analysis.

	Weighting scenario description	Weights (%)			
		R_1	R_2	R_3	R_4
Ws1	Weighting of the research project based on Delphi method	26.8	29.6	22.7	20.9
Ws2	Equal weights for all indicators	25.0	25.0	25.0	25.0
Ws3	Economic requirement decision-making driver	55.0	15.0	15.0	15.0
Ws4	Environmental requirement decision-making driver	15.0	55.0	15.0	15.0
Ws5	Social requirement decision-making driver	15.0	15.0	55.0	15.0
Ws6	Technological requirement decision-making driver	15.0	15.0	15.0	55.0

application of this technology requires special training for the precast plant personnel. However, this is characteristic of robotic-based processes, and improving this requires actions at the public administration level. Concerning *disturbances to neighbors* (I_9), this indicator displays similar results as other construction technologies, such as precast elements assembled onsite (precast reference), for the case study analyzed. These nuisances to the neighbors can be solved by improving the construction process, for example, by simplifying onsite works and automating bridge construction (Moya and Pons, 2014).

Finally, with respect to technological requirement indicators, *design flexibility* (I_{10}) achieves maximum satisfaction because this technology allows the production of multiple geometries, even complex free shapes, for which current research projects aim to achieve efficient solutions to implement in the real construction world (Breseghello and Naboni, 2022). It must be noted that the DS-3DPC container has limited space (volume); therefore, the size of the pieces also has upper boundaries. This implies higher segmentation and an increase in the number of joints, which may impact the economic, environmental, and social indicators. These aspects are also considered in the *ease of construction* (I_{11}) indicator. In this regard, the case study presents seven wet joints (see Fig. 4) treated in the same precast plant, which facilitates the operations and minimizes interactions with third parties; however, there are other technologies (i.e., a precast prestressed concrete girder) that are jointless. Finally, *the availability of suppliers and regulations* (I_{12}) indicator results in low satisfaction because, nowadays, there is only a Spanish supplier of this technology and there are reportedly no regulations, for the design and control of mechanical, geometrical, and other material and construction variables. In the absence of these regulations, the provisions for reinforced concrete and fiber-reinforced concrete structures gathered into the Spanish Structural Concrete code (MP, 2008) are satisfactorily applied to the project and construction phases of the footbridge. I_{11} and I_{12} performances are expected to improve in the

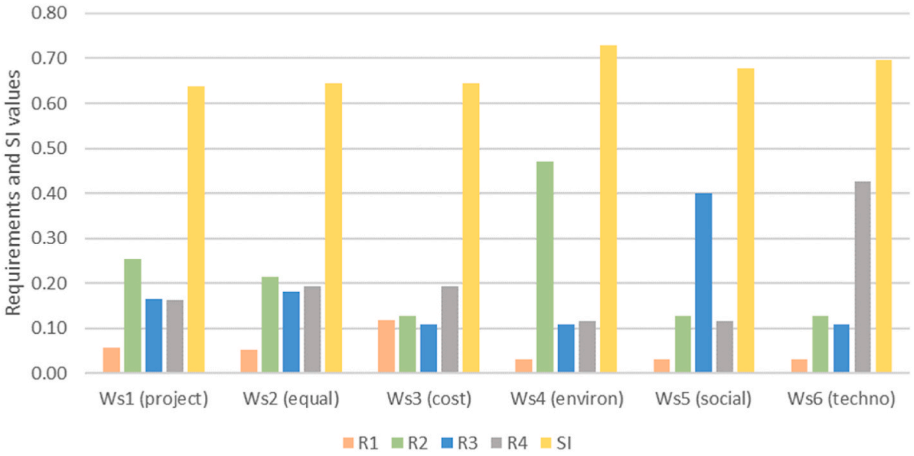

Fig. 9. Satisfaction of the requirements and SI resulting from the six different weighting scenarios (Table 7) and the economic (R1), environmental (R2), social (R3), and technological (R4) requirements.

upcoming years owing to the growing demand of this technology, which will lead to an increase in the number of suppliers and the issuing of technical recommendations and guidelines for DS-3DPC structures similar to those being prepared by the *fib* and the International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM) associations.

4.3. Requirements weight sensitivity analysis

The results and analysis presented in Section 4.2 are based on the weight set (Table 2) derived from the Delphi method (Section 2.3), which is the result of interviewing a group of representative Spanish experts who have international experience. Nonetheless, this weight set might not be representative of the sensitivities and preferences of other stakeholders, including the variables on time, country, and other circumstances (i.e., national roadmap for sustainable development). In view of this, a sensitivity analysis was carried out, which consisted of considering different weight sets (Table 7) that would simulate extreme scenarios and assess their impact on the SI (Fig. 9) for the footbridge under analysis.

The results presented in Fig. 9 demonstrate that the SI performance for the analyzed footbridge ranges between 0.64 and 0.73 (range of 0.09) considering that scenarios 3 to 4 present a decision-making driver requirement that is 3.6 times higher than the other scenarios. This could be seen as a proof of the robustness, in terms of sustainability, of the DS-3DPC technology used for constructing the footbridge analyzed in this study. Similarly, researchers can conclude that similar SIs can be obtained if the same decision-making is developed in other countries and with the preferences of other stakeholders. These replications would require studying the particularities of each context in depth and apply any required adaptations to the presented novel approach.

5. Conclusions

A multi-criteria decision-making approach based on the MIVES method to assess the sustainability performance of construction technologies for footbridges has been proposed in this research. The approach is applicable and valid for any type of construction technology, and the components of the method - weight set, indicators, and value functions - can be adapted to stakeholders' preferences and different scenarios; i.e., national sustainability and development roadmaps. As a case study, the new approach was applied to assess the sustainability index of the first worldwide pedestrian footbridge constructed using a 3D-printed concrete technique. The following conclusions can be drawn from the outcomes resulting from the application of the model.

- The economic requirement (R_1) underperformed (0.21/1.00) respect to the traditional reinforced concrete technology (de la Fuente et al., 2019). Nonetheless, this was expected owing to the total costs incurred in acquiring and implementing the technology. Costs pertaining to the innovation and low degree of maturity for this technology were also partially assigned to this footbridge. Finally, the dimensions of the segments were oversized, and a steel arch was embedded to provide further structural safety. Considering that this was the first worldwide structural application of the 3DP technology, it was deemed necessary to avoid any malfunctioning that could impact the reputation of the company and technology. The economic performance is expected to improve with increasing technological maturity.
- The high satisfaction value (0.82/1.00) of the environmental requirement (R_2) proves the potential of this technology in reducing the impact of the construction sector on the environment, particularly in terms of GHG emissions (0.94/1.00) and energy consumption (1.00/1.00) when compared to other traditional reinforced concrete technologies. The materials consumption indicator (0.62/1.00) could present a better performance as the structural safety measures are relaxed with an increase of the maturity level and the issuing of design and quality control guidelines.
- The good performance (0.73/1.00) by the social requirement (R_3) results from the generation of qualified jobs, and benefits to the company in terms of public support, marketing, publications, etc., and fewer risks of accidents during the production process. The assembly processes should be optimized to decrease the inconveniences by further automatizing operations. The low employment generation (0.17/1.00) is characteristic of robotic-based technologies, and mitigating its consequences requires actions at the public administration level.
- The technological requirement (R_4) performance (0.78/1.00) results from its flexibility in the design geometric boundaries, whilst its constructability and implementation maturity have room for improvement. The construction can become easier with easier connection of joints or no offsite connections. Nevertheless, the expected growth of demand for this technology in the coming years is likely to lead to increases in the number of suppliers, technical recommendations and guidelines for DS-3DPC, and, consequently, improvements in the performance of the technological requirement indicator.

Future research should be focused on extending the application of the sustainability-based approach presented herein to other pedestrian bridges constructed using other technologies (i.e., contour-crafting, fully-precast prestressed concrete, layer-extrusion, etc.) and reinforcement (rebar, fibers, etc.) among others. This is necessary to verify the generalization of the conclusions derived from this research. The motivation behind study is the identification and quantification of scenarios (and conditions) upon which the DS-3DPC technology can be consolidated in the construction sector by conducting a sustainability analysis, this complemented by market models and business projections.

CRediT authorship contribution statement

Oriol Pons-Valladares: Investigation, Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Maria del Mar Casanovas-Rubio:** Investigation, Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Jaume Armengou:** Investigation, Conceptualization, Methodology, Supervision. **Albert de la Fuente:** Investigation, Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Annex A. Weigh assignment

Table A1
Weight assignment and consensus in the first round

Requirement, criteria or indicator		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Mean	Median	MAD median	Consensus MAD median <10%
R1	Economic	10	20	20	30	25	55	20	40	30	30	30	20	15	15	20	10	20	50	25,9	20	8,2	Yes
R2	Environmental	20	40	40	25	40	5	40	20	30	30	30	30	35	30	30	40	30	10	30,3	30	6,2	Yes
R3	Social	25	30	25	25	15	25	10	30	25	30	20	20	20	10	20	30	30	15	22,9	25	5,0	Yes
R4	Technological	15	10	15	20	20	15	30	10	15	10	20	30	30	45	30	20	20	25	20,9	20	6,8	Yes
C2	Emissions	40	50	60	50	50	30	50	40	50	50	40	50	30	30	40	50	50	40	44,7	50	6,5	Yes
C3	Resource consumption	60	50	40	50	50	70	50	60	50	50	60	50	70	70	60	50	50	60	55,3	50	6,5	Yes
C4	Innovation	40	10	10	35	40	25	60	15	40	20	30	30	60	80	40	30	30	40	35,0	30	13,2	No
C5	Working conditions	40	75	60	35	40	70	30	35	40	50	55	30	20	10	40	50	30	30	41,8	40	12,4	No
C6	Third-party effects	20	15	30	30	20	5	10	50	20	30	15	40	20	10	20	20	40	30	23,2	20	8,5	Yes
C7	Adaptability	30	80	50	55	60	50	70	50	40	50	50	70	75	25	70	60	70	50	56,2	55	12,4	No
C8	Availability	70	20	50	45	40	50	30	50	60	50	50	30	25	75	30	40	30	50	43,8	45	12,4	No
I3	Energy consumption	30	45	30	60	60	45	80	20	50	33	60	50	20	20	70	50	40	20	44,9	45	14,2	No
I4	Material consumption	70	55	70	40	40	55	20	80	50	67	40	50	80	80	30	50	60	80	55,1	55	14,2	No
I5	Generation of qualified jobs	70	90	80	60	65	40	50	70	60	80	50	70	75	20	70	70	90	70	65,3	70	12,4	No
I6	Benefits to brand	30	10	20	40	35	60	50	30	40	20	50	30	25	80	30	30	10	30	34,7	30	12,4	No
I7	Occupational Risk Index	60	75	50	60	60	80	40	60	60	60	65	50	90	35	50	80	50	30	60,3	60	10,3	No
I8	Employment generation	40	25	50	40	40	20	60	40	40	40	35	50	10	65	50	20	50	70	39,7	40	10,3	No
I10	Design flexibility	60	35	50	55	70	40	50	30	30	50	50	50	50	75	60	30	30	60	47,9	50	10,3	No
I11	Ease of construction	40	65	50	45	30	60	50	70	70	50	50	50	50	25	40	70	70	40	52,1	50	10,3	No

Table A2
Weight assignment and consensus in the second round

Requirement, criteria or indicator		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	Mean	Median	MAD median	Consensus MAD median <10%
R1	Economic	35	20	25	27	26	45	25	35	27,5	30	30	20	25	20	20	20	25	**26,8**	25	4,7	Yes
R2	Environmental	25	35	35	29	32	20	30	25	27,5	30	30	30	30	30	30	35	30	**29,6**	30	2,4	Yes
R3	Social	25	30	25	23	22	20	21	20	22,5	22	20	20	25	20	20	25	25	**22,7**	22	2,2	Yes
R4	Technological	15	15	15	21	20	15	24	20	22,5	18	20	30	20	30	30	20	20	**20,9**	20	3,5	Yes
C2	Emissions	40	50	60	44	48	40	45	45	50	48	45	50	40	40	40	50	50	**46,2**	45	4,2	Yes
C3	Resource consumption	60	50	40	56	52	60	55	55	50	52	55	50	60	60	60	50	50	**53,8**	55	4,2	Yes
C4	Innovation	40	20	15	35	38	30	38	30	35	20	35	35	35	60	40	30	35	**33,6**	35	6,2	Yes
C5	Working conditions	40	65	55	41	40	50	40	40	40	50	43	40	40	30	40	50	35	**43,5**	40	5,2	Yes
C6	Third-party effects	20	15	30	24	22	20	22	30	25	30	22	25	25	10	20	20	30	**22,9**	22	4,1	Yes
C7	Adaptability	45	70	50	55	60	55	55	55	50	52	55	60	60	35	65	60	65	**55,7**	55	5,8	Yes
C8	Availability	55	30	50	45	40	45	45	45	50	48	45	40	40	65	35	40	35	**44,3**	45	5,8	Yes
I3	Energy consumption	35	45	35	45	55	45	46	30	45	40	50	50	40	35	50	50	40	**43,3**	45	5,4	Yes
I4	Material consumption	65	55	65	55	45	55	54	70	55	60	50	50	60	65	50	50	60	**56,7**	55	5,4	Yes
I5	Generation of qualified jobs	70	80	75	65	65	40	64	65	65	70	60	70	65	30	70	70	75	**64,6**	65	7,4	Yes
I6	Benefits to brand	30	20	25	35	35	60	36	35	35	30	40	30	35	70	30	30	25	**35,4**	35	7,4	Yes
I7	Occupational Risk Index	60	65	50	59	60	60	60	60	60	60	60	50	60	40	50	65	55	**57,3**	60	3,9	Yes
I8	Employment generation	40	35	50	41	40	40	40	40	40	40	40	50	40	60	50	35	45	**42,7**	40	3,9	Yes
I10	Design flexibility	55	45	50	49	60	50	50	40	45	50	50	50	50	65	55	45	40	**49,9**	50	4,2	Yes
I11	Ease of construction	45	55	50	51	40	50	50	60	55	50	50	50	50	35	45	55	60	**50,1**	50	4,2	Yes

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