02-015 – Multi-objective optimization of prestressed slab bridges using the CRITIC-MCDM approach – Optimización multiobjetivo de puentes de losa pretensada mediante el enfoque CRITIC-MCDM

Yepes-Bellver, Lorena[1]; *Alcalá, Julián*[1]; *Yepes, Víctor*[1]
(1) ICITECH-Universitat Politècnica de València

Spanish Spanish

The paper establishes a methodology for selecting the best design of a prestressed slab bridge by applying the CRITIC multi-criteria decision-making method (MCDM) to a set of solutions obtained by Latin hypercube sampling, including the optima of each objective function. The objective functions are the cost, CO_2 emissions, and energy required to construct a prestressed slab bridge. This methodology allows the establishment of a metric on which to plot a response surface that identifies the areas where the design variables allow the three objective functions to be reduced. In addition, the CRITIC method applied to the Pareto frontier of the solutions is analyzed, and the robustness of the best option is studied as a function of its distance from the ideal point using three Minkowski metrics. The results obtained show the consistency in the selection of the best solution.

Keywords: *Bridges; Decision-making; Optimization; CRITIC, sustainability*

El trabajo establece una metodología para seleccionar el mejor diseño de un puente de losa pretensada aplicando el método CRITIC de toma de decisiones multicriterio a un conjunto de soluciones establecidas mediante un muestreo por hipercubo latino que incluye los óptimos de cada función objetivo. Las funciones objetivo son el coste, las emisiones de CO_2 y la energía necesaria para construir una losa aligerada como paso superior. Esta metodología permite establecer una métrica sobre la que representar una superficie de respuesta que identifique las zonas donde las variables de diseño permiten reducir las tres funciones objetivo. Además, se analiza el método CRITIC aplicado a la frontera de Pareto de las soluciones y se estudia la robustez de la mejor opción en función de su distancia al punto ideal mediante tres métricas de Minkowski. Los resultados obtenidos indican la consistencia en la selección de la mejor solución.

Palabras claves: *Puentes; Toma de decisiones; Optimización; CRITIC; Sostenibilidad*

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1. Introducción

The Sustainable Development Goals (SDGs) in the 2030 Agenda promote a paradigm shift to maximize benefits and minimize adverse impacts across economic, environmental, and social dimensions. Sustainable practices are essential given the construction sector's significant economic and environmental footprint (Schmidt & Osebold, 2017; Huang et al., 2020).

Sustainability research spans infrastructure types—retaining walls (Zastrow et al., 2017), road pavements (Ozcan-Deniz & Zhu, 2015; Torres-Machi et al., 2017), rail tracks (Pons et al., 2020), and buildings (Sánchez-Garrido & Yepes, 2020)—but recent studies focus on bridges. As vital transport network elements, bridges require sustainable design and maintenance for safety and serviceability. Evaluations typically address economic, social, and environmental sustainability, though social aspects remain underexplored (Sierra et al., 2016; Pellicer et al., 2016; Navarro et al., 2024). Achieving balance among these dimensions requires structured decision-making, incorporating life-cycle assessments (Wass et al., 2014).

Balali et al. (2014) categorized decision-support systems for bridge engineering into three life-cycle phases: planning and design, construction, and operation and maintenance, aligning with Dutil, Rousse, and Quesada (2011). Bridges, key transport infrastructure, contribute significantly to CO_2 emissions, necessitating impact assessments for construction and maintenance. Economic sustainability emphasizes cost optimization (Carbonell, González-Vidosa & Yepes, 2011; Sabatino, Frangopol & Dong, 2016), while environmental analyses explore bridge geometries (García-Segura, Yepes & Frangopol, 2017) and maintenance strategies (Navarro, Yepes & Martí, 2019). Comparative studies assess life-cycle environmental impacts (Hammervold, Reenaas & Brattebø, 2013).

Sustainability assessments require individual and integrated analyses of all three dimensions. Given inherent trade-offs (Salas & Yepes, 2020), Multi-Criteria Decision-Making (MCDM) methods are essential for infrastructure sustainability evaluation (Cinelli, Coles & Kriwan, 2014), integrating diverse data, stakeholder preferences, and uncertainties (Zavadskas et al., 2016; 2016b). Literature reviews highlight MCDM's increasing adoption in civil engineering (Zavadskas et al., 2016; Jato-Espino et al., 2014), though its application to sustainable infrastructure remains recent.

Zavadskas et al. (2018) and Navarro, Yepes, and Martí (2019) examined MCDM in sustainable infrastructure, noting a surge in research since 2015, coinciding with SDG adoption. However, bridge design applications remain limited (Penadés-Plà et al., 2016). This study addresses this gap by reviewing MCDM applications in sustainable bridge design, analyzing sustainability dimensions, and identifying knowledge gaps for achieving SDG 9.

Decision-making in sustainable bridge design involves various methodologies. Hwang and Yoon (1981) classified MCDM approaches into Multiple Attribute Decision-Making (MADM) and Multiple Objective Decision-Making (MODM). MADM ranks discrete alternatives using expert-assigned weights, while MODM generates a Pareto front of optimal solutions, enabling trade-off selection.

Traditional methods struggle with real-world bridge complexities (Liou & Tzeng, 2013). Sustainable bridge engineering requires extensive data management and stakeholder integration. Hybrid MCDM models, combining multiple approaches, offer promising alternatives (Liou, 2013; Tzeng & Shen, 2017).

Unlike single-objective optimization, multi-objective approaches optimize conflicting criteria, requiring trade-offs. Pareto-optimal solutions balance objectives without compromising others (Osyczka, 1985). Sustainable bridge design necessitates identifying such trade-offs to achieve balanced outcomes.

This study contributes to sustainable bridge design by systematically evaluating sustainability dimensions and CRITIC decision-making technique. It reviews methodologies and identifies future research directions to enhance infrastructure sustainability and support SDG 9.

2. Objectives

This study aims to enhance the sustainability assessment of prestressed concrete slab bridges through MCDM techniques, integrating advanced metamodeling approaches to optimize bridge design while balancing economic, environmental, and structural efficiency considerations.

The first objective is to develop an integrated multi-criteria optimization framework by combining Kriging-based surrogate modeling with the CRITIC technique, ensuring a systematic evaluation of design alternatives. This framework aims to balance cost, CO_2 emissions, and embedded energy, aligning with sustainability principles and providing a structured approach to decision-making in bridge engineering.

The second objective is to identify key design parameters for sustainable bridge solutions by determining optimal slab depth, concrete grade, and reinforcement configurations. These parameters will be analyzed to enhance structural efficiency while minimizing environmental impact, providing quantitative insights into trade-offs between material consumption, emissions, and cost.

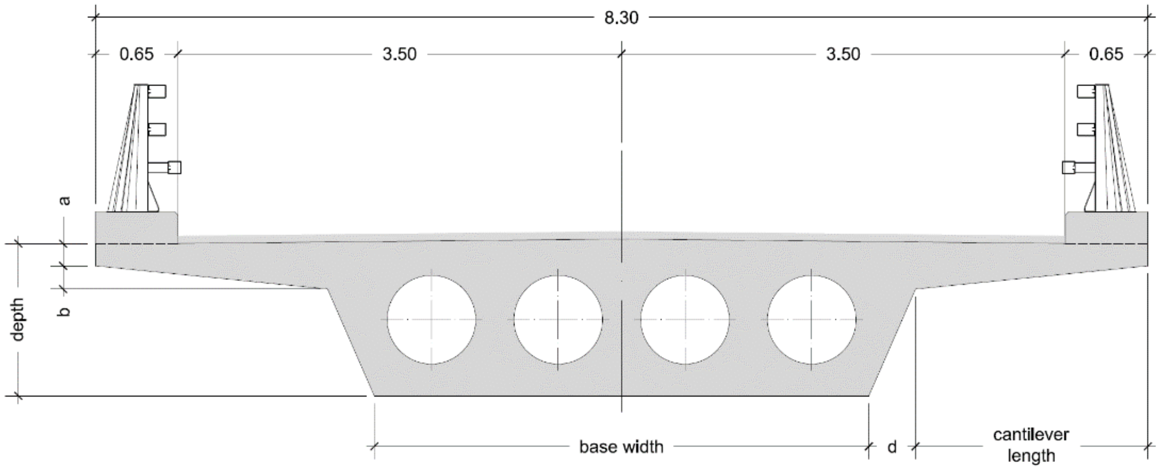
The third objective is to validate the effectiveness of multi-criteria decision-making in bridge engineering by applying the proposed methodology to a real-world case study of a post-tensioned road flyover. The robustness of the selected design solutions will be assessed through Pareto front analysis, ensuring their practical feasibility and applicability for future infrastructure projects.

3. Case study

3.1 Post-tensioned road flyover description

This study optimizes voided slab decks for in situ post-tensioned road overpasses with spans of 24-34-28 m, totaling 86 m. The design features a constant-depth slab with a straight profile and an 8.30 m deck width, accommodating two 3.50 m lanes, 0.65 m barriers on both sides, and an integrated pedestal. This configuration is standard in two-lane dual carriageways, enhancing structural efficiency (see Figure 1).

Figure 1: Cross-sectional view of the voided gull wing PC slab bridge deck.



The bridge is at kilometer 441 of the A-7 motorway in Cocentaina, Alicante. It has a 4.00 m base width, 1.35 m depth, and 1.75 m lateral cantilever. Key dimensions include *a* = 0.20 m, *b* = 0.10 m, and *d* = 0.40 m. The internal voids consist of four circular cylinders (0.60 m diameter each), yielding a void volume of 0.14 m^3/m^2. Figure 2 shows the overpass.

Figure 2: Cross-sectional view of the voided gull wing PC slab bridge deck.

The passive steel B-500S includes longitudinal and transverse reinforcement. Longitudinal bars form the deck's base, improving bending and torsion resistance. Reinforcement covers 70% of the span and 15% above piers.

Structural constraints follow Eurocode 2 serviceability and ultimate limit states, considering Eurocode 1 actions, including 44 kN/m dead loads and exposure class XC4. Checks include bending, shear, torsion, combined effects, compression, tension, cracking, vibration, constructability, and geometry.

This study used CSiBridge 21.0.0 to create a three-dimensional structural model. Various designs were assessed to evaluate sectional stresses derived from applied loads. The sectional design approach identified stress resultants per section, analyzing acting and resisting stresses per force calculations in Yepes-Bellver et al. (2022, 2023, 2025).

3.2 Objective funcions

Slab deck construction involves economic and sustainability costs, including CO_2 emissions and embedded energy, linked to concrete grade, steel quantity, formwork, and voids. These factors were analyzed using BEDEC unit costs, a widely recognized database used by national contractors for realistic cost analysis. Variations do not affect methodology applicability. Unit costs are weights in the objective function, multiplying each element's measurements. Table 1 presents costs for emissions, energy consumption, and total cost (Yepes-Bellver et al., 2022; 2023; 2025).

Table 1: Economic and sustainable unit costs of the deck.

Deck unit	Unit	Cost (EUR)	CO_2 (kg)	Energy cost (MW·h)
C-30 concrete	m^3	99.81	227.01	596.91
C-35 concrete	m^3	104.57	263.96	612.22
C-40 concrete	m^3	109.33	298.57	646.61
C-45 concrete	m^3	114.10	330.25	681.00
C-50 concrete	m^3	118.87	358.97	715.39
Steel reinforcement	kg	1.16	3.03	10.44
Steel prestressed	kg	3.40	5.64	12.99
Voids	m^3	99.81	604.42	1137.50
Formwork	m^2	33.81	2.24	8.70

4. Methodology

This section examines the CRITIC approach from MCDM to develop an indicator integrating cost, carbon emissions, and embedded energy to identify a trade-off solution. The methodology balances cost, CO_2 emissions, and embedded energy in bridge design.

First, Latin Hypercube Sampling (LHS) generates 50 seed decks uniformly distributed across key variables—deck depth, base width, and concrete grade. Each design is analyzed for reinforcement and objective function costs. Kriging generates response surfaces for each objective, ensuring accurate estimates. An additional 1,000 designs are created via LHS, with Kriging predicting values. The Pareto frontier is identified by selecting non-dominated solutions. CRITIC ranks these solutions, determining the final optimal design.

4.1 Latin hypercube sampling

Latin Hypercube Sampling (LHS) ensures uniform distribution by stratifying each variable's range into equal intervals. A random value is chosen per interval, and variables are randomly paired to form input vectors. The process determines the sample number and location. Sample size correlates with the variable count, with larger samples enhancing metamodel accuracy.

4.2 Kriging surrogate model

Metamodel use in structural optimization has increased, particularly with Kriging (Negrín, Kripka & Yepes, 2023). Based on observed data, Kriging estimates a characteristic's value at a given point, allowing output prediction without extensive structural analysis. As a deterministic model, it provides consistent results for identical inputs, free of random error.

Kriging consists of a deterministic trend function and a stochastic residual. Like regression, the trend function defines the general pattern, while the residual captures spatial correlations. The trend is based on known basis functions with coefficients determining the mean. Since Kriging lacks random error, it ensures stable and repeatable outputs for the same input parameters.

4.3 The CRITIC approach

The CRITIC (CRiteria Importance Through Intercriteria Correlation) method (Diakoulaki, Mavrotas & Papayannakis, 1995) assigns greater weight to a criterion based on its variance (higher standard deviation) and its ability to provide distinct information (lower correlation with other criteria). This approach prioritizes criteria that offer unique decision-making insights. CRITIC objectively evaluates criteria importance based on intrinsic properties, enhancing decision-making reliability.

A key feature of CRITIC is its independence from expert opinions, ensuring objective weighting. It analyzes overlap and conflict among criteria, considering measurement value ranges across alternatives via a membership function. Statistical parameters, such as standard deviation, quantify variation, strengthening the weighting process.

First, the decision matrix is normalized, converting all cost criteria into benefit criteria for consistency. In this study, where criteria involve economic or environmental costs, normalization is applied accordingly. The normalization of the matrix is done as:

$$r_{ij} = \frac{x_{Max,j} - x_{ij}}{x_{Max,j} - x_{Min,j}}, \qquad i = 1, \ldots, m \tag{1}$$

$$x_{Max,j} = \max_{i=1,\ldots,m} \{x_{ij}\}, \qquad j = 1, \ldots, n \tag{2}$$

$$x_{Min,j} = \min_{i=1,\ldots,m} \{x_{ij}\}, \qquad j = 1, \ldots, n \tag{3}$$

In the next step, the standard deviation of each criterion is calculated.

$$s_j = \sqrt{\frac{\sum_{i=1}^{m} \left[r_{ij} - \left(\frac{\sum_{i=1}^{m} r_{ij}}{m}\right)\right]^2}{m-1}}, \qquad i = 1, \ldots, m \tag{4}$$

The correlation matrix of the normalized values is constructed using the Pearson correlation coefficient, representing pairwise comparisons between the criteria.

$$R_{jk} = \frac{cov(j,k)}{s_j \cdot s_k}, \qquad j,k = 1, \ldots, n \quad (3)$$

The H_j index is calculated.

$$H_j = s_j \sum_{k=1}^{n} \left(1 - R_{jk}\right), \qquad j = 1, \ldots, n \quad (3)$$

Finally, the weight of each criterion, normalized, is calculated.

$$w_j = \frac{H_j}{\sum_{k=1}^{n} H_k}, \qquad j = 1, \ldots, n \quad (3)$$

A criterion receives a higher weight from these relationships when its variance increases and its correlation with other criteria decreases.

5. Results and discussion

LHS improves space exploration to find locally optimal solutions. Variables analyzed include concrete strength (30–50 MPa), slab depth (1.15–1.70 m), and base dimensions (3.00–5.00 m in 5 cm increments). A 30-sample size has shown favorable results in concrete structures (Penadés-Plà, García-Segura & Yepes, 2019; Mathern et al., 2022). This study used 50 "seed" decks to generate the response surface via Kriging, capturing optimal solutions for cost, carbon emissions, and embedded energy (Yepes-Bellver et al., 2022; 2023; 2025).

These seed solutions formed the basis for a Kriging surrogate model, generating 1,000 additional solutions evaluated for three objectives. The 50 seed decks are real bridges with precise assessments, while the 1,000 generated are Kriging predictions. The analysis identified the Pareto front from all 1,050 solutions. Table 2 lists the Pareto front points, with four decks (#2, #6, #10, #13) as seed solutions and the remaining 18 as predicted.

Table 2: Pareto front decks and assessment of their objective functions.

Deck	Deck depth (m)	Base width (m)	Concrete grade (MPa)	Cost (EUR x 10^3)	CO_2 (kg x 10^3)	Energy cost (MW·h)
2	1.10	3.40	35	181.53	386.51	1151.00
6	1.15	3.35	40	180.21	395.47	1051.00
10	1.15	3.55	40	190.06	391.37	1058.43
13	1.15	3.70	40	182.73	394.62	1038.28
74	1.25	3.10	30	181.98	386.60	1113.46
108	1.43	3.08	35	177.92	413.75	1093.66
185	1.42	3.01	35	176.86	413.60	1099.30
199	1.37	3.03	35	177.20	410.38	1094.46
281	1.24	3.04	45	178.62	416.97	1082.95

The lowest cost solution is #185, the lowest emissions is #475, and #13 is the lowest embodied energy. However, it is necessary to determine if a trade-off solution offers improvements across all three criteria.

When multiple objectives exist, a response surface aggregates them into a single index for trade-off assessment. The CRITIC method avoids subjectivity by determining criterion importance independently of decision-maker preferences. Table 3 shows the weights assigned to each criterion, prioritizing the one with the lowest correlation to the others. Accordingly, carbon emissions are the least correlated criterion in both seed decks and non-dominated solutions, with this effect more pronounced in the latter.

Table 3: Criteria weights for seed decks and the Pareto front applying CRITIC.

	Criteria weights		
	Cost	CO_2	Energy
Seed decks	0,3289	0,3757	0,2954
Pareto front	0.3055	0.4623	0.2322

By plotting the contour plot, the behavior of the response surfaces about the variables defining the solutions can be better visualized. Figure 3 reveals that, among the initial 50 seed decks, the most favorable solutions correspond to a deck depth between 1.15 m and 1.25 m, with a base width between 3.10 m and 3.90 m.

Figure 3: Contour plot of CRITIC-index for seed decks for deck depth and width base.

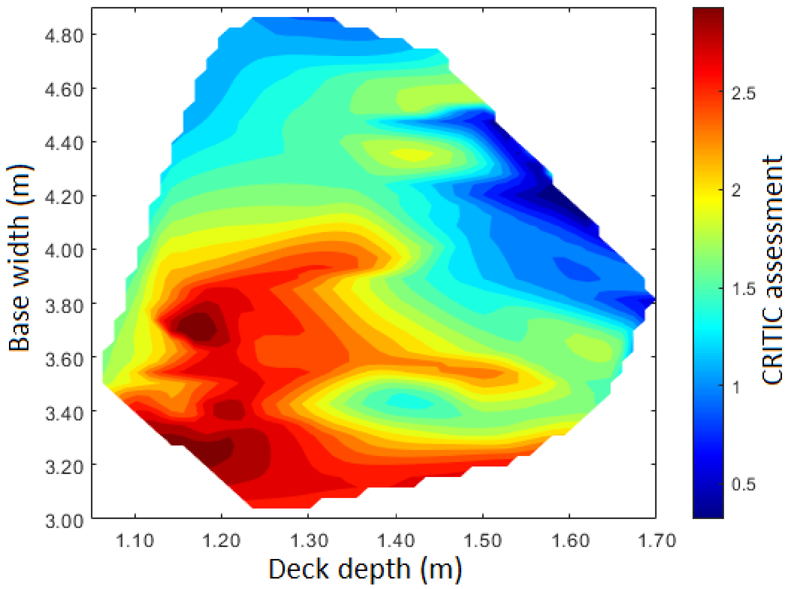


Figure 4 presents the relative scores assigned by the CRITIC method, highlighting Solution #6 as the highest-rated option. Additionally, the figure shows that Solution #13 ranks as the second-best evaluated alternative.

Figure 4: Ranking radar chart for all non-dominated solutions across CRITIC.

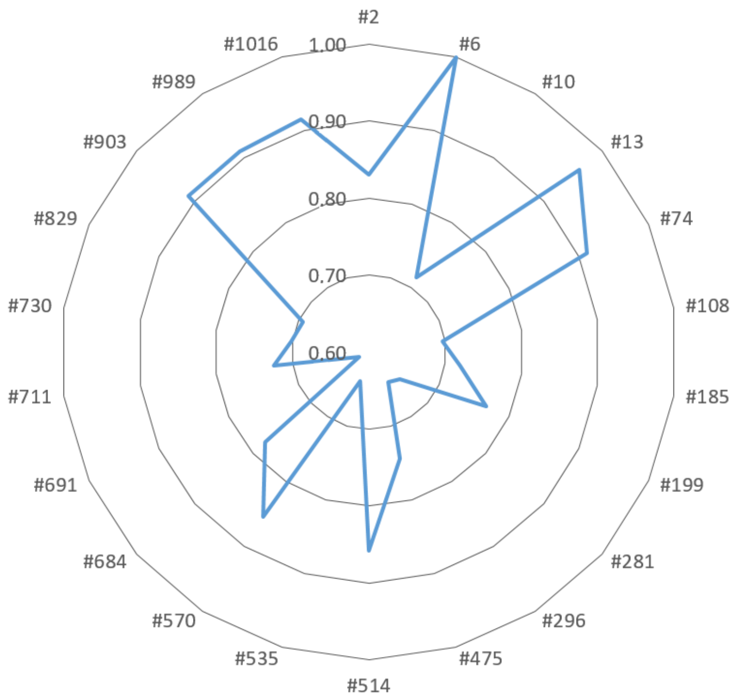


Table 4 presents the measurements corresponding to the reference bridge and the trade-off solutions (#6 and #13). The values for P.25, P.50, and P.75 represent the 25th, 50th, and 75th percentiles, respectively, based on the data reported by Yepes et al. (2009) for this bridge typology. All measurements are expressed per square meter of the bridge deck.

The percentiles presented in Table 4 serve as a helpful reference for determining whether the measurements of the selected solutions fall within or outside the interquartile range. This, in turn, facilitates the identification of notable differences in specific characteristics of these solutions. In this way, the reference deck contains a higher concrete volume, as it exceeds the 75th percentile. In contrast, the trade-off solutions fall slightly below the mean. The active and passive steel reinforcement quantities in the reference bridge are close to the study's median, while in the compromise solutions, both reinforcement quantities exceed the 75th percentile.

Additionally, solutions #6 and #13 exhibit high passive reinforcement, with values above the 75th percentile. In contrast, the opposite trend is observed for active reinforcement, which remains below the 25th percentile in all cases, including the reference deck. Furthermore, all solutions show a formwork surface area exceeding the 75th percentile and a void volume below the 25th percentile.

Table 4: Measurements of the reference deck and trade-off solutions.

Deck	Deck depth (m)	Span/deck depth	Concrete (m^3/m^2)	Passive steel (kg/m^2)	Active steel (kg/m^2)	Formwork (m^2/m^2)	Voids (m^3/m^2)
Reference	1.35	25.19	0.72	73.45	16.64	1.22	0.12
6	1.15	29.57	0.56	71.25	16.48	1.18	0.12
13	1.15	29.57	0.61	69.41	16.65	1.19	0.12
P. 25	1.13	21.74	0.56	57.76	17.99	1.09	0.16
P. 50	1.25	23.33	0.66	65.27	21.99	1.12	0.20
P. 75	1.32	26.39	0.71	69.91	26.85	1.15	0.24

6. Discussions

The Dirección General de Carreteras (DGC, 2000) suggests that the optimal ratio of deck depth to main span should fall between 1/22 and 1/30. At the same time, SETRA (1989) recommends a ratio of 1/28 for three-span concrete decks with wide lateral cantilevers. This study's trade-off decks (#6 and #13) exhibit a depth-to-main span ratio close to 1/30. This slenderness exceeds the 75th percentile of 61 voided slab bridges analyzed by Yepes et al. (2009). On the other hand, the trade-off solutions employ a concrete grade of 40 MPa, which is slightly higher than the 35 MPa used in the lowest-emission solution. However, when cost minimization is the primary objective, the lowest available concrete grade, 30 MPa, is the most economical option.

DGC (2000) recommends that for this type of bridge, the typical concrete volume ranges from 0.55 to 0.70 m³ per m² of deck. Passive reinforcement generally falls between 70 and 100 kg per m³ of concrete, while prestressed reinforcement ranges from 10 to 25 kg per m³ of concrete. Thus, the trade-off solutions reduce concrete volume near the DGC's lower limit but exceed the recommended passive and active reinforcement levels.

From the above analysis, it can be inferred that the trade-off solutions are slender, with a span-to-deck depth ratio close to 30. Additionally, these solutions exhibit a high amount of passive reinforcement, approximately 70 kg/m², while the active reinforcement quantity remains relatively low, around 16.5 kg/m². The construction process requires 1.19 m²/m² of formwork and 0.20 m³/m² of voids. Furthermore, the results indicate that the concrete grade used in the compromise solutions is 40 MPa.

Therefore, when this type of bridge design seeks to integrate environmental variables alongside economic cost, the results indicate a preference for more slender solutions, incorporating slightly more concrete but requiring lower quantities of active and passive reinforcement.

Therefore, the trade-off solutions reduce the concrete volume to a level close to the lower limit of the recommendations established by the DGT (2000). However, increased passive and active steel reinforcement offset this reduction, exceeding the recommended values.

7. Conclusion

The article focuses on multi-criteria optimization in the design of prestressed concrete slab bridges, employing a metamodeling approach. It applies a Kriging model for response estimation and alternative evaluation via the CRITIC technique. CRITIC integrates multiple criteria into a unified decision framework, enabling comprehensive evaluation across economic, environmental, and social dimensions. Findings indicate that optimal solutions feature a slab depth of 1.15–1.25 m, including a slab depth-to-span ratio near 1/30, a 40 MPa concrete grade, and optimized reinforcement, enhancing structural efficiency and balancing cost efficiency, CO_2 reduction, and embedded energy, aligning with sustainability goals. Practical recommendations emphasize stakeholder engagement to incorporate diverse perspectives in decision-making. The findings suggest that balancing sustainability with cost considerations leads to more effective infrastructure solutions. This research advances sustainable bridge design and provides a framework for optimizing future infrastructure projects aligned with global sustainability objectives.

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Use of generative artificial intelligence

Generative artificial intelligence was not used in the preparation of this work.

Communication aligned with the sustainable development goals

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

SUSTAINABLE DEVELOPMENT GOALS