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Robust decision-making design for sustainable pedestrian concrete bridges

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Abstract

In recent years, there is a trend toward the construction of sustainable structures. The goal of sustainability in structures involves several criteria that are normally opposed, leading to a decision-making process. In this process, there is a subjective portion that cannot be eliminated, such as qualitative criteria assessment of and assigning criteria importance. In these cases, decision-makers become part of the decision-making process, assessing it according to their preferences. In this work, a methodology to reduce the participation of decision-makers in achieving the goal of sustainability in structures is proposed. For this purpose, principal component analysis, kriging-based optimization, and the analytical hierarchy process are used. Principal component analysis is used to reduce the complexity of the problem according to the highly correlated criteria. Kriging-based optimization obtains sustainable solutions depending on all the perspectives of sustainability. Finally, the analytical hierarchy process is applied to reduce the optimized sustainable solutions according to the decision-maker's views. This methodology is applied a continuous concrete box-girder pedestrian bridge deck to reach sustainable designs. This methodology allows a reduction of the complexity of the decision-making problem and also obtains sustainable robust solutions.

Keywords: Post-tensioned concrete, Box-girder bridge, Sustainability assessment, Kriging, Principal Component Analysis, Decision-making, Robust design

1. INTRODUCTION

Traditionally, engineering projects seek to design structures for the lowest cost. But in recent years, the concern about the environmental and social aspects has caused a trend towards designing sustainable structures. This tendency has been supported by the work of several researchers [1–6], as they provide criteria for the development of the three main pillars of sustainability: economic, environmental and social [5,7]. Thus, the design of sustainable structures implies assessing the proper criteria to cover all the perspectives of sustainability, grouped in these three main pillars. After that, it is necessary to normalize and assign the relative importance of each criterion, which is a decision-making process [8,9]. Multi-attribute decision-making (MADM) methods have been widely used in the sustainability assessment of structural designs. Researchers have reviewed different MADM methods and criteria used in structure sustainability assessment problems [10]. These MADM methods have been applied to evaluate a *sustainability index* of different structures or choose the most sustainable structure among different alternatives [6,11]. Regardless of the criteria that the researchers considered to represent the sustainability of the structures, most of them point out that a complete sustainability assessment must cover the whole life-cycle of the structure *(from cradle to grave)* [12–14].

Summarizing, the main steps of the decision-making process are [15]: (a) choose the criteria that adequately represent the sustainable goal, (b) proposal of alternatives, (c) evaluation of the alternatives in term of criteria (which can be quantitative or qualitative criteria), normalize it, and assign it a relative importance, and finally (d) select the best alternative. Once the criteria and alternatives are proposed, evaluation of qualitative criteria and assigning relative importance of the different criteria involve subjective assessments. This implies that the sustainability assessment could be different depending on decision-making concerns. For this reason, an approach that reaches a sustainable structure that satisfies all the different interests of decision-makers would be of great value. Consequently, it is necessary to study how these different perspectives affect the design of structures. For this purpose, principal component analysis (PCA) [16], kriging-based optimization [17], and the AHP method [18] were used to seek sustainable solutions, abolishing the relationship between criteria and ensuring the sustainable robustness of the solutions against the different perspectives of the decision-maker. PCA is used to avoid assessing a cluster of criteria with a high correlation index. Instead, the criteria with a high correlation index are grouped into principal components, avoiding excessively (positively or negatively) valuing the sustainable valuation of the alternatives. Kriging-based optimization is used to obtain the most sustainable alternative according to each perspective. Due to the large number of optimizations that must be made to carry out this study, kriging-based optimization is the most appropriate because of its high calculation speed [19]. Finally, AHP is used to generate many consistent random relative importances to study the variability of each optimum alternative against all the different possible perspectives. Additionally, the problem of criteria dependence, highlighted by several researchers [20,21], is solved due to the linear independence of the principal components.

In this work, the first goal is to study the influence of uncertainty in decision-making problems and to obtain the sustainable alternatives that best represent the different interests of the decision-makers. The second goal is to determine the sustainable alternative that best satisfies all the different perspectives, regardless of the interests of the decision-makers. This solution could be called the sustainable robust solution. For this purpose, the sustainability assessment of a three-span continuous concrete box-girder pedestrian bridge was considered. This structure was chosen due to its structural performance, low dead load and construction conditions. To this end, a large set of criteria was considered to cover all the perspectives of sustainability of the bridge, taking into account its whole life-cycle. In this way, a complete sustainability assessment can be made.

2. BRIDGE DESCRIPTION

The structure considered is a continuous concrete box-girder pedestrian bridge deck with three continuous spans of 40-50-40 meters length. The width of the pedestrian bridge deck (*B*) is 3 meters. The remaining geometrical dimensions that define the cross-section of the pedestrian bridge deck are variables (Figure 1): depth (*h*), width of bottom slab (*b*), width of web inclination (*d*), thickness of top slab (*es*), thickness of external cantilever section (*ev*), thickness of bottom slab (*ei*) and thickness of webs slab (*ea*). The haunch (*t*) is obtained following Schlaich and Scheff's [22] recommendation (Equation 1).

$$t = max\left\{\frac{b-2\cdot ea}{5}, ei\right\} \quad . \tag{1}$$

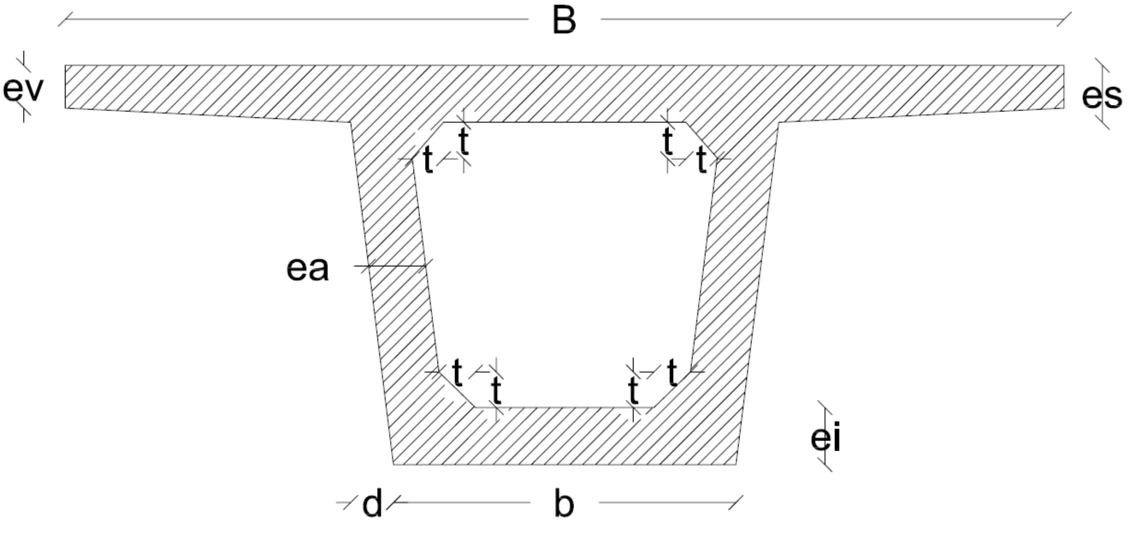

Figure 1. Box-girder cross-section

Furthermore, the concrete strength (f_{ck}) is considered as a variable. The post-tensioned steel is formed from 0.6 inch strands and is prestressed to 195.52 kN, and the ducts are symmetrically distributed through the webs with a parabolic layout. The maximum eccentricity is located where the bending moment is the minimum or maximum (Figure 2), where the distance of the ducts to the surface is 0.2 meters. In addition, the distance between the piers and the post-tensioned steel point of inflection is 5% of the length of each span.

The position of the reinforced steel is determined according to Figure 3. Longitudinal reinforcement is defined by the number of bars per meter and their diameter, placed at the top slab (LR_{n1}, $LRØ_1$), the flange (LR_{n2}, $LRØ_2$, LR_{n3}, $LRØ_3$), the web (LR_{n4}, $LRØ_4$), the bottom slab (LR_{n5}, $LRØ_5$) and the core (LR_{n6}, $LRØ_6$). Also, two extra bending reinforcements are considered. The first covers the top slab of the support area ($LRØ_7$) with the same number of bars per meter as LR_{n1}, and the other covers the bottom slab throughout the rest of the external span ($LRØ_8$) and the central span ($LRØ_9$) with the same number of bars per meter as LR_{n5}. Transverse reinforcement is defined by the diameter of the standard reinforcement ($TRØ_1$, $TRØ_2$, $TRØ_3$, $TRØ_4$, $TRØ_5$, $TRØ_6$, $TRØ_7$) and the spacing (*TRS*). Table 1 shows the other conditions employed in this study.

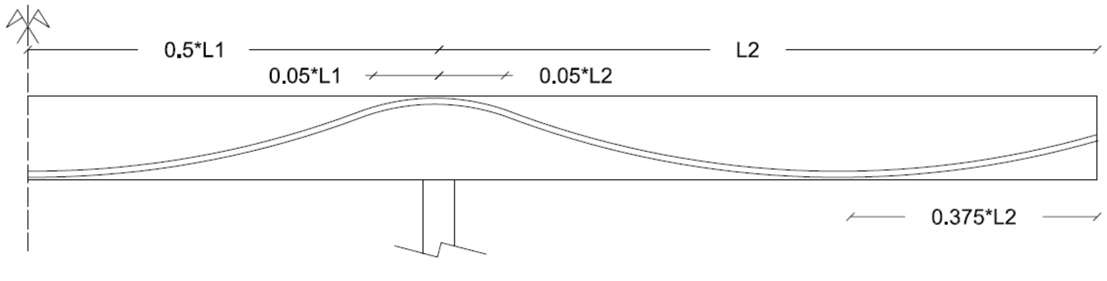

Figure 2. Pedestrian bridge and duct layout

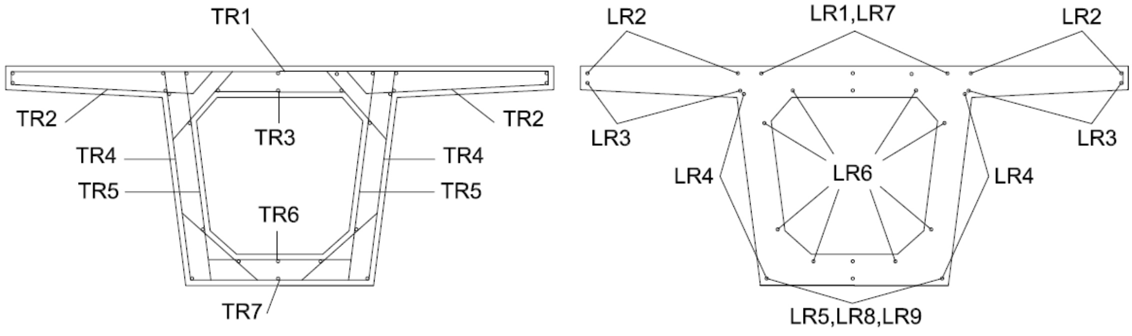

Figure 3. Transversal and longitudinal reinforcing steel disposition

***Table 1**. Parameters of the analysis*

MATERIAL DESCRIPTION	
Maximum aggregate size	*20 mm*
Reinforcing steel	*B-500-S*
Post-tensioned steel	*Y1860-S7*
Strand diameter	$\Phi_s = 0.6''$
Tensioning time	*7 days*
GEOMETRICAL DESCRIPTION	
Pedestrian bridge width *(B)*	*3 m*
Number of spans	*3*
Central span length *(L1)*	*50 m*
External span length *(L2)*	*40 m*
Clearance	*5 m*
Diaphragm thickness	*1.2 m*
LOADING RELATED DESCRIPTION	
Reinforced concrete self-weight	*25 kN/m*^{3}
Asphalt layer self-weight	*24 kN/m*^{3}
Mean asphalt thickness	*47.5 mm*
Bridge railing self-weight	*1 kN/m*
Live load	*5 kN/m*^{2}
Differential settling	*5 mm*
EXPOSURE RELATED DESCRIPTION	
External ambient conditions	*IIb*
REGULATION RELATED DESCRIPTION	
Codes	*Eurocodes / EHE-08 / IAP-11*
Service life	*100 years*

3. METHODOLOGY

This section explains the methodology used to carry out this work. Figure 4 shows a flow chart of the main steps considered. First, a sample of pedestrian bridges and the criteria that represent sustainability are defined (Section 3.1). After that, principal component analysis is used to decrease the number of criteria (Section 3.2). Then, kriging-based optimization is applied to obtain the most sustainable pedestrian bridges (Section 3.3). Later, the MADM method AHP is used to obtain the most sustainable pedestrian bridges, according to 1000 random decision-makers, that cover all the perspectives of sustainability (Section 3.4). Finally, the results are interpreted and discussed (Section 4).

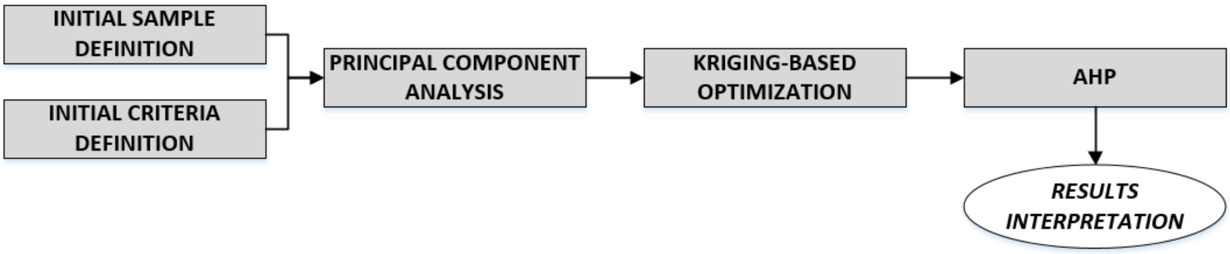

Figure 4. Overview of the methodology

3.1.Criteria and life-cycle assessment

In general, selecting the criteria that represent the decision-making problem depends on the characteristics of the goal. According to this goal, it is possible to define three different levels. The number of criteria necessary to cover the decision-making problem is different for each different level as the goal is more specific in each level, and therefore, some criteria have the same assessment for all the different alternatives. Thus, focusing on the construction sector, the (a) first level represents a decision-making problem in which the goal is to choose the best engineering project for a region/society/city; the (b) second level represents a decision-making problem in which the goal is to choose the best typology/methodology/process to carry out an already defined engineering project; and the (c) third level represents a decision-making problem in which the goal is to choose the best design. Obviously, to cover the first level of the decision-making problem, the criteria needed are higher since it concerns many aspects. Conversely, the criteria needed to cover the third level of the decision-making problem are those that are influenced by the design variables.

Figure 5 shows an overview of the three levels. Considering the decision-making performed in this work, an example of different levels is described. The criteria used in the first level must cover appropriately all the necessities of society, with alternatives being different projects (for example a road repair, construction of a pedestrian bridge, or construction of a public pool). If the project chosen is the construction of a pedestrian bridge, the criteria used in the second level must cover appropriately all the different bridge typologies (for example, a steel pedestrian bridge, a precast concrete beam pedestrian bridge, or a concrete box-girder pedestrian bridge). Finally, if the concrete box-girder pedestrian bridge is chosen, the criteria used in the third level must appropriately cover all the different designs (in this case, the designs are defined by the cross-section geometry and concrete strength).

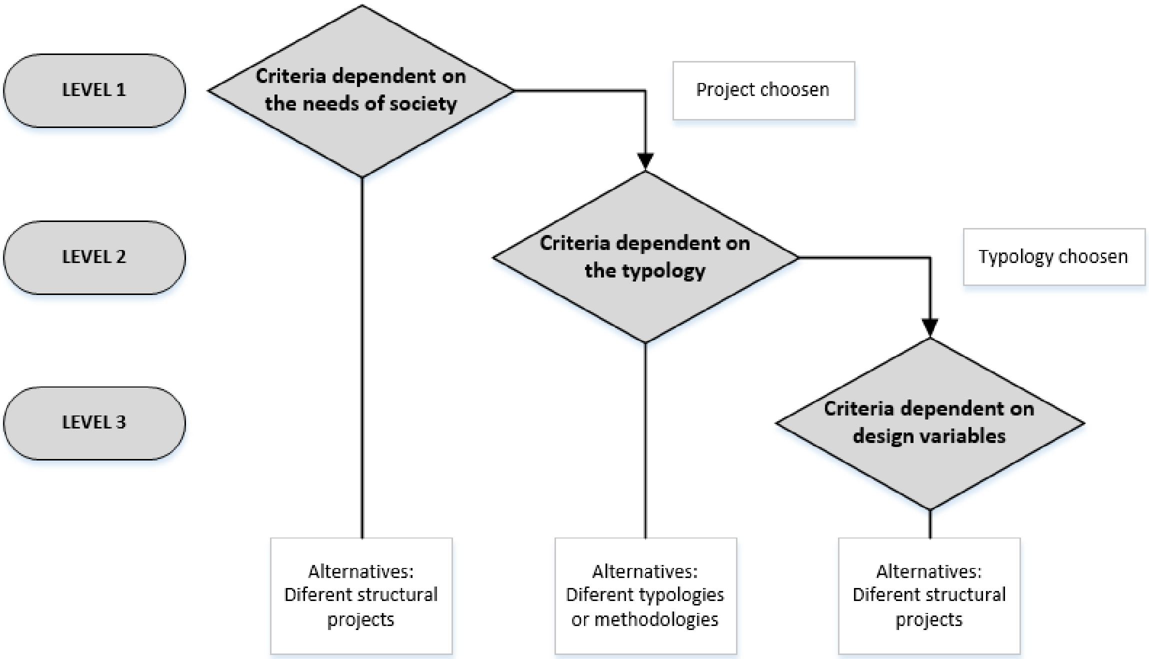

Figure 5. Decision-making problem levels

This work focuses on a third level decision-making problem. The goal was to reach the most sustainable design for a concrete box-girder pedestrian bridge according to eight variables (seven geometric variables that define the cross-section of the bridge and the concrete strength). For this purpose, the first step was to define all the criteria that cover all the perspectives of the sustainability assessment of a concrete box-girder pedestrian bridge along its whole life-cycle. Eleven criteria were considered, covering the three main pillars of sustainability and constructability of the bridge. This last group included evaluating the technical part. Figure 6 shows all the criteria considered.

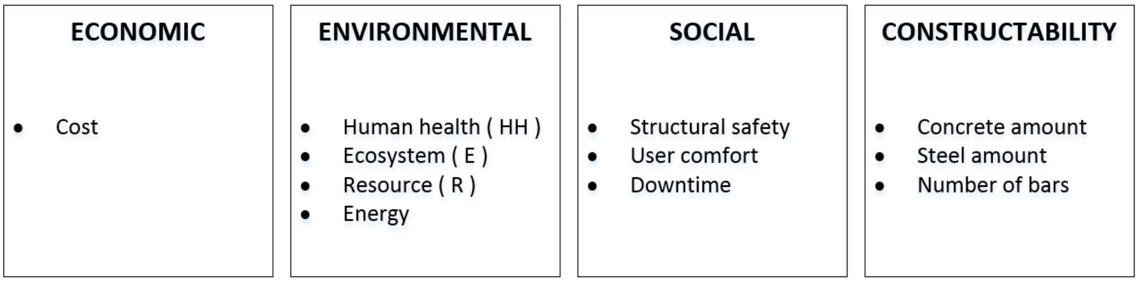

Figure 6. Sustainability criteria

A previous review of the criteria used for the sustainability assessment of bridges [10] was used as the basis for selection of the criteria considered in this work. The review shows a high consensus to assess the economic aspect, in which the total cost is the most-used criterion. This work assessed the economic aspect using information provided by the BEDEC database [23]. Review of the environmental aspect shows that it is common to use one or two criteria to define the environmental aspect (CO_2 and energy are the most-used criteria). However, to obtain a full environmental profile, it is necessary to consider a set of criteria that represent a complete environmental assessment [24]. For this purpose, this work used the endpoint approach of the life-cycle impact assessment method ReCiPe [25], using information provided by the Ecoinvent database [26] and processed using OpenLCA software. In this way, a complete environmental assessment was obtained and all the environmental impacts were considered [12,27]. Finally, the review shows that the social aspect is the most unclear. There is a high disagreement in defining the criteria that best represent the social aspect. Criteria such as detour time, dust, and noise have been used in different works [5,28,29]. Most of these criteria are associated with the different life-cycle activities on the bridge (construction and maintenance activities). For this reason, a single criterion that involves all the criteria that emerge during the work activities is considered, such as downtime. Additionally, structural safety and user comfort are included in the social aspect [1,9,11]. Furthermore, a last group of criteria has been defined to represent the technical aspect and the ease construction of the bridge. This group includes the amount of concrete, the amount of steel, and the number of bars [30].

All these criteria were calculated along the whole life-cycle of the bridge. For this purpose, according to the initial bridge design, all the impacts were obtained for each stage of the bridge life-cycle: *production, construction, use and maintenance,* and *end of life*. The production stage covers all the products, processes, and services from the extraction of raw material to material disposal at the construction site. The construction stage refers to the products, processes, and services during bridge construction activities. The use and maintenance stage involves all the products, processes, and services along the service life of the bridge, including the maintenance activities. The end of life stage includes all the products, processes, and services after the service life of the bridge ends. A large description of all the products, processes, and services considered along the whole life-cycle of the bridge is explained in Penadés-Plà et al. [13].

Table 2 shows the unit prices and the unit environmental impacts of all the materials and processes considered in the life-cycle assessment. The BEDEC database [23] provides the unit prices and the ReCiPe method [25] provides the unit damage categories (Human health, Ecosystem, and Resources). The human health category includes the years of life lost and years of life disabled, the ecosystem category refers to the loss of species during a certain time in a certain area, and resources assesses how the use of mineral and fossil resources causes changes in the effort needed to extract future resources. The unit cost and the unit damage categories consider all the progress of the materials and processes defined. The other criteria (social and constructability) are calculated once the bridge design is defined. Structural safety is the lowest safety coefficient of the ultimate limit state (ULS), user comfort corresponds to the vibration service limit state (SLS), and downtime is the days that the bridge is not operational. The concrete amount is obtained once the geometric design is defined, and the steel amount and number of bars once the bridge is designed. The assessment of all these criteria throughout the life cycle given the initial bridge design has been carried out by means of a program coded in Matlab.

Table 2. *Measurement units*

UNIT MEASUREMENTS	COST (€)	RECIPE (points)		
		Human health	Ecosystem	Resources
Truck (t*km)	0.039	6.78E-03	3.74E-03	6.60E-03
Truck mixer (t*km)	0.095	1.63E-02	8.98E-03	1.58E-02
B-500-S steel (kg)	1.16	0.09	0.03	0.11
Y1860-S7 post-tensioned steel (kg)	2.56	0.09	0.03	0.11
HP-35 concrete (m^3)	104.57	7.71	5.68	2.06
HP-40 concrete (m^3)	109.33	8.26	6.07	2.28
HP-45 concrete (m^3)	114.1	8.98	6.59	2.42
HP-50 concrete (m^3)	118.87	10.26	7.5	2.78
HP-55 concrete (m^3)	123.64	11.7	8.54	3.18
HP-60 concrete (m^3)	128.41	12.51	9.11	3.58
HP-70 concrete (m^3)	137.95	12.7	9.25	3.61
HP-80 concrete (m^3)	147.49	12.86	9.36	3.77
HP-90 concrete (m^3)	157.02	13.34	9.7	3.86
HP-100 concrete (m^3)	166.56	14.09	10.23	4.13
Formwork (m^2)	33.81	0.23	0.17	0.99
Lighting (m^3)	104.57	0.04	0.24	0.06
Concrete placement (m^3)	30.06	3.85E-03	2.25E-03	2.34E-03
Steel placement (kg)	1.0847	3.20E-04	1.80E-04	1.90E-04
Repair mortar application	16.41	2.16E-04	2.16E-04	1.40E-04
Bonding coat application	43.28			
Truck-mounted platform	53.71	7.78E-03	3.07E-03	1.22E-03
Water blasting	11.5			
Demolition (m3)	10.57	0.00047	0.00019	0.00073
Crushing (m3)	5.88	0.00064	0.00032	0.00093

At the end of the bridge assessment, each criterion has different units. Therefore, for the sustainability assessment of the bridge, it is necessary to normalize these criteria for later aggregation. For this purpose, a linear normalization was applied to the different criteria. To facilitate the aggregation of the criteria to carry out the sustainability assessment, the best-normalized value of each criterion will be 0 and the worst will be 1. Therefore, in the case that the best value of the criteria is the lowest one, Equation 2 is used. Otherwise, if the best value is the greatest one, Equation 3 is used.

$$v_i = \frac{(x_i - x_{min})}{(x_{max} - x_{min})} \quad (2)$$

$$v_i = \frac{(x_{max} - x_i)}{(x_{max} - x_{min})} \quad (3)$$

In addition, an initial sample of pedestrian bridges was defined. For this purpose, Latin hypercube sampling (LSU) was used according to Penadés-Plà et al. [19]. LHS was proposed by McKay et al. in 1979 [31]. This method determines *N* number of non-overlapping intervals for each variable, divided according to a uniform distribution, from a number of design variables (*v*) and a sample size (*N)*. Therefore, the design space is divided into N^v regions. This method guarantees that each point of the sample is in one of these regions, so each interval of each design variable range is only taken for one point of the sample. Consequently, LHS guarantees that all the design variables are represented along with their respective ranges.

In this work, an initial sample size of 500 box-girder pedestrian bridges was considered. These bridges have eight variables, concrete strength and seven geometric variables to define the cross-section of the bridge. The concrete strength (f_{ck}) ranged from 35–100 MPa. Depth *(h)* ranged from 1.25–2.5 meters, the bottom slab width *(b)* ranged from 1.2–1.8 meters, the web inclination width *(d)* ranged from 0–0.4 meters, the web slab thickness *(e_a)* ranged from 0.3–0.6 meters, and the other slab thicknesses *(e_v, e_s, e_i)* ranged from 0.15–0.4 meters.

3.2.Principal component analysis

Principal component analysis (PCA) is a statistical procedure that allows converting a set of possible correlated criteria into a set of linearly independent variables called principal components [16]. This work applied PCA to decrease the eleven original criteria into a set of principal components. This avoided excessively valuing (positively or negatively) some sustainable criteria due to their high correlation.

The first step in PCA is to obtain the total amount of variance in each original criterion that can be explained by the retained principal components (Table 3). This is represented by the communalities after the extraction. Field [32,33] stated that for a sample size higher than 300 the communalities after extraction should be over 50%. The second column of Table 3 shows that all the criteria have communalities greater than 50%.

Table 3. *Communalities*

	Initial	Afer extraction
Cost	1	0.981
Human Health	1	0.949
Ecosystem	1	0.932
Resources	1	0.967
Downtime	1	0.981
Structural safety	1	0.521
User comfort	1	0.937
Concrete amount	1	0.919
Steel amount	1	0.885
Numer of bars	1	0.684

Table 4 shows the total amount of variance that can be explained by each principal component. The first principal component is the one that explains the greatest variability of the analysis. The second one has the second greatest variability explained, and so on. In this case, the first principal component explained 50.24% of the analysis, the second explained 22.73%, and the third one 14.58%, adding to a total of 87.55%. There are two different approaches to determine the number of principal components to consider. On the one hand, Kaiser [34] stated that all the principal components that have an eigenvalue higher than one should be considered. On the other hand, the number of principal components that should be considered are those that explains more than a specific portion of the analysis variability. In this case, the first three principal components have eigenvalues higher than one and explain almost 90% of the analysis variability.

Table 4. Total variance explained

Principal component	Initial eigenvalues			Addition of loads to the square of the extraction		
	Total	% of variance	% accumulated	Total	% of variance	% accumulated
1	5.024	50.236	50.236	5.024	50.236	50.236
2	2.273	22.734	72.970	2.273	22.734	72.970
3	1.458	14.577	87.547	1.458	14.577	87.547
4	0.600	6.001	93.548			
5	0.475	4.753	98.302			
6	0.115	1.146	99.448			
7	0.049	0.495	99.943			
8	0.005	0.049	99.991			
9	0.001	0.008	100.000			
10	0.000	0.000	100.000			

Finally, the correlation between the original criteria and the principal components was obtained. In this way, the value of the first three principal components can be calculated as a linear combination of the original criteria. Table 5 shows the principal component matrix, in which the correlations between all the original variables on each principal component are displayed. Authors [32] stated that significant loadings are those with a correlation higher than 0.4, and loadings smaller than 0.4 can be excluded.

Table 5. Principal component matrix

	Component		
	1	2	3
Cost		0.937	
Human Health	0.893		
Ecosystem	0.818		
Resources	0.960		
Downtime		0.927	
Structural safety	-0.602		
User comfort	-0.879		
Concrete amount	0.792		-0.531
Steel amount	0.811		
Numer of bars			0.690

3.3.Kriging optimization

The purpose of metamodels is to build an approximate mathematical model of a detailed simulated model, which predicts the objective response from the design variables in the design space. Once the approximate mathematical model is established, all the calculations made using metamodels are much more efficient than using the detailed simulated model. Penadés-Plà et al. [19] compare a conventional heuristic optimization against a kriging model-based heuristic optimization using a simulated annealing algorithm and show that the time reduction using the kriging-based heuristic optimization is greater than 90% compared to conventional heuristic optimization. In addition, most of the time consumed by the kriging-based heuristic optimization was due to the calculation of the initial sample size. All while reaching solutions similar to the conventional heuristic optimization. A longer description of the kriging metamodel can be found in Kleijnen [35], where the corresponding mathematical development is also explained.

The objective of this work is to study the influence of the uncertainty in the decision-making problems and to obtain the sustainable alternatives that best represent the different perspectives of sustainability. For this purpose, an optimization problem that represents the most sustainable bridge according to different perspectives of sustainability was proposed. The most sustainable bridge was defined as an aggregation index (*sustainability index*) in which different relative weights were assigned to each principal component (that is correlated to the original variables), as shown in Equation 4. In this way, the most sustainable bridge according to each perspective can be obtained. In this work, 1000 random different perspectives were generated. Therefore, 1000 different optimization problems were defined and carried out. Due to the high computational cost required to cover all these optimizations, the kriging model is the best option due to its high computational efficiency.

$$I = w_1.PC_1(x_{1,}x_{2,} \dots., x_n) + w_2.PC_2(x_{1,}x_{2,} \dots., x_n) + w_3.PC_3(x_{1,}x_{2,} \dots., x_n) \qquad (4)$$

$$g_j(x_1, x_2, x_3, \dots, x_n) \leq 0 \qquad (5)$$

where $x_1, x_2, x_3, .., x_n$ are the design variables.

A total of 1000 random relative weight sets (w_1, w_2, w_3) were generated. Each of these relative weight sets provided a different sustainability index for each bridge in the initial sample size (a different objective response for each bridge) according to Equation 4, and therefore a different kriging surface. Thus, the optimization of each of these relative weight sets gives the most sustainable bridge according to each relative weight set. Hence, this optimization aims to obtain the most sustainable bridge (Equation 4) satisfying the constraints (Equation 5) that guarantee the limit states of serviceability and ultimate limit states (SLS and ULS) of vertical shear, longitudinal shear, punching shear, bending, torsion, torsion combined with bending and shear, cracking, compression and tension stress, and vibration. In addition, the geometric and constructability requirements are verified, following the Spanish regulations for this type of structure [36,37] as well as the

Eurocodes [38,39]. In this way, a total of 1000 sustainable box-girder pedestrian bridge designs were obtained according to 1000 different perspectives of sustainability.

3.4.Multi-attribute decision-making

Once the set of sustainable bridges are obtained, the decision-makers must choose one according to their preferences. Many MADM methods have been developed [8,10]. The pairwise comparison methods are popular because of their simplicity to convert subjective assessment into numerical values. In this group, the *analytical hierarchy process* (AHP) and the *analytical network process* (ANP), are the most used. The main difference between both MADM methods is that the ANP method considers the influence between criteria. In this case, due to the independence of the principal components, the use of the ANP method made no sense, and the AHP method was considered valid for the study. The AHP method was developed by Saaty in the 1970s [40], becoming one of the most popular decision-making methods due to its ease of use. Many works have used the AHP method for different decision-making problems [6,7,41]. To build the hierarchical structure, it is necessary to use a lower number of criteria since pairwise comparison can become difficult. Bahurmoz [42] stated that the maximum number of criteria must be seven, and Miller [43] stated that the number of criteria assimilable by people is 7±2. In this work, three principal components that represent all the criteria of sustainability are considered, so the AHP method is absolutely valid for this study. The relative weight of each principal component is obtained using the pairwise comparison. Saaty [18] proposed a fundamental scale to carry out the comparison among the different criteria (Table 6). After this scale, new scales were made by other authors.

Table 6. Saaty's fundamental scale

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	One activity is slightly favored over another
5	Strong importance	One activity is strongly favored over another
7	Very strong importance	One activity is very strongly favored over another
9	Extreme importance	One activity is the highest favoring over another

Once the decision-maker has made the pairwise comparisons, the consistency of the decision-making matrix is evaluated. This is made to spot contradictions in the decision-maker's assessment. The consistency is obtained by means of the *Consistency Index, CI* (Equation 6), where λ_{max} is the maximum eigenvector and N is the dimension of the decision-making matrix. A consistency index of 0 means a full consistency. After that, the *Consistency Ratio,* CR (Equation 7) is calculated, with acceptable values under 10%.

$$CI = \frac{\lambda_{max} - n}{n-1} \qquad (6)$$

$$CR = \frac{CI}{RI} \qquad (7)$$

Once the consistency is verified, the weights for each criterion of this decision-making matrix are obtained (Equation 7).

$$A \cdot w = \lambda_{max} \cdot w \qquad (8)$$

The pairwise comparison explained above refers to only one decision-maker's assessment. If different decision-makers take part in the same decision-making problem, each decision-maker will create a different decision-making matrix that generates different relative weights for the criteria, and consequently a different final sustainability index, which causes the selection of a different alternative. This work studies how this uncertainty affects different samples in the same decision-making problem. For this purpose, 1000 random decision-makers have been generated to account for all the different preferences of the decision-makers.

4. RESULTS

The procedure described in Section 3 leads to a set of solutions, which are chosen independently of the decision-maker preferences. These solutions are the most sustainable bridges according to the initial criteria considered. In this way, it is possible to reduce a large set of solutions to the most sustainable solutions, making the final selection by the decision-maker easy. In addition, independent of the final decision of the decision-maker, the bridge chosen will be a sustainable bridge. In this work, an initial set of 500 box-girder pedestrian bridges were generated by LHC. After that, a large set of sustainable bridges that cover all the perspectives of sustainability was obtained using PCA and kriging-based optimization. Finally, 1000 random decisions were generated using the AHP method, and each of these decisions leads to one bridge according to the preferences. This process allows reducing the first 500 random box-girder pedestrian bridges to four solutions that are considered the most sustainable box-girder bridge independent of the preferences of the decision-maker (Tables 7 and 8). Therefore, these solutions are the bridges that represent the different points of view of decision-makers within the best sustainable bridges. So, within the set of the most sustainable solutions, *Solution 3* is the bridge with the best safety security, comfort and lowest number of bars, *Solution 4* is the bridge with the best cost and environmental impact. *Solution 1* and *Solution 2* are intermediate solutions between *Solution 3* and *Solution 4.*

Table 7. *Variables of sustainable solutions*

	b	h	d	ev	es	ea	ei	fck	t
Solution 1	1200	1400	25	150	150	350	150	70	150
Solution 2	1200	1300	150	150	150	375	225	60	225
Solution 3	1200	1350	25	175	175	350	150	70	150
Solution 4	1200	1400	0	150	150	350	150	60	150

Table 8*. Criteria of sustainable solutions*

	Cost	Human health	Ecosystem	Resource	Downtown	Structural safety	User comfort	Concrete amount	Steel amount	Number of bars
Solution 1	179501.50	6438.11	2656.96	8831.23	120	1.209	1.939	199.11	36857.14	54
Solution 2	175467.78	5984.93	2484.44	8207.72	120	1.183	1.929	213.05	32587.36	53
Solution 3	184497.31	6733.70	2743.11	9161.72	120	1.213	1.939	201.98	40197.11	52
Solution 4	170393.64	5870.69	2463.36	8173.19	120	1.200	1.938	198.45	30925.46	64

In addition, each box-girder pedestrian bridge will have 1000 different *sustainability indices* according to the 1000 random decision-makers. Therefore, it is possible to obtain some statistical parameters (the mean, the standard deviation, and the coefficient of variation) of the sustainability index for each bridge according to the different perspectives of the decision-maker. These statistical parameters will provide useful information about the influence of the decision-maker's preferences on the final sustainability value. On the one hand, the mean *sustainability index* represents the mean sustainability assessment of all the decision-makers. Thus, a lower mean value means that the general satisfaction of the decision-makers is higher. On the other hand, the coefficient of variation represents the stability of the solution against the different perspective of decision-makers. Thus, a lower coefficient of variation means that there is a higher consensus on the *sustainability index,* which means that, regardless of the decision-maker's preferences, the *sustainability index* varies little.

In this way, it may be possible that one bridge has a good mean sustainability index but may not be the best for some decision-makers, while another bridge that has a higher mean sustainability index, may be chosen by some decision-makers. Tables 7 and 8 show the variables and criteria of the solutions that were chosen for at least one decision-maker and Table 9 shows their position according to the mean sustainability index. Solution 1 and Solution 2 also appear in the top four solutions according to the mean sustainability index. Conversely, Solution 3 and Solution 4, while preferred for some decision-makers, have a mean *sustainability index* higher than other solutions that were not chosen for any decision-maker. For example, *Solution A* has the third best mean sustainability index, but it has not been chosen by any decision-maker as the preferred solution. In addition, a low coefficient of variation shows that the sustainability assessment of that bridge design is less sensitive to a decision-maker's opinion. For example, *Solution B* has a high mean sustainable index, but its coefficient of variation is the lowest one.

Table 9. *Statistical parameters of sustainable solutions*

	General sustainable assessment		Stability of the sustainable assessment	
	Mean	Position	σ	CV
Solution 1	0.061	2	0.035	57.20%
Solution 2	0.048	1	0.018	37.66%
Solution 3	0.081	6	0.057	69.88%
Solution 4	0.072	5	0.040	56.53%
Solution A	0.066	3	0.023	34.69%
Solution B	0.681	69	0.137	20.17%

The box-girder pedestrian bridge that best satisfies the different preferences of the decision-makers is the bridge with the lowest sustainable index and the lowest coefficient of variation. The absolute positive ideal point is a sustainability index of 0 and a coefficient of variance of 0. However, the solutions with a lower mean sustainability index have a higher coefficient of variation and the solutions with a higher mean sustainability index have a lower coefficient of variation (Figure 7). Therefore, the most appropriate solution, taking into account the mean sustainable index and the coefficient of variation, will be the closest solution to the absolute positive ideal point. This solution will be called the most sustainable robust solution. This solution will have a low mean sustainable index and a low coefficient of variance, which means that stability against the different preferences of decision-makers will be strong. This indicates that the solution has a great sustainable assessment and its assessment is little influenced by the different preferences of the decision-maker. In this work, the most sustainable robust box-girder pedestrian bridge is *Solution* C, whose cross-section variables are b=1.2 m, h= 1.35 m, d=0.15 m, ev=0.15 m, es=0.15 m, ea=0.35 m, ei=0.25 m, and fck=60 MPa. This solution is shown with an arrow in Figure 7 and its distance to the absolute positive ideal is 0.353 (Table 10).

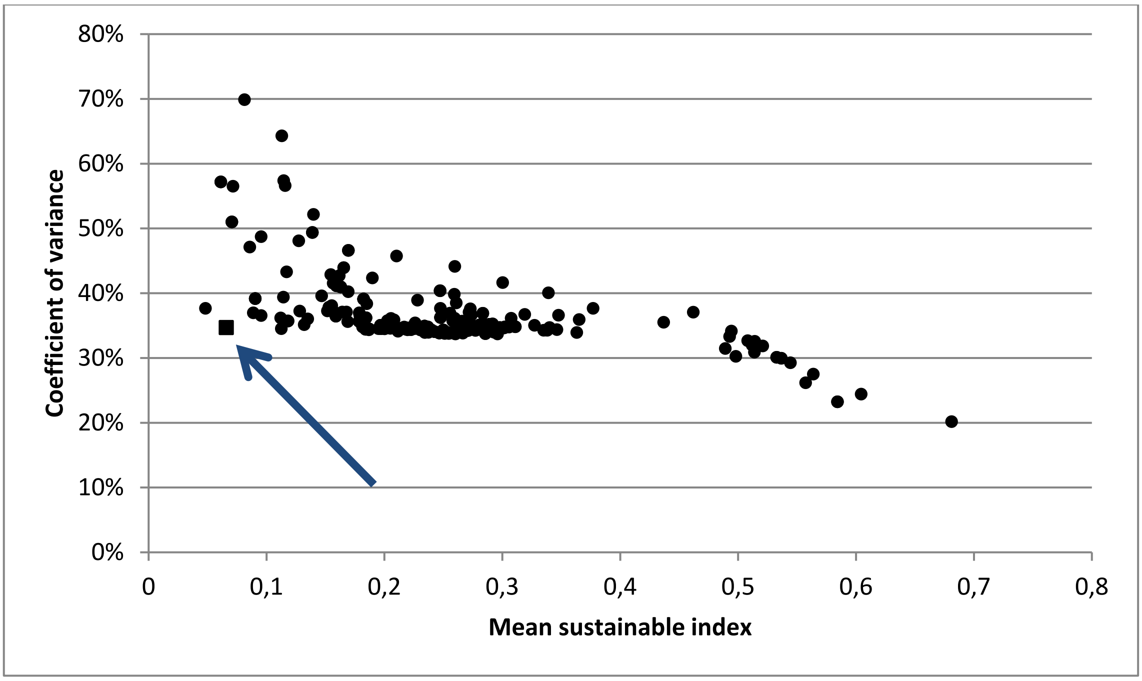

Figure 7. Pareto front of sustainable solutions

Table 10. Sustainable robustness assessment

	General sustainable assessment	Stability of the sustainable assessment		Distance	
	Mean	σ	CV	Distance	Position
Solution 1	0.061	0.035	57.20%	0.575	168
Solution 2	0.048	0.018	37.66%	0.380	7
Solution 3	0.081	0.057	69.88%	0.704	191
Solution 4	0.072	0.040	56.53%	0.570	167
Solution C	0.066	0.023	34.69%	0.353	1

5. CONCLUSIONS

In the construction sector, there is a current trend towards improving sustainability performance due to the great impact of structures in the economic, environmental and social context. However, sustainability assessment is a complex process that involves a large number of alternatives, criteria, and decision-makers who make a subjective assessment of the importance of the different criteria according to their perspective or interests. For this reason, this work shows a methodology that can reduce the participation of the decision-maker for the selection of the most sustainable alternative and reduces the sensitivity to the stakeholder's opinion. In this way, the final alternative can be considered a sustainable solution regardless of the interests of the decision-maker.

This methodology has been applied for the selection of a box-girder concrete pedestrian bridge considering its entire life cycle assessment. To this end, a set of criteria representing the sustainability goal was first defined and a random set of bridges was calculated. In order to avoid the high correlation of some criteria, PCA was used. Then, kriging-based optimization was applied to reach the most sustainable bridge according to 1000 random relative weights. In this way, all the perspectives of sustainability are covered. Finally, 1000 random decision-makers were generated using the AHP method to select the preferred bridges according to the different preferences. Each of these random decision-makers chose the most sustainable bridge according to their interests, reducing the set of eligible alternatives.

After this process, the 500 alternatives of the initial sample were reduced to four sustainable alternatives. In this way, the participation of the decision-maker was reduced to a choice between four alternatives that will be always sustainable. These four alternatives were the safest and most comfortable alternative (*Solution 3*), most economical and environmentally friendly (*Solution 4*), and intermediate alternatives between the first two (*Solution 1 and Solution 2*). In addition, the results show the alternatives that have the best mean sustainability index and those that are more stable against the preferences of decision-makers, which mean that they are more robust. This turns the decision-making process into an objective process in which the final solution does not depend on the preference of a decision-maker. A solution can have a good mean assessment while it is not chosen by any decision-maker (*Solution A*) or it is very stable against the different assessments of the decision-makers (*Solution B*). Finally, the most robust solution was obtained (*Solution C*). Comparing this solution with the most economical solution, this solution is 3.37% more expensive than the most economical solution (*Solution 2*), and the environmental impact is also a little greater (2.85% for Human Health, 2.85% for Ecosystem and 1.83% for Resources) and similar comfort (0.19% better) and structural safety (0.12% worse). In addition, the number of bars used is 16.36% lower, which improves workability. Therefore, the selected solution is optimal regarding the life-cycle sustainability criteria and it is robust against the stakeholder's opinion.

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