Life-Cycle of Structures and Infrastructure Systems – Biondini & Frangopol (Eds)

Sustainable design of lightened reinforced concrete flat slabs in coastal environment

A.J. Sánchez-Garrido, I.J. Navarro & V. Yepes
Universitat Politècnica de València, Valencia, Spain

ABSTRACT: The construction industry has a significant impact on the environment, particularly in the residential building sector, due to high resource consumption. To reduce environmental impact in the construction, service, and end-of-life phases of buildings, scholars prioritize adopting Modern Methods of Construction (MMC) to optimize material consumption and minimize the life cycle impact of buildings. This study assesses the sustainability of reinforced concrete flat slabs using a hollow structural body system, especially in environments that trigger concrete corrosion. The analysis focuses on seven design alternatives for a beachfront hotel structure, using the VIKOR technique to aggregate five sustainability criteria. The most cost-effective and environmentally beneficial option is using 10% silica fume concrete, which reduces life-cycle costs by 87% and impacts the base design by 67%. However, considering economic and environmental sustainability criteria led to better sustainable designs, such as a more extensive concrete cover for bottom reinforcing bars resulting in a 46% better sustainability index.

1 INTRODUCTION

Around half of the non-renewable resources consumed by humanity come from the construction industry, making it one of the less sustainable sectors in the world (Yepes & Lopez, 2021). If this trend continues, energy efficiency and the transition to renewable energy will no longer be enough. Against this alarming backdrop, the newly established European Green Deal aims to overcome the challenges posed by climate change by, among other objectives, the firm intention of achieving no net greenhouse gas emissions by 2050. The fact that one-third of the investments from the NextGenerationEU Recovery Plan are intended to finance the European Green Deal shows the commitment of the European Commission to achieve climate neutrality. This is only one of the many initiatives slowly trying to materialize the Sustainable Development Goals established in 2015.

In this context, the search for sustainable buildings and other infrastructures arises as a critical requirement to achieve the abovementioned carbon-neutral horizon we aspire to (Lei et al., 2021; Chan et al., 2022). Recently, research has been conducted on the sustainability assessment of several infrastructures (Navarro et al., 2020), building structures (Sánchez-Garrido et al., 2022b) or constructive elements (Pons et al, 2018; Balasbaneh & Marsono, 2020). A conclusion that is recurrently reached in recent research is that the impacts related to the maintenance of buildings and other types of structures play an essential role in the life cycle-related sustainability performance of the designs. Consequently, more and more studies focus on optimizing maintenance activities (Frangopol et al. (2017); García-Segura et al., 2017) or analyzing different material alternatives to increase the durability of conventional designs (Biondini & Frangopol, 2017; Navarro et al., 2018), trying

DOI: 10.1201/9781003323020-300

to reach conclusions on the best practices to achieve sustainable structures and buildings along their service lives.

Such impacts are particularly relevant in aggressive environments, where the maintenance demands can be significant. Such is the case for coastal regions, where concrete structures are affected by chlorides (Petcherdchoo, 2015). Consequently, studies on the performance of different design alternatives in such scenarios are essential to achieve both durable and sustainable solutions.

The present communication aims to evaluate the life cycle impacts of seven improved design alternatives on a particular type of MMC, namely "Unidome" slabs. MMCs are postulated as economically preferable alternatives to conventional construction methods and a powerful way to reduce life cycle environmental impacts by optimizing material consumption. These alternatives are intended to increase the durability of the base design, thereby reducing maintenance requirements over the life cycle of use and maintenance of the structural solution. Several economic and environmental criteria are considered to evaluate each design's sustainability.

2 MATERIALS AND METHODS

2.1 *Goal and scope definition*

This work aims to analyze the sustainable performance of different alternatives based on the reference design for the structure of a hotel building located on the coast of Chiclana, Cadiz (Spain). The reference design (hereafter REF) comprises a module of rooms between expansion joints that, with three floors and repeated longitudinally, represents more than 80% of the built area of the hotel. Structurally, the module consists of a mat foundation and three slab levels (Figure 1), designed with an innovative MMC. The system consists of reinforced concrete flat slabs lightened with hollow structural bodies (hereafter referred to as "Unidome slabs").

One of the attacks that most affect the durability of concrete is the penetration of chlorides from seawater, with varying degrees of severity. The design alternatives considered base their durability strategy on extending the service life of the concrete structure. For this purpose, different response mechanisms against chloride-induced corrosion are used, such as improving the resistance of the concrete to external aggressions, its thickness, the inhibitory protection, or the type of steel. Six alternative designs are analyzed here, along with the REF design, for comparison. Three design options are based on reducing the permeability of concrete. One way is to modify the base mix using cement with 10% silica fume (hereafter, SF-C) or adding admixtures such as 20% fly ash (hereafter, FA-A). Another way is to achieve a very compact and well-vibrated concrete by reducing the water-to-cement ratio from 0.60 in the base mix to 0.50 (W/C alternative). The duration of the protective effect of the concrete on the reinforcement can be extended over time by increasing, at most, the concrete cover from 3 cm in the baseline option to 4.5 cm (CC45 alternative). Applying a hydrophobic corrosion inhibitor impregnation (HCII) to protect the exposed surface of the slabs is also a suitable option. Using corrosion-resistant steels is also an excellent way to increase corrosion durability. In our case, we replaced conventional carbon steel reinforcing bars with galvanized steel reinforcing bars (GSR). Stainless steel is not valued because its cost for building construction is so high that, except in very justified cases, it is economically unsustainable.

In order to compare the life cycle impact assessment, it is necessary to base it on the same functional unit, according to ISO 14040. This analysis considers 1 m^2 built based on a hotel module composed of three levels of rooms and 2132 m^2 built of structure and foundations. To assess the impacts derived from both construction and maintenance activities, a "gate to gate" approach has been considered. Construction and maintenance activities are included for a nominal service life of 50 years, as required by national codes (Fomento, 2008).

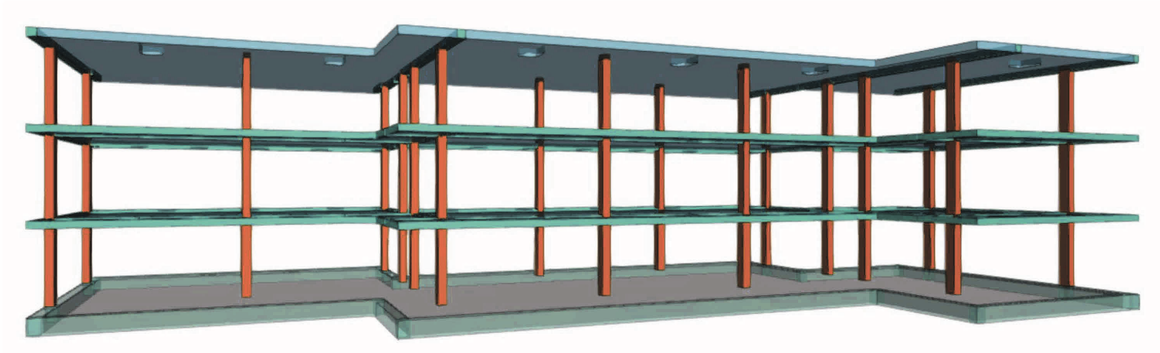

Figure 1. 3D model of the baseline (REF) structure.

2.2 *Reliability-based maintenance requirements*

A deterioration model will be chosen to determine the impact of maintenance on each of the design alternatives to be compared. A durability model has been chosen for chloride corrosion processes versus carbonation since the former is a much faster attack in a marine exposure environment such as the one in question. Concrete deterioration begins when chloride ions penetrate the concrete cover and reach the reinforcing bars at a concentration capable of triggering the steel corrosion process. This concentration is known as the critical chloride content (C_{cr}), whose reach time depends on the properties of the concrete cover. Under normal conditions, a value of 0.6% of the weight of cement is adopted according to the Spanish concrete code. The propagation stage is completed when an unacceptable steel section loss occurs, or cracks appear in the concrete cover. A two-dimensional version of the Fickean model suggested in Fib Bulletin 34 (2006), subsequently refined by Navarro et al. (2019), to evaluate the progression in chloride concentration in concrete as a function of time is used. The chloride concentration C at any time t (in years) and any depth (in mm) in the x and y directions of the analyzed cross-section can be calculated as:

$$C(x,y,t) = C_s\left[1 - erf\frac{x}{2\sqrt{D_{0,x}\cdot\left(\frac{t}{t_0}\right)^{\alpha}\cdot t}}\cdot erf\frac{y}{2\sqrt{D_{0,y}\cdot\left(\frac{t}{t_0}\right)^{\alpha}\cdot t}}\right] \tag{1}$$

where C_s = surface chloride concentration (wt%/binder); $erf(\cdot)$ = the Gaussian error function; D_0 ($x10^{-12}$ m^2/s) is the chloride diffusion coefficient (mm^2/year); α = age factor, assumed 0.5 according to the Spanish codes; t_0 = 0.0767 years (28 days).

Table 1 shows the value of the parameters used to characterize the measures analyzed and the maintenance cycles required during the structure's service life (50 years) according to the durability obtained for each alternative. After each maintenance cycle, the structure is assumed to recover its original state (Stewart et al., 2004).

Table 1. Characterization of the durability of the preventive alternatives studied.

Parameter	REF	SF-C	FA-A	W/C	CC45	HCII	GSR
C_{cement} (kg/m^3)	275	225*	200**	300	275	275	275
C_{cr} (%)	0.6	0.6	0.6	0.6	0.6	0.6	1.2
erf	0.853580	0.931932	0.977853	0.812476	0.869583	0.849931	0.524771
C_s (%)	2.62	3.20	3.60	2.40	2.74	2.62	2.62
x (mm)	30	25	25	30	45	45***	30
D_0 (x10E-12m^2/s)	25	3.4	5	15.8	25	25	25
t (years)	2	36.7	14	6.1	9.4	10.3	14
No. of repairs	25	1.36	3.57	8.20	5.32	4.85	3.57

*+10% Silica fume; **+20 Fly ash; ***effective coating increase 50%

2.3 *Impact assessment*

Two sets of criteria have been considered to assess the impacts generated along the life cycle of each of the design alternatives under study. The first set, containing economy-related criteria, includes two impacts: the costs associated with the construction of the above-described functional unit and the costs associated with the use and maintenance life cycle stage.

The second set of criteria includes the three endpoint assessment criteria associated with the environmental assessment methodology called ReCiPe: damage to human health, ecosystems, and resource availability. ReCiPe methodology converts the emissions of any activity into 18 so-called midpoint indicators, which include impacts such as an increase in various types of diseases (respiratory, cancer, and others), damage to different types of species (terrestrial marine and freshwater), and also the effects of the increasing scarcity of natural resources. These midpoint impacts are then adequately grouped and converted into the abovementioned endpoint indicators. On the one hand, the damage to human health is measured in DALYs, which stands for Disability-Adjusted Life Years. This metric takes into consideration the living years which are lost due to premature death or due to illnesses of different types.

The damage to ecosystems is measured in PDF, which stands for Potentially Disappeared Fraction. It evaluates the species that are potentially lost yearly due to the effects of anthropogenic activities occupying or converting their habitats. In addition, the PAF is also considered to evaluate the impacts on the ecosystems, which stands for Potentially Affected Fraction. This metric measures the percentage of species exposed to unbearable toxic substances. The last assessment criterion is related to the contribution of each of the alternatives under study to the scarcity of natural resources. According to the ReCiPe assessment methodology, this impact considers the energy surplus required to extract mineral resources or fossil fuels.

Finally, the subjective weightings of each criterion are determined using the Analytic Network Process (ANP) through a group of experts (Sánchez-Garrido et al., 2022c). Once the relevance is assigned to each criterion, a distance-based MCDM technique, namely VIKOR, is applied to find the design alternative with the maintenance interval that maximizes the sustainability of the structure's life cycle.

2.4 *Inventory analysis*

The material quantities associated with each alternative will be defined to evaluate the above impacts. The costs are summarized in Table 2 and include materials, labor, equipment and machinery, and direct ancillary costs. The material costs assumed in this analysis have been collected from specific and recognized Spanish construction databases developed by "CYPE Ingenieros", updated to 2022, and specific supplier data.

Table 2. Construction and repair costs considered in LCCA.

Parameters of design alternatives	Cost	Unit
Mat foundation 60 cm (25 Mpa) + steel 60 Kg/m^3	196.22	€/m^3
Concrete slab 25cm (25 Mpa) + steel 104 Kg/m^3	116.76	€/m^3
Concrete slab 30cm (25 Mpa) + steel 73.33 Kg/m^3	112.19	€/m^3
UNIDOME XS-D420 (470)	7.13	€/m^2
UNIDOME XS-120 (150)	6.85	€/m^2
UNIDOME XS-160 (190)	8.56	€/m^2
Mat foundation 60 cm +10% SF* (25 Mpa) + steel 60 Kg/m^3	321.80	€/m^3
Concrete slab 25cm +10% SF* (25 Mpa) + steel 104 Kg/m^3	191.49	€/m^3
Concrete slab 30cm +10% SF* (25 Mpa) + steel 73.33 Kg/m^3	183.99	€/m^3
Mat foundation 60 cm +20% FA** (25 Mpa) + steel 60 Kg/m^3	237.43	€/m^3
Concrete slab 25cm +20% FA** (25 Mpa) + steel 104 Kg/m^3	141.28	€/m^3

(*Continued*)

Table 2. (*Continued*)

Parameters of design alternatives	Cost	Unit
Concrete slab 30cm +20% FA** (25 Mpa) + steel 73.33 Kg/m^3	135.75	€/m^3
Mat foundation 60 cm (30 Mpa) + steel 60 Kg/m^3	219.96	€/m^3
Concrete slab 25cm (30 Mpa) + steel 104 Kg/m^3	121.40	€/m^3
Concrete slab 30cm (30 Mpa) + steel 73.33 Kg/m^3	117.67	€/m^3
Corrosion-inhibiting hydrophobic impregnation	33.81	€/m^2
Galvanizing bath for reinforcing bars + transport <10 km	0.90	€/Kg
Repair of the reinforced concrete slab edge (27cm average)	58.46	€/m
Structural concrete surface preparation, with manual means	43.08	€/m^2
Preparation of the surface of the reinforcement	8.23	€/m^2
Structural repair of concrete with polymer-modified cement mortar	88.78	€/m^2

*SF= Silica fume; **FA= Fly ash

Table 3 presents the different concrete mixes for each design alternative considered in the LCA, both for the construction and use and maintenance phases. The Ecoinvent 3.2 environmental database was used to collect the inventory data for the environmental assessment of each alternative under study.

Table 3. Materials assumed in each design option for the LCA of the construction phase and repair cycles.

Materials (per m^2 of structure)	REF	SF-C	FA-A	W/C	CC45	HCII	GSR
Cement (Kg)	86.14	70.48	62.65	93.97	90.24	86.14	86.14
Water (l)	51.68	50.90	50.90	46.98	54.14	51.68	51.68
Sand (Kg)	213.00	213.00	213.00	213.00	223.13	213.00	213.00
Gravel (Kg)	439.31	439.31	439.31	428.97	460.20	439.31	439.31
Rebar steel B-500S (Kg)	27.52	27.52	27.52	27.52	27.52	27.52	-
HD−PE* (m^3)	2.158E-05	2.158E-05	2.158E-05	2.158E-05	2.158E-05	2.158E-05	2.158E-05
Silica fume (Kg)	-	7.83	-	-	-	-	-
Fly ash (Kg)	-	-	15.66	-	-	-	-
Silane-based impregnation (l)	-	-	-	-	-	0.66	–
Galvanized steel (Kg)	-	-	-	-	-	-	28.48
Trichloroethylene solvent (l)	2.91	0.16	0.42	0.95	0.62	0.56	0.42
Aluminosilicate abrasive (Kg)	101.77	5.55	14.54	33.37	21.65	19.76	14.54
Cement (Kg)	6.11	0.33	0.87	2.00	1.30	1.19	0.87
Cement 75 N/mm^2 (Kg)	313.88	17.11	44.84	102.91	66.78	60.95	44.84
Cement 40 N/mm^2 (Kg)	900.00	49.05	128.57	295.08	191.49	174.76	128.57
Water (l)	191.54	10.44	27.36	62.80	40.75	37.19	27.36

*HD−PE= Recycled high-density polyethylene

3 RESULTS AND DISCUSSION

3.1 *LCCA results*

Figure 2 reproduces the results obtained in the life cycle economic assessment for the seven design options analyzed. It includes the costs associated with construction per square meter of structure and those related to maintenance over 50 years. Repair costs are calculated based on the reactive maintenance cycles required for each alternative, depending on the strategy adopted to extend the structure's service life.

The lower construction cost is attributed to the REF option because it is the baseline option that does not incorporate any preventive strategy. This economic reading will be distorted if the whole life cycle is not considered. By incorporating the maintenance phase, the total cost becomes a ruin by requiring 25 repairs in 50 years. However, designs such as W/C and CC45, with minimum increases of 6% over the reference cost, achieve a drastic reduction in repair frequency and, therefore, the maintenance cost of 68% and 75%, respectively.

Finally, the design option based on silica fume cement (SF-C) resulted in the lowest life-cycle costs, followed by adding fly ash (FA-A) and galvanized reinforcing bars. Their results represent cost reductions of 87%, 80%, and 79%, respectively, over the total economic impact associated with the reference design.

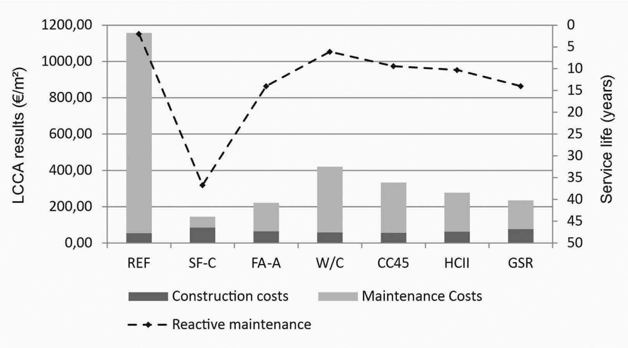

Figure 2. Results of the Life Cycle Cost Assessment (LCCA).

3.2 *LCA results*

The impacts resulting from the environmental life cycle assessment of the six alternative designs are presented in Figure 3. The endpoint approach has been adopted with three oriented damage indicators: human health, ecosystems, and availability of natural resources. The graphs highlight the most relevant environmental impacts affecting human health, followed by resource depletion, which is very similar in all the alternatives analyzed, except in the case of the REF, which is disproportionate. The options with silica fume (SF-C) and fly ash (FA-A) added to the concrete mix provide the best environmental performance by reducing REF impacts by 67% and 60%, respectively. In general, it is concluded that the greater the durability of the preventive maintenance strategy, the lower the frequency of reactive maintenance, which will reduce the resulting impact on the environment.

3.3 *LCCA-LCA sustainability assessment*

The relevance of each criterion was obtained through an expert seminar to evaluate the sustainability of each design presented. Table 4 shows the weights assigned by the group to each of the five impact categories defined.

From the obtained crisp weights, the VIKOR technique (Sánchez-Garrido et al., 2022a) is applied to aggregate the five different impact categories into a single sustainability score ($0 \leq Q_j \leq 1$) for each design option to be compared. In this case, Q_j is better the closer to 0. Figure 4 shows the results for each design alternative, considering the interval in years leading to the

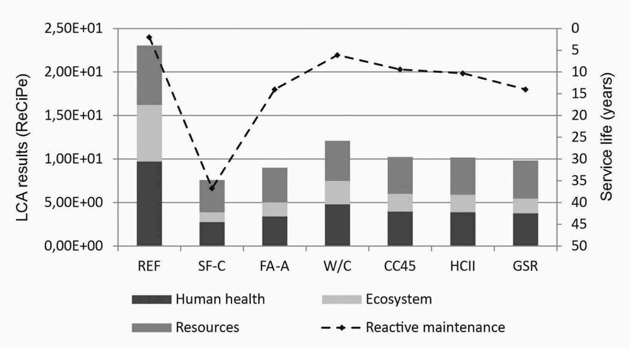

Figure 3. Results of the Life Cycle Assessment (LCA).

Table 4. Results of the weighting of criteria.

Criteria	Definition	Weight
C1	Construction Costs	0.1971
C2	Service life Costs	0.1529
C3	Human health impact	0.3059
C4	Ecosystem impact	0.0986
C5	Resources	0.2455

first maintenance and, therefore, to the repair of the cover concrete to prevent the propagation of corrosion in the reinforcement.

From a sustainability standpoint, the optimal preventive maintenance design is CC45, with an overall score of 98.3%, followed closely by FA-A with 97.6% and HCII with 95.7%. It is worth noting that the SF-C alternative, which was the best in the LCA and LCA, obtained an intermediate performance in the final sustainability evaluation, with a discrete 67.1%. On the other hand, design strategies that did not stand out in the individual evaluations have turned out to have superior performance when aggregated into a sustainability score. This has been the case for the CC45 and HCII alternatives, first and third in the ranking, with virtually equal maintenance intervals. Only FA-A, second in the ranking, has performed well economically and environmentally.

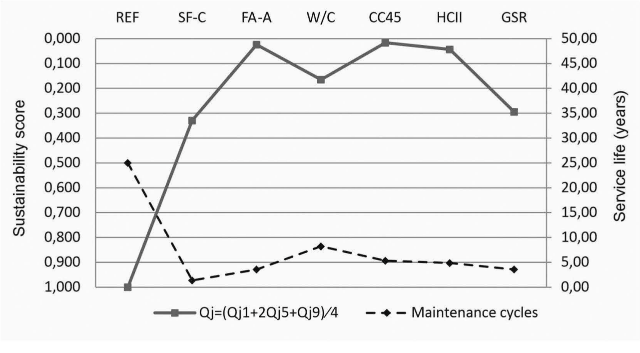

Figure 4. Results of the Sustainability Life Cycle Assessment.

4 CONCLUSIONS

The present communication shows the different durability performances over the life cycle of a concrete structure, based on MMC, exposed to aggressive environments. Several alternatives are evaluated that base the durability strategy on using different base concrete mixes, increasing the bottom cover of the slab with corrosion inhibitor impregnation, and substituting the type of reinforcing steel.

From the results, the evaluation of economic and environmental impacts by a one-dimensional life cycle analysis does not guarantee that a design is optimal from a sustainability point of view. Sustainability is a complex issue that tries to solve a multi-criteria decision-making problem, so it must be approached from a holistic perspective, simultaneously considering all the dimensions involved in the evaluation associated with the design of the structure.

ACKNOWLEDGEMENTS

Grant PID2020-117056RB-I00 funded by MCIN/AEI/ 10.13039/501100011033 and by "ERDF A way of making Europe". The authors would also like to thank the companies that provided some of the data and information necessary for this study (UNIDOME Deutschland GmbH).

REFERENCES

Balasbaneh, A.T. & Marsono, A.K.B. 2020. Applying multi-criteria decision-making on alternatives for earth-retaining walls: LCA, LCC, and S-LCA. *International Journal of Life Cycle Assessment* 25: 2140–2153.

Biondini, F. & Frangopol, D.M. 2017. Time-variant redundancy and failure times of deteriorating concrete structures considering multiple limit states. *Structure and Infrastructure Engineering* 13(1): 94–106.

Chan, M., Jin, H., van Kan, D. & Vrcelj, Z. 2022. Developing an innovative assessment framework for sustainable infrastructure development. *Journal of Cleaner Production* 368: 133185.

Frangopol, D.M., Dong, Y. & Sabatino, S. 2017. Bridge life-cy-cle performance and cost: analysis, prediction, optimisation and decision-making. *Structure and Infrastructure Engineering* 13(10): 1239–1257.

Fib. Fib Bulletin 34: Model Code for Service Life Design. Fib, Lausanne, 2006.

Fomento. 2008. EHE-08 Instrucción del Hormigón Estructural.

García-Segura, T., Yepes, V., Frangopol, D.M. & Yang, D.Y. 2017. Lifetime reliability-based optimization of post-ten-sioned box-girder bridges. *Engineering Structures* 145: 381–391.

Lei, H., Li, L., Yang, W., Bian, Y. & Li, C-Q. 2021. An analytical review on application of life cycle assessment in circular economy for built environment. *Journal of Building Engineering* 44: 103374.

Navarro, I.J., Yepes, V., Martí, J.V. & González-Vidosa, F. 2018. Life cycle impact assessment of corrosion preventive designs applied to prestressed concrete bridge decks. *Journal of Cleaner Production* 196: 698–713.

Navarro, I.J., Martí, J.V & Yepes, V. 2019. Reliability-based maintenance optimization of corrosion preventive designs under a life cycle perspective. *Environmental Impact Assessment Review* 74: 23–34.

Navarro, I.J., Yepes, V. & Martí, J.V. 2020. Sustainability assessment of concrete bridge deck designs in coastal environments using neutrosophic criteria weights. *Structure and Infrastructure Engineering*, 16 (7): 949–967.

Petcherdchoo, A. 2015. Environmental impacts of combined repairs on marine concrete structures. *Journal of Advanced Concrete Technology* 13(3): 205–213.

Pons, J.J., Penadés-Plà, V., Yepes, V., & Martí, J.V. 2018. Life cycle assessment of earth-retaining walls: An environmental comparison. *Journal of Cleaner Production* 192: 411–420.

Sánchez-Garrido, A.J., Navarro, I.J. & Yepes, V. 2022a. Multi-criteria decision-making applied to the sustainability of building structures based on Modern Methods of Construction. *Journal of Cleaner Production* 330: 129724.

Sánchez-Garrido, A.J., Navarro, I.J. & Yepes, V. 2022b. Evaluating the sustainability of soil improvement techniques in foundation substructures. *Journal of Cleaner Production* 351: 131463.

Sánchez-Garrido, A.J., Navarro, I.J., García, J. & Yepes, V. 2022c. An Adaptive ANP & ELECTRE IS-based MCDM Model Using Quantitative Variables, *Mathematics* 10(12): 2009.

Stewart, M. G., Estes, A. C., & Frangopol, D. M. 2004. Bridge deck replacement for minimum expected cost under multiple reliability constraints. *Journal of Structural Engineering* 130(9).

Yepes, V., Lopez, S. 2021. Knowledge management in the construction industry: Current state of knowledge and future research. *Journal of Civil Engineering and Management* 27(8): 671–680.