Review Article

Life-cycle thinking and performance-based design of bridges: A state-of-the-art review

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A B S T R A C T

Given the growing emphasis on life-cycle analysis in bridge design, the design community is transitioning from the concept of performance-based design in structural engineering to a performance-based design approach within a life-cycle context. This approach considers various indicators, including cost, environmental impact, and societal factors when designing bridges. This shift enables a comprehensive assessment of structural resilience by examining the bridge's ability to endure various hazards throughout its lifespan. This study provides a comprehensive review of two key research domains that have emerged in the field of bridge life-cycle analysis, namely life-cycle sustainability (LCS) and life-cycle performance (LCP). The discussion on the LCS of bridges encompasses both assessment-based and optimization-based studies, while the exploration of LCP focuses on research examining structures subjected to deterioration over their service life due to deprecating phenomena such as corrosion and relative humidity changes, as well as extreme hazards like earthquakes and floods. Moreover, this study discusses the integration between LCS and LCP, highlighting how combined consideration of these factors can minimize damage costs, improve resiliency, and extend the lifespan of the structure. A detailed evaluation encompasses various life-cycle metrics, structural performance indicators, time-dependent modelling techniques, and analysis methods proposed in the literature. Additionally, the research identifies critical gaps and trends in life-cycle analysis within the realm of bridge engineering, providing a concise yet thorough overview for advancing considerations in the life-cycle design of bridges.

1. Introduction

Bridges are often susceptible to premature deterioration due to environmental factors such as corrosion, solar radiation, and relative humidity changes. Along with these factors, bridges located in active geological zones are exposed to further risks from extreme hazards such as earthquakes, floods, and hurricanes [1]. Integrating resilience-based thinking into bridge design and maintenance, considering both time-dependent and natural hazards, is essential to enhance the safety, resilience, and service life of bridges [2]. Note that both Federal and Provincial/State Governments in North America allocate substantial portions of their yearly budgets toward the maintenance and repair of existing bridges [3]. For instance, more than two-fifths of highway bridges in Canada and nearly half of tunnels owned by rural municipalities were built before 1940[4].Nearly 40 % of these structures are currently in very poor to fair condition [5], with anticipated repair costs reaching into the hundreds of billions of dollars. These expenditures are essential for addressing the compounded effects of environmental degradation and extreme hazards. The cumulative costs and societal impacts associated with bridge failure underscore the importance of resilient design frameworks that integrate life-cycle sustainability and performance considerations.

Remarkably, the cumulative costs incurred over the service life of bridges can often rival or even exceed the initial construction expenses. Also, downtime of any part of the infrastructure networks during post-damage operations and maintenance may have substantial societal impacts, such as vehicle delay costs, additional fuel/energy consumption, and a higher rate of accidents at the traffic diversions. Thus, integrating resilience into bridge infrastructure not only safeguards public investment but also reduces downtime and mitigates indirect social costs associated with structural failure. On account of the reasons outlined in the preceding, it is of pivotal importance to consider the life cycle sustainability in its three main pillars, namely, cost, environmental impact, and social impact. While life-cycle sustainability is crucial in bridge design, bridge engineers may prioritize structural performance, measured by indicators like strength, ductility, and reliability. In fact, the struc-

tural performance degrades with time due to lifetime deterioration effects such as material ageing and degradation from chloride attack and carbonation, freeze-thaw cycles, etc.; so, in the general case, when subjected to extreme events (e.g., earthquakes, floods, and hurricanes) the structure may not be in pristine condition as is often assumed in computational models, but may have sustained a certain degree of loss in stiffness, strength, ductility and support alteration from its original design [6]. The concept of LCP of bridges has been investigated by Val et al. [7], Strauss et al. [8], Sung et al. [9], and Cavaco et al. [10]; here, the LCP of bridges is considered owing to lifetime deterioration effects only. The combined effects of lifetime deterioration and damage caused by extreme hazards were explored by Biondini et al. [11], Yanweerasak et al. [12], and Xu et al. [13].

In order to have resilient and cost-efficient designs, both the LCS and LCP should be taken into consideration. This concept is rarely considered, if at all, by the structural design industry. The highway bridge design codes such as the AASHTO LRFD Specifications [14] and Canadian Highway Bridge Design Code (CHBDC) CSA-S6 [15] do not consider the life-cycle loss due to the deterioration of bridges. On the other hand, academia is ahead in this regard, as the link between the LCS and LCP of a bridge has been part of the research agenda for the last two decades. The literature on the LCS/LCP problem is rich, but the link between the LCS and LCP is still premature, leaving several gaps and open issues for future exploration. This study addresses these gaps by presenting a resilience-focused perspective on life-cycle considerations in bridge design, emphasizing the need to integrate LCS and LCP to improve structural durability and disaster resilience. Accordingly, it aims to serve as a paradigm shift from the perspective of both academia and the structural design industry in the context of bridge design philosophy. Integration between the LCS and LCP into a single design framework was introduced first by Stewart [16]; the life-cycle sustainability assessment (LCSA) in that study was limited to cost, whereas one of the first integrated LCS/LCP approaches that took all three sustainability pillars into consideration, i.e., cost, environmental impact, and social impact, was introduced by Lounis and Daigle [17].

Six review articles within the field of life-cycle analysis of bridges were found in the literature [18–23], two of which were conducted two decades ago [18,19]. It is noted that LCS and LCP have been reviewed indiscriminately in the literature. Penadés-Plà et al. [20] discussed the previous decision-making techniques used to optimize sustainable bridge design. Also, Martínez-Muñoz [21] discussed the LCSA of the steel-girder bridges only, and Navarro et al. [22] focused on multi-criteria decision-making in the LCSA of bridges. Alaloul et al. [23] reviewed the state of the art in the LCSA field and discussed the approaches used to assess the life cycle cost, environmental impact, and social impact of the bridges. In the present study, a comprehensive state-of-the-art review is conducted in the field of life-cycle analysis (LCA) of bridges, systematically distinguishing its two key aspects: life-cycle sustainability (LCS) and life-cycle performance (LCP). By identifying and analyzing research gaps and prevalent trends in the life-cycle analysis problem in bridge engineering, this paper aims to inform stakeholders in the field about potential areas for improvement, emerging methodologies, and opportunities for enhancing the sustainability and performance of bridge infrastructure.

2. Methodology

Structural design is generally driven by two primary objectives: structural adequacy and sustainability. Traditionally, before the 1990s, structural design was primarily strength-based, focusing on ensuring structures could withstand specified force levels. In the late 1980s and 1990s, the academic community shifted toward performance-based design (PBD), which evaluates multiple performance states, particularly under seismic loads, rather than relying solely on force resistance. By the late 1990s and the early 21st century, structural design advanced further with the introduction of life-cycle performance (LCP). Leading studies,

including Ehlen [24] and Val et al. [7], integrated performance-based principles with time-dependent considerations, accounting for degradation and the service life of structures. While LCP has become the state-of-the-art approach in bridge design, it remains more prevalent in academic research than in professional practice. Also, before the 1990s, the concept of sustainability was rudimentary, primarily emphasizing conservatism, ecological balance, and resource efficiency. In the 1990s, the concept expanded into the triple bottom line (TBL) framework, assessing sustainability through three pillars: cost, environmental impact, and societal implications. The TBL term was introduced by John Elkington in 1994, and from that point forward, it captured the attention of researchers, policymakers, and businesses [25]. Post-2000, this concept evolved into life-cycle sustainability (LCS), incorporating methodologies such as LCC, environmental-LCA, and societal-LCA, which consider the entire lifespan of structures. This paper explores the state-of-the-art in life-cycle bridge design, structured into two main domains: LCP and LCS, as illustrated in Fig. 1.

The state-of-the-art review in this paper is conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, consistent with the systematic review methodology adopted by Al Hawarneh et al. [26]. Referred sources included the life-cycle assessment of bridges and the life-cycle performance of bridges. As shown in Fig. 1, the state-of-the-art review in this paper is organized into four axes, namely LCS, LCP, integrated LCS/LCP using an assessment-based approach, and integrated LCS/LCP using an optimization-based approach. The discussion on the LCS of bridges covers both assessment-based and optimization-based studies, whereas the discussion on the LCP of bridges addresses the research articles that conducted performance-based assessment in a life-cycle context. The third and fourth axes discuss the integration between LCS and LCP in the design of bridges using assessment-based and optimization-based approaches, respectively. The different life-cycle metrics, structural performance indicators, time-dependent modelling techniques and analysis methods used in the reference papers are also discussed.

3. Overview of the literature

In the subsequent sections, the published literature on the life-cycle analysis of bridges starting from 1999 is outlined, including its two branches, namely the LCS and LCP. The different life-cycle metrics, structural performance indicators, time-dependent modelling techniques and analysis methods presented in the various articles are also discussed comprehensively.

3.1. Life-cycle sustainability of bridges

Before the 1970s, life-cycle cost assessment (LCCA) was primarily conducted under the framework of cost-benefit analysis [27]. Concurrently, the 1960s and 70 s saw the emergence of environmental-LCA methodologies [28]. Initially, environmental-LCA focused on simplistic concepts, primarily centered on quantifying the embodied energy in products and materials. It was not until Mohammadi et al. [29] integrated life-cycle analysis into bridge design that its practical application in engineering became evident. The modern environmental-LCA, as we know it today, in its four main stages, namely, scope definition, inventory analysis, impact assessment, and interpretation, was formalized into ISO standards between 1997 and 2000 [30].

3.1.1. Life-cycle sustainability – assessment studies

The sustainable design of structures aims to minimize one or all of the sustainability aspects, namely the cost, the environmental impact, and the social impact [31]. Different materials or retrofit techniques have been considered in order to enhance the LCS performance of bridges. Table 1 provides an analytical review of assessment-based studies in the area of LCS of bridges, listing the life-cycle metrics and the major outcomes of each reviewed article. Ehlen [24] investigated the cost-
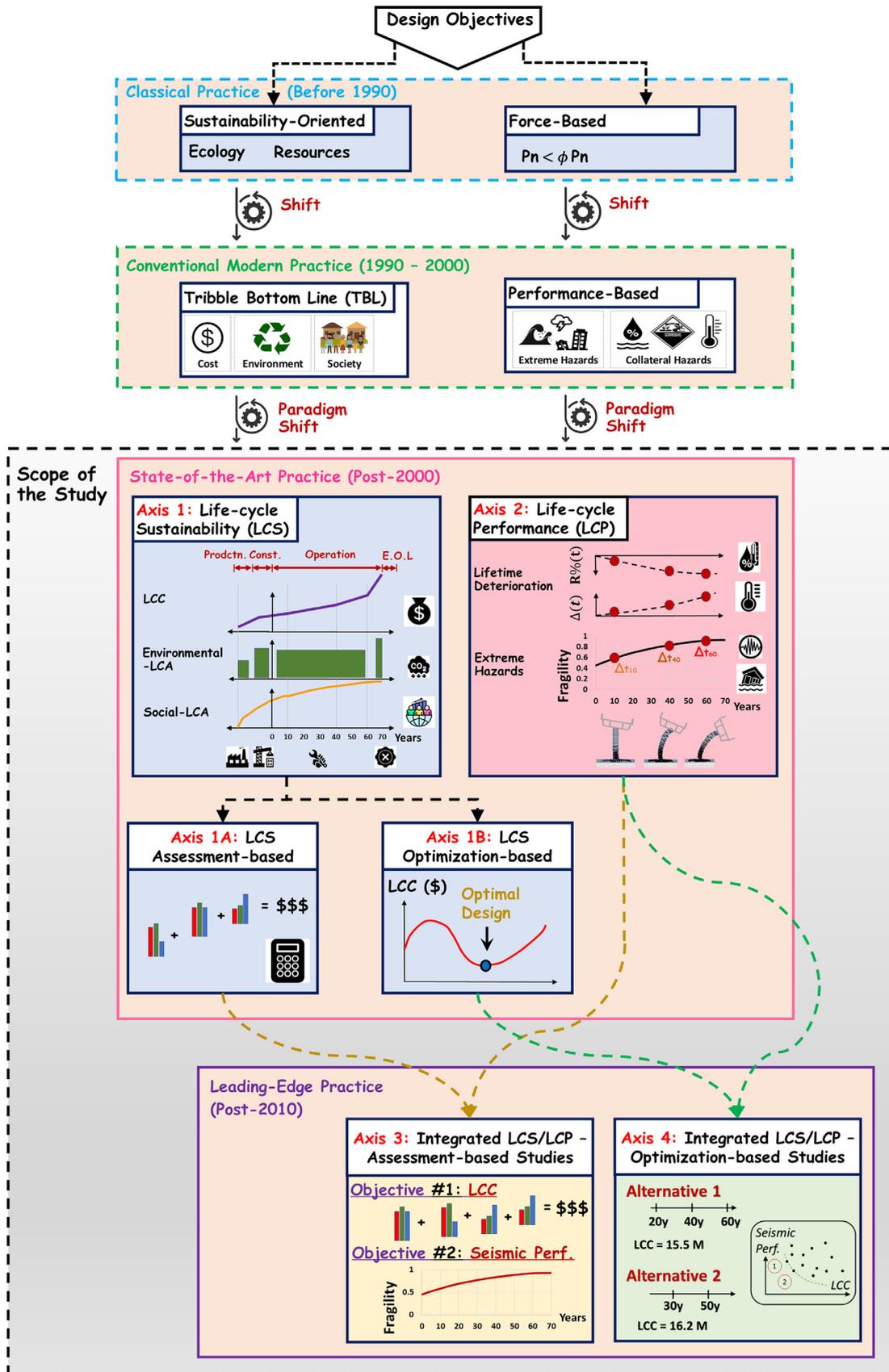
Fig. 1. Methodology framework of the state-of-the-art review.

Table 1

Review of articles in the area of LCS of bridges: assessment-based studies.

Article	Life-cycle Metrics	Bridge Elements	Reinf. Type	Major Findings
Cadenazzi [44]	Cost	Piles & Seawalls	CFRP	CFRP had a higher initial cost compared to traditional reinforcement but a lower LCC.
Hammervold et al. [36]	Env.	Deck, Girders, & Piers	Mild Steel and Prestressed Strands	The concrete bridge outperformed the wooden bridge in all environmental categories except for GWP, where the LCEI was 9.1 % higher.
Pang et al. [46]		Deck, Girders	Prestressed Strands	Strengthening the girders with steel plates is economically inferior but environmentally superior to CFRP plates, as indicated by the study.
Penadés-Plà et al. [39]		Deck, Girders	Prestressed Strands	The overall environmental damage was 11.7 % less in the case of higher-grade concrete.
Martínez-Muñoz et al. [41]		Deck	Mild Steel and Prestressed Strands	If the steel recycling ratio surpasses 90 %, composite girders become more environmentally preferable than prestressed girders.
Navarro et al. [31]	Society	Deck	Galvanized Steel, and Stainless Steel	The highest social benefit was achieved by replacing the carbon steel with stainless steel, not by changing the concrete grade or constituents.
Mistry et al. [42]	Cost & Env.	Piers	Nickel-containing Stainless Steel	The LCEI of the nickel-containing stainless steel bridge was found to be 40 – 44 % lower than the traditional reinforced bridge.
Cadenazzi et al. [43]		Deck, Girders, & Piers	CFRP, GFRP	The FRP bridge outperformed the traditional bridge by 25 % in LCC and surpassed traditional steel in all LCA aspects except ozone depletion.
Ehlen [24]	Cost & Society	Deck	Fabric materials	The WC-FRP was found the most economic option with an LCC lower than that of the SCRIM-FRP and PP- RFP by 37.7 % and 46.2 %, respectively.
Singh and Tiong [32]		Deck	Mild Steel	The savings due to using a higher grade of concrete was 40 %
Eamon et al. [35]		Deck & Girders	Cathodic-protected Steel, Epoxy-coated Steel, and CFRP	LCC was reduced by 62.7 % and 60.4 % when the CFRP was replaced with cathodic-protected steel and epoxy-coated steel, respectively.
Wang et al. [47]		Deck & Girders	Mild Steel	The LCC of replacing the deck was significantly higher than repainting it with anti-corrosion paint.
Daigle and Lounis [33]	Cost, Env., & Society	Deck	Mild Steel	The reduction in the agency cost, user cost, and CO2 emissions due to using HPC, was found to be 42.4 %, 30.4 %, and 65 %, respectively.
Kendall et al. [34]		Deck	Mild Steel	LCC was reduced by 9 % by replacing the mechanical steel expansion joints with ECC link slabs.
Soliman and Frangopol [37]		Girders	Corrosion-resistant Steel	Although the initial cost of the corrosion-resistant steel was higher, its LCC was lower than that of the conventional steel.
Penadés-Plà et al. [40]		Deck, Girders.	Prestressed Strands	Even with the inclusion of social-LCA, the order of design alternatives (e.g. various concrete grades and maintenance periods) remained unchanged.
Pedneault et al. [38]		Deck, Girders	NA	Compared to the concrete deck, the initial cost of the aluminum deck was double, but the LCC was a quarter. The LCEI was much less in all aspects.
Navarro et al. [48]		Deck & Girders	Prestressed Strands and Stainless Steel	The inclusion of social-LCA shifted the optimal design alternative to adding silica fume instead of using hydrophobic treatment.
Shen et al. [45]		Deck	Galvanized Steel & Epoxy-coated Steel	The LCA was significantly affected by parameters including the daily traffic volume, the number of highway lanes, and the thickness of the concrete cover.

effectiveness of three fiber reinforced polymer (FRP) deck types, namely, (a) the wood-core FRP, (b) Seeman composite resin infusion molded FRP, and (c) pultruded-plank FRP. Singh and Tiong [32] investigated the effect of using two different concrete compressive strengths, i.e., 30 and 45 MPa, on the LCC of the bridges. Daigle and Lounis [33] proposed high-performance concrete mixes, one with 7.5 % silica fume, one with 30 % fly ash, and one with 70 % GGBS, to enhance the LCC and environmental-LCA of the bridges. Kendall et al. [34] introduced an alternative bridge-deck system by replacing the mechanical steel expansion joints with engineered cementitious composite (ECC) link slabs to reduce the LCC of the bridge. Eamon et al. [35] investigated the LCC of concrete girders reinforced with un-coated steel with cathodic protection, epoxy-coated steel reinforcement, and Carbon Fiber-Reinforced Polymer (CFRP) reinforcement. Hammervold et al. [36] came up with a holistic LCA model that considers six environment related damage categories in the design of bridges, i.e., the global warming potential (GWP), acidification potential, eutrophication potential, photo-chemical oxidant potential (PC–OP), ozone depletion potential, and abiotic depletion potential.

The majority of published research articles in the field of LCS of bridges focus on steel-reinforced concrete bridges. Only a limited number of studies, such as Singh and Tiong [32], Soliman and Frangopol [37], and Pedneault et al. [38], addressed alternatives such as FRP-reinforced concrete, steel, and aluminum bridges, respectively. Penadés-Plà et al. [39] conducted an environmental-LCA on two different post-tensioned box-section girder bridges using two alternative maintenance schedules. Penadés-Plà et al. [40] expanded the concept of their previous work by incorporating the social-LCA. Martínez-Muñoz et al. [41] followed the same approach but took into consideration the effect of using varying steel recycling ratios in the manufacturing process of the reinforcement. Other researchers investigated alternative reinforcement options in reinforced concrete bridges. For instance, Mistry et al. [42] conducted LCCA and environmental-LCA on Nickel-containing Stainless Steel reinforced concrete bridges. Navarro et al. [31] investigated the effect of using alternative reinforcement, such as galvanized steel or stainless steel, to control corrosion.

Cadenazzi et al. [43] utilized CFRP and Glass Fiber-Reinforced Polymers (GFRP) in post-tensioned concrete bridges to slow down the cor-

rosion process and reduce the LCEI of bridges. Cadenazzi [44] developed a probabilistic approach using an experiment-based coefficient of variation to determine the LCC of CFRP-reinforced bridges. Also, Shen et al. [45] developed a probabilistic approach to determine the LCC of bridges reinforced with epoxy-coated steel, galvanized steel, and micro-composite multi-structural formable steel MMFX. Pang et al. [46] compared four strengthening options in their LCA study, involving various combinations of attaching steel plates and CFRP plates to girders and beams, along with the addition of external strands. Wang et al. [47] proposed a monetary-based approach to assess the LCSI of bridges using six indicators, the physical condition, phycological condition, personal economic condition, human settlement, socio-economic condition, and social resources. Navarro et al. [48] assessed the life-cycle loss based on ISO 14040, using two different approaches, one based on the LCC and environmental-LCA, and another based on the social-LCA.

This section reviewed a broad array of assessment-based studies on the LCS of bridges, focusing on how sustainable design can minimize cost, environmental, and social impacts over a bridge's lifetime. The analysis covers research that evaluates various materials and retrofit techniques, with studies examining alternatives ranging from the use of different FRP materials and arrangements, and different concrete mix characteristics, to advanced reinforcement options. Early studies primarily focused on cost-effectiveness, with investigations into alternative materials demonstrating significant reductions in the LCC of bridges. For instance, Singh and Tiong [32] reduced the LCC of bridge decks by 40 % using a higher grade of concrete, i.e., 45 MPa instead of 30 MPa. Cadenazzi et al. [43] reduced the LCC by 25 % using CFRP reinforcement in the piles and GFRP reinforcement in the deck, girders, bent caps, gravity walls, and traffic railings. Since every bridge is unique, it is difficult to pinpoint a universally optimal technique for reducing life-cycle costs. However, evidence suggests that straightforward measures – such as using a higher grade concrete or reducing concrete's water-to-cement ratio – tend to be more effective than many of the more complex approaches.

Over time, the research evolved to incorporate environmental considerations, as evidenced by studies that extended their assessments to include parameters such as CO_2 emissions, global warming potential, and other environmental damage indicators. This shift reflects a growing recognition of the broader environmental implications of bridge construction and maintenance. For instance, Kendall et al. [34] were able to reduce the LCEI of a bridge by 75 % by replacing the mechanical steel expansion joints in the slabs with ECC. Also, it was found that the GWP effect of a wooden bridge might be as little as 90.9 % of that of a concrete bridge [36]. Furthermore, it was found that replacing the traditional steel reinforcement in concrete piers with nickel-containing stainless-steel reinforcement contributes to a 40 – 44 % reduction in the LCEI [42]. Also, according to Penadés-Plà et al. [39], upgrading concrete quality (e.g., from 35 MPa to 50 MPa) increases the environmental impact during the production phase. However, it can mitigate the environmental burden during the maintenance phase due to fewer required maintenance cycles. Overall, despite a higher manufacturing impact, a high grade of concrete not only reduces the total environmental impact but may also lower the bridge's LCC. Comparing the effectiveness of the

previous techniques in mitigating the LCEI of bridges is not easy because the environmental-LCA results are dependent on the life-cycle inventory data and LCA approach taken. Based on previous research, incorporating anti-corrosive materials into bridge design appears to be the most cost-effective and environmentally sustainable solution. In terms of social impact, most studies did not treat it as a standalone indicator with a comprehensive framework; rather, it was integrated into the LCCA framework. Notable studies that presented comprehensive social-LCA models include [31,47,48].

3.1.2. Life-cycle sustainability – optimization studies

The optimization is used in the LCS problem to minimize one or multiple sustainability parameters, i.e., cost, environmental impact, or social impact, by optimizing the geometry, material properties, maintenance program, or retrofit techniques of the bridge. In Table 2, an analytical literature review of articles published in the area of LCS of bridges: optimization-based studies, is provided. In this table, the life-cycle metrics, bridge elements being investigated, the type of reinforcement used, and the major outcomes of each article are presented. In one of the research articles, the feasible direction method (FDM) [49] was used to optimize the design of the girders, based on the number of pre-tensioned strands in the girders and post-tensioned strands in the connections to minimize the LCC [50]. In another study, a genetic algorithm, using an improved population which was selected using the Variable-depth Neighborhood Search-based Hybrid Memetic Algorithm, was used to minimize the LCC of a bridge by optimizing the geometry of its girders [51]. On the other hand, Du and Ghavidel [52] optimized the maintenance program of a bridge using deep reinforcement learning (DRL) based on the Q-learning Algorithm (QLA).

The reviewed studies in this section highlight the critical role of optimization in improving the LCS of bridges. The findings suggest that multi-objective optimization approaches integrating cost, environmental, and social metrics should be further explored to establish a more comprehensive and automated framework for sustainable bridge management. Future research in this area should focus on hybrid optimization models that can dynamically adapt to changing material costs, climate conditions, and traffic demands, ensuring that bridge design and maintenance remain economically and environmentally sustainable throughout their lifespan.

3.2. Life-cycle performance of bridges

Performance-based design (PBD) has become the backbone of new provisions of international Structural Design Codes such as the AASHTO LRFD Specifications [14] and CSA-S6 [15] – at least so for structures with high ductility. Although PBD helps designers to come up with efficient design solutions to achieve performance requirements other than strength, such as ductility, deformation capacity and resiliency, it does consider the time-dependent performance loss due to environmental factors such as corrosion, solar radiation and relative humidity changes. The life-cycle performance-based assessment (life-cycle PBA) provides a temporal projection for the structural assessment throughout the lifec-

Table 2
Review of articles in the area of LCS of bridges: optimization-based studies.

Article	Life-cycle metrics	Bridge elements	Reinf. type	Major findings
Madhkhan et al. [50]	Cost	Deck & Girders	Prestressed Strands	By increasing the cover from 50 to 90 mm and the lateral spacing of girders from 1.83 to 2.74 m, the LCC was decreased by 14.78 % and 26.8 %.
Penadés-Plà et al. [51]	Cost & Env.	Deck & Girders	Prestressed Strands	The highest LCEI occurred during the production stage, with the GWP-related LCEI being 5–13 % higher in production than in the construction stage.
Du and Ghavidel [52]	Society	Deck, Girders & Piers	–	Compared to condition-based policies, the DRL achieved lower LCC. The P-DRL was nearly the same but with higher computational efficiency.

Table 3
Summary of the literature review on articles published in the area of LCP of bridges.

Article	Hazards	Structural modelling technique	Major findings
Val et al. [7]	Corrosion	Faraday's law of electro-chemical equivalence.	Corrosion had a more pronounced impact on the flexural reliability index during the structure's service state.
Strauss et al. [8]		• Uniform degradation function. • Non-linear degradation.	Provided plots, to identify the optimal number of tendons needed to bring the bridge back to its original safety level.
Sung et al. [9]		First Fick's law of diffusion.	Thickening the cover is the most efficient technique to mitigate carbonation.
Cavaco et al. [10]		The modified corrosion stress-strain model of Oliver et al. [59]	Robustness indices were lower in cases with uniform corrosion when the redundancy effects were ignored.
Wu et al. [56]	Scour effect.	SRICOS-EFA Method	The probability of failure due to lateral deflection was much less than that due to settlement at the early age of the bridge.
Biondini et al. [11]	Corrosion & Earthquakes	• Corrosion (Fick's 1st Law) • Earthquakes (time-history).	Increasing chloride concentration from 1 % to 3 % reduced the ultimate base shear capacity by about 27 %.
Capacci and Biondini [53]		• Corrosion (Fick's 2nd law). • Earthquakes (IDA).	Enhancing network connectivity with additional road segments significantly increased resilience.
Pang et al. [54]		• Corrosion (Fick's 2nd law). • Earthquakes (time-history).	Incorporating 1.5 % steel fibers in bridge piers boosts seismic resilience by 25 %.
Xu et al. [55]		• Corrosion (Fick's 1st Law). • Earthquakes (time-history).	High corrosion levels shift column failure from flexure to flexure-shear, considerably degrading fragility.
Xu et al. [13]	Corrosion & Tsunami	• Corrosion (Fick's 1st Law). • Tsunami (static push-over).	At 50 years of age, increasing inundation depth from 5 to 6 m raises the probability of failure from 0.29 % to 9.18 %.
Yanweerasak et al. [12]	Corrosion, Traffic loading, and Earthquakes	• Corrosion (spatial modelling). • Traffic (numerical simulation). • Earthquakes (simulated ground motion records).	Due to inspection results, the time-dependent reliability is enhanced, the maintenance periods are prolonged, and the LCC is reduced.
Al Hawarneh et al. [2]	Corrosion, Earthquakes, and Climate Change	• Corrosion (Fick's 2nd law). • Earthquakes (Time-dependent IDA). • Climate (Statistical Forecast Models).	It was proven that the traditional linear PSDA Models are inappropriate when corrosion and climate change effects are taken into consideration. Consequently, polynomial drift demand expressions were developed.
Al Hawarneh and Alam [1]		• Corrosion (Fick's 2nd law). • Earthquakes (Adaptive Time-dependent IDA). • Climate (Statistical Forecast Models).	It was found that traditional time-based fragility tools do not accurately represent bridge behavior, as they depict corrosion as an ongoing process that continuously deteriorates the bridge until its end. To address this, adaptive fragility tools were developed.

ycle of bridges. An analytical literature review of articles published in the area of LCP of bridges is provided in Table 3.

Val et al. [7] introduced the concept of life-cycle PBA of bridges; later, Strauss et al. [8] conducted a life-cycle PBA taking into consideration the degradation in the reinforcement due to corrosion, using two reinforcement degradation models, one following a linear degradation function, and one based on a non-linear function. Sung et al. [9] conducted a life-cycle PBA on bridges subjected to corrosion due to carbonation. The authors assessed the effect of changing the concrete cover on the degradation of the reliability index of the bridge girders. Biondini et al. [11], Capacci and Biondini [53], Pang et al. [54], and Xu et al. [55], developed life-cycle performance-based models to assess the structural response of bridges due to the combined effect of earthquakes and corrosion. Cavaco et al. [10] conducted a robustness analysis to assess the performance of RC bridges using a bilinear slippage-fiber model. Yanweerasak et al. [12] investigated the effect of three hazards on the bridges, namely, earthquake action, high-cyclic fatigue, and chloride-induced corrosion, using time-dependent reliability-based performance assessment. Wu et al. [56] investigated the structural performance of bridges subjected to scour using the Scour Rate in Cohesive Soil – Erosion Function Apparatus (SRICOS-EFA) method of Briaud et al. [57] based on soil parameters quantified using the Random Field Modelling [58]. On the other hand, Xu et al. [13] conducted life-cycle PBA to investigate the structural response of coastal RC bridges in a geographical location subjected to both chloride attacks and Tsunami actions, using static push-over analysis. Al Hawarneh et al. [2] employed incremental dynamic analysis (IDA) over a projected timeline to predict the future damage in existing reinforced concrete bridges. These results were further utilized to develop drift demand expressions for bridge piers under climate change scenarios. Al Hawarneh and Alam [1] highlighted the need for a realistic time-dependent fragility assessment tool for bridges

in multi-hazard environments. By integrating the effect of maintenance, a novel maintenance-adjusted fragility tool was developed.

As illustrated in Table 3, early studies primarily focused on single deterioration mechanisms, such as corrosion-induced degradation [7–9]. However, more recent research has expanded to multi-hazard environments, integrating earthquakes, fatigue, scour, climate change, and tsunami actions [11,56,13]. These studies highlight that corrosion accelerates structural degradation, reduces seismic resistance, and can shift failure modes in bridge components, necessitating advanced probabilistic models for more accurate predictions. The latest research efforts incorporate maintenance-informed fragility tools and climate-adjusted deterioration models [1], enhancing the ability to forecast future damage states and optimize maintenance planning. Overall, research in this field is less advanced than in the subsequent sections on integrated LCS/LCP of bridges. Structural performance alone is insufficient for effective design and maintenance planning; instead, factors such as LCC and environmental considerations play a crucial role in decision-making.

3.3. Integrated LCS/LCP of bridges: assessment-based studies

The integration between the LCS and LCP in one model is a way to assess the design of a structure based on its performance while taking the life-cycle consequences such as the cost, environmental impact, and social impact, into consideration. The first integration between these two aspects in one design approach was by Stewart [16]. The LCSA in this study was limited to the cost. Ang et al. [59,60] implemented a reliability-based approach to determine the LCCA of bridges based on the damage level and intensity of earthquake loads. Estes and Frangopol [61] added serviceability limit states to the conventional strength-based reliability analysis to predict the damage levels at which the bridge should be repaired. Huang et al. [62] developed a framework to design

a bridge with the lowest LCC while ensuring the minimum condition index required by design specifications. Kumar et al. [63] studied the coupled effect of chloride-induced corrosion and seismic actions on the LCC of bridges. So et al. [64] developed an LCCA approach to assess the LCP of bridges in a corrosive environment based on the damage condition and rehabilitation approach of the bridge. Padgett et al. [65] developed a framework to select the best retrofit option for an existing non-seismic bridge post-earthquake. Bocchini et al. [66] calculated the LCC of bridges based on three LCP approaches: a five-state Markov Chain Model (MCM), an exact Monte-Carlo simulation, and an approximate Monte-Carlo simulation. Dong et al. [6] presented the only multi-hazard approach that took the three compounded hazards (i.e., earthquakes, floods, and chloride-induced corrosion), into consideration in a single LCP/LCA model. Dong and Frangopol [67] considered two extreme hazards combined, namely earthquakes and floods, while accounting for the effects of climate change on the LCP. Zheng et al. [68] utilized novel cable-based bearings made of shape memory alloys (SMA) to enhance seismic resilience and reduce the LCC of bridges. Wang et al. [69] proposed a multi-objective LCA approach to design a bridge subjected to corrosion based on four objectives, the LCP, LCC, environmental-LCA, and social-LCA. Dong [70] conducted a life-cycle PBA on ultra-high performance concrete (UHPC) bridge girders in a life-cycle context. Shekhar et al. [71] conducted a seismic-based LCCA on bridges subjected to chloride attack due to three different reasons, namely, deicing salts, marine splashing, and marine atmospheric attacks. Navarro et al. [72] and Chen et al. [73] conducted LCA on bridges subjected to, using serviceability-based structural performance indicators, the time to corrosion and crack width, respectively. In a one-of-a-kind study in this field, the effect of high-cyclic fatigue on the LCP of steel bridges was investigated by Lemma et al. [74].

The LCP of bridges under earthquake risk was assessed by various studies including [75–80]. Zheng and Dong [75] investigated the LCP of piers reinforced with SMA in a life-cycle context. Li et al. [76] utilized SMA cable-based restrainers to improve the LCP of bridge piers and reduce the maintenance cost, hence the LCC of bridges. Valigura et al. [77] utilized hybrid rocking sliding HRS columns to improve the LCP of concrete bridges. Javidan and Kim [78] conducted fragility analysis using the nonlinear static pushover N2 method and assessed their toolbox's success by comparing its results with those from IDA. Wanniarachchi et al. [79] proposed a decision-based methodology to select the best bridge system using the Fuzzy Logic Method. The study by Wanniarachchi et al. [80] was a validation for the proposed framework by Wanniarachchi et al. [79] using a case study on a bridge pier reinforced with superplastic SMA. The LCP of bridges under an earthquake risk in a corrosive environment was assessed by [81–84]. Shekhar and Ghosh [81] predicted the LCC of bridges based on an improved seismic vulnerability model using the adaptive least-square boosting meta-algorithm. Messore et al. [82] took into consideration the aging effect on the LCP of bridges. Mortagi and Ghosh [83] incorporated the climate change effect in the seismic vulnerability assessment. Torti et al. [84] assessed the LCC of bridges equipped with seismic health monitoring (SHM) devices. Table 4 presents a summary of the key points of the various articles in the area of integrated LCS/LCP of bridges: assessment-based studies.

As outlined in Table 4, the integration of LCS and LCP has played a crucial role in evaluating bridge design, maintenance, and retrofit strategies while considering cost, environmental, and social impacts. As an observation, the early studies in this field primarily focused on LCCA as a standalone metric, such as Stewart [16] and Ang et al. [60], where reliability-based approaches were employed to assess structural deterioration under specific hazards like corrosion and earthquakes. Over time, research evolved into multi-hazard assessment frameworks, incorporating earthquakes, floods, climate change, and corrosion [6,71,83]. A key shift in recent studies has been the emphasis on resilience-based approaches, integrating novel materials such as shape memory alloys [68,76] and hybrid rocking sliding columns [77] to reduce damage accumulation and improve post-event performance.

While research in this area has expanded, a key reflection is that many studies still emphasize the life-cycle analysis over broader sustainability metrics, limiting their applicability in real-world decision-making. Future research should focus on bridging the gap between theoretical models and practical implementation. Additionally, efforts should be directed toward developing adaptive and real-time fragility tools to enhance the long-term resilience and sustainability of bridge infrastructure.

3.4. Integrated LCS/LCP of bridges: optimization-based studies

Optimization in this field was used either to optimize the geometry of the bridge, select optimal material constituents, or improve the maintenance program of bridges. The first optimization-based study in this field was by Kong and Frangopol [85]. The researchers in this study developed an optimization model to minimize the LCC of bridges by optimizing their maintenance program using the FDM method [49]. Then, the optimal maintenance scenario was associated with the minimum LCC. Lounis and Daigle [17] introduced an optimization-based LCS/LCP approach that considered the three sustainability metrics, i.e., cost, environmental impact, and social impact, using a multi-criteria decision-making approach which is Goal Setting and Compromise Programming. Almeida et al. [86] minimized the LCC by optimizing the maintenance schedule using a genetic algorithm. This study investigated three degradation models: Roelfstra [87], Orcesi and Cremona [88], and Devaraj [89]. On the other hand, Researchers such as Liu and Frangopol [90], Sabatino et al. [91], Tapia and Padgett [92], Sabatino et al. [93], and Xie et al. [94] employed multi-objective Genetic Algorithms (MO-GA) to minimize the LCC of bridges through the optimization of bridge maintenance programs. Liu and Frangopol [90] and Sabatino et al. [91] took into consideration one lifetime hazard, i.e., the chloride-induced corrosion. Tapia and Padgett [92] optimized the maintenance program of a bridge subjected to earthquake actions, in order to minimize the LCC of the bridge. Sabatino et al. [93] and Xie et al. [94] evaluated the time-dependent deterioration of bridges but defined no specific hazard in their approaches. Saad et al. [95] developed an optimization model to minimize the LCC of concrete bridges subjected to chloride-induced corrosion and Traffic loading, by optimizing the thickness of bridge decks. García-Segura [96] optimized the design of post-tensioned box-section girders, in two stages, optimizing the cross-section and materials properties of bridge decks, then optimizing the maintenance program, one time based on the minimum LCC, and another time based on the minimum LCEI. Li and Li [97] proposed an optimization model to maximize the life-cycle safety and minimize the LCC of bridge piers. Tao et al. [98] came up with an optimization model to minimize the LCC of bridges subjected to both earthquakes and corrosion using Dynamic Programming. Han and Frangopol [9]] performed a parametric analysis to optimize maintenance programs for bridges by implementing a risk-based life-cycle strategy aimed at maximizing life-cycle performance while minimizing costs. Al Hawarneh and Alam [3] developed a Linear Programming optimization model to improve maintenance planning for deficient reinforced concrete bridges in multi-hazard environments that have already experienced prior corrosion, ensuring both cost-effectiveness and structural resilience. Table 5 summarizes the key attributes of articles published in the area of integrated LCS/LCP of bridges: optimization-based studies.

Overall, optimization efforts in this area, where both LCS and LCP of bridges are considered, remain limited due to the complexity of the problem, particularly when multiple hazards are involved. Most studies predominantly focus on minimizing LCC by optimizing bridge maintenance programs. Early research primarily addressed single hazards, such as chloride-induced corrosion, as seen in Liu and Frangopol [90] and Almeida et al. [86]. However, later studies expanded into multi-hazard approaches, incorporating seismic risks, climate change effects, and other deteriorating factors, exemplified by Al Hawarneh and Alam [3]. Some studies, such as Tapia and Padgett [92] and Li and

Table 4
Summary of the literature review on articles published in the area of integrated LCS/LCP of bridges: assessment-based studies.

Article	Hazards	Life-cycle Metrics	LCP indicators	Major findings
Stewart [16]	Corrosion	Cost	Reliability	The impact of increasing the W/C ratio on the likelihood of cracking becomes more noticeable when thicker concrete covers are utilized
Estes and Frangopol [61]			Reliability	With the serviceability flags in the reliability models, the time to repair gets shortened and the retrofit cost gets increased.
So et al. [64]			Time-to-Corrosion	Despite its lower initial cost, carbon steel has a higher LCC than stainless or epoxy-coated steel.
Bocchini et al. [66]			Reliability	The probability of a specific operational state is nearly identical in Markov Chain Model, exact, and approximate Monte-Carlo simulations.
Huang et al. [62]		Cost & Society	Condition Index	The relationship between the maximum tolerable condition index and LCC is convex.
Navarro et al. [72]			Time to Corrosion	Achieving the highest economic benefit involved using a lower W/C ratio of 0.35 instead of 0.45, resulting in a 58.5 % reduction in LCC.
Dong [70]		Cost & Env.	Reliability	Replacing ordinary concrete with UHPC reduced CO_2 emissions by 30 %, and allowed for downsizing the dimensions of the deck.
Wang et al. [69]		Cost, Env., & Society	Strength level and Time-to-corrosion	The mean annual cost in the hierarchical approach was 25 % of the traditional approach, accompanied by a 45 % reduction in LCEI.
Chen et al. [73]			Crack width	The service life of hybrid reinforced beams with 0.5 % fibers, is at least 58 % more than that of the conventionally reinforced beams.
Lemma et al. [74]	Traffic loading	Cost, Env. & Society	High-cyclic fatigue	The use of high strength steel girders has a minor effect on the LCEI but a negligible effect on the LCC.
Padgett et al. [65]	Earthquakes	Cost	Fragility	The cost-benefit ratio for a retrofit technique depends on the local hazard curve and economic losses.
Zheng and Dong [75]			Fragility	Replacing the traditional reinforcement with SMA decreased the LCC by 15 %
Valigura et al. [77]			Drift	The construction time of HRS columns was 80 % less than that of conventional columns. Also, the repair cost was much less in the long term.
Javidan and Kim [78]			Fragility	Their toolbox's success was assessed by comparing its results with those from IDA.
Ang et al. [60]		Cost & Society	Fragility	It was found that the most important parameters in the LCCA of bridges are the user cost and indirect economic losses.
Zheng et al. [68]			Resilience	The life-cycle loss is reduced by >30 % when cable-based SMA bearings are used instead of conventional bearings.
Li et al. [76]			Fragility	The LCC of bridges retrofitted with Fe-based and NiTi SMA restrainers is 87 % and 85.4 % less than that estimated for un-retrofitted bridges.
Wanniarachchi et al. [79]		Cost, Env. & Society	Fragility	The authors came up with a tool to incorporate multiple criteria in the bridge selection process based on the design needs.
Wanniarachchi et al. [80]			Fragility	The SMA-reinforced bridge excelled in LCC and seismic performance compared to the conventional bridge but not in terms of LCEI.
Kumar et al. [63]	Corrosion & Earthquakes	Cost	Low-cycle fatigue	Cumulative seismic damage had a higher impact on failure probability than corrosion, even in corrosive environments.
Shekhar et al. [71]			Fragility	The deicing salt effect on the fragility was more than that of marine splashing and much more than that of the marine atmospheric attacks.
Shekhar and Ghosh [81]			Fragility	The proposed approach showed comparable results to the Monte-Carlo simulation but with a higher computer running efficiency.
Mortagi and Ghosh [83]			Fragility	Without the climate change effect, the LCC of steel and concrete bridges is underestimated by 6.7 % and 13.2 %, respectively.
Messore et al. [82]		Cost & Society	Fragility	The user cost at 60 years increases by 230 % with the perfect correlation approach and 55 % with the distance-based approach
Torti et al. [84]			Fragility	The economic benefit from the use of SHM is substantial only when the indirect cost is high and the discount rate is low.
Dong and Frangopol [67]	Corrosion, Earthquakes, and	Cost & Society	Resilience	The effect of climate change or time-dependent deterioration due to corrosion, on the life-cycle loss of bridges, is higher than that of aging.
Dong et al. [6]	Floods	Cost, Env. & Society	Fragility	The probability of full damage at an 80-year age, with a PGA of 0.4g, could increase by up to 25 % when considering flood hazards.

Li [97], developed optimization models for post-failure retrofit actions, while others, including Sabatino et al. [91] and Saad et al. [95], focused on preventive maintenance programs throughout the bridge's service life. A recent study by Al Hawarneh and Alam [3] integrated preventive and post-retrofit strategies within a single model, considering the entire LCC due to lifetime deterioration and post-retrofit costs. Despite these advancements, few studies fully incorporate real-world uncertainties, long-term climate effects, and AI-driven adaptive optimization techniques, which remain critical areas for future research and practical implementation.

4. Critical review of the literature

As delineated in the preceding sections, the life-cycle analysis of bridges comprises two branches: the LCP and LCS of bridges. The LCP is assessed through structural performance indicators like ductil-ity, displacement, and drift. Conversely, the LCS, as previously elucidated, is gauged utilizing three distinct sustainability metrics: LCC, environmental-LCA, and social-LCA. Section 4.1 presents the research trends in LCC within the realm of life-cycle analysis of bridges. Section 4.2 expounds on the approaches and methods employed in environmental-LCA. Sections 4.3 and 4.4 delve into the indicators employed in the literature for measuring social-LCA and life-cycle PBA, respectively.

4.1. Research trends in the LCC of bridges

The research on LCC of bridges is categorized into five distinct areas, as introduced in Table 6: materials advancement, LCC modelling approaches, design strategies, maintenance and management techniques, and manufacturing innovations. The most significant research contributions in the field of LCC for bridges are evident in the materials ad-

Table 5
Analytical literature review on articles published in the area of integrated LCS/LCP of bridges: optimization-based studies.

Article	Hazards	Life-cycle Metrics	LCP indicators	Major findings
Liu and Frangopol [90]	Corrosion	Cost	Safety Level & Condition Index	The optimal solution significantly changed when uncertainties in the deterioration model were considered.
Almeida et al. [86]			Condition Index	Devaraj's model [89] achieved the lowest LCC compared to Roelfstra [78] and Orcesi and Cremona [88] models.
Kong and Frangopol [85]		Cost & Society	Reliability	The toolbox conducted a realistic LCCA, considering uncertainties in maintenance scenarios.
Lounis and Daigle [17]		Cost, Env. & Society	Reliability	For 45 MPa concrete, the optimal alternative is a Pareto solution, while for 30 MPa, it is a dominant solution.
Sabatino et al. [93]			Reliability	In a 3-period maintenance program, the optimal sequence was to replace the deck, interior girders, and then the deck again.
García-Segura [96]			Time-to-corrosion	The minimum LCC coincided with an optimal maintenance program that likely involves fewer cycles.
Xie et al. [94]			Reliability	The preventive approach in maintenance contributed to 25 % less LCEI compared to the reactive approach.
Li and Li [97]	Earthquakes	Cost	Ductility & Safety Level	Compared to traditional multi-objective models, this model provided a global Pareto front and selected a single optimal solution.
Tapia and Padgett [92]		Cost, Env. & Society	Reliability	Elastomeric bearings and seat extenders with shear keys were identified as the optimal retrofit actions for all bridge components.
Saad et al. [95]	Corrosion and Traffic loading	Cost & Society	Reliability	Changing the corrosion level from high to extreme increased the LCC by 30 %.
Sabatino et al. [91]		Cost, Env. & Society	Reliability	In the four-objective model, replacing the entire superstructure achieved the lowest cost but the highest environmental and social scores.
Tao et al. [98]	Corrosion and Earthquakes	Cost	Reliability & Damage Index	The LCC is minimally affected by the selection of inspection intervals unless the design spectral acceleration is 0.10 g or less.
Han and Frangopol [99]			Reliability	The maintenance approach designed to keep corrosion risk below a specified threshold may lead to a risk level exceeding that threshold once seismic risk is considered.
Al Hawarneh and Alam [3]	Corrosion, Earthquakes, and Climate Change	Cost & Society	Fragility	The findings suggest that shortening the time between future maintenance actions can be advantageous up to a certain point, which depends on both the environmental conditions and design of the bridge piers.

vancement front. Regarding reinforcement options, studies have delved into alternatives such as stainless steel, cathodically-protected steel, and nickel-containing stainless steel, as investigated by So et al. [64], Eamon et al. [35], and Mistry et al. [42], respectively. In terms of concrete performance, various alternatives, including High Performance Concrete (HPC), fiber-reinforced concrete, and CFRP-reinforced concrete, have been explored by Daigle and Lounis [33], Chen et al. [73], and Cadenazzi [44]. Future research trends in this field may involve exploring other advanced materials, including high-strength steel, aluminum reinforcement, and textile-reinforced cementitious matrix.

In terms of the LCC modelling approaches, researchers have adeptly navigated diverse methodologies to refine the understanding and evaluation of LCC. Ang et al. [60] delved into reliability-based LCCA, employing a robust framework to assess the uncertainties inherent in cost estimations. Singh and Tiong [32] brought depth to the discourse through the application of probabilistic LCCA with sensitivity analysis. On the other hand, Padgett et al. [65] implemented life-cycle cost-benefit analysis in which they weighted economic benefits against incurred costs throughout the life of the bridge. More recently, Shen et al. [45] developed a probabilistic LCCA model that goes beyond conventional approaches by integrating environmental and social costs into the cost evaluation framework, offering a more comprehensive assessment. Javidan and Kim [78] extended this trajectory even further with an exploration of fragility-based LCCA, elucidating the interplay between structural vulnerabilities and life-cycle costs. Al Hawarneh and Alam [3] introduced an enhanced fragility-based LCCA framework, in which the fragility function employs an adaptive model that accounts for periodic improvements in fragility resulting from routine maintenance activities. Future directions in LCC modeling may include the application of techniques like stochastic analysis and reliability-centered maintenance management.

Within the design strategies trend, inventive approaches have optimized structural and functional facets of bridges. Kendall et al. [34] replaced the mechanical steel expansion joints in the bridge slabs with ECC. Navarro et al. [72] explored concrete mixes with fly ash and silica fume, demonstrating a commitment to sustainability. Zheng et al. [68] utilized novel cable-based bearings, made of shape memory alloys SMA. Valigura et al. [77] explored hybrid rocking sliding columns to enhance the resiliency of bridges. Pedneault et al. [38] introduced aluminum composite decks for sustainable construction. Future research work in this area might include investigating the LCC of various designs of bridges including the cable-stayed and suspension bridges.

In the maintenance and management techniques trend, strategies to extend lifespan and enhance performance have been the subject of investigation. Padgett et al. [65] scrutinized the effectiveness of various structural retrofitting techniques, such as steel jackets, elastomeric bearings, restrainer cables, seat extenders, and shear keys. Pang et al. [46] investigated the LCC of bridges retrofitted with steel plates, CFRP, and external prestressing strands. Navarro et al. [72] conducted LCC on maintenance techniques involving hydrophobic treatment and sealant surface treatment for corrosion prevention. Li et al. [76] utilized SMA cable-based restrainers to improve the LCP of bridge piers and reduce maintenance costs. Torti et al. [84] explored seismic health monitoring devices for real-time structural health management. Future research in maintenance and management techniques may develop smart and sustainable solutions that enhance the longevity and resilience of bridge structures.

There is limited literature exploring manufacturing innovations to enhance the LCC of bridges. Martínez-Muñoz et al. [41] contributed to this gap by examining the sustainability aspect through the use of recycled steel in the manufacturing process of reinforcement. Subsequent research endeavours may focus on integrating advanced manufacturing technologies and materials to bolster the overall sustainability and efficiency of bridge construction. As industries increasingly adopt green practices, innovative manufacturing techniques may encompass the utilization of eco-friendly materials and advanced fabrication methods.

Table 6
Research trends in the LCC of bridges.

Research trends in LCC	Techniques/methods utilized	Reference
Materials advancement	Fiber reinforced polymers (FRP)	[24]
	High performance concrete	[33]
	– Stainless steel	[64]
	– Epoxy-coated steel	
	– Cathodic-protected steel	
	– Epoxy-coated steel	[35]
	– CFRP	
	Corrosion-resistant steel	[37]
	Nickel-containing stainless steel	[42]
	UHPC	[70]
	– CFRP concrete	[43]
	– GFRP concrete	
	Shape memory alloys	[75]
	Hybrid reinforcement (fibers and rebars)	[73]
	CFRP concrete	[44]
LCC modelling approaches	Reliability-based LCCA	[60]
	Probabilistic LCCA with sensitivity analysis	[32]
	Life-cycle cost-benefit analysis	[65]
	Probabilistic LCCA incorporating environmental and social cost parameters	[45]
	Fragility-based LCCA	[78]
	Adaptive fragility-based LCCA	[3]
Design approaches	Engineered cementitious composite link slabs	[34]
	Various concrete design mixes (using Fly ash, Silica Fume, etc.)	[72]
	Novel cable-based bearings, made of SMA	[68]
	High strength steel girders	[74]
	various concrete design mixes (using fly ash, silica fume, etc.)	[48]
	Hybrid rocking sliding (HRS) columns	[77]
	Aluminum composite decks	[38]
Maintenance and management strategies	– Steel jackets	[65]
	– Elastomeric bearings	
	– Restrainer cables	
	– Seat extenders	
	– Shear keys	
	– Steel plates	
	– CFRP plates	[46]
	– External prestressing strands	
	– Hydrophobic treatment	
	– Sealant surface treatment	[72]
	SMA cable-based restrainers	[76]
	Maintaining slabs with anti-corrosion paint	[47]
	– Hydrophobic treatment	[48]
	– Sealant surface treatment	
	Seismic health monitoring (SHM) devices	[84]
Manufacturing techniques	Using a ratio of recycled steel in the manufacturing process of reinforcement	[41]

4.2. Environmental-LCA approaches & methods

Various approaches and LCEI methods used in the previous research work to assess the environmental-LCA of bridges are illustrated in Table 7. Three approaches are often used to assess environmental-related damages: the midpoint, endpoint, and midpoint/endpoint approaches. In LCA, the midpoint approach assesses intermediate environmental indicators such as greenhouse gas emissions and water consumption, whereas the endpoint approach considers broader environmental categories like human health impacts and ecosystem quality [99,100]. The midpoint/endpoint approach integrates environmental indicators from both methodologies, providing a comprehensive evaluation of environmental impacts. Daigle and Lounis [33] assessed the LCEI in terms of carbon dioxide emissions and urban-land occupation. Kendall et al. [34] evaluated the impact of nine environmental impact indicators, including methane, lead and sulfur oxides. Soliman and Frangopol [37] and Shen et al. [45] used one LCEI indicator, which is carbon dioxide. Others like Hammervold et al. [36] and Mistry et al. [42] investigated midpoint indicators, including the GWP, acidification potential, eutrophication potential, PC–OP, ozone depletion potential, and abiotic depletion potential. On the other hand, researchers such as Penadés-Plà et al. [39], Penadés-Plà et al. [40], Martínez-Muñoz et al. [41], Penadés-Plà et al. [51], Wanniarachchi et al. [79] assessed the LCEI based on two approaches, the midpoint approach using the former indicators and the endpoint approach using indicators including the ecosystem damage, human health risk, and resource depletion.

The most widely used methods for assessing the LCEI of bridges include CML 2001, the TRACI method, Eco-indicator 99, ReCiPe 2008, and IMPACT 2002+. The CML 2001 method was used by Hammervold et al. [36], Mistry et al. [42], and Lemma et al. [74]. On the other hand, Cadenazzi et al. [43] used the TRACI method, Pedneault et al. [38] used the IMPACT 2002+ method, while Pang et al. [46] and Xie et al. [94] used the Eco-indicator 99 method. Others like Penadés-Plà et al. [39], Navarro et al. [48], and Martínez-Muñoz et al. [41] used the ReCiPe 2008 method to perform environmental-LCA. As illustrated in Table 7, most of the research studies in this field used the midpoint or midpoint/endpoint approach to assess the LCEI of bridges. This was logical because the endpoint approach does not assess the impact of single environmental indicators and, hence, does not help the designer understand how the environment is affected by a specific design of the bridge. The most used LCEI method, as illustrated in Table 7, is the ReCiPe 2008. This method is one of the most effective methods in the LCA because it addresses environmental indicators at the midpoint level and then aggregates the midpoint scores into three endpoint environmental categories. The IMPACT 2002+ also assesses the impact on both the midpoint and endpoint level, but the Recipe 2008 is more popular and more widely used by researchers on this topic as presented in Table 7.

In the context of LCA of bridges, different materials and retrofit techniques were suggested in the literature to reduce the environmental impacts of bridges. Unlike LCC, research indicates that the LCEI is highest during the production and construction stages rather than during operation and maintenance. Prior research has shown that strategic design modifications can significantly decrease a bridge's life-cycle environmental impact. For example, substituting traditional steel expansion joints with engineered cementitious composites led to a 75 % reduction in LCEI [34], while wooden bridges may have nearly 10 % lower global warming potential compared to concrete structures [36]. Also, Wanniarachchi et al. [80] found that while SMA-reinforced bridge piers deliver superior performance in terms of LCC and seismic performance compared to conventional designs, they do not achieve comparable reductions in LCEI. Moreover, another study revealed that bridges constructed with nickel-containing stainless-steel exhibit >40 % reduction in LCEI compared to those built with traditional reinforcement [42]. Other studies have shown that retrofitting concrete girders with steel plates is more sustainable than using CFRP [46]. In contrast, upgrading to higher-grade concrete offers only modest environmental benefits [39]. On the other hand, Dong [70] reduced CO2 emissions by 30 % using UHPC. In general, it can be concluded that the environmental benefit of using a higher grade of concrete is not as significant as that of the cost-benefit, primarily because producing higher-grade concrete incurs additional environmental impacts. However, manufacturing techniques such as incorporating recycled concrete or recycled steel demonstrate the potential to reduce the environmental footprint during the production stage [41]. Further research is needed to assess the effectiveness of these methods comprehensively. Evaluating the effectiveness of the techniques mentioned earlier in reducing the LCEI of bridges is challenging, as environmental LCA results are contingent upon life-cycle inventory data and the specific LCA methodology used. Future research

Table 7

Approaches, LCEI methods, and software used to assess the environmental-LCA of bridges.

Article	Environmental-LCA approach			LCEI method					
	Mid point	End point	Midpoint/endpoint	CML 2001	TRACI	Eco-indic99	ReCiPe 2008	IMPACT 2002+	None
Daigle and Lounis [33]	◆								◆
Kendall et al. [34]	◆								◆
Hammervold et al. [36]	◆			◆					
Soliman and Frangopol [37]	◆								◆
Pang et al. [46]			◆			◆			
Mistry et al. [42]	◆			◆					
Penadés-Plà et al. [39]			◆				◆		
Cadenazzi et al. [43]	◆				◆				
Penadés-Plà et al. [40]			◆				◆		
Pedneault et al. [38]			◆					◆	
Navarro et al. [48]			◆				◆		
Martínez-Muñoz et al. [41]			◆				◆		
Shen et al. [45]	◆								◆
Penadés-Plà et al. [51]			◆				◆		
Dong et al. [6]	◆								◆
Wang et al. [69]	◆								◆
Dong [70]	◆								◆
Lemma et al. [74]	◆			◆					
Chen et al. [73]	◆								◆
Wanniarachchi et al. [79]			◆				◆		
Wanniarachchi et al. [80]			◆				◆		
Lounis and Daigle [17]	◆								◆
Sabatino et al. [91]	◆								◆
Tapia and Padgett [92]	◆								◆
Sabatino et al. [93]	◆								◆
García-Segura [96]	◆								◆
Xie et al. [94]		◆				◆			

should aim to standardize LCA methodologies, enabling more consistent comparisons and informed decision-making in sustainable bridge design.

A key consideration in bridge LCA studies is the reliance on simplifying assumptions due to the complexity of the bridge system, which consists of multiple interconnected components arranged in series or parallel configurations. These assumptions (e.g., idealization of the structural system and boundary conditions, or ignoring interactions between degradation mechanisms, etc.) can significantly influence the LCA results. Moreover, variations in functional unit definitions, system boundaries, impact assessment methods, and data sources introduce uncertainties in comparative studies. Future research should explore the sensitivity of LCA outcomes to these assumptions and develop standardized, component-based LCA frameworks that account for bridge typology and span variations. Additionally, integrating real-world monitoring data and advanced AI-driven techniques could enhance the accuracy of environmental impact assessments and support more sustainable decision-making in bridge design and maintenance planning.
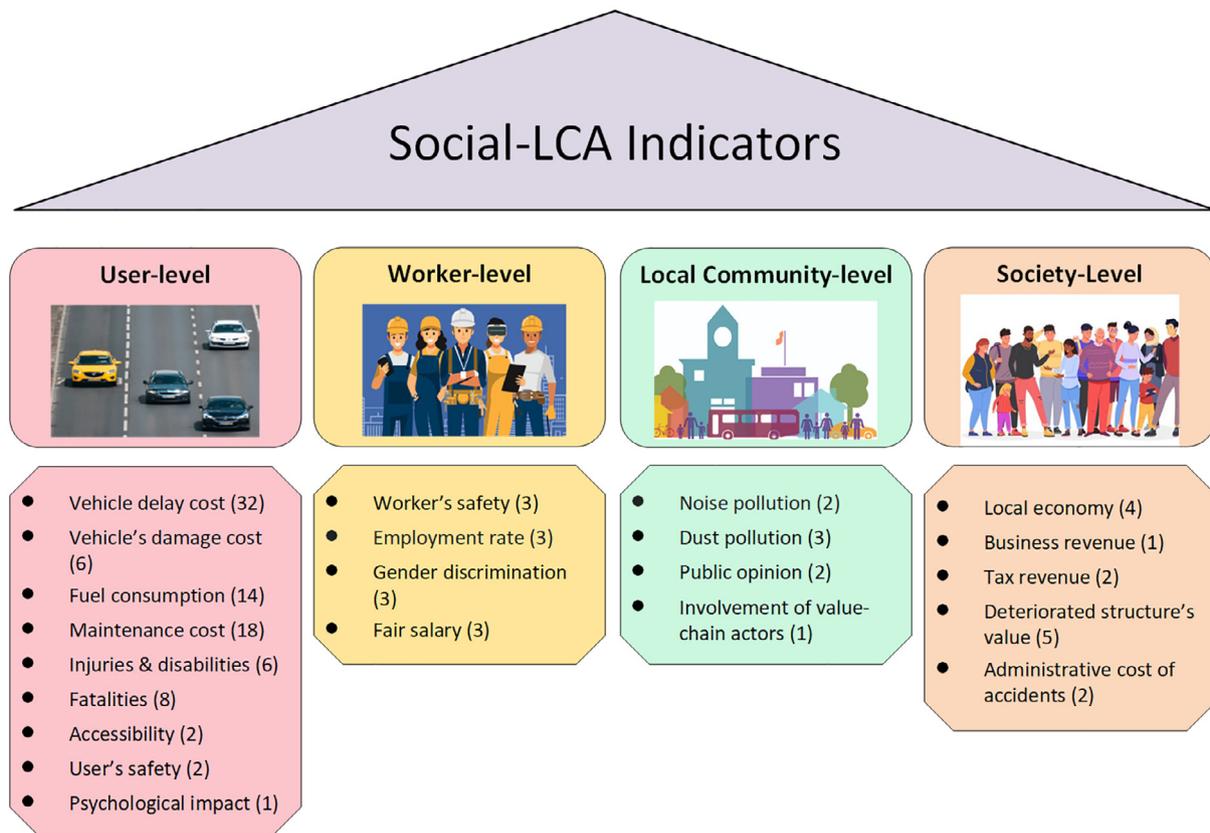
4.3. Social-LCA indicators

In most of the research studies that incorporated the social-LCA in their assessment, it was part of the LCC but not a stand-alone metric. For instance, Ang et al. [60] incorporated fuel consumption, human loss cost and vehicle damage cost in their LCCA. Dong and Frangopol [67], Zheng et al. [68], Wang et al. [69], and Lemma et al. [74] added socio-economic indicators to the LCCA model which are the vehicle delay cost and fuel/energy consumption. On the other hand, Torti et al. [84] investigated parameters such as the cost of injuries, cost of fatalities, vehicle delay cost and vehicle damage. The authors who investigated the social-LCA as an independent life-cycle metric include Navarro et al. [31], Penadés-Plà et al. [40], Wang et al. [47], and Navarro et al. [48]. Four social indicators and eight subcategories were defined by Navarro et al. [31] and Navarro et al., [48] based on the STO database and inventory data of the SNS institute in Spain. The indicators include workers, society, consumers, and the local community, while the sub-

indicators include accessibility, user safety, employment rate, gender discrimination, worker safety, fair salary, public opinion towards the maintenance activity, and local economy. On the other hand, Penadés-Plà et al. [40] utilized four indicators based on the PSILCA database: the workers, value chain actors, society, and local community. Value-chain actors represent all parties involved in the supply chain of a project - from raw material suppliers to contractors and from logistics providers to end-users. These include but are not limited to, suppliers, contractors, freight companies, and others. Six social-LCA indicators were addressed by Wang et al. [47]: the physical condition, phycological condition, personal economic condition, human settlement, socio-economic condition, and social resources. In this analytical review, the social-LCA indicators are categorized into four groups, as shown in Fig. 2, i.e., the user's level, worker's level, local community level, and society level. On the user-level, nine sub-indicators were defined in this paper, i.e., injuries and disabilities, fatalities, psychological impact, vehicle delay cost, vehicle damage cost, fuel/energy consumption, maintenance cost, accessibility, and user's safety.

On the worker's level, four sub-indicators were defined, including the employment rate, gender discrimination, worker's safety, and fair salary. On the local community-level, four sub-indicators were used, i.e., noise pollution, dust pollution, public opinion towards the maintenance activity, and involvement of value-chain actors. On the society-level, five sub-indicators were defined, the local economy, business revenue, tax revenue, deteriorated structure's value, and administration cost of accidents. Most research studies in this field investigated single social-LCA indicators. Only four of them introduced comprehensive social-LCA frameworks. These include Navarro et al. [72] and Navarro et al. [48], who used eight social-LCA indicators, Penadés-Plà et al. [40], who divided the social impact into four categories based on the PSILCA database, and Wang et al. [47] who assessed the social-LCA based on twelve indicators.

As mentioned earlier, most of the studies incorporated the social-LCA in the LCCA. The comprehensive social-LCA models in the literature are not many. For instance, Navarro et al. [31] Introduced a social-LCA methodology based on eight social indicators which are: accessibility,

Social-LCA Indicators

User-level

- Vehicle delay cost (32)
- Vehicle's damage cost (6)
- Fuel consumption (14)
- Maintenance cost (18)
- Injuries & disabilities (6)
- Fatalities (8)
- Accessibility (2)
- User's safety (2)
- Psychological impact (1)

Worker-level

- Worker's safety (3)
- Employment rate (3)
- Gender discrimination (3)
- Fair salary (3)

Local Community-level

- Noise pollution (2)
- Dust pollution (3)
- Public opinion (2)
- Involvement of value-chain actors (1)

Society-Level

- Local economy (4)
- Business revenue (1)
- Tax revenue (2)
- Deteriorated structure's value (5)
- Administrative cost of accidents (2)

* **Note:** Numbers in brackets indicate how many papers addressed each indicator.

Fig. 2. Social-LCA indicators used by articles published in the field of life-cycle analysis of bridges.

user's safety, employment rate, gender discrimination, worker's safety, fair salary, local economy, and public opinion towards the maintenance activity. It was found that using stainless-steel reinforcement is more beneficial to society than changing the concrete grade or constituents. Penadés-Plà et al. [40] divided the social life-cycle impact, based on the framework provided by the PSILCA database, into four categories. They found out that the effect of incorporating the social-LCA in the LCA of bridges is not significant. The same remark can be concluded from the results of Navarro et al. [48]. However, they found that using a mineral admixture like silica fume in concrete is more beneficial in terms of the LCSI than using a preventive maintenance technique such as treating the deck with a hydrophobic coating. Wang et al. [47] confirmed that maintaining the concrete bridge by replacing its deck is better than injecting the deck surface with an anti-corrosive material. It is not possible to provide solid feedback about the social performance of the different materials and techniques because the research work in this area is limited, and the social-LCA approaches are very subjective.

4.4. Life-cycle PBA indicators

The life-cycle PBA is conducted to evaluate the performance of structures in a life-cycle context under extreme hazards such as earthquakes, floods, hurricanes, etc., or lifetime deterioration acts such as corrosion and high-cycle fatigue due to traffic loading. The LCP has been assessed in the literature using various deformation, reliability, condition, and serviceability-based indicators. Fig. 3 presents the indicators used by the researchers in this field to conduct life-cycle PBA. Deformation-based indicators such as displacement/drift, ductility, low-cycle fatigue, and high-cycle fatigue were utilized by Al Hawarneh et al. [2], Biondini et al.

[11], Kumar et al. [63], and Lemma et al. [74], respectively, to investigate the time-variant structural response of various bridge components. Others used reliability-based indicators such as fragility, reliability, resilience, and robustness to measure the time-dependent performance of bridges. The fragility, which is a commonly used LCP indicator in the context of extreme hazards evaluation, was used by researchers such as Mortagi and Ghosh [83], Torti et al. [84], Al Hawarneh and Alam [1], and Al Hawarneh and Alam [3], while the reliability/reliability index was used by researchers such as Saad et al. [95], Xie et al. [94], and Tao et al. [98]. The resilience, which is the capacity of a structure to regain its target functionality after an extreme event, was used by researchers including Capacci and Biondini [53], Pang et al. [54], Dong and Frangopol [67]. The robustness index, which is the integrated ratio of the damaged to the intact reliability index, was addressed in one article only [10].

Researchers such as Wang et al. [69], Liu and Frangopol [47], Tao et al. [90], Li and Li [97], and Strauss et al. [8] utilized subjective measures (condition-based indicators), such as the strength level, condition index, damage index, safety index, and health index, respectively, to assess the LCP of bridges. On the other hand, serviceability-based indicators, such as the functional availability, crack width, and time to corrosion, were used by researchers such as Sabatino et al. [93], Chen et al. [73], and García-Segura [96]. According to Sabatino et al. [93], functional availability is the probability that the bridge will function at a given time instant. The highest number of research studies in this field investigated the LCP based on deformation and reliability-based indicators. The condition-based approach has not been used much in the literature because it depends on subjective evaluation approaches. Also, the serviceability-based approaches have not been used much because they are only useful for assessing the capacity of the structures in their ser-
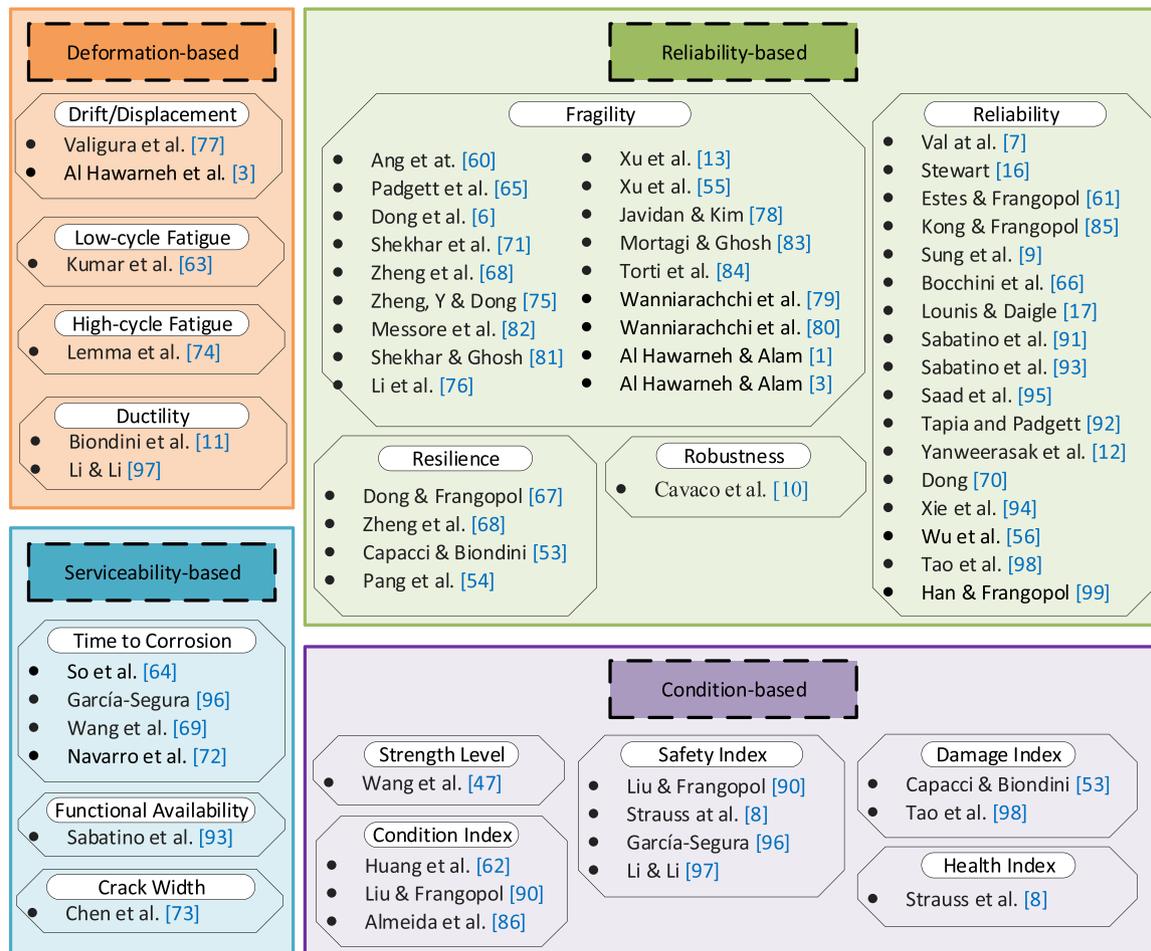
Fig. 3. Life-cycle PBA indicators used by articles published in the field of life-cycle analysis of bridges.

vice limit state. On the other hand, a lot of research studies assessed the LCP of the bridge based on its probability of failure or reliability index. The more advanced approaches, based on the resilience or robustness index, were addressed by a few research studies [10,53,54,67,68].

4.5. Optimization approaches

The optimization was used in the life-cycle design problem either to optimize the design of the bridge or its maintenance program in a life-cycle context. The optimization approaches in the previous research work include decision-based, numerical, exact, machine-learning, and heuristic-based approaches. A decision-based optimization approach, which is the goal setting and compromise programming, was used by Lounis and Daigle [17] to minimize both the LCC and LCEI of bridges. Other studies, such as those by Tao et al. [98] and Al Hawarneh and Alam [3], developed exact optimization models to optimize bridge maintenance programs. For instance, Tao et al. [98] employed the Dynamic Programming approach, while Al Hawarneh and Alam [3] formulated a Linear Programming model to enhance solution accuracy and efficiency. On the other hand, Du and Ghavidel [52] optimized the maintenance program using machine learning based on the QLA algorithm. Others, such as Kong and Frangopol [85], Madhkhan et al. [50], Saad et al. [95], and Han and Frangopol [99], developed numerical-based optimization models in the context of bridge design and maintenance. For instance, Kong and Frangopol [85] and Madhkhan et al. [50] applied the FDM Method to optimize the design of bridge deck systems, while Saad et al. [95] utilized the Gradient Descent Algorithm to enhance bridge maintenance planning. Meanwhile, Han and Frangopol [99] conducted a para-

metric analysis and contributed to a model that provides Pareto front solutions for optimal maintenance strategies.

It is worth mentioning that other researchers in this field used heuristic-based optimization methods. For instance, Almeida et al. [86] and Penadés-Plà et al. [51] used GA algorithms, while Liu and Frangopol [90], Sabatino et al. [91], Tapia and Padgett [92], Sabatino et al. [93], and Xie et al. [94] used the MO-GA algorithms to optimize the design of bridges in a life-cycle context. García-Segura [96] used the modified harmony search algorithm to optimize the design of girders by maximizing the initial cost, safety, and time to corrosion. Li and Li [97] deployed the progressively interactive evolutionary multi-objective optimization using value functions to maximize the safety and minimize LCC by optimizing the cross-section, stirrups, and longitudinal rebar ratio in the piers. The optimization methods used by researchers in the field of life-cycle analysis of bridges are presented in Fig. 4.

Overall, the multi-objectiveness attribute was addressed by a few research studies only. For instance, Sabatino et al. [91] optimized the maintenance program of bridges using three functions: cost, environmental impact, and social impact. Xie et al. [94] took three objective functions into consideration: cost, environmental impact, and probability of failure. On the other hand, Liu and Frangopol [90] optimized the maintenance program by minimizing the cost, safety, and time-dependent condition index. Other performance objectives, such as the functional availability of the structure, were addressed by Sabatino et al. [93]. Tapia and Padgett [92] proposed an optimization model for post-event repair selection, which takes into account public safety, cost, and certain aspects of environmental and social impacts following structural failure.
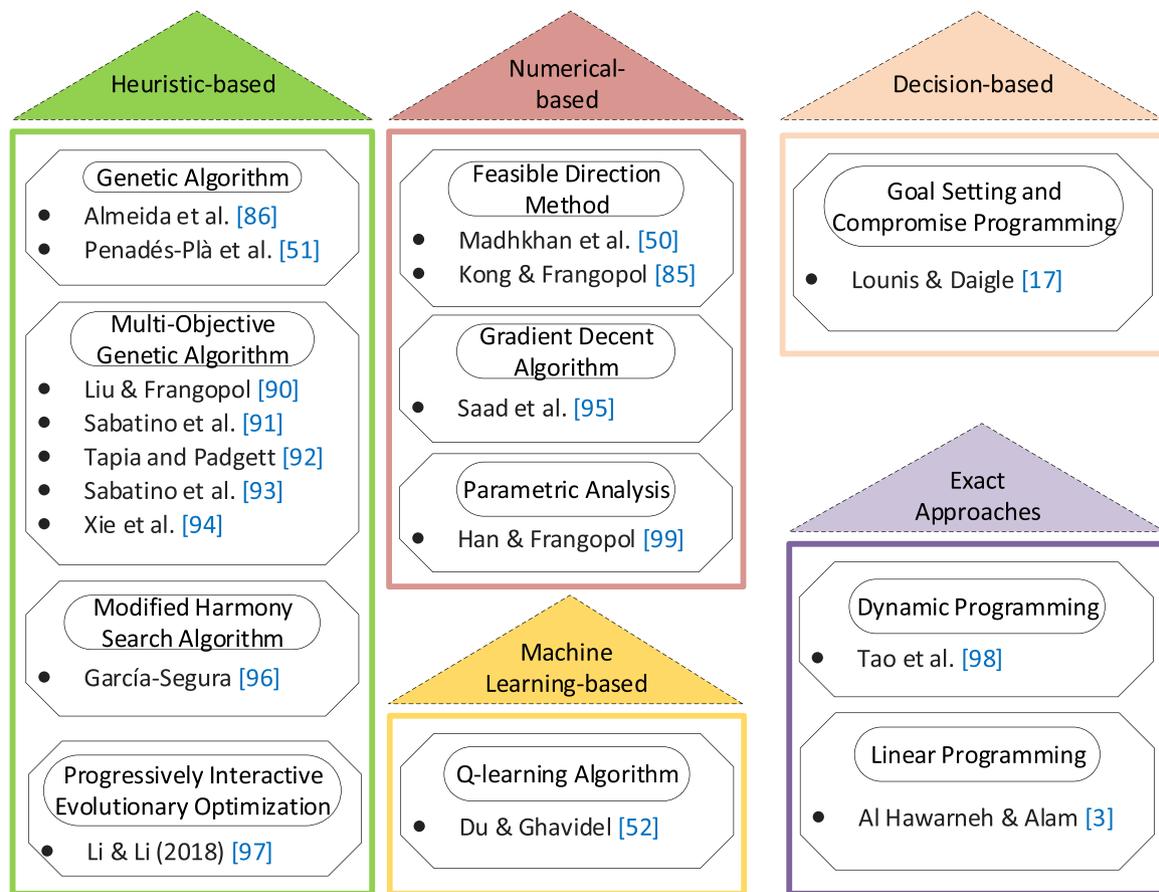
Fig. 4. Optimization methods used by articles published in the field of life-cycle analysis of bridges.

5. Conclusion and major findings

Given the multi-hazard nature of modern bridge design, it is essential to develop structures that are both resilient and cost-effective. Achieving this requires a life-cycle perspective, incorporating key metrics such as LCC, environmental-LCA, and social-LCA. Simultaneously, LCP metrics including strength, ductility, or reliability should be considered to ensure robust and durable designs. This paper categorizes its findings into three main research trends: Life-cycle Sustainability (LCS), Life-cycle Performance Assessment (LCP), and Integrated LCS/LCP of Bridges.

Life-cycle Sustainability (LCS): The LCS was addressed in the literature using three metrics: the LCC, environmental-LCA, and social-LCA. Most of the studies in this field took into consideration only one or two metrics. Few studies addressed all of them in a single model. Also, most of the research work in this field did not cover the whole life cycle of bridges in its four stages, i.e., production, construction, operation, and end-of-life. In addition to that, few studies in this field evaluated the LCS for bridges with materials other than reinforced concrete, such as FRP, steel, and aluminum bridges. On the other hand, the optimization-based studies in this field addressed prestressed concrete girder bridges only. None of them discussed the bridges made with other material alternatives. In fact, a lot of work remains to be done on aspects such as climate change and the effects of multi-hazards on bridge elements. Also, the optimization modelling in this field of study is limited and has a lot of potential work as described earlier.

Life-cycle Performance (LCP): It was found that the studies on the LCP are much fewer than those of the LCS of bridges. The life-cycle PBA analyzes the structural response of bridges subjected to either lifetime deterioration actions such as corrosion and traffic loading or to extreme hazards such as floods, earthquakes, and hurricanes. Few studies only

took into consideration the effect of combined hazards such as earthquake actions and chloride-induced corrosion. None of these took into consideration extreme events such as the floods or hurricanes. In general, most of the studies in this field investigated one or two LCS metrics. Few studies investigated all of the three metrics. Based on the discussions provided in Sections 3.3 and 3.4, two studies only investigated the three life-cycle metrics within a single multi-hazard LCS/CP approach. Moreover, the multi-hazard aspect has not yet been addressed by most of the published research articles.

Integrated LCS/LCP of Bridges: The literature on the LCS/LCP problem is rich but has gaps and opportunities for future research development. This study serves as a key reference point for researchers and bridge design engineers seeking to address these gaps and enhance existing models and frameworks. Future research directions may include evaluating the impact of multiple extreme hazards, i.e., earthquakes and floods, on life-cycle losses across the entire service life of bridges, rather than focusing solely on the operation stage. Also, the effect of other extreme hazards, including hurricanes and snowstorms, on bridge performance warrants further investigation. In addition, the optimization model in the LCS/LCP problem could be improved by incorporating decision variables for selecting appropriate material grades and reinforcement options. Furthermore, alternative heuristic optimization techniques such as particle swarm algorithm, ant colony algorithm, and simulated annealing, could be implemented to more effectively solve the problem.

Declaration of interest statement

The authors are presenting a research study that is purely scientific without any conflict of interest.

CRediT authorship contribution statement

Alaa Al Hawarneh: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **M. Shahria Alam:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Rajeev Ruparathna:** Writing – review & editing, Methodology, Conceptualization. **Stavroula J. Pantazopoulou:** Writing – review & editing, Conceptualization.

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