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Sustainable preventive maintenance of MMC-based concrete building structures in a harsh environment

Antonio J. Sánchez-Garrido[a,*], Ignacio J. Navarro[a], Víctor Yepes[b]

[a] Dept. of Construction Engineering, Universitat Politècnica de València, 46022, Valencia, Spain
[b] Institute of Concrete Science and Technology (ICITECH), Universitat Politècnica de València, 46022, Valencia, Spain

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ABSTRACT

The construction industry plays a significant role in environmental strain, attributed mainly to its substantial resource consumption, primarily driven by the surge in residential construction. Modern Methods of Construction (MMC) presents an innovative paradigm for designing and constructing infrastructure and buildings more efficiently, using conventional materials with unconventional techniques. The article aims to apply this approach to an MMC-based building structure, minimizing its life cycle impact by optimizing the consumption of building materials, with particular attention to the effects of the maintenance phase from a preventive point of view. This study focuses on assessing the sustainability of reinforced concrete flat slabs employing a hollow structural body system, explicitly emphasizing environmental aggressiveness factors contributing to corrosion, such as carbonation and chlorides. The research explores ten design options for a waterfront public residential building, examining their impact on the economy, the environment, and even society regarding the maintenance cycles required over the structure's lifetime, depending on the preventive strategy employed for each design. In assessing the sustainability of these options, researchers employed a combination of the best-worst method (BWM) and the VIKOR technique, considering nine criteria related to sustainability. The study found that 5 % silica fume concrete is the most cost-effective and environmentally friendly option, with hydrophobic impregnation reducing social impacts. However, compared to one- and two-dimensional evaluations, the study demonstrates the importance of simultaneously considering a design's life cycle's economic, environmental, and social impacts to achieve sustainability in maintenance with a holistic view. This approach led to an 86 % higher sustainability rating for a design using sulforesistant cement in the concrete mix than the baseline.

1. Introduction

The global construction industry, a resource-intensive sector, consumes around 50 % of non-renewable resources, posing a sustainability challenge [1]. Within the European Union (EU), it constitutes more than 40 % of the overall energy consumption and plays a role in 36 % of CO_2 emissions [2]. Future projections indicate that by 2050, new construction will produce 50 % of CO_2 emissions, up from the current 28 %, potentially increasing global material consumption to 90 billion tons [3]. In response to these challenges, the European Green Deal endeavors to attain net-zero greenhouse gas emissions by 2050. A key aspect of this initiative is dedicating one-third of the NextGenerationEU Recovery Plan investments to support this goal, fully aligning with the Sustainable Development

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[*] Corresponding author.
E-mail addresses: ajsangar@doctor.upv.es (A.J. Sánchez-Garrido), ignamar1@cam.upv.es (I.J. Navarro), vyepesp@cst.upv.es (V. Yepes).

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Goals (SDGs) set in 2015.

The commitment to the design and management of sustainable buildings and infrastructures has been postulated in recent years as a critical need to achieve the goal of climate neutrality [4]. In this context, implementing production and consumption models and evaluating technologies [5] focused on achieving performance towards more global sustainability are crucial. The circular economy [6], for example, stands as an approach to reduce waste generation compared to conventional systems through the reuse of components and the use of recycled materials [7], which is directly related to sustainability in environmental and economic terms. On the other hand, new modern methods of construction (MMC) [8] are emerging every day, driven by the need to accelerate deliveries, recover deadlines, and maintain productivity with more excellent safety by having less social concentration in off-site construction [9]. These efficient construction techniques promote the reduction of material waste through industrialization, which can also help mitigate potential cost increases due to material resource scarcity, in line with global sustainability goals [10].

Through concepts such as taxonomy, sustainability has become established in business and economics [11], where sustainable decision-making is essential. Tools such as the EU Taxonomy help companies and investors identify environmentally sustainable economic activities through a classification system, support the transition to a carbon-neutral future, and direct funding towards solutions to tackle the climate crisis and prevent further environmental degradation. Businesses and consumers play a central role in the circular economy [12] that goes beyond the mere reduction of greenhouse gas emissions, so it is necessary to draw on the multidimensional nature of sustainability where criteria and dimensions other than the classic economic-environmental one are considered. This holistic approach has led to the need to expand the concept of taxonomy through the creation of a social EU taxonomy [13], which, although still in its infancy, attempts to address elements such as gender equality, social inclusion, and corporate responsibility, providing the most comprehensive view of sustainability [14]. The goal is to increase transparency in sustainability's social dimensions, direct capital to projects that uphold human rights, and promote investments that improve living and working conditions. Sustainable development involves making complex decisions by balancing conflicting criteria.

There needs to be more than a one- or two-dimensional approach to the main pillars of sustainability alone for proper sustainable design. Multi-criteria decision-making (MCDM) approaches have proven effective in providing a holistic perspective in sustainability assessment [15,16]. In this context, several research studies have used MCDM tools to assess sustainability in civil engineering and architecture, especially the economic-environmental dimension, and some of them, although to a lesser extent, also include social aspects. In recent years, everything from large infrastructures, such as bridges [17], to complete building structures [18] or construction elements, such as cantilever retaining walls [19], piles [20], or load-bearing walls made of alternative construction materials [21], have been evaluated. These assessments underscore the need of considering multiple criteria in sustainability evaluation, ensuring that all relevant factors are addressed to achieve sustainable outcomes.

Recent research in the construction field highlights the importance of sustainability assessment and the consideration of impacts in the maintenance phase throughout the entire infrastructure and building cycle. It is observed that as opposed to conventional short-term assessments focused on the construction phase, more and more attention is given to improving long-term maintenance impacts [22–24] with various design alternatives or improving materials to maximize the durability of the buildings [25,26]. The study of the maintenance phase is especially determinant in construction subjected to specific environmental exposure, such as coastal regions, where concrete structures are subjected to intense and constant chloride attacks [27]. It is, therefore, necessary to increase research on the behavior of different design alternatives for structures subjected to these demanding environmental conditions that can ensure a balance between the durability and sustainability of the building. And to the authors' knowledge, no MCDM model has been used to assess the sustainability of a residential building structure based on MMC exposed to chloride attack during its life cycle to optimize preventive maintenance cycles not only from a traditional economic-environmental point of view but also integrating social impacts.

This study offers a comprehensive sustainability life cycle assessment that integrates the social dimension for various unconventional structural alternatives to bridge the identified knowledge gap. The evaluation focuses on the maintenance cycles required over the lifespan of structures exposed to chloride-induced corrosion, considering the preventive strategies employed for each design. The paper evaluates the life cycle impacts of ten construction options for designing a 1 m^2 slab within a beachfront hotel building. It adopts a "gate-to-grave" approach and is based on a specific MMC called "Unidome" slabs designed for substantial loads and spans [28]. These options aim to enhance the base design's durability, reducing maintenance needs during the structure's life cycle. The sustainability evaluation considers economic, environmental, and social factors. It covers both construction and maintenance tasks to ensure a 50-year service life in line with national standards [29]. Concrete is a material that, when properly designed and optimized, can contribute to improving sustainability in construction. Considering the substantial contribution of cement production to global greenhouse gas emissions, estimated at around 10 % [30], MMCs present an effective approach to curbing the environmental impact throughout a structure's life cycle. This is achieved by optimizing material use and minimizing concrete consumption [31].

The rest of the document follows this structure: Section 2 delves into an in-depth explanation of the methodology, offering insights into the analyzed case study, the explored design alternatives, and the key assumptions made for the life cycle assessment. Section 3 highlights the primary outcomes of the research. Section 4 expands on the discussion of the results obtained and correlations with the findings of previous literature studies and prospective applications, and lastly, Section 5 encapsulates the conclusions derived from this assessment.

2. Materials and methods

2.1. *Sustainability assessment of building structures exposed to chlorides*

When evaluating structural designs, sustainability is a crucial factor, demanding a comprehensive analysis of every dimension through both traditional and holistic methods. Well-established environmental standards, specifically ISO 14040 [32] and ISO 14044

[33], offer a strong methodology for carrying out thorough and transparent life cycle assessments with a specific focus on environmental aspects. However, standardized procedures for social life cycle assessments only became available in 2009, with the introduction of a framework based on ISO 14040 by UNEP/SETAC [34]. Consistency and comparability in each analysis require adherence to these guidelines when assessing the three dimensions. The four steps in a life cycle assessment, as per ISO 14040, encompass defining the study's purpose and scope, conducting inventory analysis, describing methods and assumptions, and presenting and discussing the results. By adhering to these guidelines, sustainable assessments of structural designs can be conducted comprehensively and effectively.

2.1.1. Preventive designs and problem definition

This study seeks to evaluate how different alternatives perform in terms of sustainability compared to the baseline design of a public residential building located on the coast of Sancti Petri, Chiclana, Cádiz (Spain). The standard choice, henceforth called REF, consists of a three-story room module with longitudinally repeated expansion joints, making up more than 80 % of the hotel's constructed space (Fig. 1). The structural system involves a mat foundation and three levels of slabs constructed using an innovative MMC-based in-situ method. These slabs utilize high-density polyethylene (HDPE) hollow structural bodies, known as "Unidome slabs," to reduce weight [28]. A critical factor affecting concrete durability is chloride penetration from seawater, which can lead to corrosion. The alternative designs in this study aim to enhance the concrete structure's durability by extending its service life, employing mechanisms like improving concrete resistance, increasing thickness, inhibitory protection, or using different steel types.

This text analyzes nine alternative designs and the REF design for a waterfront hotel building to compare their sustainable performance. Three designs aim to reduce concrete permeability. One method entails adjusting the fundamental mix by incorporating cement containing 5 % silica fume (SF–C) or introducing 10 % fly ash (FA-A) as additives. However, these admixtures are challenging to source locally and result in high supply costs due to the construction site's distance from suppliers. Thus, the use of sulforesistant cement (SR-C), more accessible in Cadiz's marine environment, is considered. An additional technique for decreasing permeability involves producing highly compact and thoroughly vibrated concrete, employing a reduced water-cement ratio from 0.60 to 0.50 (W/C alternative). Extending the concrete cover from 3 cm to 4.5 cm (alternative CC45) prolongs its protective effect on reinforcement. Oversizing structural elements by 25 % (OSE) reduces cracking and safeguards reinforcement. Applying a hydrophobic corrosion inhibitor impregnation (HCII) and cathodic corrosion protection of reinforced concrete (CPRC) are protective measures. Using galvanized steel reinforcing bars (GSR) instead of conventional carbon steel enhances durability. Stainless steel, while highly corrosion-resistant, is often not economically sustainable for building construction, except in specific cases.

To enable a valuable comparison in the life cycle impact assessment, it is necessary to adhere to the ISO 14040 standards by employing a uniform functional unit. This study specifies the functional unit as a constructed area of 1 square meter encompassing a three-level hotel module with a total constructed area of 2132 m^2 for the structure and foundation. A thorough gate-to-grave methodology has been utilized to evaluate the effects stemming from both construction and maintenance activities, covering a specified lifespan of 50 years as stipulated by national codes outlined by the Ministry of Transport, Mobility, and Urban Agenda [29].

2.1.2. Service life predictions

Establishing an appropriate maintenance program for the structure under examination throughout its service life is critical to establishing a criterion that may vary depending on the preventive designs considered. Determining the right time to carry out concrete replacement operations is essential before the reinforcement is affected. In the case of carbonation and chloride corrosion, a physical model is required to determine the time required for the attack to produce a sufficiently significant degradation. Existing deterioration models are based on Fick's second law of diffusion and assume that concrete is a homogeneous material whose porous cover favors the migration of ions through a diffusion process. Therefore, it is necessary to know the initiation period (t_i) in which chlorides pass through the concrete cover to reach the reinforcement threshold. The initiation of corrosion occurs when these chloride ions come into contact with the reinforcement until they reach a critical threshold called critical chloride content (C_{cr}). The deterministic Tuutti model [35], shown in Fig. 2, is commonly used to estimate the initiation period of structures exposed to elevated chloride levels.

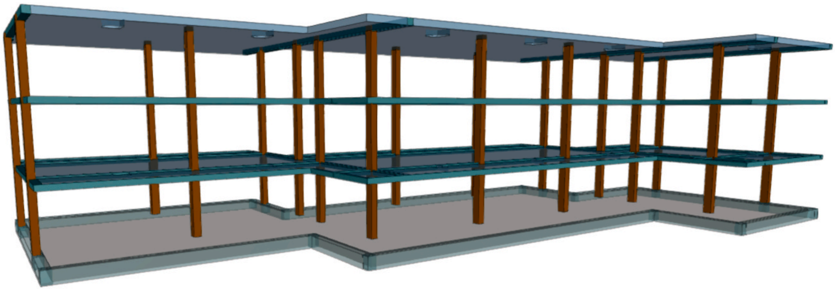

Fig. 1. Three-dimensional representation of the standard (REF) structure.

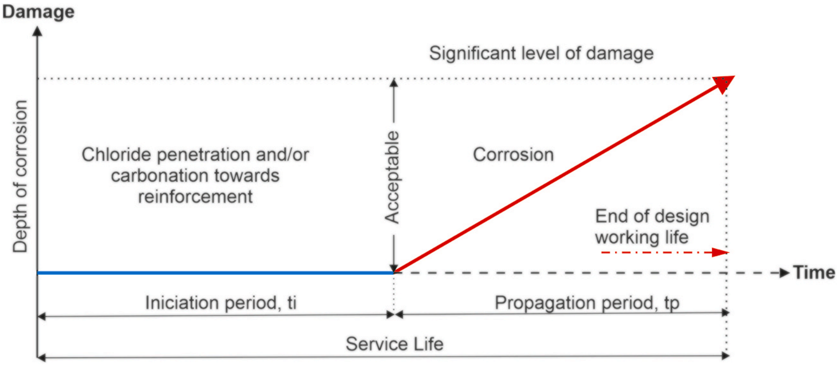

Fig. 2. Definition of service life based on the Tuutti corrosion model.

Table 1
Durability parameters assumed in each design alternative.

Variable	REF	SF-C	FA-A	SR-C	W/C	CC45	OSE	HCII	CPRC	GSR
C_{cement} (kg/m^3)	275	237.5[a]	225[b]	325	300	275	275	275	275	275
C_{cr} (%)	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.9[d]	1.2[e]
Erf	0.853	0.911	0.933	0.779	0.815	0.871	0.868	0.851	0.671	0.525
C_s (%)	2.62	3.03	3.20	2.22	2.40	2.74	2.72	2.62	2.62	2.62
x (mm)	30	25	25	30	30	45	40	50[c]	35	30
D_0 (x10E-12 m^2/s)	25	3.31	6.16	9	15.8	25	25	25	25	25
t (years)	2.0	42.4	11.1	22.2	6.0	9.3	5.9	15.6	9.7	13.9
No. of repairs	25	1.18	4.50	2.25	8.33	5.38	8.47	3.21	5.15	3.60

[a] 12.5 kg/m^3 equivalent to 5 % silica fume with respect to 250 kg/m^2 of the minimum cement content.

[b] 25 kg/m^3 equivalent to 10 % fly ash with respect to 250 kg/m^2 of the minimum cement content.

[c] Effective coating increase λ=(1 + 0.5)/2 for chloride rate around 1.1 mm/half a day.

[d] 50 % increase in corrosion threshold due to corrosion inhibitor protection.

[e] Chloride ion limit contents in the case of reinforcements with additional hot-dip galvanized protection.

Under normal conditions, a value of 0.6 % by weight of cement in C_{cr} can be adopted for testing the corrosion-related limit state of passive rebars. For other types of structures with pre-stressed active reinforcement, the value would be halved. The propagation phase concludes when there is an unacceptable loss of steel section or the appearance of cracks on the surface of the concrete cover. An enhanced version of the one-dimensional Fickian model recommended in Fib Bulletin 34 [36] is utilized to assess the evolution of chloride concentration in concrete over time. This refined model also incorporates two-dimensional corner effects, as proposed by Navarro et al. [17]. The concentration of chloride (C) at any depth (in mm) in the x and y directions of the examined cross-section, at any given time (t) in years, can be calculated using the following formula:

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

The concentration of chloride on the surface (wt%/binder) is represented by C_s, while the Gaussian error function is denoted by erf (•). The chloride diffusion coefficient (mm^2/year) is denoted by D_0, where its value is given in units of x10-12 m^2/s. The age factor is represented by α and is assumed to be 0.5 in accordance with the Spanish codes. Finally, t_0 represents the time duration of 0.0767 years (28 days).

Assuming the structure regains its initial state after each maintenance cycle [37], it is noteworthy that the carbonation of the concrete cover in harsh environments can impact chloride diffusion, reducing corrosion initiation time. In this investigation, we have not examined the impact of carbonated concrete on the corrosion process of reinforcement because the conditions that support both rapid carbonation and chloride penetration are seldom encountered [38]. Table 1 displays the parameter values used to establish the analyzed metrics and the maintenance cycles required throughout the structure's operational lifespan of 50 years, corresponding to the achieved durability for each alternative.

2.1.3. Impact assessment

To evaluate the impacts generated throughout the life cycle of each design alternative, three sets of criteria have been considered. The first set of criteria focuses on the economic aspects, including the construction costs of the functional unit described above, as well as the long-term costs, including the costs of maintenance and possible interventions (replacement, not repair) over the lifespan of the building structure. In evaluating the construction timeline, it is crucial to discount any future costs. Privately, a higher discount rate is generally preferred as it emphasizes the significance of immediate expenses while reducing the relevance of costs incurred in the distant future for economic impact assessment. In this specific instance, a low social discount rate of 2 % has been chosen, referred to as such because it aligns with the sustainability-focused cost assessment [39].

The second set of criteria assesses environmental impacts using the ReCiPe [40] environmental assessment methodology. It utilizes a dual approach, presenting environmental impacts in detail through the midpoint method while simplifying the evaluation by focusing on three critical criteria: human health, ecosystem damage, and resource availability. This approach ensures a comprehensive technical analysis and an accessible understanding for a broader audience. ReCiPe transforms emissions from any activity into 18 midpoint indicators that cover impacts such as increased respiratory and cancer diseases, damage to various terrestrial, marine, and freshwater species, as well as the effects of the growing scarcity of natural resources. These intermediate impacts are then appropriately grouped and transformed into the above-mentioned final indicators. Disability-adjusted life years (DALYs) are used to measure human health, which considers the years of life lost due to premature death or disease. The potentially missing fraction (PDF) measures ecosystem damage by assessing the potentially lost species annually due to anthropogenic activities that occupy or convert their habitats. The potentially affected fraction (PAF), which measures the percentage of species exposed to unbearable toxic substances, is also considered when evaluating ecosystem impacts. The last criterion is related to the contribution of each alternative to natural resource scarcity, taking into account the energy surplus needed to extract mineral resources or fossil fuels. In this context, the ReCiPe

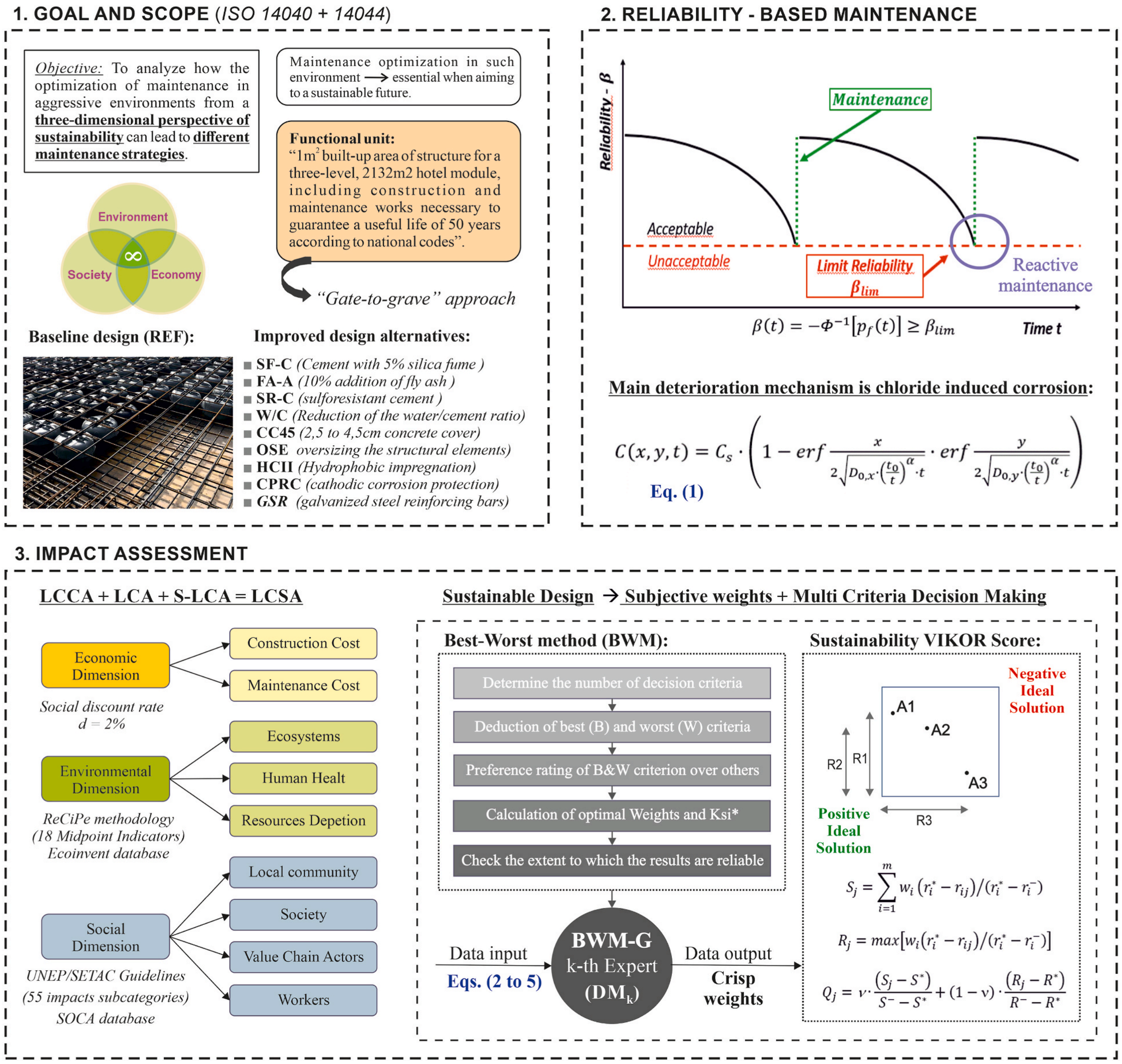

Fig. 3. Overview of the methodology.

method is implemented with a hierarchic approach, which assigns comparable importance to both short- and long-term impacts.

A third set of criteria is considered to account for the social impacts of the product under assessment. This set is based on the 4 stakeholders assumed by SOCA, a social database which adapts PSILCA database to Ecoinvent processes. These stakeholders are: Workers, Local Communities, Society and Value Chain Actors. SOCA assigns to each of these stakeholders different sets of criteria, based on the widely known UNEP/SETAC Guidelines [41] in order to quantify the social impact on them. To understand the social impact on the Workers, SOCA establishes 8 impact subcategories, namely child labour, forced labour, fair salary, working time, discrimination, health and safety, social benefits, and freedom of association. Regarding the stakeholder Local Communities, this method quantifies the social impact in terms of the access to material resources, the respect to indigenous rights, the safety and health related to the living conditions, the generation of local employment and the effect on migration. When it comes to evaluating the impact on the Society, SOCA database considers two subcategories, namely the contribution to the economic development, and the affection to the health and safety of the society in general terms. At last, to account for the impact on the Value Chain Actors, this method considers four subcategories, namely fair competition, corruption, promotion of social responsibility and prevention of conflicts. The impacts on each of these subcategories is measured using as an activity variable the worker hours [34]. Social risk is assessed through medium-risk hours, denoting the cumulative count of labor hours within the supply chain linked to particular social risks. As values rise, they indicate heightened risks, symbolizing a more adverse performance.

In summary, this sustainability assessment considers nine different impact categories: construction (C1) and maintenance (C2) costs in the economic dimension, damage to ecosystems (C3), damage to human health (C4), and depletion of natural resources (C5) in the environmental dimension and social impacts on the local community (C6), society (C7), value chain actors (C8), and workers (C9). Fig. 3 presents the framework of the study with the proposed methodology, its sequential stages and its organization.

These impact categories are used as decision criteria in this MCDM assessment. Table 4 summarizes the decision criteria and their weights, as determined by a group of experts described in Table 5. The Best-Worst Method (BWM), formulated by Rezaei [42], has been chosen for pairwise comparison. BWM identifies the most and least important criteria and uses these comparisons to determine the weights of all criteria, enhancing the consistency and reliability of the weighting process by minimizing deviations. Finally, a sustainability indicator is obtained by applying the classical VIKOR method, with results presented in Table 7. The VIKOR (VIseKriterijumska Optimizacija I Kompromisno Resenje) technique is used in MCDM to rank and select alternatives by identifying trade-off solutions. It evaluates alternatives based on their proximity to the ideal solution, considering both the distance to the best and worst options, as well as the balance among criteria. More information on the formulation and development of the method can be found in Ref. [43].

2.1.4. Inventory analysis

To evaluate the impacts of each alternative, it is necessary to determine the material quantities required for their implementation. The expenses related to each option are outlined in Table 2, encompassing not just materials but also labor, equipment and machinery, and direct ancillary expenses. The material expenditures utilized in this analysis have been sourced from dedicated and acknowledged Spanish construction databases established by "CYPE Ingenieros" and revised up to 2023 and from detailed data provided by specific suppliers. It is based on thorough market research, expert validation, and rigorous data analysis. It uses reliable sources and verifies data accuracy through historical comparisons and objective industry criteria. Frequent updates reflect market fluctuations and ensure that calculated prices are accurate and relevant to the construction industry. These sources ensure the accuracy and reliability of the cost estimates.

Table 3 offers a thorough and detailed glimpse into the diverse concrete blends incorporated into each design option’s life cycle assessment (LCA) during all construction phases, utilization, and upkeep. Concrete composition plays a vital role in shaping the overall environmental impact of the alternatives. Our study thoroughly examines the strength, longevity, and ecological ramifications of various blends, with the primary objective of reducing the carbon footprint. We obtained inventory data for each option from the reliable Ecoinvent database to ensure precise and uniform environmental analysis. The Ecoinvent 3.2 database has gained widespread recognition for its dedicated and comprehensive life cycle inventory data across various materials and processes. As a highly prized resource in the field of LCAs, it enables stakeholders to make informed choices by utilizing a standardized and trustworthy database for accurate comparisons. Its extensive coverage of different environmental impact categories - including global warming potential, eutrophication potential, ozone depletion potential, acidification potential, and human toxicity potential - allows for a thorough assessment of each available option’s overall environmental performance. Adopting a "cut-off criterion" and recognizing the comparative nature of this evaluation, identical processes standard to all alternatives were excluded from the system definition [44]. Consequently, activities related to transporting concrete and steel from nearby suppliers or plants (within $\leq$20 km) and the supply of columns and HDPE hollow bodies standard to all alternatives were omitted. However, transporting distinctive materials like silica fume or fly ash, requiring long-distance travel was considered. Additionally, following the guidelines of ISO 14040 and ISO 14044, any factor contributing less than 1 % to the total impact could be disregarded in the assessment. Hence, the energy and fuel consumption associated with the machinery used in project implementation need not be considered, as the differences between alternatives are negligible.

Table 2
Costs related to construction and maintenance taken into account in LCCA.

Alternatives	Design parameters	Cost	Unit
All	"UNIDOME" XS-D420 (470)	7.13	€/m^2
	"UNIDOME" XS-120 (150)	6.85	€/m^2
	"UNIDOME" XS-160 (190)	8.56	€/m^2
1-REF	Raft foundation 60 cm (25 Mpa) + rebars (60 kg/m^3)	210.00	€/m^3
8-HCII	Lightweight concrete slab 25 cm (25 Mpa) + rebars (104 kg/m^3)	116.30	€/m^2
9-CPRC	Lightweight concrete slab 30 cm (25 Mpa) + rebars (73.33 kg/m^3)	113.85	€/m^2
2-SF-C	Raft foundation 60 cm + 5 % SF[a] (25 Mpa) + rebars (60 kg/m^3)	331.80	€/m^3
	Lightweight concrete slab 25 cm + 5 % SF[a] (25 Mpa) + rebars (104 kg/m^3)	183.75	€/m^2
	Lightweight concrete slab 30 cm + 5 % SF[a] (25 Mpa) + rebars (73.33 kg/m^3)	179.88	€/m^2
3-FA-A	Raft foundation 60 cm + 10 % FA[b] (25 Mpa) + rebars (60 kg/m^3)	256.20	€/m^3
	Lightweight concrete slab 25 cm + 10 % FA[b] (25 Mpa) + rebars (104 kg/m^3)	141.89	€/m^2
	Lightweight concrete slab 30 cm + 10 % FA[b] (25 Mpa) + rebars (73.33 kg/m^3)	138.90	€/m^2
4-SR-C	Raft foundation 60 cm (30 Mpa−SR[c] cement) + rebars (60 kg/m^3)	239.67	€/m^3
	Lightweight concrete slab 25 cm (30 Mpa−SR[c] cement) + rebars (104 kg/m^3)	123.73	€/m^2
	Lightweight concrete slab 30 cm (30 Mpa−SR[c] cement) + rebars (73.33 kg/m^3)	122.76	€/m^2
5-W/C	Raft foundation 60 cm (30 Mpa−MR[d] cement) + rebars (60 kg/m^3)	230.68	€/m^3
	Lightweight concrete slab 25 cm (30 Mpa−MR[d] cement) + rebars (104 kg/m^3)	121.50	€/m^2
	Lightweight concrete slab 30 cm (30 Mpa−MR[d] cement) + rebars (73.33 kg/m^3)	120.08	€/m^2
6-CC45	Raft foundation 60 + 4 cm (25 Mpa) + rebars (56.25 kg/m^3)	203.90	€/m^3
	Lightweight concrete slab 25 + 2 cm (25 Mpa) + rebars (96.30 kg/m^3)	118.75	€/m^2
	Lightweight concrete slab 30 + 2 cm (25 Mpa) + rebars (68.75 kg/m^3)	116.31	€/m^2
7-OSE	Raft foundation 62 cm (25 Mpa) + rebars (72.58 kg/m^3)	230.52	€/m^3
	Lightweight concrete slab 27 cm (25 Mpa) + rebars (120.37 kg/m^3)	129.48	€/m^2
	Lightweight concrete slab 32 cm (25 Mpa) + rebars (85.94 kg/m^3)	128.08	€/m^2
10-GSR	Raft foundation 60 cm (25 Mpa) + rebars (62.10 kg/m^3)	267.00	€/m^3
	Lightweight concrete slab 25 cm (25 Mpa) + rebars (120.37 kg/m^3)	215.11	€/m^2
	Lightweight concrete slab 30 cm (25 Mpa) + rebars (85.94 kg/m^3)	183.52	€/m^2
8-HCII	Corrosion-inhibiting hydrophobic impregnation	33.51	€/m^2
9-CPRC	Cathodic protection of reinforced concrete against corrosion	115.83	€/m^2
10-GSR	Galvanizing bath for rebars + transport <10 km	0.90	€/Kg
Maintenance common to all alternatives	Restoration of the perimeter of the reinforced concrete slab (average thickness 27 cm)	61.35	€/m
	Preparation of the structural concrete surface using manual methods	45.76	€/m^2
	Surface preparation of the reinforcing material	8.68	€/m^2
	Concrete structural repair using cement mortar modified with polymers	88.38	€/m^2

[a] SF = Silica fume.
[b] FA = Fly ash.
[c] SR = sulforesistant cement.
[d] MR = seawater resistant cement.

3. Results

This section presents the life cycle assessment outcomes for each of the ten design choices, with a detailed examination of their performance across the three sustainability dimensions. Optimal results are derived from the preventive maintenance interval. Finally, we provide life cycle assessments that comprehensively address all three dimensions in a simultaneous sustainability assessment.

3.1. *LCCA results*

Fig. 4 presents the results of an economic life cycle assessment for ten design options, covering the construction costs of 1 m^2 of a hotel module and its optimal preventive maintenance expenses over a 50-year service life. Notably, despite using costly construction materials in options like SF-C, CPRC, and GSR, construction costs remain relatively similar across all alternatives. The significant differentiator is maintenance costs, which can be up to three times higher for GSR and four times higher for CPRC than SF-C. In cases with lower durability, such as REF, W/C, and OSE, the discounted maintenance costs can reach 12.1, 5.2, and 6 times the construction costs, respectively. Thus, long-term maintenance costs are crucial in determining the economic efficiency of building materials [45].

According to this study's assumptions, the most economically advantageous option is the design featuring silica fume concrete (SF–C), closely followed by the choice incorporating sulfide-resistant cement (SR-C) in the concrete mix. These designs significantly reduce maintenance costs due to their exceptional durability [17], lasting up to 42 and 22 years, respectively, without requiring repairs. The results underscore the effectiveness of preventive measures for options with higher maintenance requirements [22]. For instance, compared to REF, the CC45 alternative shows a substantial reduction of up to 39.45 % in maintenance costs when proactive repairs are applied.

Table 3
Flows for materials and transports assumed in each preventive design considered in LCA and SLCA.

Inputs (per m^2 of floor slab)	REF	SF-C	FA-A	SR-C	W/C	CC45	OSE	HCII	CPRC	GSR
Construction phase (initial impacts)										
Cement, Portland (kg)	86.14	74.39	70.48	–	–	90.24	89.28	86.14	89.78	86.14
Seawater resistant MR cement (kg)	–	–	–	–	93.97	–	–	–	–	–
Sulfate resistant SR cement (kg)	–	–	–	101.80	–	–	–	–	–	
Water (l)	51.68	50.90	50.90	50.90	46.98	54.14	53.57	51.68	54.08	51.68
Sand (kg)	213.00	213.00	213.00	207.99	207.99	223.13	220.77	213.00	213.00	213.00
Gravel (kg)	439.31	439.31	439.31	428.97	428.97	460.20	455.35	439.31	439.31	439.31
Silica fume (kg)	–	3.92	–	–	–	–	–	–	–	–
Fly ash (kg)	–	–	7.83	–	–	–	–	–	–	–
Silica sand (kg)	–	–	–	–	–	–	–	–	30.74	–
Titanium mesh (kg)	–	–	–	–	–	–	–	–	0.57	–
Rebar steel B–500S (kg)	27.52	27.52	27.52	27.52	27.52	27.52	34.40	27.52	27.52	–
Galvanized steel B–500S (kg)	–	–	–	–	–	–	–	–	–	28.48
Silane-based impregnation (l)	–	–	–	–	–	–	–	0.66	–	–
Transport, freight, lorry (t•km)	16.05	19.97	23.88	16.05	16.05	16.05	16.05	16.05	16.74	16.07
Maintenance phase (repair cycles)[a]	25	1.18	4.50	2.25	8.33	5.38	8.47	3.21	5.15	3.60
Cement, blast furnace slag 18–30 % (kg)	610.00	28.79	109.80	54.90	203.25	131.27	206.69	78.32	125.66	87.84
Cement, pozzolana, fly ash 11–35 % (kg)	59.25	2.80	10.66	5.33	19.74	12.75	20.07	7.61	12.20	8.53
Sand (kg)	1854.62	87.54	333.83	166.92	617.96	399.11	628.35	238.13	382.05	267.06
Water (l)	289.12	13.65	52.04	26.02	96.34	62.22	97.95	37.12	59.56	41.63
Aluminosilicate abrasive (Kg)	101.77	4.80	18.34	9.17	33.92	21.89	34.50	13.05	20.98	14.64

[a] Quantities for each alternative based on the number of repair cycles to complete service life.

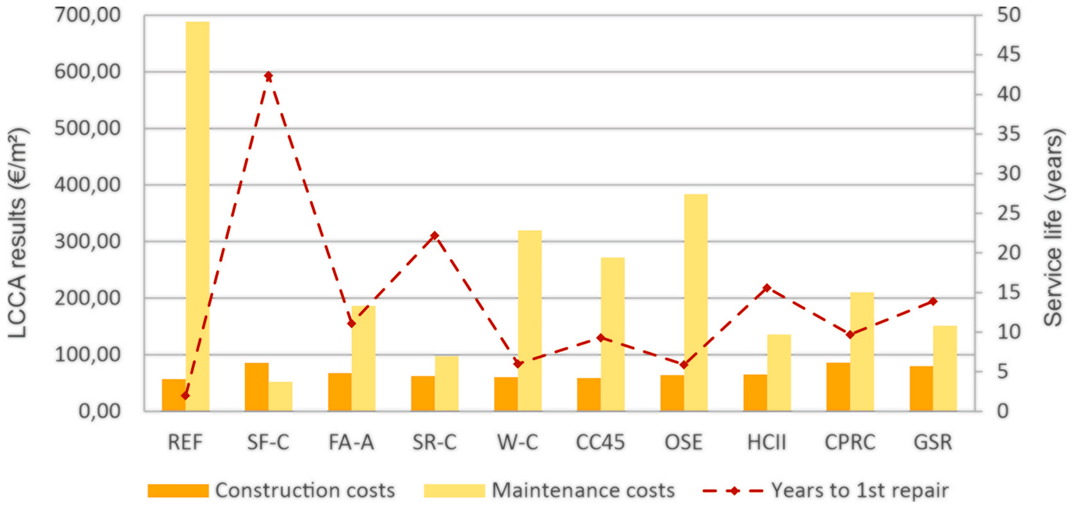

Fig. 4. Outcomes from the life cycle cost assessment.

3.2. LCA results

The environmental life cycle assessment outcomes for the ten alternative designs are illustrated in Fig. 5, encompassing their effects on the health of individuals, ecosystems, and the availability of natural resources. The differences in effects between the construction and maintenance stages are underscored. Notably, the most significant environmental impacts relate to human health (with REF contributing 48.2 % of the total) and resource depletion (where GSR accounts for 55.55 % of the overall effect). The REF design incurs 32.1 % of its impact during the maintenance phase, primarily due to the high number of required repair cycles. Conversely, the GSR option generates 53.6 % of its impact during the construction phase, mainly attributed to using 28.48 kg of galvanized steel as a distinguishing element. These impacts, although relatively more minor in proportion, remain the predominant components of the overall life cycle impact for all examined alternatives.

In a broader context, it is evident that higher design durability in SF-C, SR-C, and HCII options leads to reduced maintenance needs, resulting in lower environmental impact. Notably, the design for durability with 5 % silica fume cement exhibits the most favorable ecological performance. The durability of concrete incorporating silica fume (SF) significantly enhances the service life of structures by reducing permeability and improving resistance to chemical attack. This increased durability lowers maintenance needs and decreases the environmental impact associated with repair activities over the building's lifecycle [46]. While the overall effects during the construction phase are similar for most alternatives, except for the disproportionately high GSR, SF-C achieves superior results by

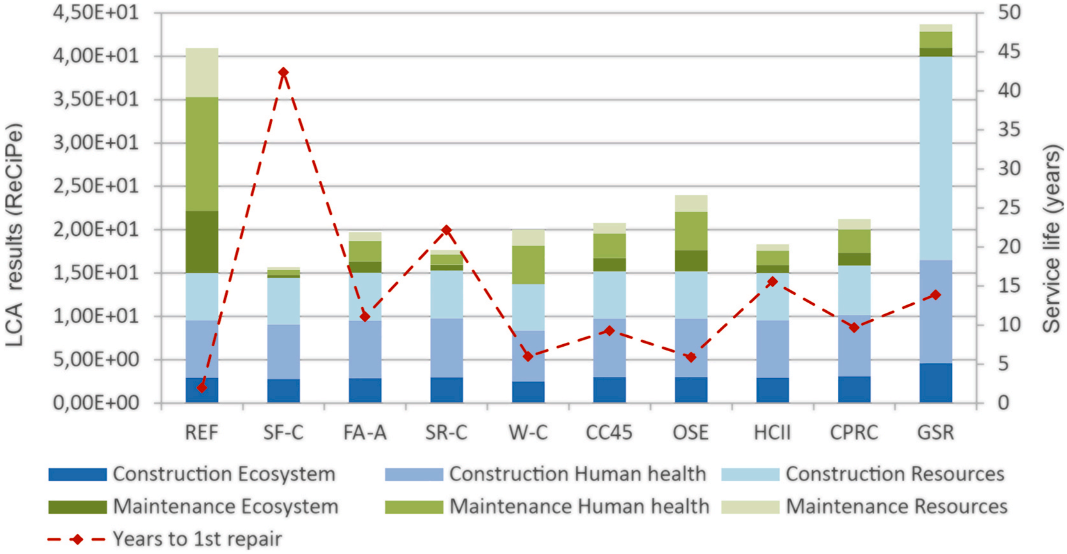

Fig. 5. Outcomes from the life cycle assessment.

minimizing material usage in the maintenance phase. It requires only 1.18 times the number of repairs over the entire life cycle, avoiding the environmental impacts of concrete production for each replacement. Preventive maintenance of SF-C, SR-C, and HCII solutions leads to a significant reduction in environmental impact, with reductions of 61.75 %, 56.91 %, and 55.24 %, respectively, compared to the base REF solution. Researchers emphasize that regular inspections and timely repairs in durable concrete structures extend service life and decrease lifecycle environmental impacts [27], aligning with benefits seen in SF-C, SR-C, and HCII options. Lastly, using alternative materials with the best economic-environmental response, such as silica fume or, more subtly, fly ash, aligns with the Circular Economy concept [6,12] by revaluing waste from other industries as additives to the concrete base mix, contributing to sustainable construction practices by reducing greenhouse gas emissions and energy consumption.

3.3. S-LCA results

This discourse delves into the findings from the social life cycle assessment involving ten design options. Fig. 6 graphically portrays the progression of impacts over time on the four key stakeholder groups under scrutiny: local communities, society, value chain actors, and workers. It's essential to acknowledge that social risks are quantified regarding medium-risk hours, signifying the number of working hours within the supply chain associated with particular social risks [47]. Hence, the most desirable solution is characterized by the lowest social score.

In this particular scenario, the design option that produces the most favorable social impact is the one that applies a hydrophobic corrosion inhibiting impregnation (HCII). However, this design is not exactly distinguished by remarkable durability. It is closely

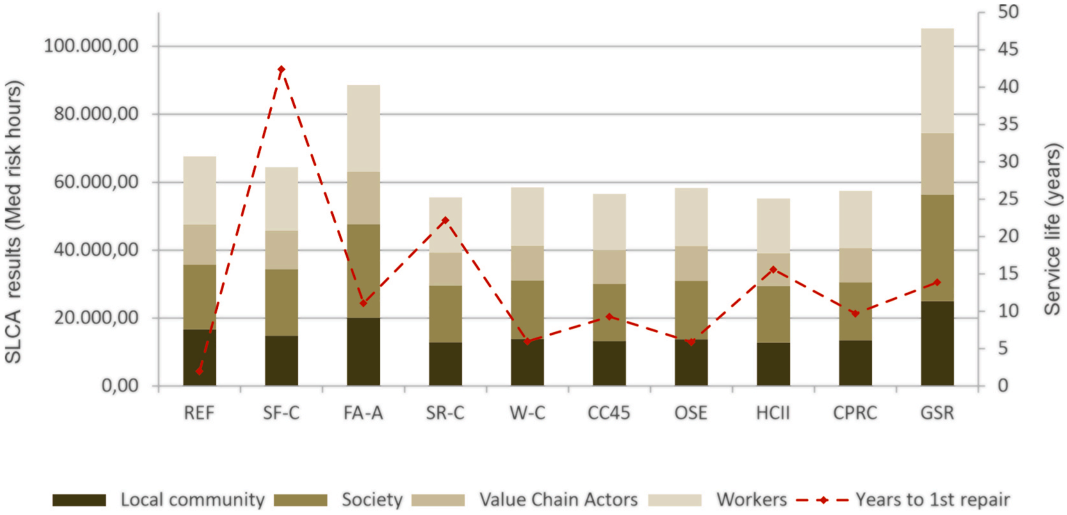

Fig. 6. Outcomes from the social life cycle assessment (SLCA).

Table 4
Social performance during construction and maintenance phases (medium-risk hours).

Stage	Criteria	1-REF	2-SF-C	3-FA-A	4-SR-C	5-W-C	6-CC45	7-OSE	8-HCII	9-CPRC	10-GSR
Construction	C6	12243.45	14613.55	19281.54	12441.84	12388.01	12273.39	12266.76	12243.60	12544.41	24358.43
	C7	16230.21	19451.97	27057.77	16494.08	16278.70	16251.47	16246.70	16230.36	16483.89	30935.08
	C8	9410.29	11221.80	15086.50	9527.35	9414.73	9429.11	9424.84	9410.40	9598.93	17801.76
	C9	15509.28	18500.10	24683.58	15773.11	15617.87	15541.86	15534.63	15509.48	15864.99	30101.48
Maintenance	C6	4391.99	207.30	790.56	395.28	1463.41	945.16	1488.01	563.93	904.75	632.45
	C7	2867.35	135.34	516.12	258.06	955.40	617.05	971.46	368.17	590.67	412.90
	C8	2424.52	114.44	436.41	218.21	807.85	521.76	821.43	311.31	499.45	349.13
	C9	4576.09	215.99	823.70	411.85	1524.75	984.78	1550.38	587.57	942.68	658.96

followed by the SR-C, CC45 and CPRC alternatives, each with a marginal increase in the risk of 1 %, 2 %, and 4 %, respectively. This comparison holds social significance, particularly in light of the challenges posed by the local availability of silica fume on-site for the SF-C alternative, which emerged as the preferred choice in the LCCA and the LCA. It must be transported from locations more than 1000 km away, leading to high transportation costs and delays. The choice of materials subject to transportation issues affecting social impacts has also been highlighted in previous research [26], analyzing the environmental and social implications of transporting materials over long distances, similar to the problems faced by silica fume in SF-C. In contrast, the design with less favorable results is based on galvanized reinforcing steel (GSR) and the addition of fly ash (FA-A).

Examining the stages (Table 4) reveals that the social effects of maintenance, in contrast to construction, are minimal for all options except the REF-based one, accounting for 21 % of the total due to its frequent repairs. According to the assessment, as maintenance requirements decrease, the impact on stakeholders, workers, and value chain actors is minimized. These two stakeholder groups collectively contribute almost half the overall social impact of all alternatives. Assessing societal and local community contributions within the building's value chain, it is evident that options relying on complex production processes for materials, such as galvanized steel or fly ash, have the most significant effects. In line with the above, other studies have confirmed how the production of these materials can contribute to economic benefits and job creation at production sites [13,14], in contrast to alternatives that require less intensive production processes. In simpler terms, the negative impact on average risk hours associated with GSR and FA-A alternatives results in favorable outcomes for production centers' economies, thanks to the substantial material needs of these solutions, leading to increased job opportunities and economic flows compared to other options.

3.4. BWM group weighting results

A team of three experts, all working professionals with experience ranging from 7 to 33 years in civil engineering, architecture, and construction, was assembled to evaluate the importance of each criterion in gauging the sustainability of the designs analyzed. The determination of the influence of expert voting in this study is based on the proposed simplified fuzzy function from the neutrosophic function [43], which builds on the theoretical framework established by Sodenkamp et al. [48]. By utilizing the neutrosophic triad of truth, indeterminacy, and falsity, this method seeks to determine the importance of individual experts and decision-makers (DMs). It carefully considers each person's self-perceived competence or credibility (δ_i) and consistency in completing the assessment matrix (ε_i) to determine their impact on voting. This is achieved by calculating the distance between their point and the ideal point of the most highly credible expert ⟨1,0⟩, resulting in the power of their vote (Φ_i) according to the following formula:

$$\varphi_i = 1 - \sqrt{\{(1-\delta_i^{2}) + \varepsilon_i^{2}\}/2} \tag{2}$$

The profiling of the expert panel approach, tailored to the parameters outlined in Table 5. This profiling encompasses two distinct parameter categories for assessing the expertise of the panel members: knowledge-related criteria and argumentation-focused criteria.

Taking into account the references cited above, the evaluation of the credibility of each $\mathrm{DM_k}$ in this case is formulated as:

$$\delta_i = 0.2\left(\frac{PA_i}{max\{PA_k\}} + \frac{SE_i}{max\{SE_k\}} \Big/ 2\right) + 0.6\left(\sum_{m=1}^{n} KF_{m,i} \Big/ n\right) + 0.2\left(\frac{LA_i}{max\{LA_k\}} + \frac{CP_i}{max\{CP_k\}} \Big/ 2\right) \tag{3}$$

Alternatively, inconsistency (ε_i) is evaluated by analyzing the discrepancies resulting from the pairwise comparisons conducted by individual experts within the group and is computed in a consolidated matrix, as depicted below.

$$\varepsilon_i = K_{si}/CR_{lim} \tag{4}$$

In this instance, the selected method for pairwise comparison is BWM [42], where $\mathrm{K_{si}}$ indicates the level of reliability of the results, with a lower value indicating better reliability, bearing in mind that the consistency coefficient must be less than 0.1 for the result to be consistent. After establishing the subjective weights (w_{ij}) for each criterion j assigned by each *i*-th expert, along with their voting influence (Φ_i), the ultimate BWM group weights for the *k*-experts are derived for each criterion using the following process:

$$W_i = \frac{\sum_k w_{ij} \cdot \Phi_i}{\sum_k \Phi_i} \tag{5}$$

Table 5
Significance of experts within the BWM group.

Description of the experts' profile	Parameter	DM_1	DM_2	DM_3
Expertise				
Years of professional dedication	PA_k	21	10	34
Years sustainability experience	SE_k	4	8	18
Research				
Lead author JCR	LA_k	6	11	15
Conferences papers	CP_k	4	10	73
Specific knowledge				
Construction Engineering	K_{C1}	5	5	5
Economic Issues	K_{C2}	4	4	4
Environmental issues	K_{C3}	2	3	3
Social Issues	K_{C4}	3	3	3
MCDM Issues	K_{C5}	4	4	4
Expert's credibility	δ_{DMk}	0.561	0.617	0.856
Expert's incoherency (BWM)	ε_{DMk}	0.791	0.802	0.707
Expert's voting influence	$\boldsymbol{\Phi}_{\mathbf{DMk}}$	**0.289**	**0.316**	**0.479**

The weightings of each impact category determined by the BWM method have relied on the participation of a panel of three experts. Table 6 presents the resulting significance attributed to each category. It is evident that when evaluating sustainability, nearly equal importance is assigned to environmental criteria, accounting for 38.6 %, and the social dimension, which represents 34.6 %.

3.5. *Tridimensional sustainability assessment*

By applying the acquired crisp weights, the VIKOR methodology combines the impacts of the nine distinct criteria, generating a consolidated sustainability rating ($0 \leq Q_j \leq 1$) for each design option in the comparative study. In this setting, a reduced Q_j value signifies an elevated sustainability level. Table 7 presents the decision-making matrix, which shows the interaction between the ten design options and their scores for the nine impact categories evaluated.

The outcomes for each design option, taking into account the duration until the first maintenance and repair of the cover concrete to prevent reinforcement corrosion, are illustrated in Fig. 7. Enhancing maintenance intervals can substantially mitigate the life cycle's impact across environmental, economic, and social domains. The optimal maintenance interval varies according to the sustainability dimension under evaluation. Moreover, sustainability exhibits varying sensitivity levels to maintenance optimization at a unidimensional level. Regarding the three-dimensional consideration of sustainability, the most advantageous selection is the design incorporating sulforesistant cement (SR-C) into the concrete mixture. At the same time, the least sustainable option employs galvanized steel (GSR), even ranking lower than the reference (REF) design. Notably, SR-C did not emerge as the top choice in individual assessments across the dimensions of economics, environment, and society, as it makes a more balanced contribution to all three sustainability dimensions. The results are in agreement with several investigations [7,19,20,21] which emphasizes the importance of considering the balanced contribution of the three dimensions when choosing sustainable building materials and designs.

There is a certain correspondence between the preferred results obtained in each evaluation and the holistic sustainability approach (SRC > HCII > CC45), together with a direct relationship with optimizing the maintenance interval. In the economic, environmental, and SF-C > SR-C > SR-C > HCII approaches, the top three positions are shared, while in the social approach, the top three alternatives are HCII > SR-C > CC45. Sustainability scores of less than 0.2 are observed in at least 50 % of the constructive solutions, including

Table 6
Determination of criteria weights by the BWM group.

Sustainability dimension	Criteria	Crisp weights obtained from the A_{DMK} pairwise comparison matrices weighted by the credibility of each expert						BWM-G
		wDM_1	ΦDM_1	wDM_2	ΦDM_2	wDM_3	ΦDM_3	
Economic	(C1) Construction cost	0.097	0.289	0.065	0.316	0.128	0.479	**0.101**
	(C2) Maintenance cost	0.129		0.308		0.096		**0.167**
Environmental	(C3) Ecosystem	0.065	0.289	0.194	0.316	0.055	0.479	**0.098**
	(C4) Human health	0.078		0.129		0.192		**0.143**
	(C5) Resources	0.309		0.097		0.077		**0.145**
Social	(C6) Local community	0.194	0.289	0.049	0.316	0.064	0.479	**0.094**
	(C7) Society	0.026		0.078		0.027		**0.041**
	(C8) Value Chain Actors	0.048		0.055		0.313		**0.168**
	(C9) Workers	0.055		0.025		0.048		**0.043**

Table 7
Multi-criteria decision making and determination of a compromise solution using VIKOR method.

Criteria	**1-REF**	**2-SF-C**	**3-FA-A**	**4-SR-C**	**5-W-C**	**6-CC45**	**7-OSE**	**8-HCII**	**9-CPRC**	**10-GSR**	**Optimal**
C1	56.82	85.51	67.70	62.37	60.69	58.73	63.87	65.24	85.93	80.05	Min.
C2	688.84	52.08	186.25	97.37	319.40	271.78	383.82	135.98	210.40	151.43	Min.
C3	1.01E+01	3.13E+00	4.19E+00	3.64E+00	2.56E+00	4.57E+00	5.45E+00	3.88E+00	4.60E+00	5.64E+00	Min.
C4	1.97E+01	6.93E+00	8.99E+00	7.97E+00	1.03E+01	9.54E+00	1.12E+01	8.30E+00	9.75E+00	1.38E+01	Min.
C5	1.11E+01	5.61E+00	6.54E+00	6.04E+00	7.23E+00	6.67E+00	7.39E+00	6.15E+00	6.86E+00	2.43E+01	Min.
C6	16635.44	14820.85	20072.10	12837.12	13851.42	13218.54	13754.76	12807.53	13449.16	24990.88	Min.
C7	19097.56	19587.31	27573.89	16752.14	17234.10	16868.52	17218.16	16598.53	17074.56	31347.98	Min.
C8	11834.81	11336.24	15522.91	9745.56	10222.59	9950.87	10246.27	9721.71	10098.38	18150.89	Min.
C9	20085.37	18716.09	25507.28	16184.96	17142.62	16526.63	17085.01	16097.05	16807.67	30760.44	Min.
S_j	0.541	0.171	0.354	0.062	0.156	0.137	0.232	0.088	0.226	0.714	Manhattan
R_j	0.167	0.100	0.115	0.019	0.070	0.057	0.087	0.029	0.101	0.168	∞ distance
Q_j	**1-REF**	**2-SF-C**	**3-FA-A**	**4-SR-C**	**5-W-C**	**6-CC45**	**7-OSE**	**8-HCII**	**9-CPRC**	**10-GSR**	ν
Q_{j0}	0.994	0.543	0.648	0.000	0.342	0.257	0.455	0.067	0.553	1.000	0.00
Q_{j1}	0.968	0.506	0.628	0.000	0.322	0.243	0.436	0.065	0.523	1.000	0.10
Q_{j2}	0.942	0.468	0.608	0.000	0.302	0.229	0.417	0.062	0.493	1.000	0.20
Q_{j3}	0.916	0.430	0.588	0.000	0.282	0.215	0.397	0.059	0.463	1.000	0.30
Q_{j4}	0.890	0.393	0.568	0.000	0.263	0.201	0.378	0.057	0.433	1.000	0.40
Q_{j5}	0.864	0.355	0.548	0.000	0.243	0.187	0.358	0.054	0.403	1.000	0.50
Q_{j6}	0.838	0.318	0.528	0.000	0.223	0.173	0.339	0.051	0.373	1.000	0.60
Q_{j7}	0.812	0.280	0.508	0.000	0.204	0.159	0.320	0.048	0.342	1.000	0.70
Q_{j8}	0.786	0.243	0.488	0.000	0.184	0.144	0.300	0.046	0.312	1.000	0.80
Q_{j9}	0.760	0.205	0.468	0.000	0.164	0.130	0.281	0.043	0.282	1.000	0.90
Q_{j10}	0.734	0.168	0.448	0.000	0.145	0.116	0.262	0.040	0.252	1.000	0.00
Score[a]	**0.864**	**0.355**	**0.548**	**0.000**	**0.243**	**0.187**	**0.358**	**0.054**	**0.403**	**1.000**	
Ranking	9th	5th	8th	1st	4th	3rd	6th	2nd	7th	10th	

[a] The closer the distance, the more favorable.

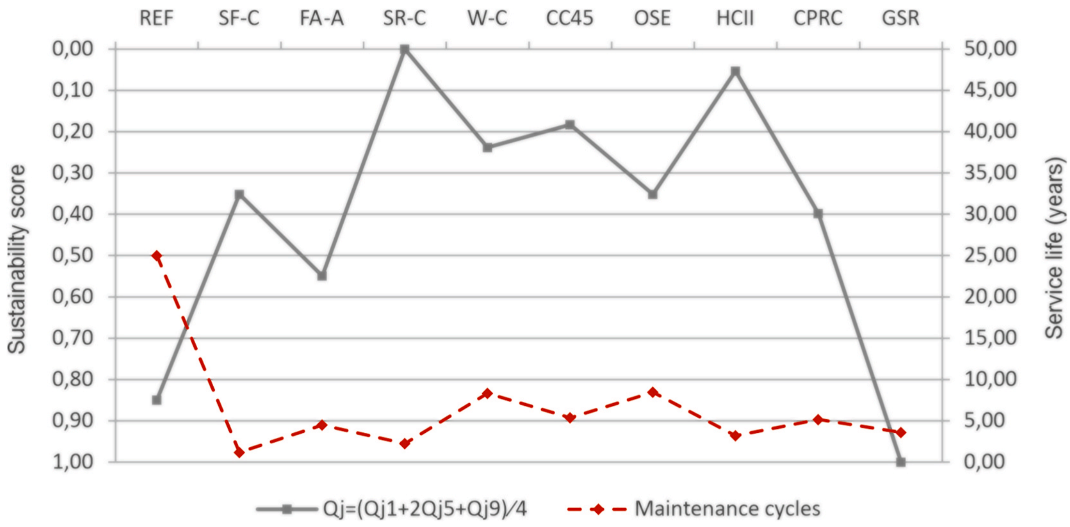

Fig. 7. Results of the sustainability life cycle assessment.

CPRC and CC45. The worst scores, notably far from the other alternatives, are found in the GSR and REF options, which involve the highest socio-environmental impacts or maintenance requirements, respectively. However, solutions with moderate durability performances, such as W/C, OSE, or FA-A, maintain a respectable score below 0.50.

One advantage that the VIKOR method has is that it can be used to perform a sensitivity study through the variable $\nu \in [0,1]$ assessing the significance of each distance by maintaining a balance between the S_j and R_j indices that correspond to the Manhattan (L_1) and Chebyshev (L_∞) distance, respectively. The results presented in Table 7 reveal that the first four positions in the ranking remain unchanged. It is as the parameter ν decreases that design option 2, called "SF-C″, begins to lose importance in favor of design option 7, called "OSE". To the extent that, for ν values between 0 and 0.4, the OSE design outperforms the SF-C option.

The results are consistent with those obtained in the research of Navarro et al. [15,17], which suggest that relying on a one-dimensional life cycle analysis for evaluating economic, environmental, and social impacts does not guarantee the optimal sustainability of a design. Addressing sustainability poses an intricate challenge involving resolving a decision-making dilemma with multiple criteria. Therefore, evaluating structural design requires a thorough approach considering all pertinent dimensions.

4. Discussion

To finalize the validation of the proposed model, this section includes a broader discussion than the previous one aimed at the presentation and discussion of the results obtained. Here, the implications of the findings obtained, beyond the results, are correlated with the latest bibliographic studies and prospective applications, structured in subsections as a response to specific hypotheses and assumptions formulated.

4.1. Study findings' applicability across structures and environments

The described building type in Section 2.1.1 is widespread in tourist areas along Spain's Atlantic and Mediterranean coasts. The study responds to a pervasive but no less serious problem in countries with many km of coastline and buildings whose lack of maintenance exposes them to dangerous structural vulnerability. Coastal buildings face significant challenges due to corrosion, a widespread problem threatening structural integrity and longevity [27]. Constant exposure to saltpeter, high humidity and harsh environmental conditions with dispersed chlorides accelerate the deterioration of materials, especially metals and reinforced concrete. This increases maintenance costs, safety risks, and potential structural failure [25].

Corrosion, although slow, is also progressive and, in addition to the apparent deterioration of the structure, produces other collateral damage and hazards, such as increased building vulnerability in an earthquake [49]. The big latent problem in many beachfront hotel buildings that have consumed half of their useful life is that this vulnerability still needs to be assessed [50]. Effective mitigation strategies, such as corrosion-resistant materials, protective coatings, and periodic inspections, are essential to preserve the durability and safety of coastal infrastructure. Addressing this problem is crucial to ensure the sustainability and resilience of buildings in coastal environments.

It should be noted that although the Life Cycle Sustainability Assessment (LCSA) methodology presented here generally applies to concrete building structures exposed to severe environments, the conclusions drawn are based on a specific building and location. Therefore, the transferability of the results depends to some extent on the particular context of the structure to be evaluated. However, the model can be adapted to different building types and locations in countries experiencing similar challenges under comparable climatic conditions, increasing the tool's practical applicability.

4.2. Adaptability of MMC to climate challenges in coastal areas

Complying with building regulations ensures robust and resilient structures. However, as climate change increasingly negatively impacts the world, more than strict compliance with construction standards is required. Climate change increases the frequency and intensity of extreme events such as hurricanes, storms, floods, and droughts, which directly affect infrastructure and buildings, disrupt services, and impact people's daily lives [51]. Adapting traditional models through innovation to the particularities of these adverse phenomena, especially in complex environments, is crucial to being able to conceive our future in a way that is not only sustainable but also resilient [52]. To address and mitigate these problems, it is essential to properly plan and design climate-resilient infrastructure and buildings, promote sustainable building practices, and develop climate change adaptation strategies at local, regional, and national scales.

In the case studied, the specific conditions of the building mean that it is located at a sufficiently safe distance from the sea so as not to be affected by the threat of rising sea levels, a challenge that port structures have to face constantly. On the other hand, innovative MMC-based structures [8], such as lightweight slabs and multiaxial concrete shapers [28], offer a considerable margin of safety [31]. These methods enable structures to withstand unforeseen events such as hurricanes, floods, storms, or earthquakes, even in areas of low seismic activity. It is also vital to address the effects of global warming, such as thermal variations and their impact on heat waves. New methodologies for assessing overheating in buildings can already be found in the literature [53]. Measures have been applied in the structure's design and calculation to control possible expansion and contraction. Excessive cracking of the structure would weaken the concrete section and leave the reinforcement more exposed to the constant cycle of chloride attack.

In any case, adapting constructions to climate change to make them resistant to these phenomena is a complex challenge that will require investment and collaboration between governments, institutions, industry, and society as a whole, as well as long-term planning to reduce the vulnerability of buildings and protect the safety and well-being of communities in an ever-changing climate world.

4.3. Implications for sustainable resilient construction in harsh environments

The sustainable construction of buildings and urban districts is directly related to up to 15 of the 17 Sustainable Development Goals of the United Nations 2030 Agenda [1]. Building retrofitting accelerates achieving several SDGs, which must continue to materialize in public policies, regulatory frameworks, and support programs designed in dialogue with professional associations, the business sector, and social agents.

Policy and regulatory frameworks for sustainable buildings in challenging coastal environments must evolve from traditional economic-environmental approaches. Focusing solely on cost reduction during construction can lead to a more significant long-term environmental impact in vulnerable areas prone to extreme weather and erosion [37]. Current policies are beginning to focus on construction methods that minimize life-cycle costs despite higher upfront costs, ensuring a positive net environmental impact [22]. This approach is in line with certifications or rating systems that are increasingly requested by companies and clients, such as

ENVISION for infrastructures or DGNB SYSTEM for sustainable buildings and districts.

A critical issue is the seismic vulnerability of older buildings in marine environments, especially those with reinforced concrete structures. These buildings, designed decades ago without considering seismic loads, face significant corrosion of steel reinforcement due to prolonged exposure to marine elements like chlorides [50]. Politically, this highlights the urgent need for structural inspection and rehabilitation policies to enhance seismic resilience. Socially, such measures protect lives and property, reducing collapse risks during seismic events and ensuring long-term public safety.

Construction engineering plays a crucial role in ensuring the resilience of buildings in harsh environments. By addressing the specific challenges of each environment and implementing suitable strategies, buildings can endure extreme temperatures, high winds, heavy rains, seismic activity, and other hazards [51]. For instance, in areas prone to high winds, the use of reinforced concrete and wind-resistant designs can be effective [54]. In regions with extreme temperatures, insulation and energy-efficient systems can help maintain a comfortable interior [2]. Current policies and regulations should prioritize protecting the interests of building owners with criteria designed to maintain structures in good condition and minimize the risk of costly repairs and structural failures. The following protocols are recommended as guidelines.

- Compliance with building codes: Ensure the building remains compliant with current building codes and local municipality bylaws to provide a safe environment for residents and reduce liability.
- Comprehensive maintenance plan: Develop a maintenance plan based on the assessment reports and conduct necessary repairs to ensure the building's optimal performance.
- Regular building condition assessments: Commission a professional team, including structural engineers, architects, and environmental specialists, to conduct a comprehensive building condition assessment every five years. This assessment will identify emerging issues, such as structural weaknesses, water damage, or environmental hazards, and recommend necessary repairs or improvements.
- Ongoing collaboration with engineering firms: Establish a continuous relationship with a professional engineering company to stay informed about the latest developments and technologies in building science, ensuring the building remains up-to-date and resilient.
- Emergency preparedness plans: Develop and implement plans tailored to the specific hazards of the building's environment, ensuring rapid response and safety during extreme events.
- Sustainable building practices: Integrate sustainable building practices to enhance the building's resilience and reduce its environmental impact, such as using eco-friendly materials and energy-efficient systems.
- Regular training for maintenance staff: Provide ongoing training to ensure they are well-versed in the latest building technologies and maintenance techniques, enabling them to manage and maintain the building's infrastructure effectively.

4.4. Limitations of the research

The databases used by Ecoinvent and SOCA have certain limitations regarding the specific building materials analyzed in this study. Consequently, the environmental and social impacts of these materials were estimated using concepts similar to those in Ecoinvent. The materials in question were part of those explicitly required for the preparation and repair of slabs and reinforcements in the maintenance phase, namely, trichloroethylene solvent, abrasive for cleaning aluminum silicate particles, fluid mortar with high mechanical strength, high modulus of elasticity and compensated shrinkage (75 N/mm^2 and E = 27000 N/mm^2) and thixotropic, fast-setting, polymer-modified mortar with compressive strength (25 N/mm^2 and E = 15000 N/mm^2).

Another limitation of the study is the use of BWM and VIKOR techniques, both widely recognized in the scientific community. The rationale for using both approaches is to achieve a more consensual result on sustainable yield. Given the absence of a universally preferred MCDM method for each assessment problem, literature reviews on MCDM applications cover a comprehensive set of techniques and their extensions, providing opportunities for future research to explore and compare the sensitivity of the results of the present study.

5. Conclusions

This study evaluates the life cycle impact of ten improved design options for the structure of a three-story hotel module with a floor area of 2132 square meters located in a coastal environment subjected to chloride environmental aggressiveness. The objective of these design alternatives is to improve the durability of the base design, thereby reducing the need for maintenance during the structure's life cycle. The reference alternative consists of a reinforced concrete structure based on MMCs, known as "Unidome" lightened slabs with multiaxial concrete shapers. MMCs are studied as a cost-effective alternative to traditional construction methods and as a way to minimize the environmental impact of construction by optimizing the use of materials.

The study employs a comprehensive three-dimensional life cycle assessment under ISO 14040 standards. It assesses the impact on the economy, environment, and society throughout a 50-year period. The analysis delves into various sustainability aspects and utilizes the BMW multi-criteria decision-making method to incorporate expert opinions. Additionally, the VIKOR method is applied to integrate sustainability parameters for each design option, ensuring precision in the assessment.

Based on the assumptions adopted in this particular case study, the specific conclusions drawn are as follows.

- From a broad perspective, it seems clear that improving the strength of structures in harsh environments translates into more positive environmental sustainability results in terms of maintenance. This is especially true when we focus on improving standard concrete mixes with additions (pozzolans, blast furnace slag or fly ash, or silica fume among the most common), thus reducing the clinker content by a percentage and CO_2 emissions.

- However, the study suggests that alternative durability design strategies, such as unconventional steel, oversizing of structural elements, or cathodic corrosion protection of concrete, only sometimes yield superior sustainability results. Conversely, solutions that require extensive maintenance may provide better results. For example, maintenance-free solutions like galvanized steel result in poorer sustainability than a high-maintenance approach involving periodic hydrophobic surface treatments.
- In economic-environmental terms, it is generally preferable to undertake several preventive maintenance cycles throughout the life of the building rather than reactive maintenance, especially when the structure is in an advanced state of deterioration due to corrosion.
- This study highlights that integrating the social aspect into the sustainability assessment throughout the life cycle, especially in the case of structures located in harsh environments such as beach hotels, which require extensive maintenance, can lead to design decisions that go beyond the results of traditional analyses focus on economic and environmental factors.
- From the consultation with the group of experts, environmental aspects were the most relevant when evaluating sustainability, at 38.6 %, social aspects at 34.6 %, and economic aspects at 26.8 %. The most highly valued criteria are the social C8 (Value Chain Actors) and economic C2 (Maintenance cost), sharing 16.7 %, followed by the environmental C4 (Human Health) and C5 (Resources), both at around 14.4 %.
- The preferred design based on the one-dimensional economic and environmental evaluations (silica fume concrete) differs from the favorite when only social impacts are considered (corrosion-inhibiting hydrophobic impregnation). However, a design that fully incorporates all three dimensions of sustainability (sulforesistant cement concrete) outperforms all other options, with a 5.4 % and 18.7 % advantage over the second (HCII) and third (CC45) alternatives, offering an impressive 86.4 % sustainability improvement over the REF baseline.
- This assessment provides a key comparison by contrasting conventional one-dimensional approaches, which only consider economic, environmental or social aspects, with a comprehensive three-dimensional sustainability perspective. It provides valuable information on the multifaceted implications associated with each sustainable design option. Sustainability is a complex issue that involves solving a multi-criteria decision-making problem. Therefore, it should be approached from a holistic perspective, simultaneously considering all dimensions of sustainability involved in the evaluation of the structure design.
- In addition to addressing economic and environmental concerns, this methodology fills a crucial gap in research by integrating social impacts into the sustainability assessment of a MMC-based building structure throughout its life cycle, emphasizing the maintenance phase. The social life cycle analysis criteria are selected based on the stakeholder approach recommended by UNEP/SETAC [34], which facilitates grouping 55 different impact categories considered within the four social categories assessed.
- Future work will seek to delve deeper into two areas. First, this methodology could explore and combine other MCDM methods to obtain subjective weights and the sustainability score. Second, it could expand the number of design alternatives oriented to reactive maintenance strategies and optimize the optimal repair interval by analyzing each year of the structure's service life compared to the preventive maintenance results obtained in this study. Further research suggests that the combined effect of some of the preventive measures presented be evaluated, and both their compatibilities and their sustainability performance should be brought to light against the alternatives considered here.

CRediT authorship contribution statement

Antonio J. Sánchez-Garrido: Writing – original draft, Validation, Software, Methodology, Investigation, Conceptualization. **Ignacio J. Navarro:** Writing – review & editing. **Víctor Yepes:** Writing – review & editing.

Declaration of competing interest

The authors whose names are listed immediately below certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

Data availability

Data will be made available on request.

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